BSIM-CMG 112.0.0

Multi-Gate MOSFET Compact Model

Technical Manual

Project Director:
Prof. Sayeef Salahuddin and Prof. Chenming Hu

Department of Electrical Engineering and Computer Sciences
University of California, Berkeley, CA 94720

Contributors:

Prof. Ali Niknejad

Current Developers:

Ahtisham Pampori
Dinesh Rajasekharan
Shivendra Singh Parihar
Chien-Ting Tung
Jen-Hao Chen

Past Developers :

Chetan Kumar Dabhi, UC Berkeley
Girish Pahwa, UC Berkeley
Ming-Yen Kao, UC Berkeley
Avirup Dasgupta, UC Berkeley
Pragya Kushwaha, UC Berkeley
Harshit Agarwal, UC Berkeley
Yen-Kai Lin, UC Berkeley
Huan-Lin Chang, UC Berkeley
Juan Pablo Duarte, UC Berkeley
Sourabh Khandelwal, UC Berkeley
Aditya Medury, UC Berkeley
Srivatsava Jandhyala, UC Berkeley
Navid Paydavosi, UC Berkeley
Sriramkumar V., UC Berkeley
Chung-Hsun Lin, UC Berkeley
Mohan Dunga, UC Berkeley
Darsen Lu, UC Berkeley
Shijing Yao, UC Berkeley
Tanvir Morshed, UC Berkeley

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1 Introduction

The continuous evolution and enhancement of planar bulk CMOS technology has fueled the growth of the microelectronics industry for the past several decades. When we reach the end of the technology roadmap for the classical CMOS, multiple gate MOSFETs (MuGFETs) will likely take up the baton. We have developed a multiple gate MOSFET compact model for technology/circuits development in the short term and for product design in the longer term [1].

Several different MuGFET structures and two different modes of operation are being pursued in the industry today. In the case of horizontal double gate (DG), the two gates will likely be asymmetric–having different work functions and underlying dielectric thicknesses, complicating the compact model. Also, the two gates are likely to be biased at two different voltages, known as independent gates. In the other double, triple, or all-around gate cases, the gates are biased at the same voltage, known as the common gate. Some designs will use lightly doped body to maximize mobility, others will use very high doping concentrations in thin body to obtain sufficient Vt adjustment.

BSIM-CMG has been developed to model the electrical characteristics of common multi-gate (CMG) structures. The details of the model will be described in this document. It will serve the needs of all circuit designer/ technology developers by providing versatility without compromising ease of use and computational efficiency. A separate model BSIM-IMG addresses independent gate devices [2].

2 Model Description

BSIM-CMG is implemented in Verilog-A. Physical surface-potential-based formulations are derived for both intrinsic and extrinsic models with finite body doping. The surface potentials at the source and drain ends are solved analytically with quantum mechanical effects. The effect of finite body doping is captured through a perturbation approach. The analytic surface potential solution agrees with 2-D device simulation results well.

All the important MG transistor behaviors are captured by this model. Volume inversion is included in the solution of Poisson's equation, hence the subsequent I-V formulation automatically captures the volume inversion effect. Analysis of the electrostatic potential in the body of MG MOSFETs provided the model equation for the short channel effects (SCE). The extra electrostatic control from the end-gates (top/bottom gates) (triple or quadruple-gate) is also captured in the short channel model.

BSIM-CMG provides the flexibility to model devices with novel materials. This includes parameters for non-silicon channel devices and High-K/ Metal-gate stack.

Other important effects, such as, mobility degradation, velocity saturation, velocity overshoot, series resistance, channel length modulation, quantum mechanical effects, gate tunneling current, gate-induced-drain-leakage, temperature effects, channel thermal noise, flicker noise, noise associated with device parasitics, and parasitic capacitance, are also incorporated in the model.

BSIM-CMG has been verified with industrial experimental data. The model is continuous and symmetric at $V_{ds} = 0$. This physics-based model is scalable and predictive over a wide range of device parameters.

3 Model Equations

3.1 Bias Independent Calculations

3.1.1 Physical Constants

Physical quantities in BSIM-CMG are in MKS units unless specified otherwise.

$$q = 1.60219 \times 10^{-19} \tag{3.1}$$

$$\epsilon_0 = 8.8542 \times 10^{-12} \tag{3.2}$$

$$\hbar = 1.05457 \times 10^{-34} \tag{3.3}$$

$$m_e = 9.11 \times 10^{-31} \tag{3.4}$$

$$k = 1.3787 \times 10^{-23} \tag{3.5}$$

$$\epsilon_{sub} = EPSRSUB \cdot \epsilon_0 \tag{3.6}$$

$EPSRSUB$ is the relative dielectric constant of the channel material.

$$\epsilon_{ox} = EPSROX \cdot \epsilon_0 \tag{3.7}$$

$EPSROX$ is the relative dielectric constant of the gate insulator.

$$C_{ox} = \frac{3.9 \cdot \epsilon_0}{EOT} \tag{3.8}$$

EOT is the SiO2 equivalent gate dielectric thickness including inversion layer thickness.

$$C_{si} = \frac{\epsilon_{sub}}{TFIN} \tag{3.9}$$

$$\epsilon_{ratio} = \frac{EPSRSUB}{3.9} \tag{3.10}$$

3.1.2 Effective Channel Width, Channel Length and Fin Number

Effective Channel Length:

$$\Delta L = LINT + \frac{LL}{(L + XL)^{LLN}} \tag{3.11}$$

$$L_{eff} = L + XL - 2\Delta L \tag{3.12}$$

Here, ΔL is the overlap/underlap between the gate and the source/drain diffusions; $LINT$ is ΔL for large devices; L is the designed (drawn) length; XL is the length variation due to process effects; LL and LLN are fitting parameters.

$$\Delta L_{CV} = DLC + \frac{LLC}{(L + XL)^{LLN}} \tag{3.13}$$

$$L_{eff,CV} = L + XL - 2\Delta L_{CV} \tag{3.14}$$

Here, ΔL_{CV} is the overlap/underlap between the gate and the source/drain diffusions for C-V calculations; DLC is ΔL_{CV} for large devices; LLC is a fitting parameter.

If $BULKMOD = 1$ then

$$L_{eff,CV,acc} = L_{eff,CV} - DLCACC \tag{3.15}$$

$$NFIN_{total} = NFIN \times NF \tag{3.16}$$

<u>**If BULKMOD not equal to zero**</u>

$$COX_{ACC} = COX \cdot \frac{EOT}{EOTACC} \tag{3.17}$$

Effective Channel Width:

for IV: $$Weff0 = Weff\_UFCM - DELTAW \tag{3.18}$$

for CV: $$WeffCV0 = Weff\_UFCM - DELTAWCV \tag{3.19}$$

If GEOMOD = 5

for IV and CV: $$WGAA_{eff} = WGAA + XW_i \tag{3.20}$$

for Binning terms: $$WGAA_{eff1} = WGAA_{eff} + DWBIN_i \tag{3.21}$$

If GEOMOD = 5 and BULKMOD = 1

$$W_{eff,CV,acc} = Weff0 - 2 \cdot NGAA \cdot DWCACC \tag{3.22}$$

$$\tag{3.23}$$

$Weff\_UFCM$ is given as follows:

$GEOMOD = 0$ - Double Gate

If the values of $TFIN\_TOP$ (Top FIN thickness of Trapezoidal FINFET) or $TFIN\_BASE$ (Base FIN thickness of Trapezoidal FINFET) are provided as model parameters and not passed as instance parameters

$$WEFF\_UFCM = 2 \cdot HFIN \tag{3.24}$$

$$ACH = HFIN \cdot TFIN \tag{3.25}$$

Else If the values of $TFIN\_TOP$ and $TFIN\_BASE$ are over-ridden with instance parameters passed from the Netlist

$$WEFF\_UFCM = 2 \cdot \sqrt{(HFIN^2 + \frac{1}{4} \cdot (TFIN\_TOP - TFIN\_BASE)^2)} \tag{3.26}$$

$$ACH = HFIN \cdot (\frac{TFIN\_TOP + TFIN\_BASE}{2}) \tag{3.27}$$

In both cases,

$$CINS = WEFF\_UFCM \cdot EPSROX \cdot \frac{\epsilon_0}{EOT} \tag{3.28}$$

$$rc = \frac{2 \cdot CINS}{WEFF\_UFCM \cdot WEFF\_UFCM \cdot \frac{\epsilon_{SUB}}{ACH}} \tag{3.29}$$

$$qdep = -1 \cdot q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.30}$$

$GEOMOD = 1$ - Triple Gate

If the values of $TFIN\_TOP$ (Top FIN thickness of Trapezoidal FINFET) or $TFIN\_BASE$ (Base FIN thickness of Trapezoidal FINFET) are provided as model parameters and not passed as instance parameters

$$WEFF\_UFCM = 2 \cdot HFIN + TFIN \tag{3.31}$$
$$ACH = HFIN \cdot TFIN \tag{3.32}$$

Else If the values of $TFIN\_TOP$ and $TFIN\_BASE$ are over-ridden with instance parameters passed from the Netlist

$$WEFF\_UFCM = 2 \cdot \sqrt{(HFIN^2 + \frac{1}{4} \cdot (TFIN\_TOP - TFIN\_BASE)^2)} + TFIN\_TOP \tag{3.33}$$
$$ACH = HFIN \cdot (\frac{TFIN\_TOP + TFIN\_BASE}{2}) \tag{3.34}$$

