Past Developers:

Navid Paydavosi, UC Berkeley
Sriramkumar Venugopalan, UC Berkeley
Pankaj Thakur, UC Berkeley
Mohammed A. Karim, UC Berkeley

BSIM6 Web Page

http://www-device.eecs.berkeley.edu/bsim/?page=BSIM6
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1 RELEASSE NOTES

1.1 Updates made in BSIM6.1.0

Model Enhancement

- Self heating effect model is added.
- New CVMOD added for consistent IV-CV.
- Length and Width shrinking parameters LMLT and WMLT added.
- Parameter BINUNIT added to select binning unit.
- New source-drain resistance model with bias independent external and bias dependent internal resistance, introduced for RDSMOD=0 (similar to RDSMOD=0 in BSIM4). The RDSMOD=0 model of BSIM6.0.0 where both bias dependent and independent parts are internal, is now accessed via RDSMOD=2 in BSIM6.0.0.
- Operating point variable TK, which returns total device temperature in Kelvin, is added.
- Binning equation pattern modified for robustness by introducing length and width reduction parameter DLBIN and DWBIN
- Calculation of effective perimeter and area of source and drain region from layout when PS, PD, AS and AD are not given, is added.

Bug Fixes

- Redundancy in gate current handling for negative $V_{ds}$ removed.
- Bugs in operating point variable ISEFF and IDEFF removed.
- Operating point variable for body and gate capacitance updated.
- NF multiplication in Flicker noise model is corrected
- Flat-band voltage between gate and S/D diffusion region (vfbsdr) redefined to have proper sign.
- Boundary value check is applied to binning variable instead of root parameter for CD-SCB, CDSCD, UC, GIDL, GISL, CKAPPAS, CKAPPAD, PDITS, PCLM, PCLMCV, PSAT, CIT, NFACTOR and K2.

Other Changes
• Mobility reduction factor \( D_r \) due to S/D resistance now considers the effect of velocity saturation \( D_{svat} \) and vertical field mobility degradation \( D_{mob} \).
• \( L_{eff} \) and \( W_{eff} \) expressions modified to align with BSIM4.
• Noise names made similar to noise names in BSIM4.
• Check is applied to ensure effective Length and Width are positive.
• Check is applied on \( \mu_{EndS} \) and \( \mu_{EndD} \) for smooth operation when any of them is zero.
• \( NFACTOR_t \) is clamped for lower bound to avoid negative values at low temperatures.
• Body bias dependency of Early voltage due to DIBL \( (V_{a,DIBL}) \) modified to avoid negative \( V_{a,DIBL} \).
• \( KVTH0WE, K2WE, KU0WE, KT1, KT2 \) and \( PSATB \) are made binnable.
• Effective length and width for binning equations modified.
• \( JTSSWGD_t \) and \( JTSSWGS_t \) in diode temperature module updated to use \( Weffcj \) (as in BSIM4) instead of \( W \) used in BSIM6.0.0.
2 BSIM6 Model Equations

2.1 Physical constants

Physical quantities are in M.K.S units unless specified otherwise.

\[ q = 1.6 \times 10^{-19} C \]  \hspace{3cm} (2.1)

\[ \epsilon_0 = 8.8542 \times 10^{-12} \ \frac{F}{m} \]  \hspace{3cm} (2.2)

\[ \epsilon_{sub} = EPSRSUB \cdot \epsilon_0 \ \frac{F}{m} \]  \hspace{3cm} (2.3)

\[ \epsilon_{ox} = EPSROX \cdot \epsilon_0 \ \frac{F}{m} \]  \hspace{3cm} (2.4)

\[ C_{ox} = \frac{3.9 \cdot \epsilon_0}{TOXE} \ \frac{F}{m^2} \]  \hspace{3cm} (2.5)

\[ \epsilon_{ratio} = \frac{EPSRSUB}{3.9} \]  \hspace{3cm} (2.6)
2.2 Effective Channel Length & Width

\[
\Delta L = L_{INT} + \frac{LL}{L_{new}^{LLN}} + \frac{LW}{W_{new}^{LWN}} + \frac{LWL}{W_{new}^{WLN}} + \frac{LWL}{L_{new}^{LLN} \cdot (W_{new}^{LWN})}
\] (2.8)

\[
\Delta W = W_{INT} + \frac{WL}{W_{new}^{WLN}} + \frac{WW}{L_{new}^{WLN}} + \frac{WWL}{W_{new}^{WWN}} + \frac{WWL}{W_{new}^{WLN} \cdot (W_{new}^{WWN})}
\] (2.9)

\[
\Delta L_1 = L_{INT} + \frac{LL}{(L_{new} + DLBIN)^{LLN}} + \frac{LW}{(W_{new} + DWBIN)^{LWN}} + \frac{LWL}{(L_{new} + DLBIN)^{LLN} \cdot (W_{new} + DWBIN)^{WWN}}
\] (2.10)

\[
\Delta W_1 = W_{INT} + \frac{WL}{(L_{new} + DLBIN)^{WLN}} + \frac{WW}{(W_{new} + DWBIN)^{WWN}} + \frac{WWL}{(L_{new} + DLBIN)^{WLN} \cdot (W_{new} + DWBIN)^{WWN}}
\] (2.11)

\[
L_{new} = L \cdot LMLT + XL;
\] (2.14)

\[
W_{new} = \frac{W}{NF} \cdot WMLT + XW;
\] (2.15)

\[
\Delta L_{CV} = DLC
\] (2.16)

\[
\Delta W_{CV} = DWC
\] (2.17)

\[
L_{eff} = L \cdot LMLT + XL - 2\Delta L
\] (2.18)

\[
W_{eff} = W \cdot WMLT + XW - 2\Delta W
\] (2.19)

\[
L_{eff, CV} = L \cdot LMLT + XL - 2\Delta L_{CV}
\] (2.20)

\[
W_{eff, CV} = W \cdot WMLT + XW - 2\Delta W_{CV}
\] (2.21)

\[
L_{eff, Bin} = L \cdot LMLT + XL - 2\Delta L_1
\] (2.22)

\[
W_{eff, Bin} = W \cdot WMLT + XW - 2\Delta W_1
\] (2.23)

2.3 Binning Calculations

For a given L and W, each model parameter PARAM\_i is calculated as a function of PARAM, and length dependent term, LPARAM, width dependent term, WPARAM, area
dependent term, PPARAM:

$$\text{PARAM}_i = \text{PARAM} + L\text{PARAM} \cdot B\text{INL} + W\text{PARAM} \cdot B\text{INW} + P\text{PARAM} \cdot B\text{INWL}$$ (2.24)

BINUNIT is the binning unit selector. When BINUNIT=1,

$$B\text{INL} = \frac{1\times 10^{-6}}{L_{\text{eff}} + D\text{LBIN}}$$ (2.25)

$$B\text{INW} = \frac{1\times 10^{-6}}{W_{\text{eff}} + D\text{WBIN}}$$ (2.26)

when BINUNIT=0,

$$B\text{INL} = \frac{1.0}{L_{\text{eff}} + D\text{LBIN}}$$ (2.27)

$$B\text{INW} = \frac{1.0}{W_{\text{eff}} + D\text{WBIN}}$$ (2.28)

and

$$B\text{INWL} = B\text{INL} \cdot B\text{INW}$$ (2.29)

For the list of binable parameters, please refer to the complete parameter list at the end of this technical note.

### 2.4 Global geometrical scaling

Following scaling formulation is used in global scaling -

$$\text{PARAM}[L] = \text{PARAM} \cdot \left[ 1 + \text{PARAML} \cdot \left( \frac{1}{L_{\text{eff}}} - \frac{1}{L\text{LONG}^\text{PARAMLEXP}} \right) \right] + \text{PARAMW} \cdot \left( \frac{1}{W_{\text{eff}}} - \frac{1}{W\text{WIDE}^\text{PARAMLEXP}} \right) + \text{PARAMWL} \cdot \left( \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{\text{PARAMLEXP}}} \right)$$ (2.30)
LLONG is the length of extracted long channel device and WWIDE is the width for extracted wide device. They are used to ensure that scaling parameters do not affect long-wide fitting. We will not mention LLONG and WWIDE part again but all of the following scaling equation use above kind of formulation.

$$\begin{align*}
NDEP[L] &= NDEP \cdot \left[ 1 + NDEPL1 \cdot \frac{1}{L_{\text{eff}}^{NDEP\text{LEXP}1}} + NDEPL2 \cdot \frac{1}{L_{\text{eff}}^{NDEP\text{LEXP}2}} \\
&\quad + NDEPW \cdot \frac{1}{W_{\text{eff}}^{NDEP\text{WEXP}}} + NDEPWL \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{NDEP\text{WLEXP}}}, \right]
\end{align*}$$

(2.31)
\[ NFACTOR[L] = NFACTOR \cdot \left[ 1 + NFACTORL \cdot \frac{1}{L_{\text{eff}}^{NFACTORL_{\text{exp}}}} \right] + NFACTORW \cdot \frac{1}{W_{\text{eff}}^{NFACTORW_{\text{exp}}}} + NFACTORWL \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{NFACTORWL_{\text{exp}}}} \]

\[ CDSCD[L] = CDSCD \cdot \left[ 1 + CDSCDL \cdot \frac{1}{L_{\text{eff}}^{CDSCDL_{\text{exp}}}} \right] \]

\[ CDSCB[L] = CDSCB \cdot \left[ 1 + CDSCBL \cdot \frac{1}{L_{\text{eff}}^{CDSCBL_{\text{exp}}}} \right] \]

\[ U0[L] = \begin{cases} U0 \cdot \left[ 1 - U0L \cdot \frac{1}{L_{\text{eff}}^{U0L_{\text{exp}}}} \right] & U0L_{\text{exp}} > 0 \\ U0 \cdot [1 - U0L] & \text{Otherwise} \end{cases} \]

\[ UA[L] = UA \cdot \left[ 1 + UAL \cdot \frac{1}{L_{\text{eff}}^{UAL_{\text{exp}}}} + UAW \cdot \frac{1}{W_{\text{eff}}^{UAW_{\text{exp}}}} + UAWL \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{UAWL_{\text{exp}}}} \right] \]

\[ EU[L] = EU \cdot \left[ 1 + EUL \cdot \frac{1}{L_{\text{eff}}^{EUL_{\text{exp}}}} + EUW \cdot \frac{1}{W_{\text{eff}}^{EUW_{\text{exp}}}} + EUWL \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{EUWL_{\text{exp}}}} \right] \]

\[ UD[L] = UD \cdot \left[ 1 + UDL \cdot \frac{1}{L_{\text{eff}}^{UDL_{\text{exp}}}} \right] \]

\[ UC[L] = UC \cdot \left[ 1 + UCL \cdot \frac{1}{L_{\text{eff}}^{UCL_{\text{exp}}}} + UCW \cdot \frac{1}{W_{\text{eff}}^{UCW_{\text{exp}}}} + UCWL \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{UCWL_{\text{exp}}}} \right] \]

\[ ETA0[L] = ETA0 \cdot \left[ \frac{1}{L_{\text{eff}}^{\Delta SUB}} \right] \]

\[ ETAB[L] = ETAB \cdot \left[ \frac{1}{L_{\text{eff}}^{ETAB_{\text{exp}}}} \right] \]

\[ PDIBLC[L] = PDIBLC \cdot \left[ 1 + PDIBLCL \cdot \frac{1}{L_{\text{eff}}^{PDIBLCL_{\text{exp}}}} \right] \]

\[ DELTA[L] = DELTA \cdot \left[ 1 + DELTAL \cdot \frac{1}{L_{\text{eff}}^{DELTA_{\text{exp}}}} \right] \]
\[ \text{FPROUT}[L] = \text{FPROUT} \cdot \left[ 1 + \text{FPROUTL} \cdot \frac{1}{L_{\text{eff}}^{\text{FPROUTLEXP}}} \right] \quad (2.44) \]

\[ \text{PCLM}[L] = \text{PCLM} \cdot \left[ 1 + \text{PCLML} \cdot \frac{1}{L_{\text{eff}}^{\text{PCLMLEXP}}} \right] \quad (2.45) \]

\[ \text{VSAT}[L] = \text{VSAT} \cdot \left[ 1 + \text{VSATL} \cdot \frac{1}{L_{\text{eff}}^{\text{VSATLEXP}}} + \text{VSATW} \cdot \frac{1}{W_{\text{eff}}^{\text{VSATWEXP}}} \right. \]
\[ \left. + \text{VSATWL} \cdot \frac{1}{(L_{\text{eff}} \cdot W_{\text{eff}})^{\text{VSATWLEXP}}} \right] \quad (2.46) \]

\[ \text{PSAT}[L] = \text{PSAT} \cdot \left[ 1 + \text{PSATL} \cdot \frac{1}{L_{\text{eff}}^{\text{PSATLEXP}}} \right] \quad (2.47) \]

\[ \text{PTWG}[L] = \text{PTWG} \cdot \left[ 1 + \text{PTWGL} \cdot \frac{1}{L_{\text{eff}}^{\text{PTWGLEXP}}} \right] \quad (2.48) \]

\[ \text{ALPHA0}[L] = \text{ALPHA0} \cdot \left[ 1 + \text{ALPHA0L} \cdot \frac{1}{L_{\text{eff}}^{\text{ALPHA0LEXP}}} \right] \quad (2.49) \]

\[ \text{AGIDL}[L] = \text{AGIDL} \cdot \left[ 1 + \text{AGIDLL} \cdot \frac{1}{L_{\text{eff}}} + \text{AGIDLW} \cdot \frac{1}{W_{\text{eff}}} \right] \quad (2.50) \]

\[ \text{AGISL}[L] = \text{AGISL} \cdot \left[ 1 + \text{AGISLL} \cdot \frac{1}{L_{\text{eff}}} + \text{AGISLW} \cdot \frac{1}{W_{\text{eff}}} \right] \quad (2.51) \]

\[ \text{AIGC}[L] = \text{AIGC} \cdot \left[ 1 + \text{AIGCL} \cdot \frac{1}{L_{\text{eff}}} + \text{AIGCW} \cdot \frac{1}{W_{\text{eff}}} \right] \quad (2.52) \]

\[ \text{AIGS}[L] = \text{AIGS} \cdot \left[ 1 + \text{AIGSL} \cdot \frac{1}{L_{\text{eff}}} + \text{AIGSW} \cdot \frac{1}{W_{\text{eff}}} \right] \quad (2.53) \]

\[ \text{AIGD}[L] = \text{AIGD} \cdot \left[ 1 + \text{AIGDL} \cdot \frac{1}{L_{\text{eff}}} + \text{AIGDW} \cdot \frac{1}{W_{\text{eff}}} \right] \quad (2.54) \]

\[ \text{PIGCD}[L] = \text{PIGCD} \cdot \left[ 1 + \text{PIGCDL} \cdot \frac{1}{L_{\text{eff}}} \right] \quad (2.55) \]

\[ \text{NDEPCV}[L] = \text{NDEPCV} \cdot \left[ 1 + \text{NDEPCVL1} \cdot \frac{1}{L_{\text{eff}}^{\text{NDEPCVLEXP1}}} \right. \]
\[ \left. + \text{NDEPCVL2} \cdot \frac{1}{L_{\text{eff}}^{\text{NDEPCVLEXP2}}} + \text{NDEPCVW} \cdot \frac{1}{W_{\text{eff}}^{\text{NDEPCVWEXP}}} \right. \]
\[ \left. + \text{NDEPCVWL} \cdot \frac{151}{(L_{\text{eff}} \cdot W_{\text{eff}})^{\text{NDEPCVWLEXP}}} \right] \quad (2.56) \]
\[
VFBCV[L] = VFBCV \cdot \left[ 1 + VFBCVL \cdot \frac{1}{L_{eff}^{VFBCVLEXP}} \right.
\]
\[
+ VFBCVW \cdot \frac{1}{W_{eff}^{VFBCVWEXP}} + VFBCVL \cdot \frac{1}{(L_{eff} \cdot W_{eff})^{VFBCVLEXP}} \left. \right]
\]

\[
VSATCV[L] = VSATCV \cdot \left[ 1 + VSATCVL \cdot \frac{1}{L_{eff}^{VSATCVLEXP}} \right.
\]
\[
+ VSATCVW \cdot \frac{1}{W_{eff}^{VSATCVWEXP}} + VSATCVL \cdot \frac{1}{(L_{eff} \cdot W_{eff})^{VSATCVLEXP}} \left. \right]
\]

\[
PCLMCV[L] = PCLMCV \cdot \left[ 1 + PCLMCVL \cdot \frac{1}{L_{eff}^{PCLMCVLEXP}} \right]
\]

\[
K2[L] = K2 \cdot \left[ 1 + K2L \cdot \frac{1}{L_{eff}^{K2LEXP}} + K2W \cdot \frac{1}{W_{eff}^{K2WEXP}} + K2WL \cdot \frac{1}{(L_{eff} \cdot W_{eff})^{K2WLEXP}} \right]
\]

\[
PRWB[L] = PRWB \cdot \left[ 1 + PRWBL \cdot \frac{1}{L_{eff}^{PRWBLEXP}} \right]
\]

\[
RSW[L] = RSW \cdot \left[ 1 + RSWL \cdot \frac{1}{L_{eff}^{RSWLEXP}} \right]
\]

\[
RDW[L] = RDW \cdot \left[ 1 + RDWL \cdot \frac{1}{L_{eff}^{RDWLEXP}} \right]
\]

\[
RDSW[L] = RDSW \cdot \left[ 1 + RDSWL \cdot \frac{1}{L_{eff}^{RDSWLEXP}} \right]
\]
2.5 Terminal Voltages

BSIM6 is a body referenced model.

\[ V_t = \frac{K.T}{q} \]  \hspace{1cm} (2.65)

\[ V_g = V_g - V_b \]  \hspace{1cm} (2.66)

\[ V_d = V_d - V_b \]  \hspace{1cm} (2.67)

\[ V_s = V_s - V_b \]  \hspace{1cm} (2.68)

\[ V_{gs} = V_g - V_s \]  \hspace{1cm} (2.69)

\[ V_{gd} = V_g - V_d \]  \hspace{1cm} (2.70)

\[ V_{gb} = V_g - V_b \]  \hspace{1cm} (2.71)

\[ V_{ds} = V_d - V_s \]  \hspace{1cm} (2.72)

\[ V_{dsx} = \sqrt{V_{ds}^2 + 0.01 - 0.1} \]  \hspace{1cm} (2.73)

\[ V_{bsx} = -\left[ V_s + \frac{1}{2}(V_{ds} - V_{dsx}) \right] \]  \hspace{1cm} (2.74)
2.6 Pinch-off Potential and Normalized Charge Calculation

2.6.1 Pinch-off Potential with Poly Depletion

\[
\phi_b = \ln \left( \frac{n_{\text{body}}}{n_i} \right) 
\]

(2.75)

\[
\gamma_0 = \frac{\sqrt{2} \cdot q \cdot \epsilon_{\text{si}} \cdot N\text{DEP}}{C_{\text{ox}} \sqrt{nV_t}} 
\]

(2.76)

\[
\gamma_g = \frac{\sqrt{2} \cdot q \cdot \epsilon_{\text{si}} \cdot N\text{GATE}}{C_{\text{ox}} \sqrt{nV_t}} 
\]

(2.77)

\[
\gamma' = \gamma_0 \cdot \sqrt{nV_t} 
\]

(2.78)

\[
\gamma'_g = \gamma_g \cdot \sqrt{nV_t} 
\]

(2.79)

\[
\delta_{PD} = \frac{N\text{DEP}}{N\text{GATE}} 
\]

(2.80)

\[
\left( \frac{\gamma_0}{\gamma_g} \right)^2 = \left( \frac{\sqrt{2} \cdot q \cdot \epsilon_{\text{si}} \cdot N\text{DEP}}{C_{\text{ox}} \sqrt{nV_t}} \right)^2 = \frac{N\text{DEP}}{N\text{GATE}} = \delta_{PD} 
\]

(2.81)

\[
\gamma = \frac{\gamma_0}{1 + \delta_{PD}} 
\]

(2.82)

In accumulation and inversion under depletion approximation, the bulk charge is given as [1]

\[
Q_b = -\text{sign}(\psi_s) \cdot \gamma' \cdot C_{\text{ox}} \cdot \sqrt{V_t \cdot (e^{-\frac{\psi_s}{V_t}} - 1) + \psi_s} 
\]

(2.83)

From potential balance equation including poly depletion,

\[
V_G = V_{FB} + \psi_S - \frac{Q_i + Q_b}{C_{\text{ox}}} + \left( \frac{Q_i + Q_b}{\gamma'_g C_{\text{ox}}} \right)^2 
\]

(2.84)

At pinch off, \( \psi_S = \psi_P \) and \( Q_i = 0 \). Substituting in (2.83) and (2.84),

\[
V_G - V_{FB} = \psi_P + \gamma' \cdot \sqrt{V_t \cdot (e^{-\frac{\psi_P}{V_t}} - 1) + \psi_P} + \left( \frac{\gamma'}{\gamma'_g} \right)^2 \left( V_t \cdot (e^{-\frac{\psi_P}{V_t}} - 1) + \psi_P \right) 
\]

(2.85)

\[
= \psi_P + \gamma' \cdot \sqrt{V_t \cdot (e^{-\frac{\psi_P}{V_t}} - 1) + \psi_P} + \delta_{PD} \left( V_t \cdot (e^{-\frac{\psi_P}{V_t}} - 1) + \psi_P \right) 
\]

(2.86)
Normalizing it,

$$v_g - v_{fb} = \psi_p + \gamma_0 \cdot \sqrt{e^{-\psi_p} + \psi_p - 1 + \delta_{PD}} \left( e^{-\psi_p} - 1 + \psi_p \right)$$  \hspace{1cm} (2.87)

Explicit expression for $\psi_p$ can be derived from above relation in the asymptotic form by inspecting the behavior in three different regions. First consider the depletion and inversion region of operation where $\psi_p \gg 0$ so that $e^{-\psi_p}$ is very small. Let $\zeta_1 = e^{-\psi_p}$

$$v_g - v_{fb} = \psi_p + \gamma_0 \cdot \sqrt{\psi_p + \zeta_1 - 1 + \delta_{PD}} \left( \zeta_1 - 1 + \psi_p \right)$$  \hspace{1cm} (2.88)

Let

$$\sqrt{\psi_p + \zeta_1 - 1} = x$$  \hspace{1cm} (2.89)

or

$$\psi_p = x^2 + 1 - \zeta_1$$  \hspace{1cm} (2.90)

Thus

$$v_g - v_{fb} = x^2 + 1 - \zeta_1 + \gamma_0 \cdot x + \delta_{PD} \cdot x^2$$  \hspace{1cm} (2.91)

or

$$x^2 + \frac{\gamma_0}{1 + \delta_{PD}} \cdot x + \frac{1 - \zeta_1}{1 + \delta_{PD}} - \frac{v_g - v_{fb}}{1 + \delta_{PD}} = 0$$  \hspace{1cm} (2.92)

This gives

$$x = \left[ \sqrt{\frac{v_g - v_{fb} - 1 + \zeta_1}{1 + \delta_{PD}}} + \left( \frac{\gamma_0}{2 \cdot (1 + \delta_{PD})} \right)^2 - \frac{\gamma_0}{2 \cdot (1 + \delta_{PD})} \right]$$  \hspace{1cm} (2.93)

$$\psi_p = x^2 + 1 - \zeta_1 = \left[ \sqrt{\frac{v_g - v_{fb} - 1 + \zeta_1}{1 + \delta_{PD}}} + \left( \frac{\gamma_0}{2 \cdot (1 + \delta_{PD})} \right)^2 - \frac{\gamma_0}{2 \cdot (1 + \delta_{PD})} \right]^2 + 1 - \zeta_1$$  \hspace{1cm} (2.94)

$$= \left[ \sqrt{\frac{v_g - v_{fb} - 1 + \zeta_1}{1 + \delta_{PD}}} + \left( \frac{\gamma}{2} \right)^2 - \frac{\gamma}{2} \right]^2 + 1 - \zeta_1$$  \hspace{1cm} (2.95)
where $\gamma = \frac{\gamma_0}{1+\delta_{PD}}$

Similarly,

when $\psi_p$ is close to 0

$$\psi_p = \frac{v_g - v_{fb}}{2} - 3(1 + \frac{\gamma}{\sqrt{2}}) + \frac{\left[\frac{v_g - v_{fb}}{2} - 3(1 + \frac{\gamma}{\sqrt{2}})\right]^2}{6(v_g - v_{fb})}$$

(2.96)

and in accumulation where $\psi_p << 0$ ($\zeta_2 = \psi_P$),

$$\psi_p = -\ln\left[1 - \zeta_2 + \left(\frac{v_g - v_{fb} - \zeta_2}{\gamma}\right)^2\right]$$

(2.97)

Thus the pinch off potential is expressed as

$$\psi_p = \begin{cases} 
-\ln\left[1 - \psi_{p0} + \left(\frac{v_g - v_{fb} - \psi_{p0}}{\gamma}\right)^2\right] & \text{if } v_g - v_{fb} < 0 \\
1 - e^{-\psi_{p0}} + \left[\sqrt{v_g - v_{fb} - 1} + e^{-\psi_{p0}} + \left(\frac{2}{\gamma}\right)^2 - \frac{\gamma}{2}\right]^2 & \text{otherwise}
\end{cases}$$

(2.98)

Note: Derivatives of $\psi_p$ are continuous in all regions.

2.6.2 Normalized Charge Density

Inversion Charge [2], [3]: Normalized inversion charge density at source/drain is newly derived for BSIM6 and can be obtained as follows.

Charge sheet model approximates inversion charge density as

$$Q_i = -\gamma \cdot C_{ox} \cdot \sqrt{V_t} \left[\sqrt{\frac{\psi_S}{V_t} + \frac{\psi_S - 2.5 \phi_F - V_{th}}{V_t}} - \sqrt{\frac{\psi_S}{V_t}}\right]$$

(2.99)

Using inversion charge linearization [3],

$$Q_i = n_q \cdot C_{ox} \cdot (\psi_S - \psi_P)$$

(2.100)

or

$$\psi_S = \psi_P + \frac{Q_i}{n_q \cdot C_{ox}}$$

(2.101)
Substituting $\psi_S$ from (2.101) in (2.99),

$$-\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} = \left[ \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}} + e^{\frac{Q_i}{n_q C_{ox}} - 2 \phi_F - V_{ch}} \right] - \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}}$$  \tag{2.102}

rearranging,

$$\left[ -\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} + \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}} \right]^2 = \left[ \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}} + e^{\frac{Q_i}{n_q C_{ox}} - 2 \phi_F - V_{ch}} \right]^2$$  \tag{2.103}

This reduces to

$$\psi_p + \frac{Q_i}{n_q C_{ox}} - 2 \phi_F - V_{ch} = \ln \left[ \left( -\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} \right)^2 - 2 \left( -\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} \right) \cdot \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}} \right]$$  \tag{2.105}

$$= \ln \left[ -\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} \left( -\frac{Q_i}{\gamma' C_{ox} \sqrt{V_t}} + 2 \cdot \sqrt{\frac{\psi_p + \frac{Q_i}{n_q C_{ox}}}{V_t}} \right) \right]$$  \tag{2.106}

Normalizing inversion charge to $-2V_t n_q C_{ox}$, all voltages to $V_t$,

$$\psi_p - 2q_i - 2 \phi_f - v_{ch} = \ln \left[ \frac{2n_q q_i}{\gamma_0} \left( \frac{2n_q q_i}{\gamma_0} + 2 \cdot \sqrt{\psi_p - 2q_i} \right) \right]$$  \tag{2.107}

which gives

$$\ln (q_i) + \ln \left[ \frac{2n_q q_i}{\gamma_0} \left( \frac{2n_q q_i}{\gamma_0} + 2 \cdot \sqrt{\psi_p - 2q_i} \right) \right] + 2q_i = \psi_p - 2 \phi_f - v_{ch}$$  \tag{2.108}

This is a general equation which can be solved to give normalized inversion charge density. The procedure of obtaining initial guess for the solution of above equation for weak inversion is described below [4]. Note that to generalized the process, subscript "i" is dropped from the term $q_i$.
Let \( v = \psi_p - 2\phi_f - v_{ch} - \ln\left(\frac{4n_s \sqrt{\psi_p}}{\gamma}\right) = \ln q + 2q \)

\[
v = \ln q + 2q \tag{2.109}
\]

\[
v = \ln q + 2e^{\ln q} \tag{2.110}
\]

\[
v = \ln q + \frac{1}{F(\ln q)} \tag{2.111}
\]

Here in second term q has been used as \( \ln(e^q) \). The function F is defined as

\[
F = \frac{1}{2e^{\ln q}} \tag{2.112}
\]

\[
= \frac{1}{2e^{(\ln q + \ln q_t - \ln q_t)}} \tag{2.113}
\]

\[
= \frac{1}{2q_t e^{\ln \frac{x}{q_t}}} \tag{2.114}
\]

\[
= \frac{1}{2q_t} e^{-\Delta} \tag{2.115}
\]

Where \( \Delta = \ln \frac{q}{q_t} \). Expanding (2.115) around \( \Delta = 0 \) using Taylor series expansion (as \( |2q| << |\ln q| \)),

\[
F = \frac{1}{2q_t} [1 - e^{-0.\Delta}] \tag{2.116}
\]

\[
= \frac{1}{2q_t} (1 - \ln \frac{q}{q_t}) \tag{2.117}
\]

substituting in (2.111),

\[
v = \ln q + \frac{2q_t}{1 - \ln q + \ln q_t} \tag{2.118}
\]

This equation is solved for \( q \). Let,

\[
\ln q = x \tag{2.119}
\]

\[
v = x + \frac{2q_t}{1 + \ln q_t - x} \tag{2.120}
\]

\[
v(1 + \ln q_t) - vx - x(1 + \ln q_t) + x^2 - 2q_t = 0 \tag{2.121}
\]

\[
x = \frac{v + (1 + \ln q_t) - \sqrt{(v + (1 + \ln q_t)^2 - 4v(1 + \ln q_t) + 8q_t)}}{2} \tag{2.122}
\]
For subthreshold region, normalized inversion charge density will be \(|q| << 1\) and \(|\ln q| >> |2q|\). The initial value is taken at a point where \(|\ln q| = 2|2q|\) which gives

\[ q_t = 0.301 \]  
\[ 1 + \ln q_t = -0.201491 \]  \hspace{1cm} (2.123) \hspace{1cm} (2.124)

Substituting in (2.122),

\[ x = \frac{v - 0.201491 - \sqrt{(v - 0.201491)^2 - 4v(-0.201491) + 8(0.301)}}{2} \]  \hspace{1cm} (2.125)

\[ x = \ln q = \frac{v - 0.201491 - \sqrt{(v + 0.402982)v + 2.446562}}{2} \]  \hspace{1cm} (2.126)

Once the initial guess is known, the final value is obtained by using analytical method as shown below

\[ n_{q0} = 1 + \frac{\gamma}{2\sqrt{\psi_p}} \]  \hspace{1cm} (2.127)

\[ v = \psi_p - 2\phi - v_{ch} - \ln \left(4.0 \cdot \frac{n_{q0}}{\gamma} \cdot \sqrt{\psi_p}\right) \]  \hspace{1cm} (2.128)

\[ \ln q_0 = \frac{1}{2} \left[v - 0.201491 - \sqrt{v \cdot (v + 0.402982) + 2.446562}\right] \]  \hspace{1cm} (2.129)

\[ q_0 = e^{\ln q_0} \]  \hspace{1cm} (2.130)

if \(\ln q_0 <= -80.0\),

\[ q_{s/d} = f = q_0 \cdot \left[1 + \psi_p - 2\phi - v_{ch} - \ln q_0 - \ln \left(2 \cdot \frac{n_{q0}}{\gamma} \left(2 \cdot q_0 \cdot \frac{n_{q0}}{\gamma} + 2 \cdot \sqrt{\psi_p}\right)\right)\right] \]  \hspace{1cm} (2.131)

In this equation, if \(\ln q_0\) becomes very large and negative then \(q_0 = e^{\ln q_0}\) may be out of range of precision limit of the simulator. Therefore it is approximated as follows

if \(\ln q_0 < -110\), \(q_0 = e^{-100}\)

if \(\ln q_0 > -90\), \(q_0 = e^{\ln q_0}\)

else \(q_0 = \exp(-100 + 20(\frac{5}{6} + \frac{z^2}{10} + z^2(\frac{10}{16} - z^2(1.25 - z^2)))\))

where \(z = \frac{\ln q_0 + 100}{20} \).

The above polynomial provides smooth derivatives for \(q\). For the derivation of polynomial coefficients, refer to Appendix A.
For $\ln q_0 > -80$

\[
f = 2q_0 + \ln \left( 2q_0 \frac{nq}{\gamma} \left( 2q_0 \frac{nq}{\gamma} + 2\sqrt{\psi_p} \right) \right) - (v_p - 2\phi_f - v_{ch}) \tag{2.132}
\]

\[
f' = 2 + \frac{1}{q_0} + \frac{nq_0}{\gamma} \cdot \frac{1}{\sqrt{\psi_p}} \tag{2.133}
\]

\[
q_1 = q_0 - \frac{f}{f'} \tag{2.134}
\]

The accuracy of this initial guess is further improved by following procedure

\[
f = 2q_1 + \ln \left( 2q_1 \frac{nq}{\gamma} \left( 2q_1 \frac{nq}{\gamma} + 2\sqrt{\psi_p} \right) \right) - (v_p - 2\phi_f - v_{ch}) \tag{2.135}
\]

\[
f' = 2 + \frac{1}{q_1} + \frac{nq_1}{\gamma} \cdot \frac{1}{\sqrt{\psi_p}} \tag{2.136}
\]

Applying Halley’s method,

\[
f'' = -\frac{1}{q_1^2} - \frac{1}{nq_1 \cdot q_1 + \sqrt{\psi_p}} \left[ \frac{nq_0}{\gamma} - \frac{1}{\sqrt{\psi_p}} \right]^2 \tag{2.137}
\]

\[
q_{s/d} = q_1 - \frac{f}{f'} \cdot \left( 1 + \frac{f \cdot f''}{2 \cdot f'^2} \right) \tag{2.138}
\]
2.7 Short Channel Effects

Vt Roll-off, DIBL, and Subthreshold Slope Degradation (Ref.: BSIM4 Model)

\[ \psi_{st} = 0.4 + PHIN + \frac{kT}{q} \cdot \ln \frac{NDEP}{n_i} \]  
\[ (2.139) \]

\[ PhistVbs = \psi_{st} - V_{bsx} \]  
\[ (2.140) \]

\[ X_{dep} = \sqrt{\frac{2 \cdot \epsilon_{sub} \cdot PhistVbs}{q \cdot NDEP}} \]  
\[ (2.141) \]

\[ n = 1 + \frac{CIT + NFACTOR + CDSCD \cdot V_{dsx} - CDSCB \cdot V_{bsx}}{Cox} \]  
\[ (2.142) \]

\[ V_t = \frac{k_b \cdot T}{q} \]  
\[ (2.143) \]

\[ nV_t = n \cdot V_t \]  
\[ (2.144) \]

\[ \Delta V_{th,VDNUD} = -K2 \cdot V_{bsx} \]  
\[ (2.145) \]

\[ \Delta V_{th,DIBL} = -(\ETA_A0 + \ETA_B \cdot V_{bsx}) \cdot V_{dsx} \]  
\[ (2.146) \]

\[ \Delta V_{th,DITS} = -n \frac{K}{q} \cdot \ln \left( \frac{L_{eff}}{L_{eff} + DVTP0 \cdot (1 + \exp(-DVTP1 \cdot V_{ds})} \right) \]  
\[ - \left( DVTP5 + \frac{DVTP2}{L_{eff}} \right) \cdot \tanh \left( DVTP4 \cdot V_{dsx} \right) \]  
\[ (2.147) \]

\[ \Delta V_{th,all} = \Delta V_{th,VDNUD} + \Delta V_{th,DIBL} + \Delta V_{th,DITS} \]  
\[ (2.148) \]

\[ V_{gfb} = V_g - V_{fb} - \Delta V_{th,all} \]  
\[ (2.149) \]

Note: Short channel effect and Reverse short channel effect are modeled using NDEPL1, NDELEXP1, NDEPL2 and NDEPLEXP2 parameters. Width scaling of \( V_{th} \) is modeled using NDEPW and NDEPWEXP parameters.

2.8 Drain Saturation Voltage

The drain saturation voltage model is calculated after the source-side charge \( (q_s) \) has been calculated. \( V_{dseff} \) is subsequently used to compute the drain-side charge \( (q_d) \).

Electric Field Calculations

Electric Field is in MV/cm
\[
\eta = \begin{cases} 
\frac{1}{2} \cdot \text{ETAMOB} & \text{for NMOS} \\
\frac{1}{3} \cdot \text{ETAMOB} & \text{for PMOS}
\end{cases}
\] (2.150)

\[
E_{effs} = 10^{-8} \cdot \left( \frac{q_{bs} + \eta \cdot q_{is}}{\epsilon_{ratio} \cdot TOXE} \right)
\] (2.151)

**Drain Saturation Voltage** \((V_{dsat})\) **Calculations** (Ref. BSIM4 & EKV Model)

\[
D_{mobs} = 1 + (UA + UC \cdot V_{bsx}) \cdot (E_{effs})^{EU} + \frac{UD}{\left[ \frac{1}{2} \cdot \left( 1 + \frac{q_{is}}{q_{bs}} \right) \right]^{UCS}}
\] (2.152)

\[
T_0 = \begin{cases} 
\frac{1}{1 + PSATB \cdot V_{bsx}} & V_{bs} \geq 0 \\
1 - PSATB \cdot V_{bsx} & V_{bs} < 0
\end{cases}
\] (2.153)

\[
\lambda_C = \frac{2 \cdot U0 \cdot nV_i}{(D_{mobs})^{PSAT} \cdot VSAT \cdot L_{eff}} \cdot [1 + PTWG \cdot \frac{10 \cdot PSAX \cdot q_{s} \cdot T_0}{10 \cdot PSAX + q_{s} \cdot T_0}]
\] (2.154)

\[
q_{dsat} = \frac{\lambda_C}{2} \cdot \frac{q_{s}^2 + q_{s}}{1 + \lambda_C \cdot (1 + q_{s})}
\] (2.155)

\[
v_{dsat} = \psi_p - \frac{2q_{bs}}{n} - 2q_{dsat} - \ln \left[ \frac{2q_{dsat} \cdot n_q}{gam} \cdot \left( \frac{2q_{dsat} \cdot n_q + \frac{gam}{n_q - 1}}{gam} \right) \right]
\] (2.156)

\[
V_{dsat} = V_{dsat} \cdot nV_i
\] (2.157)

\[
V_{dsat} = V_{dsat} - V_s
\] (2.158)

\[
V_{dseff} = \frac{V_{ds}}{1 + \left( \frac{V_{ds}}{V_{dsat}} \right)^{1/DeltaA}}^{DeltaA}
\] (2.159)

\[
v_{deff} = \frac{V_{dseff} + V_s}{nV_i}
\] (2.160)

**2.9 Mobility degradation with vertical field**

(Ref. BSIM4 Model)

\[
E_{effm} = 10^{-8} \cdot \left( \frac{q_{ba} + \eta \cdot q_{ia}}{\epsilon_{ratio} \cdot TOXE} \right)
\] (2.161)
Where $q_{ia}$ and $q_{ba}$ are the average inversion charge and bulk charge densities respectively.

$$D_{mob} = 1 + (UA + UC \cdot V_{bxx}) \cdot (E_{effm})^{EU} + \frac{UD}{\left[ \frac{1}{2} \cdot (1 + \frac{q_{ia}}{q_{ba}}) \right]^{UCS}} \quad (2.162)$$

The $D_{mob}$ goes into denominator of mobility expression.

### 2.10 Parasitic series resistance

BSIM6 offers three ways to model parasitic resistance of the MOSFET as shown below

(a) RDSMOD=0, External resistance are bias independent while internal resistance is bias dependent.

(b) RDSMOD=1, No internal resistance. Both bias dependent and independent resistor are kept externally.

(c) RDSMOD=2, No external resistance. Both bias dependent and independent resistor are kept internally.

#### 2.10.1 Bias Independent External Series Resistance, Bias Dependent Internal Resistance (RDSMOD=0)

$$T_0 = 1 + PRWG \cdot q_{ia} \quad (2.163)$$

$$T_1 = PRWB \cdot (\sqrt{\phi_s - V_{bs}} - \sqrt{\phi_s}) \quad (2.164)$$

$$T_2 = \frac{1}{T_0} + T_1 \quad (2.165)$$

$$T_3 = \frac{1}{2} \left[ T_2 + \sqrt{T_2^2 + 0.01} \right] \quad (2.166)$$

$$R_{ds}(V) = NF \cdot \left( W_{eff}^{WR} \left[ RDSWMIN + RDSW \cdot T_3 \right] \right) \quad (2.167)$$

$$D_r = 1.0 + \frac{\mu_0}{D_{mob} \cdot D_{esat}} \cdot C_{ox} \cdot \frac{W_{eff}}{L_{eff}} \cdot q_{ia} \cdot R_{ds} \quad (2.168)$$

$$R_{source} = R_{s,geo} \quad (2.169)$$

$$R_{drain} = R_{d,geo} \quad (2.170)$$
$R_{s,geo}$ and $R_{d,geo}$ are the source and drain diffusion resistances, which are described later. And, $D_r$ goes into the denominator of the final $I_{ds}$ expression.

### 2.10.2 Bias Dependent External Series Resistance ($R_s(V)$ & $R_d(V)$)

The bias-dependent external resistance model is adopted from BSIM4 and can be invoked by setting model selector $RDSMOD=1$. BSIM4 and BSIM6 allow the source extension resistance $R_s(V)$ and the drain extension resistance $R_d(V)$ to be external and asymmetric (i.e. $R_s(V)$ and $R_d(V)$ can be connected between the external and internal source and drain nodes, respectively; furthermore, $R_s(V)$ does not have to be equal to $R_d(V)$). This feature makes accurate RF CMOS simulation possible. The source/drain series resistance is the sum of a bias-independent component and a bias-dependent component.

\[
V_{gs,eff} = \frac{1}{2} \left[ V_{gs} - V_{fbsdr} + \sqrt{(V_{gs} - V_{fbsdr})^2 + 10^{-2}} \right]
\]

\[
V_{gd,eff} = \frac{1}{2} \left[ V_{gd} - V_{fbsdr} + \sqrt{(V_{gd} - V_{fbsdr})^2 + 10^{-2}} \right]
\]

\[
R_{source} = \frac{1}{W_{eff}^{WR} \cdot NF} \cdot \left( RSW_{MIN} + RSW \cdot \left[ -PR WB \cdot V_{bs} + \frac{1}{1 + PRWG_i \cdot V_{gs,eff}} \right] \right) + R_{s,geo}
\]

\[
R_{drain} = \frac{1}{W_{eff}^{WR} \cdot NF} \cdot \left( RDW_{MIN} + RDW \cdot \left[ -PR WB \cdot V_{bd} + \frac{1}{1 + PRWG_i \cdot V_{gd,eff}} \right] \right) + R_{d,geo}
\]

$R_{s,geo}$ and $R_{d,geo}$ are the source and drain diffusion resistances.

### 2.10.3 Bias Dependent Internal Resistance ($RDSMOD=2$)

\[
R_{ds}(V) = R_{s,geo} + NF \cdot \left( W_{eff}^{WR} \left[ RDSW_{MIN} + RDSW \cdot T_3 \right] \right) + R_{d,geo}
\]

\[
D_r = 1.0 + \frac{\mu_0}{D_{mob} \cdot D_{vsat}} \cdot C_{ox} \cdot \frac{W_{eff}}{L_{eff}} \cdot q_{ia} \cdot R_{ds}
\]

where $T_3$ is given by (2.166).
2.10.4 Sheet resistance model

The resistances \( R_{s,geo} \) and \( R_{d,geo} \) are simply calculated as the sheet resistances \( (RSHS,RSHD) \) times the number of squares \( (NRS,NRD) \):

\[
\begin{align*}
R_{s,geo} & = NRS \cdot RSHS \\
R_{d,geo} & = NRD \cdot RSHD
\end{align*}
\]

(2.176)

2.11 Output Conductance

The Output conductance model is taken from BSIM4 [5]

Channel Length Modulation (CLM)

\[
E_{sat} = \frac{2 \cdot V_{SAT}}{U_0} \frac{1}{D_{mob}}
\]

(2.177)

\[
F = \begin{cases} 
1 & \text{for } FPROUT \leq 0 \\
\frac{1}{1+FPROUT \sqrt{L_{eff}}} & \text{for } FPROUT > 0
\end{cases}
\]

(2.178)

\[
C_{clm} = \begin{cases} 
PCLM \cdot \left(1 + PCLMG \cdot \frac{q_{ln}}{E_{sat} L_{eff}}\right)^\frac{1}{F} & \text{for } PCLMG > 0 \\
\cdot \left(1-PCLMG \cdot \frac{q_{ln}}{E_{sat} L_{eff}}\right)^\frac{1}{F} & \text{for } PCLMG < 0
\end{cases}
\]

(2.179)

\[
V_{asat} = V_{dssat} + E_{sat}L
\]

(2.180)

\[
M_{CLM} = 1 + C_{clm} \ln \left[1 + \frac{V_{ds} - V_{dseff}}{V_{asat}} \cdot \frac{1}{C_{clm}}\right]
\]

(2.181)

Drain Induced Barrier Lowering (DIBL)

\[
PVAGfactor = \begin{cases} 
1 + PVAG \cdot \frac{q_{ln}}{E_{sat} L_{eff}} & \text{for } PVAG > 0 \\
\frac{1}{1-PVAG \cdot \frac{q_{ln}}{E_{sat} L_{eff}}} & \text{for } PVAG < 0
\end{cases}
\]

(2.182)
\[ \theta_{rout} = PDIBLC \]  
\[ V_{ADIBL} = \frac{q_{ia} + 2kT/q}{\theta_{rout}} \cdot \left(1 - \frac{V_{dssat}}{V_{dssat} + q_{ia} + 2kT/q}\right) \cdot PVAGfactor \cdot \frac{1}{1 + PDIBLCB \cdot V_{bsx}} \]  
\[ M_{DIBL} = \left(1 + \frac{V_{ds} - V_{dseff}}{V_{ADIBL}}\right) \]

Note: Length scaling parameters for PDIBLC are PDIBLCL and PDIBLCLEXP.

**Drain Induced Threshold Shift (DITS)**

\[ V_{ADITS} = \frac{1}{PDITS} \cdot F \cdot [1 + (1 + PDITSL \cdot L_{eff}) \exp(PDITSD \cdot V_{ds})] \]  
\[ M_{DITS} = \left(1 + \frac{V_{ds} - V_{dseff}}{V_{ADITS}}\right) \]

**Substrate Current induced Body Effect (SCBE)**

\[ litl = \sqrt{\left(\frac{\epsilon_{sub}}{\epsilon_{ox}}\right) \cdot TOXE \cdot XJ} \]
\[ V_{ASCBE} = \frac{L_{eff}}{PSCBE2} \cdot \exp\left(\frac{PSCBE1 \cdot litl}{V_{ds} - V_{dseff}}\right) \]  
\[ M_{SCBE} = \left(1 + \frac{V_{ds} - V_{dseff}}{V_{ASCBE}}\right) \]

\[ M_{oc} = M_{DIBL} \cdot M_{CLM} \cdot M_{DITS} \cdot M_{SCBE} \]

\( M_{oc} \) is multiplied to \( I_{ds} \) in the final drain current expression.
2.12 Velocity Saturation

Current Degradation Due to Velocity Saturation

\[ T_1 = 2 \cdot \lambda_C \cdot (q_s - q_{def}) \]  \hspace{1cm} (2.192)

\[ \lambda_C = \frac{2 \cdot U_0 \cdot nV_t}{(D_{mob})^{PSAT} \cdot VSAT \cdot L_{eff}} \cdot [1 + PTWG \cdot \frac{10 \cdot PSATX \cdot q_s \cdot T_0}{10 \cdot PSATX + q_s \cdot T_0}] \]  \hspace{1cm} (2.193)

\[ D_{vsat} = \frac{1}{2} \left[ \sqrt{1 + T_1^2} + \frac{1}{T_1} \cdot \ln(T_1 + \sqrt{1 + T_1^2}) \right] \]  \hspace{1cm} (2.194)

\[ D_{ptwg} = D_{vsat} \]  \hspace{1cm} (2.195)

\[ D_{tot} = D_{mob} \cdot D_{vsat} \cdot D_r \]  \hspace{1cm} (2.196)

where \( D_r \) is the effect of internal resistance \( (R_{dsi}) \) on current, defined as

\[ D_r = \begin{cases} 
1 & \text{if } RDSMOD = 1 \\
1 + U_0 \cdot C_{ox} \cdot \frac{W_{eff}}{L_{eff}} \cdot q_{ia} \cdot R_{dsi} & \text{if } RDSMOD = 0 
\end{cases} \]  \hspace{1cm} (2.197)

2.13 Effective Mobility

\[ \mu_{eff} = \frac{U_0}{D_{tot}} \]  \hspace{1cm} (2.198)

2.14 Drain Current Model

2.14.1 Without Velocity Saturation

The drain current expression is derived as follows,

\[ I_{ds} = I_{drift} + I_{diff} \]  \hspace{1cm} (2.199)

\[ I_{ds} = -W_{eff} \cdot Q_i \cdot \mu_{eff} \cdot \frac{d\psi_s}{dx} + W \cdot \mu_{eff} \cdot V_t \frac{dQ_i}{dx} \]  \hspace{1cm} (2.200)
from charge linearization, \( \psi_s = \psi_p + \frac{Q_i}{n_q C_{ox}} \). Thus

\[
I_{ds} = \mu_{eff} W_{eff} \left[ -\frac{Q_i}{n_q C_{ox}} + V_t \right] \frac{dQ_i}{dx} \tag{2.201}
\]

normalizing inversion charge to \(-2n_q C_{ox} V_t\) and using \( \xi = \frac{x}{L} \),

\[
I_{ds} = \mu_{eff} \frac{W_{eff}}{L_{eff}} \left[ -\frac{2n_q C_{ox} V_t q}{n_q C_{ox}} + V_t \right] \frac{d(-2n_q C_{ox} V_t q)}{d\xi} \tag{2.202}
\]

\[
= -2 \cdot n_q \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2 \cdot (2q + 1) \frac{dq}{d\xi} \tag{2.203}
\]

Total drain current,

\[
I_{DS} = \int_0^1 I_{ds} d\xi = -2 \cdot n_q \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2 \cdot \int_{q_s}^{q_d} (2q + 1) dq \tag{2.204}
\]

which gives

\[
I_{DS} = 2 \cdot n_q \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2 \cdot [(q_s - q_{deff})(q_s + q_{deff} + 1)] \tag{2.205}
\]

\( n_q \) is the slope factor in charge based model and \( nV_t \) is \( n \cdot \frac{K_T}{q} \) with \( n \) given by (2.142).