In both cases,

$$CINS = WEFF\_UFCM \cdot EPSROX \cdot \frac{\epsilon_0}{EOT} \tag{3.35}$$
$$rc = \frac{2 \cdot CINS}{WEFF\_UFCM \cdot WEFF\_UFCM \cdot \frac{\epsilon_{SUB}}{ACH}} \tag{3.36}$$
$$qdep = -1 \cdot q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.37}$$

$GEOMOD = 2$ - Quadruple Gate

If the values of $TFIN\_TOP$ (Top FIN thickness of Trapezoidal FINFET) or $TFIN\_BASE$ (Base FIN thickness of Trapezoidal FINFET) are provided as model parameters and not passed as instance parameters

$$WEFF\_UFCM = 2 \cdot HFIN + 2 \cdot TFIN \tag{3.38}$$
$$ACH = HFIN \cdot TFIN \tag{3.39}$$

Else If the values of $TFIN\_TOP$ and $TFIN\_BASE$ are over-ridden with instance parameters passed from the

Netlist

$$WEFF\_UFCM = 2 \cdot \sqrt{(HFIN^2 + \frac{1}{4} \cdot (TFIN\_TOP - TFIN\_BASE)^2)} + (TFIN\_TOP + TFIN\_BASE) \tag{3.40}$$

$$ACH = HFIN \cdot (\frac{TFIN\_TOP + TFIN\_BASE}{2}) \tag{3.41}$$

In both cases,

$$CINS = WEFF\_UFCM \cdot EPSROX \cdot \frac{\epsilon_0}{EOT} \tag{3.42}$$

$$rc = \frac{2 \cdot CINS}{WEFF\_UFCM \cdot WEFF\_UFCM \cdot \frac{\epsilon_{SUB}}{ACH}} \tag{3.43}$$

$$qdep = -1 \cdot q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.44}$$

$GEOMOD = 3$ - Cylindrical Gate

If the values of $TFIN\_TOP$ (Top FIN thickness of Trapezoidal FINFET) or $TFIN\_BASE$ (Base FIN thickness of Trapezoidal FINFET) are provided as model parameters and not passed as instance parameters

$$WEFF\_UFCM = \pi \cdot D \tag{3.45}$$

$$CINS = 2 \cdot \pi \cdot EPSROX \cdot \frac{\epsilon_0}{ln\left(1 + 2 \cdot \frac{EOT}{D}\right)} \tag{3.46}$$

$$ACH = \pi \cdot D \cdot \frac{D}{4} \tag{3.47}$$

$$rc = \frac{2 \cdot CINS}{WEFF\_UFCM \cdot WEFF\_UFCM \cdot \frac{\epsilon_{SUB}}{ACH}} \tag{3.48}$$

$$qdep = -1 \cdot q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.49}$$

$GEOMOD = 4$ - Unified Model

$$rc = \frac{2 \cdot CINS}{WEFF\_UFCM \cdot WEFF\_UFCM \cdot \frac{\epsilon_{SUB}}{ACH}} \tag{3.50}$$

$$qdep = -1 \cdot q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.51}$$

$$C_{ox} = \frac{CINS}{WEFF\_UFCM} \tag{3.52}$$

$GEOMOD = 5$ - Gate-All-Around FET (GAAFET)

This module is specifically designed for GAAFETs.

$$W_{eff,i} = 2(WGAA_{eff} + TGAA) + DWS_i;\ i = 1, 2..NGAA \tag{3.53}$$

$$W_{eff\_UFCM} = \sum_{i=1}^{NGAA} W_{eff,i} \tag{3.54}$$

$$A_{ch,i} = WGAA_{eff} \cdot TGAA + DACH_i;\ i = 1, 2..NGAA \tag{3.55}$$

$$A_{ch} = \sum_{i=1}^{NGAA} A_{ch,i} \tag{3.56}$$

$$C_{ins} = W_{eff\_UFCM} EPSROX \frac{\epsilon_0}{EOT} \tag{3.57}$$

The calculation of rc, $qdep$ and C_{ox} is the same as in $GEOMOD = 4$.

3.1.3 Geometry-dependent source/drain resistance

Please refer to section 3.15.

3.1.4 Quantum Mechanical Effects

The following bias-independent calculations are for the threshold voltage shift and bias dependence of inversion charge centroid due to quantum mechanical confinement. See section on "Surface Potential Calculation" and "Quantum Mechanical Effects" for more details.

$$m_x = 0.916 \cdot m_e \tag{3.58}$$

$$m'_x = 0.190 \cdot m_e \tag{3.59}$$

$$m_d = 0.190 \cdot m_e \tag{3.60}$$

$$m'_d = 0.417 \cdot m_e \tag{3.61}$$

$$g' = 4.0 \tag{3.62}$$

$$g = 2.0 \tag{3.63}$$

MTcen and T_{cen0} are defined as follows in the UFCM formulation. Note that this formulation reduces to those used in BSIMCMG108.0.0 if ACH and WEFF_UFCM are replaced by their definitions:

$$MTcen = 1.0 + AQMTCEN \cdot exp\left(-\frac{\left(\frac{2 \cdot ACH}{WEFF\_UFCM}\right)}{BQMTCEN}\right) \tag{3.64}$$

$$T_{cen0} = \left(\frac{2 \cdot ACH}{WEFF\_UFCM}\right) \cdot MTcen \tag{3.65}$$

If $GEOMOD = 0$ then

$$MTcen = 1 + AQMTCEN \cdot exp(-\frac{TFIN}{BQMTCEN}) \tag{3.66}$$

$$T_{cen0} = TFIN \cdot MTcen \tag{3.67}$$

If $GEOMOD = 1$ then

$$MTcen = 1 + AQMTCEN \cdot exp(-\frac{min(HFIN, TFIN)}{BQMTCEN}) \tag{3.68}$$

$$T_{cen0} = min(TFIN, HFIN) \cdot MTcen \tag{3.69}$$

If $GEOMOD = 2$ then

$$MTcen = 1 + AQMTCEN \cdot exp(-\frac{min(HFIN, TFIN)}{BQMTCEN}) \tag{3.70}$$

$$T_{cen0} = min(TFIN, HFIN) \cdot MTcen \tag{3.71}$$

If $GEOMOD = 3$ then

$$MTcen = 1 + AQMTCEN \cdot exp(-\frac{R}{BQMTCEN}) \tag{3.72}$$

$$T_{cen0} = R \cdot MTcen \tag{3.73}$$

3.1.5 Binning Calculations

The optional binning methodology [3] is adopted in BSIM-CMG.

For a given L, NFIN, each model parameter $PARAM_i$ is calculated as a function of PARAM, a length dependent term LPARAM, a number of fin per finger(NFIN) dependent term NPARAM, and a product $L \times NFIN$ term, PPARAM:

$$\Delta L1 = LINT + \frac{LL}{(L + DLBIN)^{LLN}} \tag{3.74}$$

$$L_{eff1} = L + DLBIN - 2\Delta L1 \tag{3.75}$$

$$PARAM_i = PARAM + \frac{1.0e-6}{L_{eff1} + DLBIN} \cdot LPARAM + \frac{1.0}{NFIN} \cdot NPARAM + \frac{1.0e-6}{NFIN \cdot (L_{eff1} + DLBIN)} \cdot PPARAM \tag{3.76}$$

If GEOMOD=5 (for gate-all-around FETs) is selected, two additional binning terms are available for every parameter: a WGAA dependent term and a second product term depending on WGAA × L. In this case, the binning equation becomes

$$PARAM_i = PARAM + \frac{1.0e-6}{L_{eff1}+DLBIN} \cdot LPARAM + \frac{1.0}{NFIN} \cdot NPARAM + \frac{1.0e-6}{NFIN \cdot (L_{eff1}+DLBIN)} \cdot PPARAM + \frac{1.0e-6}{WGAA} \cdot WPARAM + \frac{1.0e-12}{WGAA \times L_{eff1}} \cdot P2PARAM \tag{3.77}$$

All binning parameters have a default value of 0. For the list of binable parameters, please refer to the complete parameter list in the end of this technical note. If PARAM1 defaults to PARAM2, the binning parameters for PARAM1 also default to the corresponding binning parameters of PARAM2.

3.1.6 NFIN scaling equations

$$PHIG[L,N] = PHIG_i \times \left[1.0 + \frac{PHIGN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{PHIGN2}\right)\right] \times [1.0 + (NFIN - NFINNOM) \cdot PHIGLT \cdot L_{eff}] \tag{3.78}$$

$$ETA0[L,N] = ETA0_i \times \left[1.0 + \frac{ETA0N1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{ETA0N2}\right)\right] \times [1.0 + (NFIN - NFINNOM) \cdot ETA0LT \cdot L_{eff}] \tag{3.79}$$

$$CDSC[N] = CDSC_i \times \left[1.0 + \frac{CDSCN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{CDSCN2}\right)\right] \tag{3.80}$$

$$CDSCD[N] = CDSCD_i \times \left[1.0 + \frac{CDSCDN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{CDSCDN2}\right)\right] \tag{3.81}$$

$$CDSCDR[N] = CDSCDR_i \times \left[1.0 + \frac{CDSCDRN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{CDSCDRN2}\right)\right] \tag{3.82}$$

$$NBODY[N] = NBODY_i \times \left[1.0 + \frac{NBODYN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{NBODYN2}\right)\right] \tag{3.83}$$

$$VSAT[N] = VSAT_i \times \left[1.0 + \frac{VSATN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{VSATN2}\right)\right] \tag{3.84}$$

$$VSAT1[N] = VSAT1_i \times \left[1.0 + \frac{VSAT1N1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{VSAT1N2}\right)\right] \tag{3.85}$$

$$VSAT1R[N] = VSAT1R_i \times \left[1.0 + \frac{VSAT1RN1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{VSAT1RN2}\right)\right] \tag{3.86}$$

$$U0[L,N] = U0_i \times \left[1.0 + \frac{U0N1}{NFIN} \times \ln\left(1.0 + \frac{NFIN}{U0N2}\right)\right] \times [1.0 + (NFIN - NFINNOM) \cdot U0LT \cdot L_{eff}] \tag{3.87}$$

3.1.7 Length scaling equations

$$PHIG[L,N] = PHIG[N] + PHIGL \cdot Leff \tag{3.88}$$

$$U0[L,N] = \begin{cases} U0[N] \cdot \left[1 - UP_i \cdot L_{eff}{}^{-LPA}\right] & LPA > 0 \\ U0[N] \cdot [1 - UP_i] & \text{Otherwise} \end{cases} \tag{3.89}$$

$$\begin{cases} MEXP[L] = MEXP_i + AMEXP \cdot L_{eff}{}^{-BMEXP} & \text{if } ASYMMOD = 0 \\ MEXPR[L] = MEXPR_i + AMEXPR \cdot L_{eff}{}^{-BMEXPR} & \text{if } ASYMMOD = 1 \end{cases} \tag{3.90}$$

$$PCLM[L] = PCLM_i + APCLM \cdot \exp\left(-\frac{L_{eff}}{BPCLM}\right) \tag{3.91}$$

$$UA[L] = UA_i + AUA \cdot \exp\left(-\frac{L_{eff}}{BUA}\right) \tag{3.92}$$

$$UD[L] = UD_i + AUD \cdot \exp\left(-\frac{L_{eff}}{BUD}\right) \tag{3.93}$$

If $RDSMOD = 0$ or 2 then

$$RDSW[L] = RDSW_i + ARDSW \cdot \exp\left(-\frac{L_{eff}}{BRDSW}\right) \tag{3.94}$$

If $RDSMOD = 1$ then

$$RSW[L] = RSW_i + ARSW \cdot \exp\left(-\frac{L_{eff}}{BRSW}\right) \tag{3.95}$$

$$RDW[L] = RDW_i + ARDW \cdot \exp\left(-\frac{L_{eff}}{BRDW}\right) \tag{3.96}$$

$$PTWG[L] = PTWG_i + APTWG \cdot \exp\left(-\frac{L_{eff}}{BPTWG}\right) \tag{3.97}$$

$$PTWGR[L] = PTWGR_i + APTWG \cdot \exp\left(-\frac{L_{eff}}{BPTWG}\right) \tag{3.98}$$

$$VSAT[L,N] = VSAT[N] + AVSAT \cdot \exp\left(-\frac{L_{eff}}{BVSAT}\right) \tag{3.99}$$

$$VSAT1[L,N] = VSAT1[N] + AVSAT1 \cdot \exp\left(-\frac{L_{eff}}{BVSAT1}\right) \tag{3.100}$$

$$VSAT1R[L,N] = VSAT1R[N] + AVSAT1 \cdot \exp\left(-\frac{L_{eff}}{BVSAT1}\right) \tag{3.101}$$

$$VSATCV[L] = VSAT_i + AVSATCV \cdot \exp\left(-\frac{L_{eff}}{BVSATCV}\right) \tag{3.102}$$

$$PSAT[L] = PSAT_i + APSAT \cdot \exp\left(-\frac{L_{eff}}{BPSAT}\right) \tag{3.103}$$

3.1.8 Temperature Effects

$$T = \$temperature + DTEMP \tag{3.104}$$

CRYOMOD = 0

The functional form of temperature dependence of parameters fall in two categories:

Type A

$$PARAM[T] = PARAM[L](1 \pm PARAM_T(T - Tnom)) \tag{3.105}$$

Type B

$$PARAM[T] = PARAM[L] \pm PARAM_T(T - Tnom) \tag{3.106}$$

where $PARAM_T$ is a model temperature coefficient and $Tnom$ is the temperature in Kelvin at which the model is extracted. BSIM-CMG allows users the option to change the functional form of temperature dependence of a group of selected parameters via temperature selector switch TEMPMOD. TEMPMOD=0 is the default temperature dependence of the parameter expressed in the following equations. Selecting TEMPMOD=1 changes the Type A functional forms to Type B for following parameters: UC, ETA0, ETA0R, ETAMOB, VSAT, VSAT1, VSATR, VSATCV, RSDR, RDDR, PTWG, PTWGR, K0, K1S1, K0S1, K1, K1SAT, A1, A2,

AIGBINV, AIGBACC, AIGC, AIGS, AIGD, BGIDL, BGISL, ALPHA0, ALPHA1, ALPHAII0, ALPHAII1, CJS, CJD, CJSWS, CJSWD, CJSWGS, CJSWGD, PBS, PBD, PBSWS, PBSWD, PBSWGS, PBSWGD.

$$E_{g,Tnom} = BG0SUB - \frac{TBGASUB \cdot Tnom^2}{Tnom + TBGBSUB} \tag{3.107}$$

$$E_g = BG0SUB - \frac{TBGASUB \cdot T^2}{T + TBGBSUB} \tag{3.108}$$

$$n_i = NI0SUB \cdot \left(\frac{T}{300.15}\right)^{\frac{3}{2}} \cdot \exp\left(\frac{BG0SUB \cdot q}{2k \cdot 300.15} - \frac{E_g \cdot q}{2k \cdot T}\right) \tag{3.109}$$

$$N_c = NC0SUB \cdot \left(\frac{T}{300.15}\right)^{\frac{3}{2}} \tag{3.110}$$

$$\Theta_{SS} = 1 + TSS_i \cdot (T - Tnom) \tag{3.111}$$

$$V_{bi} = \frac{kT}{q} \cdot \ln\left(\frac{NSD \cdot NBODY_i[N]}{n_i^2}\right) \tag{3.112}$$

$$\Phi_B = \frac{kT}{q} \cdot \ln\left(\frac{NBODY_i[N]}{n_i}\right) \tag{3.113}$$

$$\Delta V_{th,temp} = \left(KT1 + \frac{KT1L}{L_{eff}}\right) \cdot \left(\frac{T}{Tnom} - 1\right) \tag{3.114}$$

$$ETA0(T) = ETA0 \cdot (1 - TETA0 \cdot (T - Tnom)) \tag{3.115}$$

$$ETA0CV(T) = ETA0CV \cdot (1 - TETA0CV \cdot (T - Tnom)) \tag{3.116}$$

$$ETA0R(T) = ETA0R \cdot (1 - TETA0R \cdot (T - Tnom)) \tag{3.117}$$

$$\mu_0(T) = U0[L, N] \cdot \left(\frac{T}{Tnom}\right)^{UTE_i} + UTL_i \cdot (T - Tnom) \tag{3.118}$$

$$\mu_{0,cv}(T) = U0CV[L, N] \cdot \left(\frac{T}{Tnom}\right)^{UTECV_i} + UTLCV_i \cdot (T - Tnom) \tag{3.119}$$

$$ETAMOB(T) = ETAMOB_i \cdot [1 + EMOBT_i \cdot (T - Tnom)] \tag{3.120}$$

$$UA(T) = UA[L] + UA1_i \cdot (T - Tnom) \tag{3.121}$$

$$UACV(T) = UACV[L] + UA1CV_i \cdot (T - Tnom) \tag{3.122}$$

$$UC(T) = UC_i \cdot [1 + UC1_i \cdot (T - Tnom)] \tag{3.123}$$

$$UCCV(T) = UCCV_i \cdot [1 + UC1CV_i \cdot (T - Tnom)] \tag{3.124}$$

$$UD(T) = UD[L] \cdot \left(\frac{T}{Tnom}\right)^{UD1_i} \tag{3.125}$$

$$UDCV(T) = UDCV[L] \cdot \left(\frac{T}{Tnom}\right)^{UD1CV_i} \tag{3.126}$$

$$UCS(T) = UCS_i \cdot \left(\frac{T}{Tnom}\right)^{UCSTE_i} \tag{3.127}$$

$$VSAT(T) = VSAT[L,N] \cdot (1 - AT \cdot (T - Tnom)) \tag{3.128}$$

$$VSAT1(T) = VSAT1[L,N] \cdot (1 - AT \cdot (T - Tnom)) \tag{3.129}$$

$$VSAT1R(T) = VSAT1R[L,N] \cdot (1 - AT \cdot (T - Tnom)) \tag{3.130}$$

$$VSATCV(T) = VSATCV[L] \cdot (1 - ATCV \cdot (T - Tnom)) \tag{3.131}$$

$$PTWG(T) = PTWG[L] \cdot (1 - PTWGT \cdot (T - Tnom)) \tag{3.132}$$

$$PTWGR(T) = PTWGR[L] \cdot (1 - PTWGT \cdot (T - Tnom)) \tag{3.133}$$

$$\begin{cases} MEXP(T) = MEXP[L] \cdot (1 + TMEXP \cdot (T - Tnom)) & \text{if } ASYMMOD = 0 \\ MEXPR(T) = MEXPR[L] \cdot (1 + TMEXPR \cdot (T - Tnom)) & \text{if } ASYMMOD = 1 \end{cases} \tag{3.134}$$