### 2.14.2 Including Velocity Saturation

As the device is getting smaller and smaller, the lateral electric field strength and therefore kinetic energy of the carriers increases. On reaching optical phonon energy levels, they releases optical phonon by virtue of reduction in kinetic energy and therefore loses velocity [6]. The effect of velocity saturation on mobility is captured as follows

\[
\mu = \frac{\mu_{eff}}{\sqrt{1 + \left( \frac{E}{E_c} \right)^2}} \tag{2.206}
\]

\[
= \frac{\mu_{eff}}{\sqrt{1 + \left( \frac{1}{E_c} \cdot \frac{d\psi_s}{dx} \right)^2}} \tag{2.207}
\]
from (2.203) and (2.207),

\[
I_{ds} = -2 \cdot n_q \cdot \frac{\mu_{eff} \cdot W_{eff} \cdot C_{ox} \cdot nV_t^2 \cdot (2q + 1)}{\sqrt{1 + \left(\frac{1}{E_c} \cdot \frac{d\psi_s}{dx}\right)^2}} \frac{dq}{d\xi} \tag{2.208}
\]

\[
= z \cdot \frac{(2q + 1) \frac{dq}{d\xi}}{\sqrt{1 + \left(\frac{1}{E_c} \cdot \frac{d\psi_s}{dx}\right)^2}} \tag{2.209}
\]

with 

\[z = -2\mu_{eff} \cdot n_q \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2\]

Total current,

\[
I_{DS} = \int_0^1 I_{ds} \, d\xi = z \cdot \int_{q_s}^{q_d} \frac{(2q + 1)}{\sqrt{1 + \left(\frac{1}{E_c} \cdot \frac{d\psi_s}{dx}\right)^2}} \, dq \tag{2.210}
\]

\[
I_{DS} \int_0^1 \sqrt{1 + \left(\frac{1}{E_c} \cdot \frac{d\psi_s}{dx}\right)^2} \, d\xi = z \cdot \int_{q_s}^{q_d} (2q + 1) \, dq \tag{2.211}
\]

from (2.205),

\[
\int_{q_s}^{q_d} (2q + 1) \, dq = -(q_s - q_{deff})(q_s + q_{deff} + 1) \tag{2.212}
\]

Now consider the LHS of (2.211). Using charge linearization, \(\psi_s = \psi_p + \frac{Q_i}{n_qC_{ox}}\),

\[
\frac{1}{E_c} \frac{d\psi_s}{dx} = \frac{1}{E_c \cdot n_q \cdot C_{ox}} \frac{Q_i}{dx} = -\frac{2V_t}{E_c \cdot L} \frac{dq}{d\xi} = -\lambda_c \cdot \frac{dq}{d\xi} \tag{2.213}
\]

Let

\[
D_{usat} = \int \sqrt{1 + \left(\frac{1}{E_c} \cdot \frac{d\psi_s}{dx}\right)^2} \, d\xi
\]

It is evaluated by assuming that lateral electric field \((-\frac{d\psi_s}{dx})\) increases linearly from 0 at source to 2 \(\left(\frac{\psi_{s,D} - \psi_{s,S}}{L}\right)\) at drain [7] i.e.

\[
-\frac{d\psi_s}{dx} = 2 \cdot \frac{\psi_{s,D} - \psi_{s,S}}{L} \cdot \frac{x}{L} = 2 \cdot \frac{\psi_{s,D} - \psi_{s,S}}{L} \cdot \xi \tag{2.214}
\]
From charge linearization (2.101),
\[ \psi_{s,S} = \psi_P + \frac{Q_S}{n_q C_{ox}} = \psi_P - 2V_t q_s \] (2.215)
\[ \psi_{s,D} = \psi_P + \frac{Q_D}{n_q C_{ox}} = \psi_P - 2V_t q_d \] (2.216)
\[ \psi_{s,D} - \psi_{s,S} = 2V_t (q_s - q_d) \] (2.217)

Substituting in (2.214),
\[ -\frac{d\psi_s}{dx} = 2 \cdot \frac{2V_t (q_s - q_d)}{L} \cdot \xi \] (2.218)
\[ -\frac{1}{E_c} \frac{d\psi_s}{dx} = 2 \cdot \frac{2V_t}{E_c L} (q_s - q_d) \xi = 2\lambda_c (q_s - q_d) \xi \] (2.219)
where \( \lambda_c = \frac{2V_t}{E_c L} \). Thus \( D_{vsat} \) can be given as
\[ D_{vsat} = \int \sqrt{1 + \left( \frac{1}{E_c} \cdot \frac{d\psi_s}{dx} \right)^2} d\xi \] (2.220)
\[ = \int \sqrt{1 + (2\lambda_c (q_s - q_d) \xi)^2} d\xi = \int \sqrt{1 + (2\lambda_c \Delta q \xi)^2} d\xi \] (2.221)
\[ = \frac{1}{2} \left[ \sqrt{1 + (2\lambda_c \Delta q)^2} + \frac{1}{2\lambda_c \Delta q} \ln \left( 2\lambda_c \Delta q + \sqrt{1 + (2\lambda_c \Delta q)^2} \right) \right] \] (2.222)

with \( \Delta q = q_s - q_d \). From (2.211), (2.212) and (2.222),
\[ I_{DS} = 2 \cdot n_q \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2 \cdot [(q_s - q_{deff}) (q_s + q_{deff} + 1)] \cdot M_{scbe} \] (2.223)
where \( \mu_{eff} = \frac{U_0}{D_{tot}} \) and \( D_{tot} = D_{mod} D_{vsat} D_r \)

### 2.15 Impact Ionization Model

The impact ionization current model in BSIM6 is the same as that in BSIM4, and is modeled by
\[ I_{ii} = \alpha_0 \cdot (V_{ds} - V_{deff}) \cdot \exp\left( -\frac{BETA_0}{V_{ds} - V_{deff}} \right) \cdot \frac{I_{ds}}{M_{scbe}} \] (2.224)
where parameters \( \text{\textit{ALPHA}}_{0} \) and \( \text{\textit{BETA}}_{0} \) are impact ionization coefficients. \( \text{\textit{ALPHA}}_{0L} \) and \( \text{\textit{ALPHA}}_{0\text{LEXP}} \) are length scaling parameters for \( \text{\textit{ALPHA}}_{0} \).

Note: The order of \( \text{\textit{ALPHA}}_{0} \) in BSIM6 = \( 10^{6} \) X order of \( \text{\textit{ALPHA}}_{0} \) in BSIM4.

### 2.16 GIDL/GISL Current Model

GIDL/GISL currents are set using model selector \( \text{GIDLMOD}=1 \). The GIDL/GISL current and its body bias effect are modeled by

\[
I_{\text{GIDL}} = AGIDL \cdot W_{\text{eff}} \cdot NF \cdot \frac{V_{\text{ds}} - V_{gse} - E_{GIDL}}{3 \cdot T_{\text{oxe}}} \cdot \exp \left( -\frac{3 \cdot T_{\text{oxe}} \cdot B_{GIDL}}{V_{\text{ds}} - V_{gse} - E_{GIDL}} \right) \cdot \frac{V_{\text{db}}^{3}}{C_{GIDL} + V_{\text{db}}^{3}} \tag{2.225}
\]

\[
I_{\text{GISL}} = AGISL \cdot W_{\text{eff}} \cdot NF \cdot \frac{-V_{\text{ds}} - V_{gde} - E_{GISL}}{3 \cdot T_{\text{oxe}}} \cdot \exp \left( -\frac{3 \cdot T_{\text{oxe}} \cdot B_{GISL}}{-V_{\text{ds}} - V_{gde} - E_{GISL}} \right) \cdot \frac{V_{\text{sb}}^{3}}{C_{GISL} + V_{\text{sb}}^{3}} \tag{2.226}
\]

where \( AGIDL, B_{GIDL}, C_{GIDL} \) and \( E_{GIDL} \) are model parameters for the drain side and \( AGISL, B_{GISL}, C_{GISL} \) and \( E_{GISL} \) are the model parameters for the source side. \( C_{GIDL} \) and \( C_{GISL} \) account for the body-bias dependence of \( I_{\text{GIDL}} \) and \( I_{\text{GISL}} \) respectively. \( W_{\text{eff}} \) and \( NF \) are the effective width of the source/drain diffusions and the number of fingers. Further explanation of \( W_{\text{eff}} \) and \( NF \) can be found in the chapter of the layout-dependence model. Check scaling parameters in the parameter list at the end.

\( I_{\text{GIDL}}/I_{\text{GISL}} \) can be switched off by setting \( \text{GIDLMOD} = 0 \).

### 2.17 Gate Tunneling Current Model

As the gate oxide thickness is scaled down to 3\( \text{nm} \) and below, gate leakage current due to carrier direct tunneling becomes important. This tunneling happens between the gate and silicon beneath the gate oxide. To reduce the tunneling current, high-k dielectrics are
being used in place of gate oxide. In order to maintain a good interface with substrate, multi-layer dielectric stacks are being used. The BSIM6 gate tunneling model (taken from BSIM4) has been shown to work for multi-layer gate stacks as well. The tunneling carriers can be either electrons or holes, or both, either from the conduction band or valence band, depending on (the type of the gate and) the bias regime. In BSIM6, the gate tunneling current components include the tunneling current between gate and substrate ($I_{gb}$), and the current between gate and channel ($I_{gc}$), which is partitioned between the source and drain terminals by $I_{gc} = I_{gcs} + I_{gcd}$. The third component happens between gate and source/drain diffusion regions ($I_{gs}$ and $I_{gd}$). Figure 1 shows the schematic gate tunneling current flows.

2.17.1 Model Selectors

Two global selectors are provided to turn on or off the tunneling components. \texttt{IGCMOD} = 1 turns on $I_{gc}$, $I_{gs}$, and $I_{gd}$; \texttt{IGBMOD} = 1 turns on $I_{gb}$. When the
selectors are set to zero, no gate tunneling currents are modeled.

\[ V_{ox} = nVt \cdot (v_g - v_{fb} - \psi_p + q_s + q_{deff}) \]  \hspace{1cm} (2.227)

\[ V_{oxacc} = \frac{1}{2} \left( -V_{ox} + \sqrt{V_{ox}^2 + 10^{-4}} \right) \]  \hspace{1cm} (2.228)

\[ V_{oxdepinv} = \frac{1}{2} \left( V_{ox} + \sqrt{V_{ox}^2 + 10^{-4}} \right) \]  \hspace{1cm} (2.229)

Eq. (2.228) and (2.229) are valid and continuous from accumulation through depletion to inversion.

### 2.17.2 Equations for Tunneling Currents

**Note:** All gate tunneling current equations use operating temperature in the calculations.

**Gate-to-Substrate Current** \( I_{gb} = I_{gacc} + I_{gbinv} \): \( I_{gacc} \), determined by ECB (Electron tunneling from Conduction Band), is significant in accumulation and given by

\[
I_{gacc} = NF \cdot W_{eff}L_{eff} \cdot A \cdot T_{oxRatio} \cdot V_{gb} \cdot V_{aux} \cdot i_{gtemp} \\
\times \exp[-B \cdot TOXE(A_{IGBACC} - B_{IGBACC} \cdot V_{oxacc}) \cdot (1 + C_{IGBAC} \cdot V_{oxacc})]
\]  \hspace{1cm} (2.230)

where the physical constants \( A = 4.97232e - 7 \ A/V^2 \), \( B = 7.45669e11(g/F - s^2)^{0.5} \), and

\[
T_{oxRatio} = \left( \frac{TOXREF}{TOXE} \right)^{NTOX} \cdot \frac{1}{TOXE^2}
\]  \hspace{1cm} (2.231)

\[
V_{aux} = NIGBACC \cdot V_t \cdot \log \left( 1 + \exp \left( -\frac{V_{oxacc}}{NIGBACC \cdot V_t} \right) \right)
\]  \hspace{1cm} (2.232)
\(I_{gbinv}\), determined by EVB (Electron tunneling from Valence Band), is significant in inversion and given by

\[
I_{gbinv} = NF \cdot W_{eff} L_{eff} \cdot A \cdot T_{oxRatio} \cdot V_{gb} \cdot V_{aux} \cdot i_{gtemp}
\]

\[
\cdot \exp[-B \cdot TOXE(AIGBINV - BIGBINV \cdot V_{oxdepinv}) \cdot (1 + CIGBINV V_{oxdepinv})]
\]

(2.233)

where \(A = 3.75956 \times 10^{-7} \, A/V^2\), \(B = 9.82222 \times 10^{11} (g/F - s^2)^{0.5}\), and

\[
V_{aux} = NIGBINV \cdot V_t \cdot \log\left(1 + \exp\left(\frac{V_{oxdepinv} - EIGBINV}{NIGBINV \cdot V_t}\right)\right)
\]

(2.234)

\[
I_{gb} = I_{gbacc} + I_{gbinv}
\]

(2.235)

**Gate-to-Channel Current \(I_{gc0}\) and Gate-to-S/D \(I_{gs}\) and \(I_{gd}\):** \(I_{gc0}\), determined by ECB for NMOS and HVB (Hole tunneling from Valence Band) for PMOS at \(V_{ds} = 0\), is formulated as

\[
I_{gc0} = NF \cdot W_{eff} L_{eff} \cdot A \cdot T_{oxRatio} \cdot V_{gse} \cdot V_{aux} \cdot i_{gtemp}
\]

\[
\cdot \exp[-B \cdot TOXE(AIGC - BIGC \cdot V_{oxdepinv}) \cdot (1 + CIGCV_{oxdepinv})]
\]

(2.236)

where \(A = 4.97232 \, A/V^2\) for NMOS and 3.42537 \(A/V^2\) for PMOS, \(B = 7.45669 \times 10^{11} (g/F - s^2)^{0.5}\) for NMOS and 1.16645 \(10^{12} (g/F - s^2)^{0.5}\) for PMOS.

\[
V_{aux} = n_q \cdot nVt \cdot (q_s + q_{deff})
\]

(2.237)

**Partition of \(I_{gc}\):** To consider the drain bias effect, \(I_{gc}\) is split into two components, \(I_{gcs}\) and \(I_{gcd}\), that is \(I_{gc} = I_{gcs} + I_{gcd}\), and

\[
I_{gcs} = I_{gc0} \cdot \frac{PIGCD \cdot V_{dseffx} + \exp(-PIGCD \cdot V_{dseffx}) - 1 + 10^{-4}}{PIGCD \cdot V_{dseffx}^2 + 2 \cdot 10^{-4}}
\]

(2.238)

and

\[
I_{gcd} = I_{gc0} \cdot \frac{1 - (PIGCD \cdot V_{dseffx} + 1) \cdot \exp(-PIGCD \cdot V_{dseffx}) + 10^{-4}}{PIGCD \cdot V_{dseffx}^2 + 2 \cdot 10^{-4}}
\]

(2.239)
where
\[ V_{dseffx} = \sqrt{V_{dseff} + 0.01} - 0.1 \]  
(2.240)

At \( V_{ds} = 0 \), \( I_{gcs} = I_{gcd} = \frac{1}{2} I_{gc0} \). Thus \( I_{gc0} \) is the gate to channel current \( I_{gc} \) at \( V_{ds} = 0 \).

\( I_{gs} \) and \( I_{gd} \): \( I_{gs} \) represents the gate tunneling current between the gate and the source diffusion region, while \( I_{gd} \) represents the gate tunneling current between the gate and the drain diffusion region. \( I_{gs} \) and \( I_{gd} \) are determined by ECB for NMOS and HVB for PMOS, respectively.

\[
I_{gs} = NF \cdot W_{eff} \cdot DLCIG \cdot A \cdot T_{oxRatioEdge} \cdot V_{gs} \cdot V'_{gs} \cdot i_{gttemp} \\
\cdot \exp[-B \cdot TOXE \cdot POXEDGE \cdot (AIGS - BIGS \cdot V'_{gs}) \cdot (1 + CIGSV'_{gs})] 
\]
(2.241)

and

\[
I_{gd} = NF \cdot W_{eff} \cdot DLCIGD \cdot A \cdot T_{oxRatioEdge} \cdot V_{gd} \cdot V'_{gd} \cdot i_{gttemp} \\
\cdot \exp[-B \cdot TOXE \cdot POXEDGE \cdot (AIGD - BIGD \cdot V'_{gd}) \cdot (1 + CIGDV'_{gd})] 
\]
(2.242)

where \( A = 4.97232 \, A/V^2 \) for NMOS and \( 3.42537 \, A/V^2 \) for PMOS, \( B = 7.45669 \times 10^{11} (g/F - s^2)^{0.5} \) for NMOS and \( 1.16645 \times 10^{12} (g/F - s^2)^{0.5} \) for PMOS, and

\[
T_{oxRatioEdge} = \left( \frac{TOXREF}{TOXE \cdot POXEDGE} \right)^{NTOX} \cdot \frac{1}{(TOXE \cdot POXEDGE)^2} 
\]
(2.243)

\[
V'_{gs} = \sqrt{(V_{gs} - V_{fbsd})^2 + 10^{-4}} 
\]
(2.244)

\[
V'_{gd} = \sqrt{(V_{gd} - V_{fbsd})^2 + 10^{-4}} 
\]
(2.245)

\( V_{fbsd} \) is the flat-band voltage between gate and S/D diffusions calculated as

If \( NGATE > 0.0 \)

\[
V_{fbsd} = -devsign \cdot \frac{k_BT}{q} \log \left( \frac{NGATE}{NSD} \right) + VFBSDOFF 
\]
(2.246)

Else \( V_{fbsd} = 0.0 \).
2.18 Gate resistance and Body resistance network Model

2.18.1 Gate Electrode Electrode and Intrinsic-Input Resistance (IIR) Model

**General Description:** BSIM6 provides four options for modeling gate electrode resistance (bias-independent) and intrinsic-input resistance (IIR, bias-dependent). The IIR model considers the relaxation-time effect due to the distributive RC nature of the channel region, and therefore describes the first-order non-quasi-static effect. Thus, the IIR model should not be used together with the charge-deficit NQS model at the same time. The model selector RGATEMOD is used to choose different options.

**Model Option and Schematic:** There are four model selectors for gate resistance network.

- **RGATEMOD = 0** (zero-resistance): In this case, no gate resistance is generated (see Figure 2).

- **RGATEMOD = 1** (constant-resistance): In this case, only the electrode gate resistance (bias-independent) is generated by adding an internal gate node. $R_{geltd}$ is given by

  $$R_{geltd} = \frac{R_{SHG} \cdot (XGW + \frac{W_{eff}}{3 \cdot NGCON})}{NGCON \cdot (L_{drawn} - XGL) \cdot NF} \quad (2.247)$$

- **RGATEMOD = 2** (IIR model with variable resistance): In this case, the gate resistance is the sum of the electrode gate resistance $R_{geltd}$ (2.247) and the intrinsic-input resistance $R_{ii}$ as given by (2.248). An internal gate node will be generated.

  $$\frac{1}{R_{ii}} = XRCRG \cdot NF \cdot \left( \frac{I_{ds}}{V_{dseff}} + XRCRG2 \cdot \frac{W_{eff} \mu_{eff} C_{oxeff} V_{t}}{L_{eff}} \right)$$

  or

  $$\frac{1}{R_{ii}} \approx XRCRG \cdot NF \cdot \left( \mu_{eff} \left( \frac{W_{eff}}{L_{eff}} \right) C_{ox} \cdot q_{ia} + XRCRG2 \cdot \frac{W_{eff} \mu_{eff} C_{oxeff} V_{t}}{L_{eff}} \right) \quad (2.248)$$

- **RGATEMOD = 3** (IIR model with two nodes): In this case, the gate electrode resistance $R_{geltd}$ is in series with the intrinsic-input resistance $R_{ii}$ through two internal gate nodes, so that the overlap capacitance current will not pass through the intrinsic-input resistance.
Figure 2: Gate resistance network for (a) \( RGATEMOD = 0 \) (b) \( RGATEMOD = 1 \) (c) \( RGATEMOD = 2 \) (d) \( RGATEMOD = 3 \).
2.18.2 Substrate Resistance Network

**General Description:** For CMOS RF circuit simulation, it is essential to consider the high frequency coupling through the substrate. BSIM6 offers a flexible built-in substrate resistance network. This network is constructed such that little simulation efficiency penalty will result. Note that the substrate resistance parameters should be extracted for the total device, not on a per-finger basis.

**Model Selector and Topology** The model selector RBODYMOD can be used to turn on or turn off the resistance network.

- **RBODYMOD = 0 (Off):**
  No substrate resistance network is generated at all.

- **RBODYMOD = 1 (On):**
  All five resistances RBPS, RBPD, RBPB, RBSB, and RBDB in the substrate network as shown schematically below are present simultaneously.

  A minimum conductance, GBMIN, is introduced in parallel with each resistance and therefore to prevent infinite resistance values, which would otherwise cause poor convergence. GBMIN is merged into each resistance to simplify the representation of the model topology. Note that the intrinsic model substrate reference point in this case is the internal body node bNodePrime, into which the impact ionization current $I_{ii}$ and the GIDL current $I_{GIDL}$ flow.

- **RBODYMOD = 2 (On : Scalable Substrate Network):**
  The schematic is similar to RBODYMOD = 1 but all the five resistors in the substrate network are now scalable with a possibility of choosing either five resistors, three resistors or one resistor as the substrate network.

  The resistors of the substrate network are scalable with respect to channel length (L), channel width (W) and number of fingers (NF). The scalable model allows to account for both horizontal and vertical contacts.

  The scalable resistors RBPS and RBPD are evaluated through

  \[
  RBPS = RBPS0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBPSL} \cdot \left( \frac{W}{10^{-6}} \right)^{RBPSW} \cdot NF^{RBPSNF} \tag{2.249}
  \]

  \[
  RBPD = RBPD0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBPDL} \cdot \left( \frac{W}{10^{-6}} \right)^{RBPDW} \cdot NF^{RBPDNF} \tag{2.250}
  \]
Figure 3: Topology with the substrate resistance network turned on.