$$BETA0(T) = BETA0_i \cdot \left(\frac{T}{Tnom}\right)^{IIT} \tag{3.135}$$

$$SII0(T) = SII0_i \left(1 + TII \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.136}$$

$$K0(T) = K0_i + K01_i \cdot (T - Tnom) \tag{3.137}$$

$$K1(T) = K1_i + K11_i \cdot (T - Tnom) \tag{3.138}$$

$$K0SI(T) = K0SI_i + K0SI1_i \cdot (T - Tnom) \tag{3.139}$$

$$K1SI(T) = K1SI_i + K1SI1_i \cdot (T - Tnom) \tag{3.140}$$

$$K1SAT(T) = K1SAT_i + K1SAT1_i \cdot (T - Tnom) \tag{3.141}$$

$$A1(T) = A1_i + A11_i \cdot (T - Tnom) \tag{3.142}$$

$$A2(T) = A2_i + A21_i \cdot (T - Tnom) \tag{3.143}$$

$$AIGBINV(T) = AIGBINV_i + AIGBINV1_i \cdot (T - Tnom) \tag{3.144}$$

$$AIGBACC(T) = AIGBACC_i + AIGBACC1_i \cdot (T - Tnom) \tag{3.145}$$

$$AIGC(T) = AIGC_i + AIGC1_i \cdot (T - Tnom) \tag{3.146}$$

$$AIGS(T) = AIGS_i + AIGS1_i \cdot (T - Tnom) \tag{3.147}$$

$$AIGD(T) = AIGD_i + AIGD1_i \cdot (T - Tnom) \tag{3.148}$$

$$BGIDL(T) = BGIDL_i \cdot (1 + TGIDL \cdot (T - Tnom)) \tag{3.149}$$

$$BGISL(T) = BGISL_i \cdot (1 + TGIDL \cdot (T - Tnom)) \tag{3.150}$$

$$ALPHA0(T) = ALPHA0_i + ALPHA01_i \cdot (T - Tnom) \tag{3.151}$$

$$ALPHA1(T) = ALPHA1_i + ALPHA11_i \cdot (T - Tnom) \tag{3.152}$$

$$ALPHAII0(T) = ALPHAII0_i + ALPHAII01_i \cdot (T - Tnom) \tag{3.153}$$

$$ALPHAII1(T) = ALPHAII1_i + ALPHAII11_i \cdot (T - Tnom) \tag{3.154}$$

$$RDSWMIN(T) = RDSWMIN \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.155}$$

$$RDSW(T) = RDSW[L] \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.156}$$

$$RSWMIN(T) = RSWMIN \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.157}$$

$$RDWMIN(T) = RDWMIN \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.158}$$

$$RSW(T) = RSW[L] \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.159}$$

$$RDW(T) = RDW[L] \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.160}$$

$$RSDR(T) = RSDR \cdot (1 + TRSDR \cdot (T - Tnom)) \tag{3.161}$$

$$RSDRR(T) = RSDRR \cdot (1 + TRSDR \cdot (T - Tnom)) \tag{3.162}$$

$$RDDR(T) = RDDR \cdot (1 + TRDDR \cdot (T - Tnom)) \tag{3.163}$$

$$RDDRR(T) = RDDRR \cdot (1 + TRDDR \cdot (T - Tnom)) \tag{3.164}$$

$$R_{s,geo}(T) = R_{s,geo} \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.165}$$

$$R_{d,geo}(T) = R_{d,geo} \cdot (1 + PRT \cdot (T - Tnom)) \tag{3.166}$$

$$Igtemp = \left(\frac{T}{Tnom}\right)^{IGT_i} \tag{3.167}$$

$$T_{3s} = exp\left(\frac{\frac{qE_{g,Tnom}}{k\cdot Tnom} - \frac{qE_g}{kT} + XTIS \cdot ln\left(\frac{T}{Tnom}\right)}{NJS}\right) \tag{3.168}$$

$$J_{ss}(T) = JSS \cdot T_{3s} \tag{3.169}$$

$$J_{ssws}(T) = JSWS \cdot T_{3s} \tag{3.170}$$

$$J_{sswgs}(T) = JSWGS \cdot T_{3s} \tag{3.171}$$

$$T_{3d} = exp\left(\frac{\frac{qE_{g,Tnom}}{k\cdot Tnom} - \frac{qE_g}{kT} + XTID \cdot ln\left(\frac{T}{Tnom}\right)}{NJD}\right) \tag{3.172}$$

$$J_{sd}(T) = JSD \cdot T_{3d} \tag{3.173}$$

$$J_{sswd}(T) = JSWD \cdot T_{3d} \tag{3.174}$$

$$J_{sswgd}(T) = JSWGD \cdot T_{3d} \tag{3.175}$$

$$J_{tss}(T) = JTSS \cdot exp\left(\frac{E_{g,Tnom} \cdot XTSS \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \tag{3.176}$$

$$J_{tsd}(T) = JTSD \cdot exp\left(\frac{E_{g,Tnom} \cdot XTSD \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \tag{3.177}$$

$$J_{tssws}(T) = JTSSWS \cdot exp\left(\frac{E_{g,Tnom} \cdot XTSSWS \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \tag{3.178}$$

$$J_{tsswd}(T) = JTSSWD \cdot exp\left(\frac{E_{g,Tnom} \cdot XTSSWD \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \tag{3.179}$$

$$\begin{aligned} J_{tsswgs}(T) = JTSSWGS \times \left(\sqrt{JTWEFF/W_{eff0}} + 1.0\right) \times \\ exp\left(\frac{E_{g,Tnom} \cdot XTSSWGS \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \end{aligned} \tag{3.180}$$

$$\begin{aligned} J_{tsswgd}(T) = JTSSWGD \times \left(\sqrt{JTWEFF/W_{eff0}} + 1.0\right) \times \\ exp\left(\frac{E_{g,Tnom} \cdot XTSSWGD \cdot \left(\frac{T}{Tnom} - 1\right)}{kT/q}\right) \end{aligned} \tag{3.181}$$

$$NJTS(T) = NJTS \times \left(1 + TNJTS \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.182}$$

$$NJTSD(T) = NJTSD \times \left(1 + TNJTSD \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.183}$$

$$NJTSSW(T) = NJTSSW \times \left(1 + TNJTSSW \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.184}$$

$$NJTSSWD(T) = NJTSSWD \times \left(1 + TNJTSSWD \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.185}$$

$$NJTSSWG(T) = NJTSSWG \times \left(1 + TNJTSSWG \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.186}$$

$$NJTSSWGD(T) = NJTSSWGD \times \left(1 + TNJTSSWGD \cdot \left(\frac{T}{Tnom} - 1\right)\right) \tag{3.187}$$

$$CJS(T) = CJS \cdot [1 + TCJ \cdot (T - Tnom)] \tag{3.188}$$

$$CJD(T) = CJD \cdot [1 + TCJ \cdot (T - Tnom)] \tag{3.189}$$

$$CJSWS(T) = CJSWS \cdot [1 + TCJSW \cdot (T - Tnom)] \tag{3.190}$$

$$CJSWD(T) = CJSWD \cdot [1 + TCJSW \cdot (T - Tnom)] \tag{3.191}$$

$$CJSWGS(T) = CJSWGS \cdot [1 + TCJSWG \cdot (T - Tnom)] \tag{3.192}$$

$$CJSWGD(T) = CJSWGD \cdot [1 + TCJSWG \cdot (T - Tnom)] \tag{3.193}$$

$$PBS(T) = PBS(Tnom) - TPB \cdot (T - Tnom) \tag{3.194}$$

$$PBD(T) = PBD(Tnom) - TPB \cdot (T - Tnom) \tag{3.195}$$

$$PBSWS(T) = PBSWS(Tnom) - TPBSW \cdot (T - Tnom) \tag{3.196}$$

$$PBSWD(T) = PBSWD(Tnom) - TPBSW \cdot (T - Tnom) \tag{3.197}$$

$$PBSWGS(T) = PBSWGS(Tnom) - TPBSWG \cdot (T - Tnom) \tag{3.198}$$

$$PBSWGD(T) = PBSWGD(Tnom) - TPBSWG \cdot (T - Tnom) \tag{3.199}$$

3.1.9 Cryogenic Temperature Model

These models are introduced to capture the device physics and temperature effects down to low cryogenic temperatures, such as for the CMOS circuits used in quantum computing applications [4].

CRYOMOD = 1 or 2 enables the cryogenic models. CRYOMOD = 1 provides the most physical cryogenic temperature models. For CRYOMOD = 2, all the cryogenic temperature expressions are smoothly converged to CRYOMOD = 0 temperature expressions for T > 210 K. CRYOMOD = 0 turns off the cryogenic models and the temperature models presented in 3.1.8 are used instead. The physical quantities not included in this section have the same temperature dependency as that in CRYOMOD = 0.