The resistor RBPB consists of two parallel resistor paths, one to the horizontal contacts and other to the vertical contacts. These two resistances are scalable and RBPB is given by a parallel combination of these two resistances.

\[
R_{BPB_X} = R_{BPB X0} \cdot \left( \frac{L}{10^{-6}} \right)^{R_{BPB X L}} \cdot \left( \frac{W}{10^{-6}} \right)^{R_{BPB X W}} \cdot N^{R_{BPB D N}}_{BPB} \tag{2.251}
\]

\[
R_{BPB_Y} = R_{BPB Y0} \cdot \left( \frac{L}{10^{-6}} \right)^{R_{BPB Y L}} \cdot \left( \frac{W}{10^{-6}} \right)^{R_{BPB Y W}} \cdot N^{R_{BPB D N}}_{BPB} \tag{2.252}
\]

\[
R_{BPB} = \frac{R_{BPB X} \cdot R_{BPB Y}}{R_{BPB X} + R_{BPB Y}} \tag{2.253}
\]

The resistors RBSB and RBDB share the same scaling parameters but have different scaling prefactors. These resistors are modeled in the same way as RBPB. The equations
for RBSB are shown below. The calculation for RBDB follows RBSB.

\[
RBSBX = RBSBX_0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBSBXL} \cdot \left( \frac{W}{10^{-6}} \right)^{RBSBXW} \cdot NF^{RBSDNF}(2.254)
\]

\[
RBSBY = RBSBY_0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBSBYL} \cdot \left( \frac{W}{10^{-6}} \right)^{RBSBYW} \cdot NF^{RBSDNF}(2.255)
\]

\[
RBSB = \frac{RBSBX \cdot RBSBY}{RBSBX + RBSBY} (2.256)
\]

Similarly, the equations for RBDB is as follows

\[
RBDBX = RBDBX_0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBDBXL} \cdot \left( \frac{L}{10^{-6}} \right)^{RBDBWX} \cdot (NF)^{RBDBXNF}(2.257)
\]

\[
RBDBY = RBDBY_0 \cdot \left( \frac{L}{10^{-6}} \right)^{RBDBYL} \cdot \left( \frac{L}{10^{-6}} \right)^{RBDBYW} \cdot (NF)^{RBDBYNF}(2.258)
\]

\[
RBDB = \frac{RBDBX \times RBDBY}{RBDBX + RBDBY} (2.259)
\]

The implementation of \textbf{RBODYMOD} = 2 allows the user to chose between the 5-R network (with all five resistors), 3-R network (with RBPS, RBPD and RBPB) and 1-R network (with only RBPB).

If the user does not provide both the scaling parameters RBSBX0 and RBSBY0 for RBSB or both the scaling parameters RBDBX0 and RBDBY0 for RBDB, then the conductances for both RBSB and RBDB are set to GBMIN. This converts the 5-R schematic to 3-R schematic where the substrate network consists of the resistors RBPS, RBPD and RBPB. RBPS, RBPD and RBPB are then calculated using (2.249), (2.250), and (2.253).

If the user chooses not to provide either of RBPS0 or RBPD0, then the 5-R schematic is converted to 1-R network with only one resistor RBPB. The conductances for RBSB and RBDB are set to GBMIN. The resistances RBPS and RBPD are set to 1e-3 Ohm. The resistor RBPB is then calculated using (2.253).

In all other situations, 5-R network is used with the resistor values calculated from the equations aforementioned.
2.19 Noise Modeling

The following noise sources in MOSFETs are modeled in BSIM6 for SPICE noise analysis: flicker noise (also known as 1/f noise), channel thermal noise and induced gate noise and their correlation, thermal noise due to physical resistances such as the source/drain, gate electrode, and substrate resistances, and shot noise due to the gate dielectric tunneling current.

<table>
<thead>
<tr>
<th>Noise models in BSIM 6.0.0</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flicker noise model</td>
<td>BSIM4 Unified Model (FNOIMOD=1)</td>
</tr>
<tr>
<td>Thermal noise(TNOIMOD=0)</td>
<td>BSIM4 (TNOIMOD=0)</td>
</tr>
<tr>
<td>Thermal noise (TNOIMOD=1)</td>
<td>BSIM4 (TNOIMOD=2)</td>
</tr>
<tr>
<td>Gate current shot noise</td>
<td>BSIM4 gate current noise</td>
</tr>
<tr>
<td>Noise associated with parasitic resistances</td>
<td>BSIM4 parasitic resistance noise</td>
</tr>
</tbody>
</table>

2.19.1 Flicker Noise Models

BSIM6’s flicker noise model is same as FNOIMOD=1 in BSIM4. The unified physical flicker noise model is smooth over all bias regions.

The physical mechanism for the flicker noise is trapping/detrapping-related charge fluctuation in oxide traps, which results in fluctuations of both mobile carrier numbers and mobilities in the channel. The unified flicker noise model captures this physical process. In the inversion region, the noise density is expressed as [8]

\[ S_{id,inv}(f) = \frac{kTq^2\mu_{eff}I_{ds}}{C_{ox}L_{effNOI}^2f_{EF} \cdot 10^{10}} \left( NOIA \cdot \log \left( \frac{N_0 + N^*}{N_l + N^*} \right) 
+ NOIB \cdot (N_0 - N_l) + \frac{NOIC}{2} (N_0^2 - N_l^2) \right) \]

\[ \frac{kTq^2\mu_{eff}I_{ds}}{L_{clm} \cdot W_{eff}L_{effNOI}^2f_{EF} \cdot 10^{10}} \left( \frac{NOIA + NOIB \cdot N_l + NOIC \cdot N_l^2}{(N_l + N^*)^2} \right)^2 \]

where \( L_{effNOI} = L_{eff} - 2 \cdot LINTNOI \), \( \mu_{eff} \) is the effective mobility at the given bias condition, and \( L_{eff} \) and \( W_{eff} \) are the effective channel length and width, respectively.
The parameter $N_0$ is the charge density at the source side given by

$$N_0 = \frac{2n_q C_{ox} V_t q_s}{q} \quad (2.261)$$

The parameter $N_l$ is the charge density at the drain end given by

$$N_l = \frac{2n_q C_{ox} V_t q_{deff}}{q} \quad (2.262)$$

and $N^*$ is given by

$$N^* = \frac{V_t (C_{ox} + C_d + CIT)}{q} \quad (2.263)$$

where CIT is a model parameter from DC IV and $C_d$ is the depletion capacitance.

$\Delta L_{clm}$ is the channel length reduction due to channel length modulation and given by

$$\Delta L_{clm} = \frac{l_{itl} \cdot \log \left( \frac{V_{ds} - V_{dseff}}{l_{itl}} \right)}{E_{sat}} + EM \quad (2.264)$$

$$E_{sat} = \frac{2VSAT}{\mu_{eff}}$$

In the subthreshold region, the noise density is written as

$$S_{id,subVt}(f) = \frac{NOIA \cdot k \cdot T \cdot I_{ds}^2}{W_{eff} L_{eff} f E_F N^*^2 \cdot 10^{10}} \quad (2.265)$$

The total flicker noise density is

$$S_{id}(f) = \frac{S_{id,inv} \cdot S_{id,subVt}}{S_{id,inv} + S_{id,subVt}} \quad (2.266)$$

### 2.19.2 Channel Thermal Noise

There are two channel thermal noise models in BSIM6. One is a charge-based model (default model) similar to that used in BSIM3v3.2 and BSIM4.7.0 (TNOIMOD=0). The other is the holistic model similar to BSIM4.7.0 (TNOIMOD=2). These two models can be selected through the model selector TNOIMOD.
TNOIMOD = 0 (Charge based Model): The noise current is given by

\[ Q_{inv} = \left| Q_{s,intrinsic} + Q_{d,intrinsic} \right| \times NFIN_{total} \]  \hspace{1cm} (2.267)

\[ \overline{v_d^2} = \begin{cases} 
NTNOI \cdot \frac{4kT\Delta f}{L_{eff}^2} & \text{if } RDSMOD = 0 \\
NTNOI \cdot \frac{4kT\Delta f}{L_{eff}^2} \cdot \mu_{eff} Q_{inv} & \text{if } RDSMOD = 1 
\end{cases} \]  \hspace{1cm} (2.268)

where \( R_{ds}(V) \) is the bias-dependent LDD source/drain resistance, and the parameter NTNOI is introduced for more accurate fitting of short-channel devices. \( Q_{inv} \) is the total inversion charge in the channel.

TNOIMOD = 1 (Holistic Model): In this thermal noise model (similar to TNOIMOD = 2 in BSIM4.7.0), all the short-channel effects and velocity saturation effect incorporated in the IV model are automatically included, hence the name ”holistic thermal noise model”. In this thermal noise model both the gate and the drain noise are implemented as current noise sources. The drain current noise flows from drain to source; whereas the induced gate current noise flows from the gate to the source. The correlation between the two noise sources is independently controllable and can be tuned using the parameter RNOIC, although the use of default value 0.395 is recommended when measured data is not available. As illustrated in Fig. 4, TNOIMOD=1 shows good physical behavior in both the weak and strong inversion regions. The white noise gamma factor \( \gamma_{WN} = \frac{S_{Id}}{4kT_{0}g_{m}} \) shows a value of 1 at low \( V_{ds} \), as expected. At high \( V_{ds} \), it correctly goes to 2/3 for strong inversion and 1/2 in sub-threshold [9]. The relevant formulations of TNOIMOD=2 are given below. For more details, see Ph.D. thesis of Darsen Lu and BSIM4 manual.

\[ \beta_{tnoi} = RNOIA \cdot \left[ 1.0 + TNOIA \cdot L_{eff} \cdot \left( \frac{q_i a}{E_{sat,noi} L_{eff}} \right)^2 \right] \]  \hspace{1cm} (2.269)

\[ \theta_{tnoi} = RNOIB \cdot \left[ 1.0 + TNOIB \cdot L_{eff} \cdot \left( \frac{q_i a}{E_{sat,noi} L_{eff}} \right)^2 \right] \]  \hspace{1cm} (2.270)

\[ c_{tnoi} = RNOIC \cdot \left[ 1.0 + TNOIC \cdot L_{eff} \cdot \left( \frac{q_i a}{E_{sat,noi} L_{eff}} \right)^2 \right] \]  \hspace{1cm} (2.271)
\[ S_{id} = 4KT \cdot \mu C_{ox} \frac{W_{eff}}{L_{vsat}} V_{i} D_{ptwg} M_{oc} \left[ \frac{q_{s} + q_{deff}}{2} + \frac{(q_{s} - q_{deff})^2}{12 \left( \frac{1+q_{s}+q_{deff}}{2} \right)} \right] \cdot (3 \cdot \beta_{tnoi}^2) \] (2.273)

\[ S_{ig} = 4KT \cdot \frac{1}{12 \cdot NF \cdot W_{eff} \mu_{eff} \cdot D_{ptwg} M_{oc} C_{ox} \cdot V_{i} L_{eff}^2} \left[ \frac{q_{s}+q_{deff}}{2} \right]^{3} \left( \frac{1+q_{s}+q_{deff}}{2} \right)^{2} \]
\[ - \frac{6 \left( \frac{1+q_{s}+q_{deff}}{2} \right) (q_{s} - q_{deff})^2}{60 \left( \frac{1+q_{s}+q_{deff}}{2} \right)^4} + \frac{(q_{s} - q_{deff})^4}{144 \left( \frac{1+q_{s}+q_{deff}}{2} \right)^5} \] \cdot \left( \frac{15}{4} \cdot \theta_{tnoi}^2 \right) \] (2.274)

\[ S_{ig,id} = -j \omega \cdot 4KT \cdot \mu C_{ox} D_{ptwg} M_{oc} V_{i} \frac{L_{vsat}}{L_{eff}} \left[ \frac{(q_{s} - q_{deff})}{12 \left( \frac{1+q_{s}+q_{deff}}{2} \right)} - \frac{(q_{s} - q_{deff})^3}{144 \left( \frac{1+q_{s}+q_{deff}}{2} \right)^3} \right] \cdot c_{tnoi} \] (2.275)

\[ c = \frac{S_{ig,id}}{\sqrt{S_{ig} \cdot S_{id}}} \] (2.276)

Figure 4: TNOIMOD=1 shows good physical behavior at high and low \(V_{ds}\) from sub-threshold to strong inversion regions.
2.19.3 Gate Current Shot Noise

\[
\overline{i_{gs}^2} = 2q(I_{gcs} + I_{gs}) \tag{2.277}
\]
\[
\overline{i_{gd}^2} = 2q(I_{gcd} + I_{gd}) \tag{2.278}
\]
\[
\overline{i_{gb}^2} = 2qI_{gbinv} \tag{2.279}
\]

2.19.4 Resistor Noise

The noise associated with each parasitic resistors in BSIM6 are calculated If \( RDSMOD = 1 \) then

\[
\overline{i_{RS}^2} = 4kT \cdot \frac{1}{R_{\text{source}}} \tag{2.280}
\]
\[
\overline{i_{RD}^2} = 4kT \cdot \frac{1}{R_{\text{drain}}} \tag{2.281}
\]

If \( RGATEMOD = 1 \) then

\[
\overline{i_{RG}^2} = 4kT \cdot \frac{1}{R_{\text{geltd}}} \tag{2.282}
\]

2.20 Self Heating Model

Effect of self heating is modeled by employing a thermal network consisting of thermal resistance \( R_{th} \) and capacitance \( C_{th} \) as shown in Fig.5. The voltage at thermal node T gives the rise in temperature, which is added to the ambient temperature and all the temperature sensitive variables in the model are updated accordingly.

\[
R_{th} = \frac{RTH0}{(WTH0 + Weff) \cdot NF}
\]

\[
C_{th} = CTH0 \ast (WTH0 + Weff) \cdot NF
\]
3 Asymmetrical MOS Junction Diode Models

3.1 Junction Diode IV Model

In BSIM6, there is only one diode model (DIOMOD=2 from BSIM4), which includes resistance and breakdown. BSIM6 models the diode breakdown with current limiting in both forward IJTHSFWD or IJTHDFWD and reverse operations XJBVS, XJBVD, BVS, and BVD.

**Source/Body Junction Diode**  The equations for the source-side diode are as follows:

\[ I_{bs} = I_{sbs} \left[ \exp \left( \frac{V_{bs}}{NJS \cdot V_t} \right) - 1 \right] \cdot f_{breakdown} + V_{bs} \cdot G_{min} \]  \hspace{1cm} (3.1)

where \( I_{sbs} \) is the total saturation current consisting of the components through the gate-edge (Jssws) and isolation-edge sidewalls (Jssws) and the bottom junction (Jss),

\[ I_{sbs} = A_{seff}J_{ss}(T) + P_{seff}J_{ssws}(T) + W_{effcj} \cdot NF \cdot J_{ssws}(T) \]  \hspace{1cm} (3.2)
where the calculation of the junction area and perimeter is discussed in section Layout-Dependent Parasitics Models, and the temperature-dependent current density model is given in Section Temperature Dependence of Junction Diode IV. The exponential term in equation given below is linearized at both the limiting current $I_{JTHFWD}$ in the forward-bias mode and the limiting current $I_{JTHREV}$ in the reverse-bias mode. In (3.1), $f_{breakdown}$ is given by

$$f_{breakdown} = 1 + X_{JBVS} \cdot \exp\left(- \frac{(BVS + V_{bs})}{NJS \cdot V_t}\right)$$

where $X_{JBVS} \leq 0.0$, it is reset to 1.0.

**Drain/Body Junction Diode** The equations for the drain-side diode are as follows:

$$I_{bd} = I_{sbd} \left[ \exp\left( \frac{V_{bd}}{NJD \cdot V_t} \right) - 1 \right] \cdot f_{breakdown} + V_{bd} \cdot G_{min}$$

where $I_{sbs}$ is the total saturation current consisting of the components through the gate-edge ($J_{sswgs}$) and isolation-edge sidewalls ($J_{ssws}$) and the bottom junction ($J_{ss}$),

$$I_{sbd} = A_{defj} J_{sd}(T) + P_{defj} J_{sswd}(T) + W_{effcj} \cdot \frac{NF}{J_{sswgd}(T)}$$

where the calculation of the junction area and perimeter is discussed in section Layout-Dependent Parasitics Models, and the temperature-dependent current density model is given in Section Temperature Dependence of Junction Diode IV. The exponential term in (3.6) is linearized at both the limiting current $I_{JTHFWD}$ in the forward-bias mode and the limiting current $I_{JTHREV}$ in the reverse-bias mode. In (3.1), $f_{breakdown}$ is given by

$$f_{breakdown} = 1 + X_{JBVD} \cdot \exp\left(- \frac{(BVD + V_{bd})}{NJD \cdot V_t}\right)$$

where $X_{JBVD} \leq 0.0$, it is reset to 1.0.

**Total Junction Source/Drain Diode Including Tunneling** Total diode current including the carrier recombination and trap-assisted tunneling current in the space-
charge region is modeled by:

\[ I_{bs,totle} = I_{bs} - W_{effcj} \cdot NF \cdot J_{tsswg}(T) \cdot \left[ \exp\left(\frac{-V_{bs}}{NJTSSWG(T) \cdot Vtm0 \cdot VTSSWGS - V_{bs}}\right) \right] - P_{s,deff}J_{tssws}(T) \left[ \exp\left(\frac{-V_{bs}}{NJTSSW(T) \cdot Vtm0 \cdot VTSSWS - V_{bs}}\right) - 1 \right] - A_{s,deff}J_{tss}(T) \left[ \exp\left(\frac{-V_{bs}}{NJTSSW(T) \cdot Vtm0 \cdot VTSSWS - V_{bs}}\right) - 1 \right] + g_{min} \cdot V_{bs} \quad (3.7) \]

\[ I_{bd,totle} = I_{bd} - W_{effcj} \cdot NF \cdot J_{tsswd}(T) \cdot \left[ \exp\left(\frac{-V_{bd}}{NJTSSWD(T) \cdot Vtm0 \cdot VTSSWGD - V_{bd}}\right) \right] - P_{d,deff}J_{tsswd}(T) \left[ \exp\left(\frac{-V_{bd}}{NJTSSWD(T) \cdot Vtm0 \cdot VTSSWGD - V_{bd}}\right) - 1 \right] - A_{d,deff}J_{tsd}(T) \left[ \exp\left(\frac{-V_{bd}}{NJTSD(T) \cdot Vtm0 \cdot VTSD - V_{bd}}\right) - 1 \right] + g_{min} \cdot V_{bd} \quad (3.8) \]

### 3.2 Junction Diode CV Model

Source and drain junction capacitances consist of three components: the bottom junction capacitance, sidewall junction capacitance along the isolation edge, and sidewall junction capacitance along the gate edge. An analogous set of equations are used for both sides but each side has a separate set of model parameters.

**Source/Body Junction Diode** The source-side junction capacitance can be calculated by

\[ C_{bs} = A_{seff}C_{jbs} + P_{seff}C_{jbsw} + W_{effcj} \cdot NF \cdot C_{jbswg} \quad (3.9) \]

where \( C_{jbs} \) is the unit-area bottom S/B junciton capacitance, \( C_{jbsw} \) is the unit-length S/B junction sidewall capacitance along the isolation edge, and \( C_{jbswg} \) is the unit-length S/B junction sidewall capacitance along the gate edge. The effective area and perimeters in (3.9) are given in Section Layout-Dependent Parasitics Models.
Cjbs is calculated by

\[
C_{jbs} = \begin{cases} 
    C_{JS}(T) \cdot \left(1 - \frac{V_{bs}}{P_{BS}(T)} \right)^{-MJS} & \text{if } \frac{V_{bs}}{P_{BS}(T)} \leq x_0 \\
    C_{JS}(T) \cdot \frac{1}{(1-x_0)^{MJS}} \cdot \left[ 1 + MJS \left(1 + \frac{V_{bs}}{P_{BS}(T)} - 1 \right) \right] & \text{otherwise}
\end{cases}
\]  

(3.10)

where the value of \(x_0\) is taken as 0.9.

Cjbssw is calculated by

\[
C_{jbsw} = \begin{cases} 
    C_{JSWS}(T) \cdot \left(1 - \frac{V_{bs}}{P_{BSWS}(T)} \right)^{-MJSWS} & \text{if } \frac{V_{bs}}{P_{BSWS}(T)} \leq x_0 \\
    C_{JSWS}(T) \cdot \frac{1}{(1-x_0)^{MJSWS}} \cdot \left[ 1 + MJSWS \left(1 + \frac{V_{bs}}{P_{BSWS}(T)} - 1 \right) \right] & \text{otherwise}
\end{cases}
\]  

(3.11)

where the value of \(x_0\) is taken as 0.9.

Cbsswg is calculated by

\[
C_{jbswg} = \begin{cases} 
    C_{JSWGS}(T) \cdot \left(1 - \frac{V_{bs}}{P_{BSWGS}(T)} \right)^{-MJSWGS} & \text{if } \frac{V_{bs}}{P_{BSWGS}(T)} \leq x_0 \\
    C_{JSWGS}(T) \cdot \frac{1}{(1-x_0)^{MJSWGS}} \cdot \left[ 1 + MJSWGS \left(1 + \frac{V_{bs}}{P_{BSWGS}(T)} - 1 \right) \right] & \text{otherwise}
\end{cases}
\]  

(3.12)

where the value of \(x_0\) is taken as 0.9.

Drain/Body Junction Diode The drain-side junction capacitance can be calculated by

\[
C_{bd} = A_{deff} C_{jbd} + P_{deff} C_{jbdsw} + W_{effcj} \cdot NF \cdot C_{jbswg}
\]  

(3.13)
where $C_{jbd}$ is the unit-area bottom D/B junction capacitance, $C_{jbdsw}$ is the unit-length D/B junction sidewall capacitance along the isolation edge, and $C_{jbdswg}$ is the unit-length D/B junction sidewall capacitance along the gate edge. The effective area and perimeters in (3.13) are given in Section Layout-Dependent Parasitics Models.

**$C_{jbd}$ is calculated by**

$$C_{jbd} = \begin{cases} 
C_{JD}(T) \cdot \left(1 - \frac{V_{bs}}{PBD(T)}\right)^{-MJD} & \text{if } \frac{V_{bs}}{PBD(T)} \leq x_0 \\
C_{JD}(T) \cdot \frac{1}{(1-x_0)MJD} \cdot \left[1 + MJD \left(1 + \frac{V_{bs}}{PBD(T)}\right)\right] & \text{otherwise}
\end{cases}$$

(3.14)

where the value of $x_0$ is taken as 0.9.

**$C_{jbdsw}$ is calculated by**

$$C_{jbdsw} = \begin{cases} 
C_{JSWD}(T) \cdot \left(1 - \frac{V_{bs}}{PBSWD(T)}\right)^{-MJSWS} & \text{if } \frac{V_{bs}}{PBSWD(T)} \leq x_0 \\
C_{JSWD}(T) \cdot \frac{1}{(1-x_0)MJSWD} \cdot \left[1 + MJSWD \left(1 + \frac{V_{bs}}{PBSWD(T)}\right)\right] & \text{otherwise}
\end{cases}$$

(3.15)

where the value of $x_0$ is taken as 0.9.

**$C_{jbdswg}$ is calculated by**

$$C_{jbdswg} = \begin{cases} 
C_{JSWGD}(T) \cdot \left(1 - \frac{V_{bs}}{PBSWGD(T)}\right)^{-MJSWGD} & \text{if } \frac{V_{bs}}{PBSWGD(T)} \leq x_0 \\
C_{JSWGD}(T) \cdot \frac{1}{(1-x_0)MJSWGD} \cdot \left[1 + MJSWGD \left(1 + \frac{V_{bs}}{PBSWGD(T)}\right)\right] & \text{otherwise}
\end{cases}$$

(3.16)

where the value of $x_0$ is taken as 0.9.
4 Layout dependent Parasitics Models

4.1 Layout-Dependent Parasitics Models

BSIM6 provides a comprehensive and versatile geometry/layout-dependent parasitics model taken from BSIM4. It supports modeling of series (such as isolated, shared, or merged source/drain) and multi-finger device layout, or a combination of these two configurations. This model has impact on every BSIM6 sub-models except the substrate resistance network model. Note that the narrow-width effect in the per-finger device with multi-finger configuration is accounted for by this model. A complete list of model parameters and selectors can be found at the end.

4.1.1 Geometry Definition

Figure 6 schematically shows the geometry definition for various source/drain connections and source/drain/gate contacts. The layout parameters shown in this figure will be used to calculate resistances and source/drain perimeters and areas.
4.1.2 Model Formulation and Options

Effective Junction Perimeter and Area: In the following, only the source-side case is illustrated. The same approach is used for the drain side. The effective junction perimeter on the source side is calculated by

If (PS is given)
   if (perMod=0)
       \( P_{seff} = PS \)
   else

Else
\( P_{seff} \) computed from NF, DWJ, geoMod, DMCG, DMCI, DMDG, DMCGT, RSH, and MIN.

The effective junction area on the source side is calculated by

If (AS is given)
   \( A_{seff} = AS \)

Else
\( A_{seff} \) computed from NF, DWJ, geoMod, DMCG, DMCI, DMDG, DMCGT, RSH, and MIN.

In the above, \( P_{seff} \) and \( A_{seff} \) will be used to calculate junction diode IV and CV. \( P_{seff} \) does not include the gate-edge perimeter.