Band Tail States/Traps Modeling

<u>CRYOMOD = 1</u>

In cryogenic temperature characterization, subthreshold swing (SS) is usually found to saturate w.r.t decrease in temperature and has been attributed to the presence of band tail states and interface traps. Sometimes a rise in the SS with a further decrease in temperature is also observed. Moreover, since the BSIM-CMG is based on the Maxwell-Boltzmann statistics of the charge carriers, a threshold correction at low temperatures is also required to capture the actual Fermi-Dirac statistics and the impact of band tail/interface traps. The following methodology is used to capture the aforementioned effects.

- To capture the SS saturation and/or rise effect, an effective temperature (T_{eff}) concept is used. The temperature appearing in the SS factor (nV_{tm}) calculation below a temperature $TLOW$ is smoothly clamped to $TLOW$ given as

$$T_{low0}(T) = \frac{T + TLOW + \sqrt{(T - TLOW)^2 + 0.25 \cdot DTLOW^2}}{2} \tag{3.200}$$

To capture the rise of SS with temperature reduction for even lower temperatures, a linear temperature function is used below another smaller temperature $TLOW1$.

$$T_{low1}(T) = \frac{KLOW1 \cdot (TLOW1 - T) + \sqrt{[KLOW1 \cdot (TLOW1 - T)]^2 + 0.25 \cdot DTLOW1^2}}{2} \tag{3.201}$$

Finally, T_{eff} is calculated as
If $T_{nom} > TLOW$ then

$$T1 = T_{low0}(T) + T_{low1}(T) - T_{low0}(T_{nom}) - T_{low1}(T_{nom}) + T_{nom} \tag{3.202}$$

end else

$$T1 = T_{low0}(T) + T_{low1}(T) - T_{low0}(T_{nom}) - T_{low1}(T_{nom}) + TLOW \tag{3.203}$$

end

$$T_{eff} = \frac{T + T1 + \sqrt{(T - T1)^2 + 0.25 \cdot 0.04}}{2} \tag{3.204}$$

- T_{eff} is further used in the calculation of effective density of states, N_c as

$$N_C = NC0SUB \cdot \left(\frac{T_{eff}}{300.15}\right)^{3/2} \tag{3.205}$$

- A threshold voltage shift is applied

$$\Delta V_{\text{th,temp}} = \frac{KT11}{1 + \exp\left[KT12 \cdot (T - TVTH)\right]} - \frac{KT11}{1 + \exp\left[KT12 \cdot (T_{nom} - TVTH)\right]} + \left(KT1 + \frac{KT1L}{L_{eff}}\right) \cdot \left(\frac{T}{T_{nom}} - 1\right) \tag{3.206}$$

<u>CRYOMOD = 2</u>

If $T_{nom} > 210$ then

$$T1 = T_{low0}(T) + T_{low1}(T) - T_{low0}(210) - T_{low1}(210) + 210 \tag{3.207}$$

$$T_{eff} = \frac{T + T1 + \sqrt{(T - T1)^2 + 0.25 \cdot 0.04}}{2} \tag{3.208}$$

end else

If $T_{nom} > TLOW$ then

$$T1 = T_{low0}(T) + T_{low1}(T) - T_{low0}(T_{nom}) - T_{low1}(T_{nom}) + T_{nom} \tag{3.209}$$

end else

$$T1 = T_{low0}(T) + T_{low1}(T) - T_{low0}(T_{nom}) - T_{low1}(T_{nom}) + TLOW \tag{3.210}$$

end

$$T2 = \frac{T + T1 + \sqrt{(T - T1)^2 + 0.25 \cdot 0.04}}{2} \tag{3.211}$$

$$w_h = 0.5 + 0.5 \cdot \tanh[0.5 \cdot (T - 210)] \tag{3.212}$$

$$w_l = 1 - w_h \tag{3.213}$$

$$T_{eff} = w_l \cdot T2 + w_h \cdot T \tag{3.214}$$

end

end

$$N_C = NC0SUB \cdot \left(\frac{T_{eff}}{300.15}\right)^{3/2} \tag{3.215}$$

$$T_1 = \frac{T + 210 - \sqrt{(T - 210)^2 + 0.25 \cdot 4 \cdot 10^{-2}}}{2}$$

$$T_2 = \frac{T_{nom} + 210 - \sqrt{(T_{nom} - 210)^2 + 0.25 \cdot 4 \cdot 10^{-2}}}{2}$$

$$\Delta V_{\mathrm{th,temp}} = \frac{KT11}{1 + \exp\left[KT12 \cdot (T_1 - TVTH)\right]} - \frac{KT11}{1 + \exp\left[KT12 \cdot (T_2 - TVTH)\right]} + \left(KT1 + \frac{KT1L}{L_{eff}}\right) \cdot \left(\frac{T}{T_{nom}} - 1\right) \tag{3.216}$$

Temperature Model of Mobility

CRYOMOD = 1

$$\mu_0(T) = U0_i \cdot \left(\frac{T}{T_{nom}}\right)^{UTE_i + UTE1_i \cdot \left(\frac{T}{T_{nom}}\right)} + UTL_i \cdot (T - T_{nom}) \tag{3.217}$$

$$\mu_{0,cv}(T) = U0CV_i \cdot \left(\frac{T}{T_{nom}}\right)^{UTECV_i + UTE1CV_i \cdot \left(\frac{T}{T_{nom}}\right)} + UTLCV_i \cdot (T - T_{nom}) \tag{3.218}$$

$$UD(T) = UD_i \cdot \left(\frac{T}{T_{nom}}\right)^{UD1_i + UD2_i \cdot \left(\frac{T}{T_{nom}}\right)} \tag{3.219}$$

$$UDCV(T) = UDCV_i \cdot \left(\frac{T}{T_{nom}}\right)^{UD1CV_i + UD2CV_i \cdot \left(\frac{T}{T_{nom}}\right)} \tag{3.220}$$

$$UCS(T) = UCS_i \cdot \left(\frac{T}{T_{nom}}\right)^{UCSTE_i + UCSTE1_i \cdot \left(\frac{T}{T_{nom}}\right)} \tag{3.221}$$

$$UA(T) = UA_i \cdot \left(\frac{T}{T_{nom}}\right)^{UA1_i + UA2_i \cdot \left(\frac{T}{T_{nom}}\right)} \tag{3.222}$$

$$UACV(T) = UACV_i \cdot \left(\frac{T}{T_{nom}}\right)^{UA1CV_i + UA2CV_i \cdot \left(\frac{T}{T_{nom}}\right)} \tag{3.223}$$

$$EU(T) = EU_i \cdot [1 + EU1_i \cdot (T - T_{nom})] \tag{3.224}$$

$$UDS(T) = UDS_i \cdot \left[\exp\left(UDS1_i \cdot \left(\frac{T}{T_{nom}} - 1\right)\right) - 1\right] \tag{3.225}$$

$$UDD(T) = UDD_i \cdot \left[\exp\left(UDD1_i \cdot \left(\frac{T}{T_{nom}} - 1\right)\right) - 1\right] \tag{3.226}$$

$$UDS_{eff}(T) = 0.5 + UDS(T) \tag{3.227}$$

$$UDD_{eff}(T) = 0.5 + UDD(T) \tag{3.228}$$

CRYOMOD = 2

$$T_1 = \frac{T + 210 - \sqrt{(T - 210)^2 + 0.25 \cdot 10^{-2}}}{2} \tag{3.229}$$

$$\Delta T_1 = T_1 - \frac{T_{nom} + 210 - \sqrt{(T_{nom} - 210)^2 + 0.25 \cdot 10^{-2}}}{2} \tag{3.230}$$

$$\mu_0(T) = U0_i \cdot \left(\frac{T}{T_{nom}}\right)^{UTE_i + UTE1_i \cdot \left(\frac{T_1 - 210}{T_{nom}}\right)} + UTL_i \cdot (T - T_{nom}) \tag{3.231}$$

$$\mu_{0,cv}(T) = U0CV_i \cdot \left(\frac{T}{T_{nom}}\right)^{UTECV_i + UTE1CV_i \cdot \left(\frac{T_1 - 210}{T_{nom}}\right)} + UTLCV_i \cdot (T - T_{nom}) \tag{3.232}$$

$$UD(T) = UD_i \cdot \left(\frac{T}{T_{nom}}\right)^{UD1_i + UD2_i \cdot \left(\frac{T_1 - 210}{T_{nom}}\right)} \tag{3.233}$$

$$UDCV(T) = UDCV_i \cdot \left(\frac{T}{T_{nom}}\right)^{UD1CV_i + UD2CV_i \cdot \left(\frac{T_1 - 210}{T_{nom}}\right)} \tag{3.234}$$

$$UCS(T) = UCS_i \cdot \left(\frac{T}{T_{nom}}\right)^{UCSTE_i + UCSTE1_i \cdot \left(\frac{T_1 - 210}{T_{nom}}\right)} \tag{3.235}$$