Source/Drain Diffusion Resistance: The source diffusion resistance is calculated by

If (number of sources NRS is given)
ELSE if (rgeoMod=0)
   Source diffusion resistance \( R_{sdiff} \) is not generated.

Else
\( R_{sdiff} \) computed from NF, DWJ, geoMod, DMCG, DMCI, DMDG, DMCGT, RSH, and MIN.

where the number of source squares NRS is an instance parameter. Similarly, the drain diffusion resistance is calculated by

If (number of sources NRD is given)
ELSE if (rgeoMod=0)
   Drain diffusion resistance \( R_{ddiff} \) is not generated.

Else
Table 1: geoMod options.

<table>
<thead>
<tr>
<th>geomod</th>
<th>End Source</th>
<th>End drain</th>
<th>Note</th>
</tr>
</thead>
<tbody>
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<td>isolated</td>
<td>NF=Odd</td>
</tr>
<tr>
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<td>NF=Odd, Even</td>
</tr>
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<td>shared</td>
<td>NF=Odd, Even</td>
</tr>
<tr>
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<td>shared</td>
<td>isolated</td>
<td>NF=Odd, Even</td>
</tr>
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<td>merged</td>
<td>NF=Odd</td>
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<td>merged</td>
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<td>isolated</td>
<td>NF=Odd</td>
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<td>shared</td>
<td>NF=Odd, Even</td>
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</tr>
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<td>sha/iso</td>
<td>NF=Even</td>
</tr>
</tbody>
</table>

$R_{ddiff}$ computed from NF, DWJ, geoMod, DMCG, DMCI, DMDG, DMCGT, RSH, and MIN.

**Gate Electrode Resistance:** The gate electrode resistance with multi-finger configuration is modeled by

$$R_{geltd} = \frac{RSHG \cdot \left( XGW + \frac{W_{effc}}{3NGCON} \right)}{NGCON \cdot \left( L_{\text{drawn}} - XGL \right) \cdot NF} \quad (4.1)$$

**Option for Source/Drain Connections:** Table 1 lists the options for source/drain connections through the model selector geoMod. For multi-finger devices, all inside S/D diffusions are assumed shared.

**Option for Source/Drain Contacts:** Table 2 lists the options for source/drain contacts through the model selector rgeoMod.
5 Temperature dependence Models

5.1 Temperature Dependence Model

Accurate modeling of the temperature effects on MOSFET characteristics is important to predict circuit behavior over a range of operating temperatures (T). The operating temperature might be different from the nominal temperature (TNOM) at which the BSIM6 model parameters are extracted. This chapter presents the BSIM6 temperature dependence models for threshold voltage, mobility, saturation velocity, source/drain resistance, and junction diode IV and CV.
5.1.1 Length Scaling of Temperature parameters

\[ UTE = UTE \cdot \left(1 + UTEL \frac{1}{L_{eff}} \right) \] (5.1)

\[ UA1 = UA1 \cdot \left(1 + UA1L \frac{1}{L_{eff}} \right) \] (5.2)

\[ UD1 = UD1 \cdot \left(1 + UD1L \frac{1}{L_{eff}} \right) \] (5.3)

\[ AT = AT \cdot \left(1 + ATL \frac{1}{L_{eff}} \right) \] (5.4)

\[ PTWGT = PTWGT \cdot \left(1 + PTWGTL \frac{1}{L_{eff}} \right) \] (5.5)

\[ PTWGT = PTWGT \cdot \left(1 + PTWGTL \frac{1}{L_{eff}} \right) \] (5.6)

5.1.2 Temperature Dependence of Threshold Voltage

The temperature dependence of \( V_{th} \) is modeled by

\[ V_{th}(T) = V_{th}(TNOM) + \left(KT1_i + KT2_i \cdot V_{breff} \right) \cdot \left( \frac{T}{TNOM} \right)^{KT1EXP} - 1 \] (5.7)

\[ V_{fb}(T) = V_{fb}(TNOM) - KT1 \cdot \left( \frac{T}{TNOM} - 1 \right) \] (5.7)

\[ VFBSDOFF(T) = VFBSDOFF(TNOM) \cdot [1 + TVFBSDOFF \cdot (T - TNOM)] \] (5.8)

\[ NFACTOR(T) = NFACTOR(TNOM) + TFACTOR \cdot \left( \frac{T}{TNOM} - 1 \right) \] (5.8)

\[ ETA0(T) = ETA0(TNOM) + TETA0 \left( \frac{T}{TNOM} - 1 \right) \] (5.9)
5.1.3 Temperature Dependence of Mobility

\[ U_0(T) = U_0(T_{NOM}) \cdot (T/T_{NOM})^{UTE} \]  
\[ (5.10) \]

\[ U_A(T) = U_A(T_{NOM})[1 + U_A1 \cdot (T - T_{NOM})] \]  
\[ (5.11) \]

\[ U_C(T) = U_C(T_{NOM})[1 + U_C1 \cdot (T - T_{NOM})] \]  
\[ (5.12) \]

\[ U_D(T) = U_D(T_{NOM}) \cdot (T/T_{NOM})^{UD1} \]  
\[ (5.13) \]

\[ U_{CS}(T) = U_{CS}(T_{NOM}) \cdot (T/T_{NOM})^{UCSTE} \]  
\[ (5.14) \]

5.1.4 Temperature Dependence of Saturation Velocity

\[ V_{SAT}(T) = V_{SAT}(T_{NOM}) \cdot (T/T_{NOM})^{-AT} \]  
\[ (5.16) \]

5.1.5 Temperature Dependence of LDD Resistance

\[ rd_{temp} = (T/T_{NOM})^{PRT} \]  
\[ (5.17) \]

\[ rd_{temp} = (T/T_{NOM})^{PRT} \]  
\[ (5.18) \]

**RDSMOD** = 0 (internal source/drain LDD resistance)

\[ RDSW(T) = RDSW(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.19) \]

\[ RDSW_{MIN}(T) = RDSW_{MIN}(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.20) \]

**RDSMOD** = 1 (external source/drain LDD resistance)

\[ RDW(T) = RDW(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.21) \]

\[ RDW_{MIN}(T) = RDW_{MIN}(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.22) \]

\[ RSW(T) = RSW(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.23) \]

\[ RSW_{MIN}(T) = RSW_{MIN}(T_{NOM}) \cdot rd_{temp} \]  
\[ (5.24) \]
5.1.6 Temperature Dependence of Junction Diode IV

- **Source-side diode** The source-side diode is turned off if both $A_{seff}$ and $P_{seff}$ are zero. Otherwise, the source-side saturation current is given by

$$I_{sbs} = A_{seff} J_{ss}(T) + P_{seff} J_{ssws}(T) + W_{effcj} \cdot NF \cdot J_{sswgs}(T) \quad (5.25)$$

where

$$J_{ss}(T) = JSS(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{v_t(TNOM)} - \frac{E_a(T)}{v_t(T)} + XTIS \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJS \right)$$

$$J_{ssws}(T) = JSSWS(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{v_t(TNOM)} - \frac{E_a(T)}{v_t(T)} + XTIS \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJS \right)$$

$$J_{sswgs}(T) = JSSWGS(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{k_b TNOM} - \frac{E_a(T)}{k_b T} + XTIS \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJS \right) \quad (5.26)$$

where $E_g$ is given in Temperature Dependences of $E_g$ and $n_i$.

- **Drain-side diode** The drain-side diode is turned off if both $A_{seff}$ and $P_{seff}$ are zero. Otherwise, the drain-side saturation current is given by

$$I_{sbd} = A_{deff} J_{sd}(T) + P_{deff} J_{sswd}(T) + W_{effcj} \cdot NF \cdot J_{sswgd}(T) \quad (5.27)$$

where

$$J_{sd}(T) = JSD(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{k_b TNOM} - \frac{E_a(T)}{k_b T} + XTID \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJD \right)$$

$$J_{sswd}(T) = JSSWD(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{k_b TNOM} - \frac{E_a(T)}{k_b T} + XTID \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJD \right)$$

$$J_{sswgd}(T) = JSSWGD(TNOM) \cdot \exp \left( \frac{E_a(TNOM)}{k_b TNOM} - \frac{E_a(T)}{k_b T} + XTID \cdot \ln \left( \frac{T}{TNOM} \right) \cdot NJD \right) \quad (5.28)$$
5.1.7 Temperature Dependence of Junction Diode CV

- Source-side diode: The temperature dependences of zero-bias unit-length/area junction capacitances on the source side are modeled by

\[
C_{JS}(T) = C_{JS(TNOM)} + T_{CJ} \cdot (T - T_{NOM}) \tag{5.29}
\]
\[
C_{JSWS}(T) = C_{JSWS(TNOM)} + T_{CJSW} \cdot (T - T_{NOM}) \tag{5.30}
\]
\[
C_{JSWGS}(T) = C_{JSWGS(TNOM)} + T_{CJSWG} \cdot (T - T_{NOM}) \tag{5.31}
\]

The temperature dependences of the built-in potentials on the source side are modeled by

\[
P_{BS}(T) = P_{BS(TNOM)} - T_{PB} \cdot (T - T_{NOM}) \tag{5.32}
\]
\[
P_{BSWS}(T) = P_{BSWS(TNOM)} - T_{PBSW} \cdot (T - T_{NOM}) \tag{5.33}
\]
\[
P_{BSWGS}(T) = P_{BSWGS(TNOM)} - T_{PBSWG} \cdot (T - T_{NOM}) \tag{5.34}
\]

- Drain-side diode: The temperature dependences of zero-bias unit-length/area junction capacitances on the drain side are modeled by

\[
C_{JS}(T) = C_{JS(TNOM)}[1 + T_{CJ} \cdot (T - T_{NOM})] \tag{5.35}
\]
\[
C_{JSWS}(T) = C_{JSWS(TNOM)} + T_{CJSW} \cdot (T - T_{NOM}) \tag{5.36}
\]
\[
C_{JSWGS}(T) = C_{JSWGS(TNOM)}[1 + T_{CJSWG} \cdot (T - T_{NOM})] \tag{5.37}
\]

The temperature dependences of the built-in potentials on the drain side are modeled by

\[
P_{BD}(T) = P_{BD(TNOM)} - T_{PB} \cdot (T - T_{NOM}) \tag{5.38}
\]
\[
P_{BSD}(T) = P_{BSD(TNOM)} - T_{PB} \cdot (T - T_{NOM}) \tag{5.39}
\]
\[
P_{BSWD}(T) = P_{BSWGD(TNOM)} - T_{PB} \cdot (T - T_{NOM}) \tag{5.40}
\]
• trap-assisted tunneling (TAT) and recombination current

\[ J_{\text{tssws}}(T) = J_{\text{tssws}}(TNOM) \cdot \left( \sqrt{\frac{JTWEFF}{W_{\text{effc}}} + 1} \right) \cdot \exp \left[ \frac{-E_g(TNOM)}{k_b T} \cdot X_{\text{tssws}} \cdot \left( 1 - \frac{T}{TNOM} \right) \right] \]  

\[ J_{\text{tss}}(T) = J_{\text{tss}}(TNOM) \cdot \exp \left[ \frac{-E_g(TNOM)}{k_b T} \cdot X_{\text{tss}} \cdot \left( 1 - \frac{T}{TNOM} \right) \right] \]  

\[ J_{\text{tssgd}}(T) = J_{\text{tssgd}}(TNOM) \cdot \left( \sqrt{\frac{JTWEFF}{W_{\text{effc}}} + 1} \right) \cdot \exp \left[ \frac{-E_g(TNOM)}{k_b T} \cdot X_{\text{tssgd}} \cdot \left( 1 - \frac{T}{TNOM} \right) \right] \]  

\[ J_{\text{tsd}}(T) = J_{\text{tsd}}(TNOM) \cdot \exp \left[ \frac{-E_g(TNOM)}{k_b T} \cdot X_{\text{tsd}} \cdot \left( 1 - \frac{T}{TNOM} \right) \right] \]  

\[ N_{JTSSWG}(T) = N_{JTSSWG}(TNOM) \cdot \left[ 1 + T N_{JTSSWG} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

\[ N_{JTSSW}(T) = N_{JTSSW}(TNOM) \cdot \left[ 1 + T N_{JTSSW} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

\[ N_{JTSSWD}(T) = N_{JTSSWD}(TNOM) \cdot \left[ 1 + T N_{JTSSWD} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

\[ N_{JTSSWD}(T) = N_{JTSSWD}(TNOM) \cdot \left[ 1 + T N_{JTSSWD} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

\[ N_{JTSSWD}(T) = N_{JTSSWD}(TNOM) \cdot \left[ 1 + T N_{JTSSWD} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

\[ N_{JTSD}(T) = N_{JTSD}(TNOM) \cdot \left[ 1 + T N_{JTSD} \left( \frac{T}{TNOM} - 1 \right) \right] \]  

(5.43)
5.1.8 Temperature Dependences of $E_g$ and $n_i$

- Energy-band gap of channel ($E_g$): The temperature dependence of $E_g$ is modeled by

$$E_{g0} = B G_{0 SUB} - \frac{T B G A \times T \times T \text{nom}^2}{T \text{nom} + T B G B \times T \times T \text{nom}}$$

$$E_g = B G_{0 SUB} - \frac{T B G A \times T \times T}{T + T B G B \times T \times T}$$

- Intrinsic carrier concentration of non-silicon channel ($n_i$)

$$n_i = N I 0 \times \left(\frac{T}{T \text{nom}}\right)^{(3/2)} \times \exp\left(\frac{E_g}{2kT \text{nom}} - \frac{E_g}{2kT} \right)$$

6 Stress effect Model Development

6.1 Stress Effect Model

CMOS feature size aggressively scaling makes shallow trench isolation (STI) very popular active area isolation process in advanced technologies. Recent years, strain channel materials have been employed to achieve high device performance. The mechanical stress effect induced by these process causes MOSFET performance function of the active area size (OD: oxide definition) and the location of the device in the active area. And the necessity of new models to describe the layout dependence of MOS parameters due to stress effect becomes very urgent in advance CMOS technologies. Influence of stress on mobility has been well known since the 0.13um technology. The stress influence on saturation velocity is also experimentally demonstrated. Stress-induced enhancement or suppression of dopant diffusion during the processing is reported. Since the doping profile may be changed due to different STI sizes and stress, the threshold voltage shift and changes of other second-order effects, such as DIBL and body effect, were shown in process integration. BSIM4 considers the influence of stress on mobility, velocity saturation, threshold voltage, body effect, and DIBL effect.
6.1.1 Stress Effect Model Development

Experimental analysis show that there exist at least two different mechanisms within the influence of stress effect on device characteristics. The first one is mobility-related and is induced by the band structure modification. The second one is Vth-related as a result of doping profile variation. Both of them follow the same 1/LOD trend but reveal different L and W scaling. We have derived a phenomenological model based on these findings by modifying some parameters in the BSIM model. Note that the following equations have no impact on the iteration time because there are no voltage-controlled components in them.

Mobility-related Equations: This model introduces the first mechanism by adjusting the U0 and Vsat according to different W, L and OD shapes. Define mobility relative change due to stress effect as :

\[
\rho_{\mu_{\text{eff}}} = \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}0}} = \frac{(\mu_{\text{eff}} - \mu_{\text{eff}0})}{\mu_{\text{eff}0}} = \frac{\mu_{\text{eff}} - \mu_{\text{eff}0}}{\mu_{\text{eff}0}} - 1 \quad (6.1)
\]

So,

\[
\frac{\mu_{\text{eff}}}{\mu_{\text{eff}0}} = 1 + \rho_{\mu_{\text{eff}}} \quad (6.2)
\]

Figure 7 shows the typical layout of a MOSFET on active layout surrounded by STI isolation. SA, SB are the distances between isolation edge to Poly from one and the other side, respectively. 2D simulation shows that stress distribution can be expressed by a simple function of SA and SB. Assuming that mobility relative change is proportional to stress distribution. It can be described as function of SA, SB(LOD effect), L, W, and
Figure 8: Stress distribution within MOSFET channel using 2D simulation

T dependence:

\[ \rho_{\mu_{\text{eff}}} = \frac{KU_0}{K_{\text{stress}0}} \cdot (\text{Inv}_{\text{sa}} + \text{Inv}_{\text{sb}}) \]  \hspace{1cm} (6.3)

where:

\[ \text{Inv}_{\text{sa}} = \frac{1}{SA + 0.5 \cdot L_{\text{drawn}}} \]  \hspace{1cm} (6.4)

\[ \text{Inv}_{\text{sb}} = \frac{1}{SB + 0.5 \cdot L_{\text{drawn}}} \]  \hspace{1cm} (6.5)

\[ K_{\text{stress}0} = \left( L_{\text{drawn}} + XL \right)^{L_{\text{LOD}}KU_0} \]

\[ \cdot \left( W_{\text{drawn}} + XW + WLOD \right)^{W_{\text{LOD}}KU_0} \]

\[ + \left( L_{\text{drawn}} + XL \right)^{L_{\text{LOD}}KU_0} \cdot \left( W_{\text{drawn}} + XW + WLOD \right)^{W_{\text{LOD}}KU_0} \]

\[ \times \left( 1 + TU_{0} \cdot \left( \frac{\text{Temperature}}{TNOM} - 1 \right) \right) \]  \hspace{1cm} (6.6)

So that:

\[ \mu_{\text{eff}} = \frac{1 + \mu_{\text{eff}}(SA, SB)}{1 + \mu_{\text{eff}}(SA_{ref}, SB_{ref})^{\mu_{\text{eff}0}}} \]  \hspace{1cm} (6.7)

\[ \nu_{\text{sattemp}} = \frac{1 + KV_{\text{SAT}} \cdot \mu_{\text{eff}}(SA, SB)}{1 + KV_{\text{SAT}} \cdot \mu_{\text{eff}}(SA_{ref}, SB_{ref})^{\nu_{\text{sattemp}0}}} \]  \hspace{1cm} (6.8)
and $SA_{ref}$, $SB_{ref}$ are reference distances between OD edge to poly from one and the other side.

**Vth-related Equations:** $Vth_0$ (threshold voltage without stress effect), $K2$ and $ETA_0$ are modified to cover the doping profile change in the devices with different LOD. They use the same 1/LOD formulas as shown in earlier sections, but different equations for W and L scaling:

\[
\begin{align*}
VTH_0 &= VTH_{0\text{original}} + \frac{KVTH_0}{K_{\text{stress,vth}0}} \cdot (\text{Inv}_{sa} + \text{Inv}_{sb} - \text{Inv}_{sa_{\text{ref}}} - \text{Inv}_{sb_{\text{ref}}}) \\
K2 &= K_{2\text{original}} + \frac{STK2}{K_{\text{stress,vth}0}LODK2} \cdot (\text{Inv}_{sa} + \text{Inv}_{sb} - \text{Inv}_{sa_{\text{ref}}} - \text{Inv}_{sb_{\text{ref}}}) \\
ETA0 &= ETA_{0\text{original}} + \frac{STETA0}{K_{\text{stress,vth}0}LODETA0} \cdot (\text{Inv}_{sa} + \text{Inv}_{sb} - \text{Inv}_{sa_{\text{ref}}} - \text{Inv}_{sb_{\text{ref}}})
\end{align*}
\]

where:

\[
\begin{align*}
\text{Inv}_{sa_{\text{ref}}} &= \frac{1}{SA_{\text{ref}} + 0.5 \cdot L_{\text{drawn}}} \\
\text{Inv}_{sb_{\text{ref}}} &= \frac{1}{SB_{\text{ref}} + 0.5 \cdot L_{\text{drawn}}} \\
K_{\text{stress,vth}0} &= \left(1 + \frac{LKVTH_0}{(L_{\text{drawn}} + XL)^{LODKVTH}} \right) + \frac{WKVTH0}{(W_{\text{drawn}} + XW + WLOD)^{WLODKVTH}} + \frac{PKVTH0}{(L_{\text{drawn}} + XL)^{LODKVTH} \cdot (W_{\text{drawn}} + XW + WLOD)^{WLODKVTH}}
\end{align*}
\]

**Multiple Finger Device:** For multiple finger device, the total LOD effect is the average of LOD effect to every finger. That is (see Figure 9) for the layout for multiple
Figure 9: Layout of multiple finger MOSFET

finger device):

\[
Inv_{sa} = \frac{1}{NF} \sum_{i=0}^{NF-1} \frac{1}{SA + 0.5 \cdot L_{\text{drawn}} + i \cdot (SD + L_{\text{drawn}})}
\]  

(6.13)

\[
Inv_{sb} = \frac{1}{NF} \sum_{i=0}^{NF-1} \frac{1}{SB + 0.5 \cdot L_{\text{drawn}} + i \cdot (SD + L_{\text{drawn}})}
\]  

(6.14)

\[
(6.15)
\]

6.1.2 Effective SA and SB for Irregular LOD

General MOSFET has an irregular shape of active area shown in Figure 10. To fully describe the shape of OD region will require additional instance parameters. However, this will result in too many parameters in the net lists and would massively increase the read-in time and degrade the readability of parameters. One way to overcome this difficulty is the concept of effective SA and SB similar to [10]. Stress effect model as described earlier allows an accurate and efficient layout extraction of effective SA and
Figure 10: A typical layout of MOS devices with more instance parameters (swi, sai and sbi) in addition to the traditional L and W SB while keeping fully compatibility of the LOD model. They are expressed as:

\[
\frac{1}{SA_{\text{eff}} + 0.5 \cdot L_{\text{drawn}}} = \sum_{i=1}^{n} \frac{sw_i}{W_{\text{drawn}}} \cdot \frac{1}{sa_i + 0.5 \cdot L_{\text{drawn}}}
\]

(6.16)

\[
\frac{1}{SB_{\text{eff}} + 0.5 \cdot L_{\text{drawn}}} = \sum_{i=1}^{n} \frac{sw_i}{W_{\text{drawn}}} \cdot \frac{1}{sb_i + 0.5 \cdot L_{\text{drawn}}}
\]

(6.17)

\[
(6.18)
\]

7 Well Proximity Effect Model

8 Well Proximity Effect Model

Retrograde well profiles have several key advantages for highly scaled bulk complementary metal oxide semiconductor (CMOS) technology. With the advent of high-energy implanters and reduced thermal cycle processing, it has become possible to provide a relatively heavily doped deep nwell and pwell without affecting the critical device-related doping at the surface. The deep well implants provide a low resistance path and suppress parasitic bipolar gain for latchup protection, and can also improve soft error rate
and noise isolation. A deep buried layer is also key to forming triple-well structures for isolated-well NMOSFETs. However, deep buried layers can affect devices located near the mask edge. Some of the ions scattered out of the edge of the photoresist are implanted in the silicon surface near the mask edge, altering the threshold voltage of those devices [11]. It is observed a threshold voltage shifts of up to 100 mV in a deep boron retrograde pwell, a deep phosphorus retrograde nwell, and also a triple-well implementation with a deep phosphorus isolation layer below the pwell over a lateral distance on the order of a micrometer [11]. This effect is called well proximity effect. BSIM6 considers the influence of well proximity effect on threshold voltage, mobility, and body effect. This well proximity effect model is developed by the Compact Model Council [12].

8.1 Well Proximity Effect Model

Experimental analysis [11] shows that well proximity effect is strong function of distance of FET from mask edge, and electrical quantities influenced by it follow the same geometrical trend. A phenomenological model based on these findings has been developed by modifying some parameters in the BSIM model. Note that the following equations have no impact on the iteration time because there are no voltage controlled components in them. Well proximity affects threshold voltage, mobility and the body effect of the device. The effect of the well proximity can be described through the following equations:

\[
\begin{align*}
    V_{th0} &= V_{th0_{org}} + K_{VTH0WE} \cdot (SCA + WEB \cdot SCB + WEC \cdot SCC) \\
    K2 &= K_{2_{org}} + K_{2WE} \cdot (SCA + WEB \cdot SCB + WEC \cdot SCC) \\
    \mu_{eff} &= \mu_{eff_{org}} \cdot (1 + KU_{0WE} \cdot (SCA + WEB \cdot SCB + WEB \cdot SCC))
\end{align*}
\] (8.1)

where SCA, SCB, SCC are instance parameters that represent the integral of the first/second/third distribution function for scattered well dopant. The guidelines for calculating the instance parameters SCA, SCB, SCC have been developed by the Compact Model Council which can be found at the CMC website [12].
9 C-V Model

**Inversion Charge:** Total inversion charge (excluding velocity saturation, CLM and poly depletion) can be expressed explicitly in terms of normalized charge densities at source and drain sides as follows,

\[ Q_I = W \cdot \int_0^L Q_i \, dx \]  
\[ = -WL \cdot C_{ox} \cdot V_t \int_0^1 2nq \cdot q \, d\xi \]  
\[ - \frac{Q_I}{WL \cdot C_{ox} V_t} = q_I = 2nq \cdot \int_0^1 q \, d\xi \]  

Here \( \xi = \frac{x}{L} \). Inversion charge density is normalized to \(-2nq.C_{ox}.V_t\) and voltages to \(V_t\). From (2.204),

\[ I_{ds} = -2nq \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2 \cdot (2q + 1) \frac{dq}{d\xi} \]  

Normalizing current with \(2nq \cdot \mu_{eff} \cdot \frac{W_{eff}}{L_{eff}} \cdot C_{ox} \cdot nV_t^2\),

\[ i = -(2q + 1) \frac{dq}{d\xi} \]  

which gives \(d\xi = \frac{(2q+1)}{(2q+1)} dq = \frac{(2q+1)}{(qs - q_d)(1 + qs + q_d)} dq\). Substituting in (9.3)

\[ q_I = -\frac{2nq}{(qs - q_d)(1 + qs + q_d)} \int_{qs}^{qd} q(2q + 1) \, dq \]  
\[ = -\frac{2nq}{(qs - q_d)(1 + qs + q_d)} \left[ \frac{2}{3}(qd^3 - qs^3) + \frac{1}{2}(qd^2 - qs^2) \right] \]  

on rearranging,

\[ q_I = nq \cdot \left[ qs + q_d + \frac{1}{3} \frac{(qs - q_d)^2}{1 + qs + q_d} \right] \]  

**Bulk Charge:** Bulk charge density is given as

\[ Q_b = -C_{ox} \cdot (V_G - V_{FB} - \psi_S) - Q_i \]  

(9.9)
using charge linearization

\[ Q_b = -C_{ox} \cdot (V_G - V_{FB} - \psi_P) - Q_i \left( 1 - \frac{1}{n_q} \right) \]  \hspace{1cm} (9.11)

Total bulk charge,

\[ Q_B = W \cdot \int_0^L Q_b \, dx \]  \hspace{1cm} (9.12)

\[ = -W L \cdot C_{ox} \cdot \left[ V_G - V_{FB} - \psi_P + \left( 1 - \frac{1}{n_q} \right) \cdot \int_{q_s}^{q_d} \frac{Q_i \, d\xi}{C_{ox}} \right] \]  \hspace{1cm} (9.13)

Normalizing the bulk charge to \(-W.L.C_{ox}.V_t\),

\[ q_B = v_g - v_{fb} - \psi_p - 2(n_q - 1) \cdot \int_0^1 q \, d\xi \]  \hspace{1cm} (9.14)

We know that \(i_{ds} = -(2q + 1) \frac{dq}{d\xi}\) with \(i_{ds}\) given by (2.212). Thus \(d\xi = -\frac{(2q+1)}{i_{ds}} \, dq\),

\[ q_B = v_g - v_{fb} - \psi_p + \frac{2(n_q - 1)}{i_{ds}} \cdot \int_{q_s}^{q_d} q(2q + 1) \, dq \]  \hspace{1cm} (9.15)

\[ = v_g - v_{fb} - \psi_p + \frac{2(n_q - 1)}{(q_s - q_d)(1 + q_s + q_d)} \int_{q_s}^{q_d} \left[ \frac{2q^3}{3} + \frac{q^2}{2} \right] \]  \hspace{1cm} (9.16)

\[ = v_g - v_{fb} - \psi_p + \frac{2(n_q - 1)}{(q_s - q_d)(1 + q_s + q_d)} \left[ \frac{2}{3} \cdot (q_d - q_s)(q_d^2 + q_s^2 + q_d q_s) + \frac{1}{2} \cdot (q_d - q_s)(q_d + q_s) \right] \]  \hspace{1cm} (9.17)

which on rearrangement becomes,

\[ q_B = v_g - v_{fb} - \psi_p - (n_q - 1) \left[ q_s + q_d + \frac{1}{3} \cdot \frac{(q_s - q_d)^2}{1 + q_s + q_d} \right] \]  \hspace{1cm} (9.18)

Bulk charge with poly depletion effect:

\[ q_B = A + B + \frac{1}{3} \Delta q^2 \cdot \frac{4}{8} \cdot \left( C^2 + P.Q \right) \cdot \frac{1}{1 + q_s + q_d} + \frac{2}{\gamma^2} \]  \hspace{1cm} (9.19)
where

\[ P = \sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_s}{\gamma_g^2}} \]  \hspace{1cm} (9.20)

\[ Q = \sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_d}{\gamma_g^2}} \]  \hspace{1cm} (9.21)

\[ A = \frac{v_g - v_{fb} - \psi_p + 2q_s}{1 + 2\sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_s}{\gamma_g^2}}} \]  \hspace{1cm} (9.22)

\[ B = \frac{v_g - v_{fb} - \psi_p + 2q_d}{1 + 2\sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_s}{\gamma_g^2}}} \]  \hspace{1cm} (9.23)

\[ C = \sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_s}{\gamma_g^2}} + \sqrt{\frac{1}{4} + \frac{v_g - v_{fb} - \psi_p + 2q_d}{\gamma_g^2}} \]  \hspace{1cm} (9.24)

**Source and Drain Charges**

\[ Q_s = \frac{n_q}{3} \left[ 2q_s + q_{deff} + \frac{1}{2} \left( 1 + \frac{4}{5}q_s + \frac{6}{5}q_{deff} \right) \left( \frac{q_s - q_{deff}}{1 + q_s + q_{deff}} \right)^2 \right] \]  \hspace{1cm} (9.25)

\[ Q_d = \frac{n_q}{3} \left[ q_s + 2q_{deff} + \frac{1}{2} \left( 1 + \frac{6}{5}q_s + \frac{4}{5}q_{deff} \right) \left( \frac{q_s - q_{deff}}{1 + q_s + q_{deff}} \right)^2 \right] \]  \hspace{1cm} (9.26)

**Quantum Mechanical Effect**

\[ X_{inv}^{DC} = \frac{ADOS \cdot (1.9 \cdot 10^{-9})}{1 + \left[ \frac{Q_i + ETAQM \cdot Q_{QM}}{Q_{QM}} \right]^{0.7_{B/DOS}}} \]  \hspace{1cm} (9.28)

\[ C_{inv}^{ox} = \frac{3.9 \cdot \epsilon_0}{TOXP \cdot \frac{3.9}{EPSROX} + \frac{X_{inv}^{DC}}{\epsilon_{ratio}}} \]  \hspace{1cm} (9.29)

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Intrinsic Charge expressions:

\[ WLCOXV_{t_{inv}} = NF \cdot W_{act} \cdot L_{act} \cdot C_{ox}^{inv} \cdot nVt \]  (9.30)

\[ QB_i = -NF \cdot W_{act} \cdot L_{act} \cdot \left( \frac{\epsilon_0 \cdot EPSROX}{TOXP} \right) \cdot nVt \cdot Q b \]  (9.31)

\[ QS_i = -WLCOXVt_{inv} \cdot Q_s \]  (9.32)

\[ QD_i = -WLCOXVt_{inv} \cdot Q_d \]  (9.33)

\[ QG_i = QS_i + QD_i + QB_i \]  (9.34)

Bias-dependent overlap capacitance model

An accurate overlap capacitance model is essential. This is especially true for the drain side where the effect of the capacitance is amplified by the transistor gain. The overlap capacitance changes with gate to source and gate to drain biases. In LDD MOSFETs a substantial portion of the LDD region can be depleted, both in the vertical and lateral directions. This can lead to a large reduction of the overlap capacitance. This LDD region can be in accumulation or depletion. We use a single equation for both regions by using such smoothing parameters as \( V_{gs,overlap} \) and \( V_{gd,overlap} \) for the source and drain side, respectively. Unlike the case with the intrinsic capacitance, the overlap capacitances are reciprocal. In other words, \( C_{gs,overlap} = C_{sg,overlap} \) and \( C_{gd,overlap} = C_{dg,overlap} \).

The bias-dependent overlap capacitance model in BSIM6 is adopted from BSIM4. The overlap charge is given by:

\[ \frac{Q_{gs,ov}}{NF \cdot W_{eff}CV} = CGSO \cdot V_{gs} + CGSL \cdot \left[ V_{gs} - V_{fbd} - V_{gs,overlap} - \frac{CKAPPAS}{2} \left( \sqrt{1 - \frac{4V_{gs,overlap}}{CKAPPAS}} - 1 \right) \right] \]  (9.35)
\[
\frac{Q_{gd,ov}}{NF \cdot W_{effCV}} = CGDO \cdot V_{gd} + 
\]
\[
CGDL \cdot \left[ V_{gd} - V_{fbsd} - V_{gd,overlap} - \frac{CKAPPAD}{2} \left( \sqrt{1 - \frac{4V_{gd,overlap}}{CKAPPAD}} - 1 \right) \right] 
\]
\[\text{(9.36)}\]
\[
V_{gs,overlap} = \frac{1}{2} \left[ V_{gs} - V_{fbsd} + \delta_1 - \sqrt{(V_{gs} - V_{fbsd} + \delta_1)^2 + 4\delta_1} \right] 
\]
\[\text{(9.37)}\]
\[
V_{gd,overlap} = \frac{1}{2} \left[ V_{gd} - V_{fbsd} + \delta_1 - \sqrt{(V_{gd} - V_{fbsd} + \delta_1)^2 + 4\delta_1} \right] 
\]
\[\text{(9.38)}\]
\[
\delta_1 = 0.02V 
\]
\[\text{(9.39)}\]

**Outer Fringing Capacitance**

The fringing capacitance consists of a bias-independent outer fringing capacitance and a bias-dependent inner fringing capacitance. Only the bias-independent outer fringing capacitance is modeled. If \( CF \) is not given then outer fringe capacitance is calculated as

\[
CF = \frac{2 \cdot EPSROX \cdot \epsilon_0}{\pi} \cdot ln[CFRCOEFF \cdot (1 + \frac{0.4e - 6}{TOX})] 
\]
\[\text{(9.40)}\]
10 Parameter Extraction Procedure

The objective of this section is to provide guidelines for the extraction of the main model parameters. The procedure is structured in such a way that parameters linked to specific psychological phenomena are extracted from analyses where these effects are prominent. Although parameter extraction is not always a straightforward procedure, the aim is to minimize the effort invested and the number of the essential loops performed.

If all the steps of the described procedure are followed then a global model card is obtained which means that the model can be used across the entire width/length plane of the technology. If a local fitting is targeted, then only the parameters of Section 10.1 need to be extracted for each DUT. However, in that case binning is necessary if the model card is to be used for the entire geometry range of the technology. Irrespective of the choice between global and local fitting, different model cards should be extracted for nmos and pmos devices or for different technologies.

Before proceeding to the extraction of any parameter, it is very important that $TNOM$ is set to the value of the temperature at which the measurements were carried out. Also, it is recommended that if they are available, the values of the process parameters are provided. The most common process parameters are shown in Table 3.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Physical Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPSROX</td>
<td>Relative Gate Dielectric Constant</td>
</tr>
<tr>
<td>EPSRSUB</td>
<td>Relative Dielectric Constant of the Channel</td>
</tr>
<tr>
<td>TOXE</td>
<td>Electrical Gate Equivalent Oxide Thickness</td>
</tr>
<tr>
<td>TOXP or DTOX</td>
<td>Physical Gate Equivalent Oxide Thickness</td>
</tr>
<tr>
<td>NDEP</td>
<td>Channel Doping Concentration</td>
</tr>
<tr>
<td>NGATE</td>
<td>Gate Doping Concentration</td>
</tr>
<tr>
<td>NSD</td>
<td>S/D Doping Concentration</td>
</tr>
<tr>
<td>XJ</td>
<td>S/D Junction Depth</td>
</tr>
<tr>
<td>XW/XL</td>
<td>Channel W/L Offset due to Mask/Etch Effect</td>
</tr>
</tbody>
</table>

Table 3: Process parameters which are recommended to be provided before parameter extraction.
10.1 Extraction of Geometry Independent Parameters

The first part of the model parameter extraction procedure is to extract the parameters that are related to the main physical phenomena, which define transistor’s behavior, and are also geometry independent. For that, a wide and long channel device should be chosen. At this point, WWIDE and LLONG parameters must be assigned to the values of the width and length of this large chosen DUT. This ensures that once the behavior of the long/wide channel device is fitted, it cannot be further affected by the values scaling parameters that will be extracted in the next steps.

10.1.1 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_S = 0$ V, $V_D = 0$ V & $V_B = 0$ V

At this step process parameters and parameters related to quantum mechanical effect are extracted. Even if values have been already assigned to process parameters, a fine tuning should be made in order to fit accurately the electrical behavior of the device. From $C_{GG}$ vs. $V_G$ analysis the following process parameters can be extracted: NDEP, TOXE, VFB and NGATE. Each of these parameters affects a different region or in a different way the $C_{GG}$ capacitance, so they should be extracted accordingly. More specifically:

- **VFB** is defining the flat-band voltage of the device and it can be extracted by studying the region from depletion till the onset of strong-inversion.
- **NDEP** is affecting $C_{GG}$ in the depletion region. If possible, NDEP, which defines the doping level, is better to be extracted from $C_{GB}$ vs. $V_G$ analysis (S and D terminals are grounded).
- **TOXE** is affecting the deep accumulation and strong-inversion regions.
- **NGATE** is related to the poly-silicon depletion effect, so it affects the slope of $C_{GG}$ in the strong-inversion region.

Furthermore, the value of $C_{OX}$ is affected by the Quantum Mechanical effect. So, the parameters: ADOS, BDOS, QM0 and ETAQM are also extracted from $C_{GG}$ vs. $V_G$ analysis, when focusing at the slope of $C_{GG}$ at the onset of the strong-inversion region.
10.1.2 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$, $V_S = 0$ V & $V_B = 0$ V

In this step, the $V_G$ dependence of the drain current - $I_D$, is extracted. Different parameters are extracted in two different regions of operation, namely linear mode (i.e. $V_D \ll V_G - V_{TH}$) and saturation (i.e. $V_D \gg V_G - V_{TH}$). It is very important that during extraction in this step, both $I_D$ and the transconductance - $g_m$ (even $g'_m$ and $g'\prime\prime_m$) are extracted at once.

Linear Mode

- Focusing in weak-inversion region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), NFACTOR, which is related to the sub-threshold slope of the $I_D$, can be extracted. Furthermore, a fine tuning of the NDEP and VFB parameters is performed. In case the values of NDEP and VFB obtained during the fitting of $I_D$ vs. $V_G$ characteristic differ much from those obtained during the fitting of $C_{GG}$ vs. $V_G$ characteristic (Section 10.1.1), parameters NDEPCV and VFBCV can be used for dynamic operation (CV) and NDEP and VFB for static operation (IV). In general, using different values for NDEP and NDEPCV for IV and CV operation is not recommended unless necessary.

- From strong-inversion region, the mobility $U_0$, the parameter for the effective field ETAMOB, the parameters related to the effect of mobility reduction due to vertical field $U_A$ and $E_U$ and the parameters for the coulomb scattering effect $U_D$ and UCS, are extracted. Furthermore, the parameters for S/D series resistances are also extracted under the same bias conditions. If RDSMOD = 0 (internal S/D series resistances), RDSW is extracted. Otherwise, RSW and RDW are extracted.

Saturation

- From weak-inversion region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), CDSCD parameter, which is linked to the dependence of the sub-threshold slope on drain bias, is extracted.

- Focusing in strong-inversion region, the parameters that are connected to the velocity saturation effect, namely VSAT, PSAT, PTWG and PSATX, can be extracted. PSATX does need to be changed.
Finally, from accumulation to depletion region, in both linear mode and saturation, the parameters related to GIDL effect are extracted. First, the selector `GIDLMOD` should be set to 1 to activate GIDL/GILS currents and then the parameters `AGIDL`, `BGIDL`, `CGIDL` and `EGIDL` are extracted. Ideally GIDL and GILS currents should be equal, so it is sufficient to extract `AGIDL`, `BGIDL`, `CGIDL` and `EGIDL` parameters. But in case GIDL and GILS currents differ, then parameters `AGISL`, `BGISL`, `CGISL` and `EGISL` can also be used.

### 10.1.3 Gate Current $I_G$ vs. $V_G$ Analysis @ various $V_D$, $V_S = 0$ V & $V_B = 0$ V

From $I_G$ vs. $V_G$ analysis, parameters related to the gate current can be extracted. First, the tunneling components should be activated by setting to 1 the selectors `IGC-MOD` and `IGBMOD`. Different parameters are extracted in different regions of operation and more specifically:

**Accumulation to weak-inversion Region**

- **AIGBACC, BIGBACC, CIGBACC** and **NIGBACC**, which are linked to the gate-to-substrate current component determined by ECB.
- **AIGS, BIGS** and **CIGS**, which are linked to the tunneling current between the gate and the source diffusion region and **AIGD, BIGD** and **CIGD**, which are linked to the tunneling current between the gate and the drain diffusion region.
- **DLCIG** and **DLCIGD**, which are linked to the S/D overlap length for $I_{GS}$ and $I_{GD}$ respectively.

**Weak to strong-inversion Region**

- **AIGBINV, BIGBINV, CIGBINV, EIGBINV** and **NIGBINV**, which are linked to the gate-to-substrate current component determined by EVB.
- **AIGC, BIGC, CIGC, NIGC** and **PIGCD**, which are linked to the gate-to-channel current. **PIGCD** is expressing the $V_D$ dependence of gate-to-channel current.
10.1.4 Drain Current $I_D$ vs. $V_D$ Analysis @ various $V_G$, $V_S = 0$ V & $V_B = 0$ V

In this step, both $I_D$ vs. $V_D$ and output conductance - $g_{ds}$ (even $g^{'ds}$) vs. $V_D$ characteristics are studied at once. Different effects impact both the characteristics, so the parameters related to those effects are extracted. In detail,

- **DELTA**, which is a smoothing factor for the transition between $V_{DS}$ and $V_{DS,sat}$.
- **PDITS** and **PDITSD**, linked to DITS effect.
- **PCLM**, **PCLMG** and **FPROUT** linked to the CLM effect.
- **PDIBLC**, linked to the impact of DIBL effect on $R_{out}$.
- **PVAG**, linked to the $V_G$ dependence on Early voltage.

10.1.5 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_{DS} \neq 0$ V & $V_B = 0$ V

Velocity saturation (VS) and channel length modulation (CLM) effects not only affect the static behavior of the transistor but the dynamic as well. The extraction of **VSAT** and **PCLM** from $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics should be sufficient in order to capture these effects for CV operation. To verify that, $C_{GG}$ vs. $V_G$ characteristic for different $V_{DS} \neq 0$ V, from linear mode to saturation must be studied. If different values for **VSAT** and **PCLM** are necessary for accurate fitting of the CV behavior at different $V_D$ biases, then **VSATCV** and **PCLMCV** can be used.

10.1.6 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$ & various $V_B$

In this step almost the same procedure as in Section 10.1.2 will be repeated in order to extract the parameters that are linked to the body effect. Similar to Section 10.1.2, it is also very important that during the extraction in this step both $I_D$ and $g_m$ are studied at once.

Linear Mode

- Focusing in *weak-inversion* region, **CDSCB**, which is linked to the $V_B$ (or $V_S$) dependence of the sub-threshold slope, is extracted. Also **K2**, which is linked to the $V_{TH}$ shift due to vertical non-uniform doping, is extracted in the same region.
• In *strong-inversion* region, UC, which is linked to the $V_B$ (or $V_S$) dependence of mobility, is extracted. The parameter for $V_B$ (or $V_S$) dependence of S/D series resistances, PRWB, is also extracted under the same bias conditions.

Saturation

• In *strong-inversion* region, the parameter that is connected to $V_B$ (or $V_S$) dependence of the velocity saturation effect, i.e. PSATB, is extracted.

In order to validate that the values of the parameters, which are linked to $V_B$ (or $V_S$) dependencies, are correctly extracted, it is useful to check $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$ & $V_B \neq 0$ V (or $V_S \neq 0$ V) and, if needed, to fine tune the values of the parameters.

10.1.7 Fitting Verification

When all the extraction steps of this part have been performed, the fitting of the model should be checked for all the analyses carried out up to this point. Parameters can be fine tuned for better fitting in all regions.

10.2 Extraction of Short Channel Effects & Length Scaling Parameters

Once the behavior of the wide/long channel device has been accurately modeled, the next step is the extraction of the parameters that are either related to short channel effects or express the different length dependencies. So at this part, devices across the entire length range of the technology, from the shortest to the longest one, are studied simultaneously. In order to avoid the impact of narrow channel effects or of the width dependencies these devices should have the same **wide** channel. The extraction that is carried out follows the same flow as in Section 10.1, but now a set of devices with constant **wide** channel but different channel lengths is used.
10.2.1 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_S = 0$ $V$, $V_D = 0$ $V$ & $V_B = 0$ $V$

In this step, parameters related to overlap and fringing capacitances as well as those that are linked to the length dependence of doping concentration and flat-band voltage are extracted. More specifically:

- **NDEPL1, NDEPLEXP1, NDEPL2 and NDEPLEXP2**, which are the length scaling parameters for the doping concentration, are extracted from $C_{GG}$ in the depletion region. If possible, it is recommended that those parameters are extracted from $C_{GB}$ vs. $V_G$ analysis (S and D terminals are grounded).

- Extraction of parameters related to overlap and fringing capacitances is carried out by studying the entire range of $V_G$ bias of $C_{GG}$ vs. $V_G$ characteristic. These parameters are: $CGSO$, $CGDO$, $CGBO$, $CGSL$, $CGDL$, $CKAPPAS$, $CKAPPAD$ and $CF$. If possible, it is recommended that $CGSO$, $CGDO$, $CGBO$ and $CF$ are extracted from $C_{GD}$ vs. $V_G$ at low $V_B$ (when S and D terminals are connected together and B terminal is grounded), while $CGSL$, $CGDL$, $CKAPPAS$ and $CKAPPAD$ are extracted from $C_{GD}$ vs. $V_G$ at high $V_B$ (when S, D and B terminals are connected together).

- **DLC**, which is the channel-length offset parameter for the CV model, is extracted in the strong-inversion region of $C_{GG}$.

- **VFBCVL** and **VFBCVLEXP**, which express the length dependence of flat-band voltage at CV, are extracted from depletion region till the onset of strong-inversion. In order to be able to use **VFBCVL** and **VFBCVLEXP** parameters, **VFBCV** must be $\neq 0$.

10.2.2 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$, $V_S = 0$ $V$ & $V_B = 0$ $V$

In this step, parameters related to short channel effects or to length dependencies of $I_D$ vs. $V_G$, are extracted. Similar to the procedure described in Section 10.1.2, the parameters are divided in two groups, those which are extracted in *linear mode* (i.e. $V_D \ll V_G - V_{TH}$) and those which are extracted in *saturation* (i.e. $V_D \gg V_G - V_{TH}$). It is very important that during the extraction both $I_D$ and $g_m$ of all the devices are studied at once.
Linear Mode

- Focusing in weak-inversion region \((I_D \text{ vs. } V_G \text{ characteristic when y-axis is in logarithmic scale})\), \text{NFACTORL} and \text{NFACTORLEXP}, which are related to the length dependence of the sub-threshold slope of \(I_D \text{ vs. } V_G\), can be extracted. Furthermore, \text{LINT}, which is the channel length offset parameter, is used to fit both the sub-threshold slope and the \(V_{TH}\). For fitting the \(V_{TH}\) of the devices also \text{DVTP0} and \text{UD} can prove to be useful. \text{UD} should be used only for fine tuning because it mainly affects the region above threshold. It is recommended that the parameters \text{NDEPL1}, \text{NDEPLEXP1}, \text{NDEPL1} and \text{NDEPLEXP1} keep the values extracted from the \(C_{GG} \text{ vs. } V_G\) analysis (Section 10.2.1). But, if the fitting of the \(V_{TH}\) across the entire length range cannot be achieved without changing the values of \text{NDEPL1}, \text{NDEPLEXP1}, \text{NDEPL1} and \text{NDEPLEXP1}, then these parameters are used for static operation (IV) and \text{NDEPCVL1}, \text{NDEPCVLEXP1}, \text{NDEPCVL1} and \text{NDEPCVLEXP1} parameters are used for dynamic operation (CV).

- In strong-inversion region, the parameters related to the length dependence of: i) the mobility; \text{U0L} and \text{U0LEXP}, ii) the effect of mobility reduction due to vertical field; \text{UAL}, \text{UALEXP}, \text{EUL} and \text{EULEXP} and iii) the coulomb scattering effect; \text{ULD} and \text{UDLEXP}, are extracted. Furthermore, parameters for the length dependence of S/D series resistances, namely \text{RDSWL} and \text{RDSWLEXP} (when \text{RDSMOD} = 0) or \text{RSWL}, \text{RSWLEXP}, \text{RDWL} and \text{RDWLEXP} (when \text{RDSMOD} = 1), are also extracted under the same bias conditions.