If TEMPMOD = 1 then

$$EU(T) = EU_i + EU1_i \cdot \Delta T_1 \tag{3.236}$$

end else

$$EU(T) = EU_i \cdot (1 + EU1_i \cdot \Delta T_1) \tag{3.237}$$

end

If $\left|UDS1_i \cdot \frac{T_1 - 210}{T_{nom}}\right| < 10^{-6}$ then

$$UDS(T) = UDS_i \cdot \left[\exp\left(UDS1_i \cdot \frac{T_1 - 210}{T_{nom}}\right) - 1\right] \tag{3.238}$$

end else

$$UDS(T) = UDS \cdot \frac{\exp\left(UDS1 \cdot \frac{T_1 - 210}{T_{nom}}\right) - 1}{|\exp\left(UDS1 \cdot \frac{T_{nom} - 210}{T_{nom}}\right) - 1|} \tag{3.239}$$

end

If $\left|UDD1_i \cdot \frac{T_1 - 210}{T_{nom}}\right| < 10^{-6}$ then

$$UDD(T) = UDD_i \cdot \left[\exp\left(UDD1_i \cdot \frac{T_1 - 210}{T_{nom}}\right) - 1\right] \tag{3.240}$$

end else

$$UDD(T) = UDD \cdot \frac{\exp\left(UDD1 \cdot \frac{T_1 - 210}{T_{nom}}\right) - 1}{|\exp\left(UDD1 \cdot \frac{T_{nom} - 210}{T_{nom}}\right) - 1|} \tag{3.241}$$

end

$$UDS_{eff}(T) = 0.5 + UDS_i(T) \tag{3.242}$$

$$UDD_{eff}(T) = 0.5 + UDD_i(T) \tag{3.243}$$

If $T_{nom} > 210$ then

$$T2 = 210 \cdot \frac{UA1_i}{UA_i + UA1_i \cdot (210 - T_{nom})} - UA2_i \cdot \frac{\log\left(\frac{210}{T_{nom}}\right) + 1}{T_{nom}} \tag{3.244}$$

$$T1 = \frac{UA_i + UA1_i \cdot (210 - T_{nom})}{\left(\frac{210}{T_{nom}}\right)^{T2 + UA2_i \cdot \frac{210}{T_{nom}}}} \tag{3.245}$$

$$UA_{tl} = T1 \cdot \left(\frac{T}{T_{nom}}\right)^{T2 + UA2_i \cdot \frac{T}{T_{nom}}} \tag{3.246}$$

$$UA_{th} = UA_i + UA1_i \cdot (T - T_{nom}) \tag{3.247}$$

end else

$$T2 = UA_i \cdot \left(\frac{210}{T_{nom}}\right)^{UA1_i + UA2_i \cdot \frac{210}{T_{nom}}} \cdot \left(\frac{UA1_i}{210} + UA2_i \frac{\log\left(\frac{210}{T_{nom}}\right) + 1}{T_{nom}}\right) \tag{3.248}$$

$$T1 = UA_i \cdot \left(\frac{210}{T_{nom}}\right)^{UA1_i + UA2_i \cdot \frac{T}{T_{nom}}} - T2 \cdot (210 - T_{nom}) \tag{3.249}$$

$$UA_{tl} = UA_i \cdot \left(\frac{T}{T_{nom}}\right)^{UA1_i + UA2_i \cdot \frac{T}{T_{nom}}} \tag{3.250}$$

$$UA_{th} = T1 + T2 \cdot (T - T_{nom}) \tag{3.251}$$

end

$$UA(T) = w_l \cdot UA_{tl} + w_h \cdot UA_{th} \tag{3.252}$$

$UACV(T)$ is calculated in the same way as $UA(T)$ with $UA1_i$ and $UA2_i$ replaced by $UA1CV_i$ and $UA2CV_i$, respectively.

Temperature Model for Saturation Region

CRYOMOD = 1

If TEMPDEP = 1 then

$$VSAT(T) = VSAT_i - AT_i \cdot (T - T_{nom}) + AT2 \cdot (T - T_{nom})^2 \tag{3.253}$$

$$VSAT1(T) = VSAT1_i - AT_i \cdot (T - T_{nom}) + AT2 \cdot (T - T_{nom})^2 \tag{3.254}$$

$$VSATCV(T) = VSATCV_i - ATCV_i \cdot (T - T_{nom}) + AT2CV \cdot (T - T_{nom})^2 \tag{3.255}$$

$$KSATIV(T) = KSATIV_i + KSATIVT1 \cdot (T - T_{nom}) + KSATIVT2 \cdot (T - T_{nom})^2 \tag{3.256}$$

$$PCLM(T) = PCLM_i + PCLMT \cdot (T - T_{nom}) \tag{3.257}$$

end else

$$VSAT(T) = VSAT_i \cdot [1 - AT_i \cdot (T - T_{nom}) + AT2 \cdot (T - T_{nom})^2] \tag{3.258}$$

$$VSAT1(T) = VSAT1_i \cdot [1 - AT_i \cdot (T - T_{nom}) + AT2 \cdot (T - T_{nom})^2] \tag{3.259}$$

$$VSATCV(T) = VSATCV_i \cdot [1 - ATCV_i \cdot (T - T_{nom}) + AT2CV \cdot (T - T_{nom})^2] \tag{3.260}$$

$$KSATIV(T) = KSATIV_i \cdot [1 + KSATIVT1 \cdot (T - T_{nom}) + KSATIVT2 \cdot (T - T_{nom})^2] \tag{3.261}$$

$$PCLM(T) = PCLM_i \cdot [1 + PCLMT \cdot (T - T_{nom})] \tag{3.262}$$

end

$$MEXP(T) = MEXP_i \cdot [1 + TMEXP \cdot (T - T_{nom}) + TMEXP2 \cdot (T - T_{nom})^2] \tag{3.263}$$

CRYOMOD = 2

If TEMPDEP = 1 then

$$VSAT(T) = VSAT_i - AT_i \cdot (T - T_{nom}) + AT2 \cdot \Delta T_1^2 \tag{3.264}$$

$$VSAT1(T) = VSAT1_i - AT_i \cdot (T - T_{nom}) + AT2 \cdot \Delta T_1^2 \tag{3.265}$$

$$VSATCV(T) = VSATCV_i - ATCV_i \cdot (T - T_{nom}) + AT2CV \cdot \Delta T_1^2 \tag{3.266}$$

$$KSATIV(T) = KSATIV_i + KSATIVT1 \cdot (T - T_{nom}) + KSATIVT2 \Delta T_1^2 \tag{3.267}$$

$$PCLM(T) = PCLM_i + PCLMT \cdot \Delta T_1 \tag{3.268}$$

end else

$$VSAT(T) = VSAT_i \cdot [1 - AT_i \cdot (T - T_{nom}) + AT2 \cdot \Delta T_1^2] \tag{3.269}$$

$$VSAT1(T) = VSAT1_i \cdot [1 - AT_i \cdot (T - T_{nom}) + AT2 \cdot \Delta T_1^2] \tag{3.270}$$

$$VSATCV(T) = VSATCV_i \cdot [1 - ATCV_i \cdot (T - T_{nom}) + AT2CV \cdot \Delta T_1^2] \tag{3.271}$$

$$KSATIV(T) = KSATIV_i \cdot [1 + KSATIVT1 \cdot (T - T_{nom}) + KSATIVT2 \cdot \Delta T_1^2] \tag{3.272}$$

$$PCLM(T) = PCLM_i \cdot (1 + PCLMT \cdot \Delta T_1) \tag{3.273}$$

end

$$MEXP(T) = MEXP_i \cdot [1 + TMEXP \cdot (T - T_{nom}) + TMEXP2 \cdot \Delta T_1^2] \tag{3.274}$$

Temperature Model of Source/Drain Resistances

At low temperatures, the temperature coefficient of resistivity of silicon can have a different value than that at the room temperature. To capture this effect, a dual-slope resistivity model is used. For high temperatures, the temperature coefficient is given by PRT and for low temperatures it is given by $PRT1$.

<u>CRYOMOD = 1</u>

If $PRT_i = PRT1_i$ then

$$rdstemp = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.275}$$

end else if $TR0_i < T_{nom}$ then

$$rdstemp0 = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.276}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - TR0_i) + PRT_i \cdot (TR0_i - T_{nom}) \tag{3.277}$$

$$T3 = (PRT_i - PRT1_i) \cdot (TR0_i - T_{nom}) \tag{3.278}$$

If $PRT1_i < PRT_i$ then

$$rdstemp = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot {SPRT_i}^2}}{2} - \frac{T3 + \sqrt{T3^2 + 0.25 \cdot {SPRT_i}^2}}{2} \tag{3.279}$$

end else

$$rdstemp = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot {SPRT_i}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot {SPRT_i}^2}}{2} \tag{3.280}$$

end

end else

$$rdstemp0 = 1 + PRT1_i \cdot (T - T_{nom}) \tag{3.281}$$

$$rdstemp1 = 1 + PRT_i \cdot (T - TR0_i) + PRT1_i \cdot (TR0_i - T_{nom}) \tag{3.282}$$

$$T3 = (PRT1_i - PRT_i) \cdot (TR0_i - T_{nom}) \tag{3.283}$$

If $PRT1_i < PRT_i$ then

$$rdstemp = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 + \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.284}$$

end else

$$rdstemp = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.285}$$

end

end

<u>CRYOMOD = 2</u>

If $PRT_i = PRT1_i$ then

$$rdstemp = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.286}$$

end else if $TR0_i < 210$ then

If $T_{nom} > 210$ then

$$rdstemp0 = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.287}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - TR0_i) + PRT_i \cdot (TR0_i - T_{nom}) \tag{3.288}$$

$$T3 = 1 + PRT_i \cdot (210 - T_{nom}) \tag{3.289}$$

$$T4 = 1 + PRT1_i \cdot (210 - TR0_i) + PRT_i \cdot (TR0_i - T_{nom}) \tag{3.290}$$

If $PRT1_i < PRT_i$ then

$$T5 = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 + T4 + \sqrt{(T3 - T4)^2 + 0.25 \cdot SPRT_i{}^2}}{2} + T3 \tag{3.291}$$

$$rdstemp = \frac{T5 + rdstemp0 + \sqrt{(T5 - rdstemp0)^2 + 0.25 \cdot 10^{-6}}}{2} \tag{3.292}$$

end else

$$T5 = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i^2}}{2} - \frac{T3 + T4 - \sqrt{(T3 - T4)^2 + 0.25 \cdot SPRT_i^2}}{2} + T3 \tag{3.293}$$

$$rdstemp = \frac{T5 + rdstemp0 - \sqrt{(T5 - rdstemp0)^2 + 0.25 \cdot 10^{-6}}}{2} \tag{3.294}$$

end

end else if $T_{nom} > TR0_i$ then

$$rdstemp0 = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.295}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - TR0_i) + PRT_i \cdot (TR0_i - T_{nom}) \tag{3.296}$$

$$T3 = (PRT_i - PRT1_i) \cdot (TR0_i - T_{nom}) \tag{3.297}$$

$$T4 = 1 + PRT_i \cdot (210 - T_{nom}) \tag{3.298}$$

$$T5 = 1 + PRT1_i \cdot (210 - TR0_i) + PRT_i \cdot (TR0_i - T_{nom}) \tag{3.299}$$

$$\tag{3.300}$$

If $PRT1_i < PRT_i$ then

$$T6 = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i^2}}{2} - \frac{T3 + \sqrt{T3^2 + 0.25 \cdot SPRT_i^2}}{2} \tag{3.301}$$

$$T7 = \frac{T4 + T5 + \sqrt{(T4 - T5)^2 + 0.25 \cdot SPRT_i^2}}{2} - \frac{T3 + \sqrt{T3^2 + 0.25 \cdot SPRT_i^2}}{2} \tag{3.302}$$

$$T8 = T7 + PRT_i \cdot (T - 210) \tag{3.303}$$

$$rdstemp = \frac{T6 + T8 + \sqrt{(T6 - T8)^2 + 0.25 \cdot SPRT_i^2}}{2} \tag{3.304}$$

end else

$$T6 = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i^2}}{2} \tag{3.305}$$

$$T7 = \frac{T4 + T5 - \sqrt{(T4 - T5)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.306}$$

$$T8 = T7 + PRT_i \cdot (T - 210) \tag{3.307}$$

$$rdstemp = \frac{T6 + T8 - \sqrt{(T6 - T8)^2 + 0.25 \cdot 10^{-6}}}{2} \tag{3.308}$$

end

end else

$$rdstemp0 = 1 + PRT_i \cdot (T - TR0_i) + PRT1_i \cdot (TR0_i - T_{nom}) \tag{3.309}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - T_{nom}) \tag{3.310}$$

$$T3 = (PRT1_i - PRT_i) \cdot (TR0_i - T_{nom}) \tag{3.311}$$

$$T4 = 1 + PRT1_i \cdot (210 - T_{nom}) \tag{3.312}$$

$$T5 = 1 + PRT_i \cdot (210 - TR0_i) + PRT1_i \cdot (TR0_i - T_{nom}) \tag{3.313}$$

If $PRT1_i < PRT_i$ then

$$T6 = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 + \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.314}$$

$$T7 = \frac{T4 + T5 + \sqrt{(T4 - T5)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.315}$$

$$T8 = T7 + PRT_i \cdot (T - 210) \tag{3.316}$$

$$rdstemp = \frac{T6 + T8 - \sqrt{(T6 - T8)^2 + 0.25 \cdot 10^{-6}}}{2} \tag{3.317}$$

end else

$$T6 = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.318}$$

$$T7 = \frac{T4 + T5 - \sqrt{(T4 - T5)^2 + 0.25 \cdot SPRT_i{}^2}}{2} - \frac{T3 - \sqrt{T3^2 + 0.25 \cdot SPRT_i{}^2}}{2} \tag{3.319}$$

$$T8 = T7 + PRT_i \cdot (T - 210) \tag{3.320}$$

$$rdstemp = \frac{T6 + T8 - \sqrt{(T6 - T8)^2 + 0.25 \cdot 10^{-6}}}{2} \tag{3.321}$$

end else

If $T_{nom} > TR0_i$ then

$$rdstemp0 = 1 + PRT_i \cdot (T - T_{nom}) \tag{3.322}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - 210) + PRT_i \cdot (210 - T_{nom}) \tag{3.323}$$

If $PRT1_i < PRT_i$ then

$$rdstemp = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot 10^{-4}}}{2} \tag{3.324}$$

end else

$$rdstemp = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot 10^{-4}}}{2} \tag{3.325}$$

end

end else

$$rdstemp0 = 1 + PRT_i \cdot (T - 210) + PRT1_i \cdot (210 - T_{nom}) \tag{3.326}$$

$$rdstemp1 = 1 + PRT1_i \cdot (T - T_{nom}) \tag{3.327}$$

If $PRT1_i < PRT_i$ then

$$rdstemp = \frac{rdstemp0 + rdstemp1 + \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot 10^{-4}}}{2} \tag{3.328}$$

end else

$$rdstemp = \frac{rdstemp0 + rdstemp1 - \sqrt{(rdstemp0 - rdstemp1)^2 + 0.25 \cdot 10^{-4}}}{2} \tag{3.329}$$

end

end

end

3.1.10 Body Doping and Gate Workfunction

$$NBODY = NBODY_i \tag{3.330}$$

$$qbs = q \cdot NBODY_i \cdot \frac{ACH}{CINS} \tag{3.331}$$

If $NGATE_i > 0$ then

$$\Delta\phi = max(0, \frac{E_g}{2} - \frac{kT}{q} \cdot \ln(\frac{NGATE_i}{n_i})) \tag{3.332}$$

else

$$\Delta\phi = \begin{cases} PHIG[L,N] - EASUB & \text{for NMOS,} \\ -\left[PHIG[L,N] - (EASUB + E_g)\right] & \text{for PMOS.} \end{cases} \tag{3.333}$$

$$\phi_B = \frac{kT}{q} \cdot \ln(\frac{NBODY_i}{n_i}) \tag{3.334}$$

$$\phi_{SD} = min\left[\frac{E_g}{2}, \frac{kT}{q} \cdot \ln(\frac{NSD_i}{n_i})\right] \tag{3.335}$$

$$\phi_G = \frac{kT}{q} \cdot \ln(\frac{NGATE}{n_i}) \tag{3.336}$$

If $NGATE_i > 0$ then

$$V_{fbsd} = \begin{cases} \phi_{SD} - \phi_G & \text{for NMOS,} \\ -\left[-\phi_{SD} - \phi_G\right] & \text{for PMOS.} \end{cases} \tag{3.337}$$

else

$$V_{fbsd} = \begin{cases} PHIG[L,N] - (EASUB + \frac{E_g}{2} - \phi_{SD}) & \text{for NMOS,} \\ -\left[PHIG[L,N] - (EASUB + \frac{E_g}{2} + \phi_{SD})\right] & \text{for PMOS.} \end{cases} \tag{3.338}$$

$$t_{ox} = \begin{cases} \frac{EOT \cdot \epsilon_{ox}}{3.9} & \text{if } GEOMOD \neq 3 \\ R \cdot \left(exp\,(\frac{EOT \cdot \epsilon_{ox}}{R \cdot 3.9}) - 1\right) & \text{if } GEOMOD = 3 \end{cases} \tag{3.339}$$

$$q_{bs} = \begin{cases} \frac{q \cdot NBODY_i \cdot TFIN}{2 \cdot C_{ox}} & \text{if } GEOMOD \neq 3 \\ \frac{q \cdot NBODY_i \cdot R}{2 \cdot C_{ox}} & \text{if } GEOMOD = 3 \end{cases} \tag{3.340}$$

3.1.11 Short Channel Effects

The degree of V_{th} roll-off has been modeled through the characteristic field penetration (scl), which is written in the unified FINFET model formulation, thus it can be used for FINFETs with complex cross sections.

$$scl = \sqrt{(\frac{EPSRSUB \cdot ACH}{CINS}) \cdot (1 + \frac{ACH \cdot CINS}{2 \cdot EPSRSUB \cdot WEFF\_UFCM \cdot WEFF\_UFCM})} \tag{3.341}$$

$$V_{bi} = \frac{kT}{q} \cdot \ln\left(\frac{NSD_i \cdot NBODY_i}{n_i^2}\right) \tag{3.342}$$

$$H_{eff} = \sqrt{\frac{HFIN}{8} \cdot (HFIN + 2 \cdot \epsilon_{ratio} \cdot EOT)} \tag{3.343}$$

$$\lambda = \begin{cases} \sqrt{\frac{\epsilon_{ratio}}{2}\left(1 + \frac{TFIN}{4\epsilon_{ratio}EOT}\right) TFIN \cdot EOT} & \text{if } GEOMOD = 0 \\ \frac{1}{\sqrt{\frac{1}{\frac{\epsilon_{ratio}}{2}\left(1+\frac{TFIN}{4\epsilon_{ratio}EOT}\right)TFIN \cdot EOT} + \frac{1}{4H_{eff}^2}}} & \text{if } GEOMOD = 1 \\ \frac{0.5}{\sqrt{\frac{1}{\frac{\epsilon_{ratio}}{2}\left(1+\frac{TFIN}{4\epsilon_{ratio}EOT}\right)TFIN \cdot EOT} + \frac{1}{4H_{eff}^2}}} & \text{if } GEOMOD = 2 \\ \sqrt{\frac{\epsilon_{ratio}}{2}\left(1 + \frac{R}{2\epsilon_{ratio}EOT}\right) R \cdot EOT} & \text{if } GEOMOD = 3 \end{cases} \tag{3.344}$$

3.1.12 GAAFET quantum subband model

This section describes the GAAFET subband model [5]. This can be turned on by SUBBANDMOD=1 (0=off; default).