Saturation

- In weak-inversion region \((I_D \text{ vs. } V_G \text{ characteristic when y-axis is in logarithmic scale})\), \text{CDSCDL} and \text{CDSCDLEXP} parameters, which are linked to the length dependence of the sub-threshold slope dependence on drain bias, are extracted. Moreover, parameters for DIBL effect, which control \(V_{TH}\) when \(V_{DS} \neq 0\), namely \text{ETA0} and \text{DSUB}, are also extracted in the same region.

- Focusing in strong-inversion region, the length scaling parameters linked to the velocity saturation effect, i.e \text{VSATL}, \text{VSATLEXP}, \text{PSATL}, \text{PSATLEXP}, \text{PTWGL} and \text{PTWGLEXP}, can be extracted.
Finally, from *accumulation* to *depletion* region, in both *linear mode* and *saturation*, the parameters $AGIDLL/AGISLL$, which are related the length dependence of GIDL effect (GIDL/GISL currents), are extracted.

### 10.2.3 $I_G$ vs. $V_G$ Analysis @ various $V_D$, $V_S = 0$ V & $V_B = 0$ V

From $I_G$ vs. $V_G$ analysis, parameters related to the length dependence of gate current are extracted. These parameters are: $AIGCL$, $AIGSL$, $AIGDL$ and $PIGCDL$.

### 10.2.4 $I_D$ vs. $V_D$ Analysis @ various $V_G$, $V_S = 0$ V & $V_B = 0$ V

In this step, both $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics should be studied at once. Similar to the procedure described in Section 10.2.4 the parameters that are extracted are:

- **DELTAL** and **DELTALEXP**, which are related to the length dependence of the smoothing factor for the transition between $V_{DS}$ and $V_{DS,sat}$.
- **PDITSL**, linked to the length dependence of DITS effect.
- **PCLML**, **PCLMLEXP**, **FPROUTL** and **FPROUTLEXP** linked to the length dependence of CLM effect.
- **PDIBLCL** and **PDIBLCLEXP**, linked to the length dependence of the impact of DIBL effect on $R_{out}$.

It is very important to be mentioned here, that if the slope of $g_{ds}$ vs. $V_D$ characteristic at low levels of inversion is steeper than the measurements, then $ETA0$ should be decreased and $DVTP1$ can be used to achieve an accurate fit for the $V_{TH}$ in *saturation*.

### 10.2.5 $C_{GG}$ vs. $V_G$ Analysis @ $V_{DS} \neq 0$ V & $V_B = 0$ V

The extraction of the length scaling parameters of $VSAT$ and $PCLM$ from $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics (Steps 10.2.2 and 10.2.4) should be sufficient in order to capture $VS$ and $CLM$ effects for CV operation. To verify that, $C_{GG}$ vs. $V_G$ characteristic of all devices, for different $V_{DS} \neq 0$ V, from linear mode to saturation, must be studied. If different values for $VSATL$, $VSATLEXP$, $PCLML$ and $PCLMLEXP$ are necessary.
for accurate fitting of the CV behavior across L, then VSATCVL, VSATCVLEXP, PCLMCVL and PCLMCVLEXP can be used.

10.2.6  $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$ & various $V_B$ (or various $V_S$)

In this step almost the same procedure as in Section 10.1.6 will be repeated in order to extract the length scaling parameters that are linked to the body effect. Similar to Section 10.1.6, it is also very important that during the extraction in this step both $I_D$ and $g_m$ of all devices are studied at once.

Linear Mode

- Focusing in weak-inversion region, $K2L$ and $K2LEXP$, which are linked to the length dependence $V_{TH}$ shift due to vertical non-uniform doping, are extracted.

- In strong-inversion region, $UCL$ and $UCLEXP$, which are linked to the length dependence of mobility reduction with $V_B$ (or $V_S$) bias, are extracted. The parameters for the length dependence of S/D series resistances with $V_B$ (or $V_S$) bias, namely $PRWBL$ and $PRWBLEXP$, are also extracted under the same bias conditions.

Saturation

- In weak-inversion region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), the parameters related to length dependence of DIBL effect dependence on $V_B$ (or $V_S$) bias, namely $ETAB$ and $ETABEXP$, are extracted.

In order to validate that the values of the length scaling parameters, which are linked to $V_B$ (or $V_S$) dependencies, are correctly extracted, it is useful to check $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$ & $V_B \neq 0$ V (or $V_S \neq 0$ V) and, if needed, to fine tune the values of the parameters.

10.2.7  Fitting Verification

When all the steps for the extraction of short channel effects and length scaling parameters have been performed, the fitting of the model should be checked for all the analyses carried out in Section 10.2 and parameters can be fine tuned for better fitting.
10.3 Extraction of Narrow Channel Effects & Width Scaling Parameters

The next step in the parameter extraction procedure is the extraction of the parameters that are either related to narrow channel effects or express the different width dependencies. So at this part, devices across the entire width range of the technology, from the narrowest to the widest one, are studied simultaneously. In order to avoid the impact of short channel effects or of the length dependencies these devices should have the same long channel. The extraction that is carried out follows the same flow as in Section 10.2, but now a set of devices with constant long channel but different channel widths is used.

10.3.1 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_S = 0$ V, $V_D = 0$ V & $V_B = 0$ V

In this step, parameters related to the width dependencies of the CV behavior of the device, e.g. width dependence of the doping concentration and flat-band voltage, are extracted. More specifically:

- **NDEPW** and **NDEPWEXP**, which are the width scaling parameters for the doping concentration, are extracted from $C_{GG}$ in the depletion region. If possible, it is recommended that those parameters are extracted from $C_{GB}$ vs. $V_G$ analysis (S and D terminals are grounded).

- **DWC**, which is the channel-width offset parameter for the CV model, is extracted in the strong-inversion region of $C_{GG}$.

- **VFBCVW** and **VFBCVWEXP**, which express the width dependence of flat-band voltage at CV, are extracted along the entire $V_G$ bias range of $C_{GG}$ characteristic. In order to be able to use **VFBCVW** and **VFBCVWEXP** parameters, **VFBCV** must be $\neq 0$.

10.3.2 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin},V_{D,\text{sat}}]$, $V_S = 0$ V & $V_B = 0$ V

In this step, parameters related to width dependencies of $I_D$ vs. $V_G$, are extracted. Similar to the procedure described in Section 10.1.2, the parameters are divided in two
groups, those which are extracted in linear mode (i.e. $V_D \ll V_G - V_{TH}$) and those which are extracted in saturation (i.e. $V_D \gg V_G - V_{TH}$). It is very important that during the extraction both $I_D$ and $g_m$ of all the devices are studied at once.

Linear Mode

- Focusing in weak-inversion region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), NFACTORW and NFACTORWEXP, which are related to the width dependence of the sub-threshold slope of $I_D$ vs. $V_G$, can be extracted. Furthermore, WINT, which is the channel width offset parameter, is used to fit both the sub-threshold slope and the $V_{TH}$ across W. It is recommended that the parameters NDEPW and NDEPWEXP keep the values extracted from the $C_{GG}$ vs. $V_G$ analysis (Section 10.3.1). But, if the fitting of the $V_{TH}$ across the entire width range cannot be achieved without changing the values of NDEPW and NDEPWEXP, then these parameters are used for static operation (IV) and NDEPCVW and NDEPCVWEXP parameters are used for dynamic operation (CV).

- In strong-inversion region, the parameters related to the width dependence of mobility reduction due to vertical field effect, namely UAW, UAWEXP, EUW and EUWEXP, are extracted.

Saturation

- Focusing in strong-inversion region, the width scaling parameters linked to the velocity saturation effect, i.e. VSATW and VSATWEXP, can be extracted.

Finally, from accumulation to depletion region, in both linear mode and saturation, the parameters AGIDLW/AGISLW, which are related the width dependence of GIDL effect (GIDL/GISL currents), are extracted.

In order to validate that the values of the width scaling parameters are correctly extracted, it is useful to check $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$, $V_S = 0 V$ & $V_B = 0 V$ (or $V_S \neq 0 V$) and, if needed, to fine tune the values of the parameters.

10.3.3 Gate Current $I_G$ vs. $V_G$ Analysis @ various $V_D$, $V_S = 0 V$ & $V_B = 0 V$

From $I_G$ vs. $V_G$ analysis, parameters related to the width dependence of gate current are extracted. These parameters are: AIGCW, AIGSW and AIGDW.
10.3.4 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_{DS} \neq 0\,V$ & $V_B = 0\,V$

The extraction of the width scaling parameters of $V_{SATW}$ and $V_{SATWEXP}$ from $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics (Step 10.3.2) should be sufficient in order to capture VS for CV operation. To verify that, $C_{GG}$ vs. $V_G$ characteristic of all devices, for different $V_{DS} \neq 0\,V$, from linear mode to saturation, must be studied. If different values for $V_{SATW}$ and $V_{SATWEXP}$ are necessary for accurate fitting of the CV behavior across W, then $V_{SATCVW}$ and $V_{SATCVWEXP}$ can be used.

10.3.5 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$ & various $V_B$
(or various $V_S$)

In this step, from weak-inversion region of linear mode, $K2W$ and $K2WEXP$, which are linked to the width dependence $V_{TH}$ shift due to vertical non-uniform doping, can be extracted. For validation purposes, it is useful to check: i) $I_D$ vs. $V_G$ and $g_m$ vs. $V_G$ characteristics in weak and strong-inversion and for both linear mode and saturation, and ii) $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$ & $V_B \neq 0\,V$ (or $V_S \neq 0\,V$) and, if needed, extract $K2W$ and $K2WEXP$ to fit both (i) and (ii).

10.3.6 Fitting Verification

When all the extraction steps for the width scaling have been performed, the fitting of the model should be checked for all the analyses carried out in Section 10.3 and parameters can be further tuned for better fitting.

10.4 Extraction of Parameters for Narrow/Short Channel Devices

The final part in the parameter extraction procedure from a geometrical point of view, is the extraction of the parameters for narrow/short channel devices. These devices have the minimum dimensions so it is more difficult to capture their behavior. Since the narrow/short channel device parameters can affect the already performed fitting across length and width, it is recommended that two different sets of devices are studied simultaneously, i.e. one set with a constant short channel but different channel widths.
(from narrowest to widest) and one set with a constant narrow channel but different channel lengths (from the shortest to the longest one).

10.4.1 Gate Capacitance $C_{GG}$ vs. $V_G$ Analysis @ $V_S = 0 \, V$, $V_D = 0 \, V$ & $V_B = 0 \, V$

In this step, geometry dependent parameters for modeling the CV behavior of the narrow/short channel devices, are extracted. More specifically:

- **NDEPWL** and **NDEPWLEXP**, which are used to fit the doping concentration of small channel devices, are extracted from $C_{GG}$ in the depletion region. If possible, it is recommended that those parameters are extracted from $C_{GB}$ vs. $V_G$ analysis (S and D terminals are grounded).

- **LWLC** and **WWLC**, which are coefficients of length/width dependencies for CV model, are extracted in the strong-inversion region of $C_{GG}$.

- **VFBCVWL** and **VFBCVWLEXP**, which are used to fit the flat-band voltage at CV, are extracted from depletion till the onset of strong-inversion region of $C_{GG}$ characteristic. In order to be able to use **VFBCVWL** and **VFBCVWLEXP** parameters, $VFBCV$ must be $\neq 0$.

10.4.2 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin}, V_{D,sat}]$, $V_S = 0 \, V$ & $V_B = 0 \, V$

In this step, geometry dependent parameters for modeling $I_D$ of the narrow/short channel devices, are extracted. Similar to the procedure described in Section 10.1.2, the parameters are divided in two groups, those which are extracted in *linear mode* (i.e. $V_D \ll V_G - V_{TH}$) and those which are extracted in *saturation* (i.e. $V_D \gg V_G - V_{TH}$). It is very important that during the extraction both $I_D$ and $g_m$ of all the devices are studied at once.

Linear Mode

- Focusing in *weak-inversion* region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), **FACTORWL** and **FACTORWLEXP**, which are used to fit
the sub-threshold slope of $I_D$ vs. $V_G$ for small channel devices, can be extracted. It is recommended that the parameters $\text{NDEPWL}$ and $\text{NDEPWLEXP}$ keep the values extracted from the $C_{GG}$ vs. $V_G$ analysis (Section 10.4.1). But, if the fitting of the $V_{TH}$ for both sets of devices cannot be achieved without changing the values of $\text{NDEPWL}$ and $\text{NDEPWLEXP}$, then these parameters are used for static operation (IV) and $\text{NDEPCVWL}$ and $\text{NDEPCVWLEXP}$ parameters are used for dynamic operation (CV).

- In strong-inversion region, the parameters which are used to model the effect of mobility reduction due to vertical field in small channel devices, namely $\text{UAWL}$, $\text{UAWLEXP}$, $\text{EUWL}$ and $\text{EUWLEXP}$, are extracted.

Saturation

- Focusing in strong-inversion region, the parameters which are used to model to the velocity saturation effect in small channel devices, i.e. $\text{VSATWL}$ and $\text{VSATWLEXP}$, can be extracted.

In order to validate that the values of the parameters, modeling the behavior of narrow/short channel devices, are correctly extracted, it is useful to check $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$, $V_S = 0$ V & $V_B = 0$ V and, if needed, to fine tune the values of the parameters.

10.4.3 $C_{GG}$ vs. $V_G$ Analysis @ $V_{DS} \neq 0$ V & $V_B = 0$ V

The extraction of the parameters, which are used to model to the velocity saturation effect in small channel devices, $\text{VSATWL}$ and $\text{VSATWLEXP}$, from $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics (Step 10.4.2) should be sufficient in order to capture $V_S$ for CV operation. To verify that, $C_{GG}$ vs. $V_G$ characteristic of all devices, for different $V_{DS} \neq 0$ V, from linear mode to saturation, must be studied. If different values for $\text{VSATWL}$ and $\text{VSATWLEXP}$ are necessary for accurate fitting of the CV behavior for both sets of devices, then $\text{VSATCVWL}$ and $\text{VSATCVWLEXP}$ can be used.

10.4.4 Drain Current $I_D$ vs. $V_G$ Analysis @ $V_D = [V_{D,lin},V_{D,sat}]$ & various $V_B$ (or various $V_S$)

In this step, from weak-inversion region of linear mode, $\text{K2WL}$ and $\text{K2WLEXP}$, which are linked to the $V_{TH}$ shift due to vertical non-uniform doping in small channel
devices, can be extracted. For validation purposes, it is useful to check: i) $I_D$ vs. $V_G$ and $g_m$ vs. $V_G$ characteristics in weak and strong-inversion and for both linear mode and saturation, and ii) $I_D$ vs. $V_D$ and $g_{ds}$ vs. $V_D$ characteristics @ various $V_G$ & $V_B \neq 0 \text{V}$ (or $V_S \neq 0 \text{V}$) and, if needed, extract K2WL and K2WLEXP to fit both (i) and (ii).

### 10.4.5 Fitting Verification

When all the steps for narrow/short channel devices have been performed, the fitting of the model should be checked for all the analyses carried out in Section 10.4 and parameters can be fine tuned for better fitting.

### 10.5 Extraction of Temperature Dependence Parameters

Up to this point of the parameter extraction procedure, the temperature dependence of the parameters has been ignored since all the parameters were extracted at $TNOM$. In this part, the parameters that are related to the impact of temperature on the behavior of devices are extracted, and for that, data across the temperature range of the technology are necessary. The behavior of devices is studied with the same geometrical sequence as the previous steps, while the temperature dependence parameters are extracted in the same regions of operation as the parameters of the corresponding physical effects.

#### 10.5.1 Wide & Long Channel Devices

The first step, in the extraction of temperature dependence parameters, is to extract the behavior of a long and wide channel device @ different $T$ and for different analyses. It is recommended that the same device as the one in Section 10.1 is used. In detail:

$I_D$ vs. $V_G$ analysis @ $V_D = V_{D,\text{lin}}$, $V_S = 0 \text{V}$ & $V_B = 0 \text{V}$

- From weak-inversion region ($I_D$ vs. $V_G$ characteristic when y-axis is in logarithmic scale), the parameters TBGASUB and TBGBSUB, which control the temperature dependence of $E_g$, are extracted. Also, TNFACTOR is extracted in order to fit the sub-threshold slope of $I_D$ in different $T$, while KT1 and KT1EXP are extracted for fitting the $V_{TH}$ across $T$. 
• From strong-inversion region, the mobility temperature exponent, UTE and the temperature coefficients: i) for mobility reduction due to vertical field effect, namely UA1 and UD1, ii) for coulomb scattering effect, UCSTE and iii) for S/D series resistances, PRT, are extracted.

\[ I_D \text{ vs. } V_G \text{ analysis } @ V_D = V_{D,\text{sat}}, V_S = 0 \text{ V & } V_B = 0 \text{ V} \]

• From strong-inversion region, the parameters that are used to model to the temperature dependence of velocity saturation effect, i.e. AT and PTWGT, are extracted.

It is very important that in the above analyses both \( I_D \) and \( g_m \) of all the devices are studied at once. Furthermore, from accumulation to depletion region, in both linear mode and saturation of \( I_D \) vs. \( V_G \) analysis, the parameter TGIDL, which controls the temperature dependence of GIDL effect, is extracted.

\[ I_D \text{ vs. } V_D \text{ Analysis } @ \text{ various } V_G, V_S = 0 \text{ V & } V_B = 0 \text{ V} \]

From \( I_D \) vs. \( V_D \) analysis in different temperatures, TDELTAs, which is related to the temperature dependence of the smoothing factor for the transition between \( V_{DS} \) and \( V_{DS,\text{sat}} \), is extracted.

\[ I_D \text{ vs. } V_G \text{ Analysis } @ V_D = V_{D,\text{lin}} \text{ & various } V_B \text{ (or various } V_S) \]

• From weak-inversion region (\( I_D \) vs. \( V_G \) characteristic when y-axis is in logarithmic scale) KT2, which is linked to the temperature dependence of \( V_{TH} \) shift due to vertical non-uniform doping with \( V_B \text{ (or } V_S) \) bias, is extracted.

• From strong-inversion region, the temperature coefficient for mobility reduction with \( V_B \text{ (or } V_S) \) bias, namely UC1, is extracted.

For validation purposes, it is useful to check: i) \( I_D \) vs. \( V_G \) and \( g_m \) vs. \( V_G \) characteristics in weak and strong-inversion and for both linear mode and saturation, and ii) \( I_D \) vs. \( V_D \) and \( g_{ds} \) vs. \( V_D \) characteristics @ various \( V_G \) & \( V_B \neq 0 \text{ V (or } V_S \neq 0 \text{ V) and, if needed, extract KT2 and UC1 to fit both (i) and (ii).} \)

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10.5.2 Length Scaling of Wide Channel Devices

The following step in the extraction of temperature dependence parameters, is to study the temperatures dependences across L. For this, data of a set of devices with constant wide channel but different channel lengths are used.

\[ I_D \text{ vs. } V_G \text{ analysis @ } V_D = V_{D,\text{lin}}, V_S = 0 \text{ V} \& V_B = 0 \text{ V} \]

- From weak-inversion region (\( I_D \text{ vs. } V_G \) characteristic when y-axis is in logarithmic scale), the parameter \( K_{T1L} \) is extracted for fitting the \( V_{TH} \) across L, at different T.

- From strong-inversion region, the length scaling parameters for: i) mobility temperature exponent, \( U_{TEIL} \) and for the temperature coefficients or mobility reduction due to vertical field effect, namely \( U_{A1L} \) and \( U_{D1L} \), are extracted.

\[ I_D \text{ vs. } V_G \text{ analysis @ } V_D = V_{D,\text{sat}}, V_S = 0 \text{ V} \& V_B = 0 \text{ V} \]

- From weak-inversion region (\( I_D \text{ vs. } V_G \) characteristic when y-axis is in logarithmic scale), the parameter \( TETA0 \), which is related to the temperature dependence of DIBL effect and thus is controlling the \( V_{TH} \) in saturation, is extracted.

- From strong-inversion region, the parameters that are used to model the temperature dependence of velocity saturation effect across L, i.e. \( ATL \) and \( PTWGTL \), are extracted.

It is very important that in the above analyses both \( I_D \) and \( g_m \) of all the devices are studied at once. For validating that the values of length scaling parameters for temperature dependence parameters are extracted correctly, it is useful to check also \( I_D \text{ vs. } V_D \) and \( g_{ds} \text{ vs. } V_D \) characteristics and, if needed, to fine tune their value by repeating Step 10.5.2.
Figure 11: Parameters Extraction Procedure.
## Instance Parameters

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### 12 Model Controllers and Process Parameters

Note: binnable parameters are marked as: \(^{(b)}\)

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<td>Distance of Mid-Contact to Gate edge in Test</td>
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## 13 Basic Model Parameters

Note: binnable parameters are marked as: \(^{(b)}\)

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<th>Name</th>
<th>Unit</th>
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<th>Min</th>
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<tr>
<td>LLONG</td>
<td>(m)</td>
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<td>Length of extracted long channel device</td>
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<td>WWIDE</td>
<td>(m)</td>
<td>10(\mu m)</td>
<td>-</td>
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<td>Width of extracted long channel device</td>
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<td>CIT(^{(b)})</td>
<td>(F/m^2)</td>
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<td>NFACTOR(^{(b)})</td>
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<td>Subthreshold Swing factor. Global Scaling Parameters - NFACTORL, NFACTORLEXP, NFACTORW, NFACTORWEXP, NFACTORWL</td>
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<td>CDSCD(^{(b)})</td>
<td>(F/m^2)</td>
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<td>Drain-bias sensitivity of Subthreshold Swing. Global Scaling Parameters - CDSCDL, CDSCDLEXP</td>
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<td>CDSCB(^{(b)})</td>
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<td>Body-bias sensitivity of Subthreshold Swing. Global Scaling Parameters - CDSCBL, CDSCBLEXP</td>
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<td>DVTP0(^{(b)})</td>
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<td>$V_{th}$ shift due to nonuniform vertical doping. Global Scaling Parameters - K2L, K2LEXP, K2W, K2WEXP</td>
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<td>ETA0&lt;sup&gt;(b)&lt;/sup&gt;</td>
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<td>U0&lt;sup&gt;(b)&lt;/sup&gt;</td>
<td>Low field mobility. Global Scaling Parameters - U0L, U0LEXP</td>
<td>$m^2/V - s$</td>
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<td>Phonon / surface roughness scattering parameter. Global Scaling Parameters - UAL, UALEXP, UAW, UAWEXP, UAWL</td>
<td>(cm/MV)&lt;sup&gt;EU&lt;/sup&gt;</td>
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<td>&gt; 0.0</td>
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<td>EU&lt;sup&gt;(b)&lt;/sup&gt;</td>
<td>Phonon / surface roughness scattering parameter. Global Scaling Parameters - EUL, EULEXP, EUW, EUWEXP, EUWL</td>
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<td>VSAT&lt;sup&gt;(b)&lt;/sup&gt;</td>
<td>Saturation velocity. Global Scaling Parameters - VSATL, VSALEXP, VSATW, VSATWEXP</td>
<td>m/s</td>
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<td>RSWMIN</td>
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<td>Exponent</td>
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<td>((F_s^2/g)^{0.5})</td>
<td>1.36e-2 (NMOS) and 9.8e-3 (PMOS)</td>
<td>Parameter for (I_{gcs}) and (I_{gcd}). Global Scaling Parameters - AIGCL, AIGCW</td>
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<tr>
<td>BIGC(^{(b)})</td>
<td>((F_s^2/g)^{0.5})</td>
<td>1.71e-3 (NMOS) and 7.59e-4 (PMOS)</td>
<td>Parameter for (I_{gcs}) and (I_{gcd})</td>
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<td>CIGC(^{(b)})</td>
<td>((F_s^2/g)^{0.5})</td>
<td>0.075 (NMOS) and 0.03 (PMOS)</td>
<td>Parameter for (I_{gcs}) and (I_{gcd})</td>
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<td>AIGS(^{(b)})</td>
<td>((F_s^2/g)^{0.5})</td>
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<td>Parameter for (I_g). Global Scaling Parameters - AIGSL, AIGSW</td>
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<tr>
<td>BIGS&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>1.71e-3 (NMOS) and 7.59e-4 (PMOS)</td>
<td>Parameter for (I_{gs})</td>
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<tr>
<td>CIGS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>((Fs^2/g)^{0.5})</td>
<td>0.075 (NMOS) and 0.03 (PMOS)</td>
<td>Parameter for (I_{gs})</td>
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<td>DLCIG&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(m)</td>
<td>LINT</td>
<td>Source/Drain overlap length for (I_{gs})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIGD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>((Fs^2/g)^{0.5})</td>
<td>1.36e-2 (NMOS) and 9.8e-3 (PMOS)</td>
<td>Parameter for (I_{gd}). Global Scaling Parameters - AIGDL, AIGDW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIGD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>((Fs^2/g)^{0.5})</td>
<td>1.71e-3 (NMOS) and 7.59e-4 (PMOS)</td>
<td>Parameter for (I_{gd})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIGD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>((Fs^2/g)^{0.5})</td>
<td>0.075 (NMOS) and 0.03 (PMOS)</td>
<td>Parameter for (I_{gd})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLCIGD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(m)</td>
<td>DLCIG</td>
<td>Source/Drain overlap length for (I_{gd})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POXEDGE&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
<td>1.0</td>
<td>Factor for the gate oxide thickness in source/drain overlap regions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIGCD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
<td>1.0</td>
<td>(V_{ds}) dependence of (I_{gcs}) and (I_{gcd}). Global Scaling Parameters - PIGCDL, PIGCDLEXP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTOX&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
<td>1.0</td>
<td>Exponent for the gate oxide ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOXREF</td>
<td>(m)</td>
<td>3.0e-9</td>
<td>Nominal gate oxide thickness for gate dielectric tunneling current model only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VFBSDOFF&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(V)</td>
<td>0.0</td>
<td>Flatband Voltage Offset Parameter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NDEPCV<sup>(b)</sup> | $m^{-3}$ | NDEP | - | - |
| VFBCV<sup>(b)</sup> | $m^{-3}$ | VFB | - | - |
| VSATCV<sup>(b)</sup> | $m/s$ | VSAT | - | - |
| PCLMCV<sup>(b)</sup> | - | PCLM | - | - |
| CF<sup>(b)</sup> | $F/m$ | 0 | 0.0 | - |
| CFRCOEFF<sup>(b)</sup> | $F/m$ | 1 | 1 | - |
| CGSO | $F/m$ | calculated | 0.0 | - |
| CGDO | $F/m$ | calculated | 0.0 | - |
| CGSL<sup>(b)</sup> | $F/m$ | 0 | 0.0 | - |
| CGDL<sup>(b)</sup> | $F/m$ | 0 | 0.0 | - |
| CKAPPAS<sup>(b)</sup> | $V$ | 0.6 | 0.02 | - |
| CKAPPAD<sup>(b)</sup> | $V$ | 0.6 | 0.02 | - |
| CGBO | $F/m$ | 0 | 0.0 | - |

Global Scaling Parameters:
- NDEPCVL1, NDEPCVLEXP1, NDEPCVL2, NDEPCVLEXP2, NDEPCVW, NDEPCVWEXP, NDEPCVWL, NDEPCVWLEXP
- VFBCVL, VFBCVLEXP, VFBCVW, VFBCVWEXP, VFBCVWL, VFBCVWLEXP
- VSATCVL, VSAVL-EXP, VSATCVW, VSATCVWEXP
- PCLMCVL, PCLMCVLEXP
- Non LDD region source-gate overlap capacitance per unit channel width
- Non LDD region drain-gate overlap capacitance per unit channel width
- Overlap capacitance between gate and lightly-doped source region
- Overlap capacitance between gate and lightly-doped drain region
- Coefficient of bias-dependent overlap capacitance for the source side
- Coefficient of bias-dependent overlap capacitance for the drain side
- Gate-substrate overlap capacitance per unit channel length
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADOS</td>
<td>Quantum mechanical effect prefactor cum switch in inversion</td>
<td></td>
</tr>
<tr>
<td>BDOS</td>
<td>Charge centroid parameter - slope of CV curve under QME in inversion</td>
<td></td>
</tr>
<tr>
<td>QM0</td>
<td>Charge centroid parameter - starting point for QME in inversion</td>
<td></td>
</tr>
<tr>
<td>ETAQM</td>
<td>Bulk charge coefficient for charge centroid in inversion</td>
<td></td>
</tr>
<tr>
<td>DLBIN</td>
<td>Length reduction parameter for binning</td>
<td></td>
</tr>
<tr>
<td>DWBIN</td>
<td>Width reduction parameter for binning</td>
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</tr>
<tr>
<td>LMLT</td>
<td>Length shrinking factor</td>
<td></td>
</tr>
<tr>
<td>WMLT</td>
<td>Width shrinking factor</td>
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## 14 High-Speed/RF Model Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>XRCRG1 (b)</td>
<td>Parameter for distributed channel-resistance effect for both intrinsic-input resistance and charge-deficit NQS models (Warning message issued if binned XRCRG1 ≤ 0.0 ) distributed channel-resistance effect for both intrinsic-input resistance and charge-deficit NQS models (Warning message issued if binned XRCRG1 ≤ 0.0 )</td>
<td>12.0</td>
</tr>
<tr>
<td>XRCRG2 (b)</td>
<td>Parameter to account for the excess channel diffusion resistance for both intrinsic input resistance and charge-deficit NQS models</td>
<td>1.0</td>
</tr>
<tr>
<td>RBPB</td>
<td>Resistance connected between bNodePrime and bNode</td>
<td>50.0ohm</td>
</tr>
<tr>
<td>RBPD</td>
<td>Resistance connected between bNodePrime and dbNode (If less than 1.0e-3ohm, reset to 1.0e-3ohm )</td>
<td>50.0ohm</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>RBPS</td>
<td>Resistance connected between bNodePrime and sbNode (If less than 1.0e-3ohm, reset to 1.0e-3ohm)</td>
<td>50.0ohm</td>
</tr>
<tr>
<td>RBDB</td>
<td>Resistance connected between dbNode and bNode</td>
<td>50.0ohm</td>
</tr>
<tr>
<td>RBSB</td>
<td>Resistance connected between sbNode and bNode</td>
<td>50.0ohm</td>
</tr>
<tr>
<td>GBMIN</td>
<td>Conductance in parallel with each of the five substrate resistances to avoid potential numerical instability due to unreasonably too large a substrate resistance (Warning message issued if less than 1.0e-20 mho)</td>
<td>1.0e-12mho</td>
</tr>
<tr>
<td>RBPS0</td>
<td>Scaling prefactor for RBPS</td>
<td>50 Ohms</td>
</tr>
<tr>
<td>RBPSL</td>
<td>Length Scaling parameter for RBPS</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPSSW</td>
<td>Width Scaling parameter for RBPS</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPSNF</td>
<td>Number of fingers Scaling parameter for RBPS</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPDO</td>
<td>Scaling prefactor for RBPD</td>
<td>50 Ohms</td>
</tr>
<tr>
<td>RBPDL</td>
<td>Length Scaling parameter for RBPD</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPDW</td>
<td>Width Scaling parameter for RBPD</td>
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</tr>
<tr>
<td>RBPDNF</td>
<td>Number of fingers Scaling parameter for RBPD</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBX0</td>
<td>Scaling prefactor for RBPBX</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>RBPBXL</td>
<td>Length Scaling parameter for RBPBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBXW</td>
<td>Width Scaling parameter for RBPBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBXXNF</td>
<td>Number of fingers Scaling parameter for RBPBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBY0</td>
<td>Scaling prefactor for RBPBY</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>RBPBYL</td>
<td>Length Scaling parameter for RBPBY</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBYW</td>
<td>Width Scaling parameter for RBPBY</td>
<td>0.0</td>
</tr>
<tr>
<td>RBPBYNF</td>
<td>Number of fingers Scaling parameter for RBPBY</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSBX0</td>
<td>Scaling prefactor for RBSBX</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>RBSBY0</td>
<td>Scaling prefactor for RBSBY</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>RBDBX0</td>
<td>Scaling prefactor for RBDBX</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>RBDBY0</td>
<td>Scaling prefactor for RBDBY</td>
<td>100 Ohms</td>
</tr>
<tr>
<td>RBSDBXL</td>
<td>Length Scaling parameter for RBSBX and RBDBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSDBXW</td>
<td>Width Scaling parameter for RBSBX and RBDBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSDBXNF</td>
<td>Number of fingers Scaling parameter for RBSBX and RBDBX</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSDBYL</td>
<td>Length Scaling parameter for RBSBY and RBDBY</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSDBYW</td>
<td>Width Scaling parameter for RBSBY and RBDBY</td>
<td>0.0</td>
</tr>
<tr>
<td>RBSDBYNF</td>
<td>Number of fingers Scaling parameter for RBSBY and RBDBY</td>
<td>0.0</td>
</tr>
</tbody>
</table>
## 15 Flicker and Thermal Noise Model Parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOIA</td>
<td>Flicker noise parameter A</td>
<td>(6.25e41(eV)^{-1}s^{1-EF}m^{-3}) for NMOS; (6.188e40(eV)^{-1}s^{1-EF}m^{-3}) for PMOS</td>
</tr>
<tr>
<td>NOIB</td>
<td>Flicker noise parameter B</td>
<td>(3.125e26(eV)^{-1}s^{1-EF}m^{-1}) for NMOS; (1.5e25(eV)^{-1}s^{1-EF}m^{-1}) for PMOS</td>
</tr>
<tr>
<td>NOIC</td>
<td>Flicker noise parameter C</td>
<td>(8.75(eV)^{-1}s^{1-EF}m)</td>
</tr>
<tr>
<td>EM</td>
<td>Saturation field</td>
<td>(4.1e7V/m)</td>
</tr>
<tr>
<td>AF</td>
<td>Flicker noise exponent</td>
<td>1.0</td>
</tr>
<tr>
<td>EF</td>
<td>Flicker noise frequency exponent</td>
<td>1.0</td>
</tr>
<tr>
<td>KF</td>
<td>Flicker noise coefficient</td>
<td>(0.0^{A2-EF}s^{1-EF})</td>
</tr>
<tr>
<td>LINTNOI</td>
<td>Length Reduction Parameter Offset</td>
<td>0.0 m</td>
</tr>
<tr>
<td>NTNOI</td>
<td>Noise factor for short-channel devices for TNOIMOD=0 only</td>
<td>1.0</td>
</tr>
<tr>
<td>TNOIA</td>
<td>Coefficient of channel-length dependence of total channel thermal noise</td>
<td>1.5</td>
</tr>
<tr>
<td>TNOIB</td>
<td>Channel-length dependence parameter for channel thermal noise partitioning</td>
<td>3.5</td>
</tr>
<tr>
<td>TNOIC</td>
<td>Length dependent parameter for Correlation Coefficient</td>
<td>0</td>
</tr>
<tr>
<td>RNOIA</td>
<td>Thermal Noise Coefficient</td>
<td>0.577</td>
</tr>
<tr>
<td>RNOIB</td>
<td>Thermal Noise Coefficient</td>
<td>0.5164</td>
</tr>
<tr>
<td>RNOIC</td>
<td>Correlation Coefficient parameter</td>
<td>0.395</td>
</tr>
<tr>
<td>Parameter Name</td>
<td>Description</td>
<td>Default Value</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>DMCG</td>
<td>Distance from S/D contact center to the gate edge</td>
<td>0.0m</td>
</tr>
<tr>
<td>DMCI</td>
<td>Distance from S/D contact center to the isolation edge in the channel-length direction</td>
<td>DMCG</td>
</tr>
<tr>
<td>DMDG</td>
<td>Same as DMCG but for merged device only</td>
<td>0.0m</td>
</tr>
<tr>
<td>DMCGT</td>
<td>DMCG of test structures</td>
<td>0.0m</td>
</tr>
<tr>
<td>NF (instance parameter only)</td>
<td>Number of device fingers (Fatal error if less than one )</td>
<td>1</td>
</tr>
<tr>
<td>DWJ</td>
<td>Offset of the S/D junction width</td>
<td>DWC (in CVmodel)</td>
</tr>
<tr>
<td>MIN (instance parameter only)</td>
<td>Whether to minimize the number of drain or source diffusions for even-number fingered device</td>
<td>0 (minimize the drain diffusion number)</td>
</tr>
<tr>
<td>XGW (Also an instance parameter)</td>
<td>Distance from the gate contact to the channel edge</td>
<td>0.0m</td>
</tr>
<tr>
<td>XGL</td>
<td>Offset of the gate length due to variations in patterning</td>
<td>0.0m</td>
</tr>
<tr>
<td>XL</td>
<td>Channel length offset due to mask/etch effect</td>
<td>0.0m</td>
</tr>
<tr>
<td>XW</td>
<td>Channel width offset due to mask/etch effect</td>
<td>0.0m</td>
</tr>
<tr>
<td>NGCON (Also an instance parameter)</td>
<td>Number of gate contacts (Fatal error if less than one; if not equal to 1 or 2, warning message issued and reset to 1 )</td>
<td>1</td>
</tr>
</tbody>
</table>
## 17 Asymmetric Source/Drain Junction Diode Model Parameters

<table>
<thead>
<tr>
<th>Parameter Name (separate for source and drain side as indicated in the names)</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJTHSREV IJTHDREV</td>
<td>Limiting current in reverse bias region</td>
<td>IJTHSREV = 0.1A, IJTHDREV = IJTHSREV</td>
</tr>
<tr>
<td>IJTHSFWD IJTHDFWD</td>
<td>Limiting current in forward bias region</td>
<td>IJTHSFWD = 0.1A, IJTHDFWD = IJTHSFWD</td>
</tr>
<tr>
<td>XJBVS XJBVD</td>
<td>Fitting parameter for diode breakdown</td>
<td>XJBVS = 1.0, XJBVD = XJBVS</td>
</tr>
<tr>
<td>BVS BVD</td>
<td>Breakdown voltage (If not positive, reset to 10.0V)</td>
<td>BVS = 10.0V, BVD = BVS</td>
</tr>
<tr>
<td>JSS JSD</td>
<td>Bottom junction reverse saturation current density</td>
<td>JSS = 1.0e-4A/m2, JSD = JSS</td>
</tr>
<tr>
<td>JSWS JSWD</td>
<td>Isolation-edge sidewall reverse saturation current density</td>
<td>JSWS = 0.0A/m, JSWD = JSWS</td>
</tr>
<tr>
<td>JSWGJSWGD</td>
<td>Gate-edge sidewall reverse saturation current density</td>
<td>JSWG = 0.0A/m, JSWG = JSWG</td>
</tr>
<tr>
<td>JTSS JTSD</td>
<td>Bottom trap-assisted saturation current density</td>
<td>JTSS = 0.0A/m JTSD = JTSS</td>
</tr>
<tr>
<td>JTSSWS JTSSWD</td>
<td>STI sidewall trap-assisted saturation current density</td>
<td>JTSSWS = 0.0A/m2 JTSSWD = JTSSWS</td>
</tr>
<tr>
<td>JTSSWGS JTSSWGD</td>
<td>Gate-edge sidewall trap-assisted saturation current density</td>
<td>JTSSWGS = 0.0A/m JTSSWGD = JTSSWGS</td>
</tr>
<tr>
<td>JTWEFF</td>
<td>Trap-assistant tunneling current density width dependence</td>
<td>0.0</td>
</tr>
<tr>
<td>NJTS NJTSD</td>
<td>Non-ideality factor for JTSS and JTSD</td>
<td>NJTS = 20.0 NJTSD = NJTS</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>NJTSSW</td>
<td>Non-ideality factor for JTSSWS and JTSSWD</td>
<td>20.0</td>
</tr>
<tr>
<td>NJTSSWD</td>
<td>Non-ideality factor for JTSSWD</td>
<td>NJTSSW</td>
</tr>
<tr>
<td>XTSS, XTSD</td>
<td>Power dependence of JTSS, JTSD on temperature</td>
<td>XTSS = 0.02 XTSD = 0.02</td>
</tr>
<tr>
<td>XTSSWS, XTSSWD</td>
<td>Power dependence of JTSSWS, JTSSWD on temperature</td>
<td>XTSSWS = 0.02 XTSSWD = 0.02</td>
</tr>
<tr>
<td>XTSSWGS, XTSSWGD</td>
<td>Power dependence of JTSSWGS, JTSSWG on temperature</td>
<td>XTSSWGS = 0.02 XTSSWGD = 0.02</td>
</tr>
<tr>
<td>VTSS, VTSD</td>
<td>Bottom trap-assisted voltage dependent parameter</td>
<td>VTSS = 10V VTSD = VTSS</td>
</tr>
<tr>
<td>VTSSWS, VTSSWD</td>
<td>STI sidewall trap-assisted voltage dependent parameter</td>
<td>VTSSWS = 10V VTSSWD = VTSSWS</td>
</tr>
<tr>
<td>VTSSWGS, VTSSWGD</td>
<td>Gate-edge sidewall trap-assisted voltage dependent parameter</td>
<td>VTSSWGS = 10V VTSSWGD = VTSSWGS</td>
</tr>
<tr>
<td>TNJTS, TNJTSD</td>
<td>Temperature coefficient for NJTS and NJTSD</td>
<td>TNJTS=0.0 TNJTSD = TNJTS</td>
</tr>
<tr>
<td>TNJTSSW, TNJTSSWD</td>
<td>Temperature coefficient for JTSSWS and JTSSWD</td>
<td>TNJTSSW=0.0 TNJTSSWD = TNJTS</td>
</tr>
<tr>
<td>CJS, CJD</td>
<td>Bottom junction capacitance per unit area at zero bias</td>
<td>CJS=5.0e-4 F/m² CJD=CJS</td>
</tr>
<tr>
<td>MJS, MJD</td>
<td>Bottom junction capacitance grating coefficient</td>
<td>MJS=0.5 MJD=MJS</td>
</tr>
<tr>
<td>MJSWS, MJSWD</td>
<td>Isolation-edge sidewall junction capacitance grading coefficient</td>
<td>MJSWS = 0.33 MJSWD = MJSWS</td>
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<tr>
<td>CJSWS, CJSWD</td>
<td>Isolation-edge sidewall junction capacitance per unit area</td>
<td>CJSWS= 5.0e-10 F/m CJSWD = CJSWS</td>
</tr>
<tr>
<td>CJSSWG, CJSSWGD</td>
<td>Gate-edge sidewall junction capacitance per unit length</td>
<td>CJSSWG = CJSSWS CJSSWGD = CJSSWS</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Equations</td>
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<tr>
<td>MJSWGS</td>
<td>Gate-edge sidewall junction capacitance grading coefficient</td>
<td>MJSWGS = MJSWS</td>
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<tr>
<td>MJSWGD</td>
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<td>MJSWGD = MJSWS</td>
</tr>
<tr>
<td>PBS</td>
<td>Source-side bulk junction built-in potential</td>
<td>1.0V</td>
</tr>
<tr>
<td>PBD</td>
<td>Drain-side bulk junction built-in potential</td>
<td>PBD = PBS</td>
</tr>
<tr>
<td>PBSWS</td>
<td>Isolation-edge sidewall junction built-in potential</td>
<td>PBSWS = 1.0V, PBSWD = PBSWS</td>
</tr>
<tr>
<td>PB-SWD</td>
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<td></td>
</tr>
<tr>
<td>PBSWGS</td>
<td>Gate-edge sidewall junction built-in potential</td>
<td>PBSWGS = PBSWS, PB-SWGD = PBSWS</td>
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<tr>
<td>PB-SWGD</td>
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## 18 Temperature Dependence and Self Heating Parameters

<table>
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<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>Default Value</th>
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# 19 Stress Effect Model Parameters

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<td>SD (Instance Parameter)</td>
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## Well-Proximity Effect Parameters

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<td>Integral of the first distribution function for scattered well dopant (If not given, calculated)</td>
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## 21 Parameter equivalence between BSIM6 & BSIM4

The equivalent parameters are the closest match between two models. There values may be different in two models.

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Taken from BSIMSOI
22 Appendix A : Smoothing Function

22.1 Polynomial Smoothing

The polynomial smoothing is used for a smooth transition between boundaries, maintaining exact values at all the corner points. Consider the function

\[ f(x) = \begin{cases} x & \text{if } x > \frac{\Delta x}{2} \\ k & \text{if } x < -\frac{\Delta x}{2} \end{cases} \]  

where k is some constant. The function is undefined for the region \(-\frac{\Delta x}{2} < x < \frac{\Delta x}{2}\). If this region is approximated by a polynomial function, the complete function and even derivatives can be made continuous. Now consider the more generalized case

\[ f(x) = \begin{cases} x & \text{if } x > x_1 \\ k & \text{if } x < x_2 \end{cases} \]  

To express (22.4) in the form of (22.2), x is linearly transformed into z. Defining

\[ x_0 = \frac{x_1 + x_2}{2} \]  
\[ \Delta x = x_1 - x_2 \]  

then the boundary points becomes

\[ x_1 = x_0 + \frac{\Delta x}{2} \]  
\[ x_2 = x_0 - \frac{\Delta x}{2} \]  

Let \( z = \frac{x-x_0}{\Delta x} \). Thus the above boundary points in z domain becomes,

\[ z_1 = \frac{x_1 - x_0}{\Delta x} = \frac{1}{2} \]  
\[ z_2 = \frac{x_2 - x_0}{\Delta x} = -\frac{1}{2} \]
so that the function becomes

\[ f(z) = \begin{cases} 
  z \Delta x - x_0 & \text{if } z > \frac{1}{2} \\
  k & \text{if } z < -\frac{1}{2}
\end{cases} \] (22.11)

\[ f(z) = \begin{cases} 
  124
\end{cases} \] (22.12)

the region \(-\frac{1}{2} \leq z \leq \frac{1}{2}\) is modeled by the polynomial function whose order depends on the number of boundary conditions. For example, to have continuous derivatives up to third order, we need seventh order polynomial as there are 8 boundary conditions.

\[ f(z) = a.z^7 + b.z^6 + c.z^5 + d.z^4 + e.z^3 + f.z^2 + g.z + 1 \] (22.13)

Then boundary conditions can be applied to derivatives to determine the polynomial coefficients. For the case of continuous third order derivatives, we found that

\[ f(x) = x_0 + \Delta x \cdot \left[ \frac{5}{64} + \frac{z}{2} + z^2 \cdot \left( \frac{15}{16} - \frac{z^2}{4} \right) \right] \] (22.14)

while for continuous second order derivative

\[ f(x) = x_0 + \Delta x \cdot \left[ \frac{3}{32} + \frac{z}{2} + z^2 \cdot \left( \frac{3}{4} - \frac{z^2}{4} \right) \right] \] (22.15)

with \( z = \frac{x-x_0}{\Delta x} \). Figure 12 illustrate the concept of polynomial smoothing.

**An Example**: Let the function be given as

\[ f(x) = \begin{cases} 
  x & \text{if } x > -90 \\
  -100 & \text{if } x < -110
\end{cases} \] (22.16)

(22.17)

with the condition that third derivative to exist. From (22.6)

\[ x_0 = -100 \] (22.18)

\[ \Delta x = 20 \] (22.19)

\[ z = \frac{x + 100}{20} \] (22.20)

and function becomes,

\[ f(z) = \begin{cases} 
  20.z + 100 & \text{if } z > \frac{1}{2} \\
  -100 & \text{if } z < -\frac{1}{2}
\end{cases} \] (22.21)

(22.22)
Figure 12: Illustration of Polynomial Smoothing

Boundary Conditions

\[
\begin{align*}
    f\left(\frac{1}{2}\right) &= -90, f\left(-\frac{1}{2}\right) = -100 \\
    f'\left(\frac{1}{2}\right) &= 20, f'\left(-\frac{1}{2}\right) = 0 \\
    f''\left(\frac{1}{2}\right) &= 0, f''\left(-\frac{1}{2}\right) = 0 \\
    f'''\left(\frac{1}{2}\right) &= 0, f'''\left(-\frac{1}{2}\right) = 0
\end{align*}
\]

(22.23) (22.24) (22.25) (22.26)

We have 8 boundary conditions. So let

\[f(z) = a.z^7 + b.z^6 + c.z^5 + d.z^4 + e.z^3 + f.z^2 + g.z + 1\]

(22.27)

Now we have 8 equations and 8 unknowns and hence all the coefficients can be derived. By substituting (22.23-22.26) in (22.27) we get

\[
\begin{align*}
    a &= 0, \\
    b &= 20, \\
    c &= 0, \\
    d &= -25, \\
    e &= 0, \\
    f &= \frac{75}{4}, \\
    g &= 10, \\
    h &= -\frac{6300}{64}
\end{align*}
\]

(22.28) (22.29)

125
Thus

\[ f(z) = 20.z^6 - 25.z^4 + \frac{75}{4}.z^2 + 10.z - \frac{6300}{64} \]  

(22.30)

Figure 13 shows the above function. As can be seen that due to polynomial nature, the approximated function undergoes smooth transitions around the boundary points.
References


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