Electrostatic Dimension scaling:

The three dimensions d_1, d_2 and d_3 correspond to the first, second and third subbands, respectively.

$$d_1 = \frac{DIM1H - DIMENSION1_i}{1 + exp\left(\frac{WDIM0 - WGAA}{WDIMR \cdot 1e-9}\right)} + DIMENSION1_i \tag{3.345}$$

$$d_2 = \frac{DIM2H - DIMENSION2_i}{1 + exp\left(\frac{WDIM0 - WGAA}{WDIMR \cdot 1e-9}\right)} + DIMENSION2_i \tag{3.346}$$

$$d_3 = \frac{DIM3H - DIMENSION3_i}{1 + exp\left(\frac{WDIM0 - WGAA}{WDIMR \cdot 1e-9}\right)} + DIMENSION3_i \tag{3.347}$$

Pre-factors for charge calculation:

The three geometry-dependent pre-factors $qnd10$, $qnd20$ and $qnd30$ correspond to the first, second and third subbands, respectively.

$$nc1l0 = 107\left(\frac{4}{TGAA \cdot 1e9}\right)^{TSRQ1}; nc2l0 = 103\left(\frac{4}{TGAA \cdot 1e9}\right)^{TSRQ2}; nc3l0 = 833\left(\frac{4}{TGAA \cdot 1e9}\right)^{TSRQ3} \tag{3.348}$$

$$\begin{aligned} pnc1l &= 0.7 + 0.1\left(TGAA \cdot 1e9 - \left[\frac{TGAA^2 \cdot 1e18}{2} - 1.5e9 \cdot TGAA + 2\right]\right)^{TDWSQ1} \\ pnc2l &= 1.5\left(\frac{4}{TGAA \cdot 1e9}\right)^{TDWSQ2}; pnc3l = 3.4\left(\frac{4}{TGAA \cdot 1e9}\right)^{TDWSQ3} \end{aligned} \tag{3.349}$$

$$N_{c1l} = min\left(\frac{nc1l0}{\sqrt{1+5(WGAA\cdot 1e9)^{WSFQ1\cdot pnc1l}}}, 0.1\right);\ N_{c2l} = min\left(\frac{nc2l0}{\sqrt{1+5(WGAA\cdot 1e9)^{WSFQ2\cdot pnc2l}}}0.1\right)$$

$$N_{c3l} = min\left(\frac{nc3l0}{\sqrt{1+5(WGAA\cdot 1e9)^{WSFQ3\cdot pnc3l}}}0.1\right) \tag{3.350}$$

$$N_{c1} = MFQ1NOM_i + MFQ1(N_{c1l} - N_{c1l}|_{WGAA=WGAANOM})$$
$$N_{c2} = MFQ2NOM_i + MFQ2(N_{c2l} - N_{c2l}|_{WGAA=WGAANOM})$$
$$N_{c3} = MFQ3NOM_i + MFQ3(N_{c3l} - N_{c3l}|_{WGAA=WGAANOM}) \tag{3.351}$$

$$qnd10 = q\frac{d_1\pi^{d_1/2}}{2\Gamma\left(1+\frac{d_1}{2}\right)}N_{c1}^{d_1}C_{norm,1};\ C_{norm,1} = \frac{W_{eff}^{min(d1-1,1)}\left(\frac{A_{ch}}{W_{eff}}\right)^{min(d1-2,1)}}{C_{ins}} \tag{3.352}$$

$$qnd20 = q\frac{d_2\pi^{d_2/2}}{2\Gamma\left(1+\frac{d_2}{2}\right)}N_{c2}^{d_2}C_{norm,2};\ C_{norm,2} = \frac{W_{eff}^{min(d2-1,1)}\left(\frac{A_{ch}}{W_{eff}}\right)^{min(d2-2,1)}}{C_{ins}} \tag{3.353}$$

$$qnd30 = q\frac{d_3\pi^{d_3/2}}{2\Gamma\left(1+\frac{d_3}{2}\right)}N_{c3}^{d_3}C_{norm,3};\ C_{norm,3} = \frac{W_{eff}^{min(d3-1,1)}\left(\frac{A_{ch}}{W_{eff}}\right)^{min(d3-2,1)}}{C_{ins}} \tag{3.354}$$

$$Nc_{3d0} = max\left(\frac{1}{1+exp\left(\frac{2.75-TGAA\cdot 1e9}{0.78}\right)}, 0.5\right) \tag{3.355}$$

$$Nc_{3d} = Nc_{3d0} + (1-Nc_{3d0})\frac{d_1 - DIMNSION1_i}{DIM1H - DIMENSION1_i} \tag{3.356}$$

$$Nc_q = \frac{1}{1+exp\left(\frac{Nc_{3d}-0.999}{1e-4}\right)} \tag{3.357}$$

Subband energy calculation:

The geometry-dependent subband energies for the second and third subbands given by $qe2$ and $qe3$, respectively.

$$ne2h = T0 + 90.59e4 \left(\frac{TGAA \cdot 1e9 - \left[\frac{TGAA^2 \cdot 1e18}{2} - 1.5e9 \cdot TGAA + 2 \right]}{2} \right)^{TSRE2}$$

$$ne3h = 120.66 \left(\frac{4}{TGAA \cdot 1e9} \right)^{TSRE3} \tag{3.358}$$

$$pe2h = 5.5 + 2.5 \left(\frac{TGAA \cdot 1e9 - \left[\frac{TGAA^2 \cdot 1e18}{2} - 1.5e9 \cdot TGAA + 2 \right]}{2} \right)^{TDWSE2}$$

$$pe3h = 2 \left(\frac{4}{TGAA \cdot 1e9} \right)^{TDWSE3} \tag{3.359}$$

$$qe2n = \frac{ne2h}{(WGAANOM \cdot 1e9)^{WSFE2 \cdot pe2h}};\ qe3n = \frac{ne2h}{(WGAANOM \cdot 1e9)^{WSFE3 \cdot pe3h}} \tag{3.360}$$

$$qe2 = E2NOM_i + MFE2 \left(\frac{ne2h}{(WGAA \cdot 1e9)^{WSFE2 \cdot pe2h}} - qe2n \right) \tag{3.361}$$

$$qe3 = E3NOM_i + MFE3 \left(\frac{ne3h}{(WGAA \cdot 1e9)^{WSFE3 \cdot pe3h}} - qe3n \right) \tag{3.362}$$

$$\tag{3.363}$$

3.1.13 GAAFET mobility scaling

This modules deals with various geometry dependent effects on mobility for the GAAFET structure [6]. This module is turned on by MOBSCMOD=1 (0=off; default).

$$ETAMOB_i = ETAMOBTHIN + \frac{ETAMOB_i - ETAMOBTHIN}{1 + exp\left(\frac{ETAMOBTNI - TGAA}{ETAMOBIR \cdot 1e-9}\right)} \tag{3.364}$$

$$UA_i = UATHIN + \frac{UA_i - UATHIN + (TGAA - UATSAT) \cdot UARTSC \cdot 1e9}{1 + exp\left(\frac{UATNI - TGAA}{UAIR \cdot 1e-9}\right)} \tag{3.365}$$

$$EU_i = min\left[370 \frac{EUTHIN - EU_i}{(TGAA \cdot 1e9)^{EUPTSC}} + \frac{EUTHIN - EU_i}{1 + exp\left(\frac{TGAA - EUTNI}{EUIR \cdot 1e-9}\right)} + EU_i, EUTHIN \right] \tag{3.366}$$

$$\mu_{t3} = \frac{WGAA}{WGAA + TGAA} \tag{3.367}$$

$$\mu_{t4} = EGBULK \cdot TGAA^2 \cdot 1e18 - U0EMSM1 \cdot 1e3 \tag{3.368}$$

$$\mu_{t5} = \frac{\mu_{t4} + \sqrt{\mu_{t4}^2 + 4e-3 \cdot U0EMSM1(EGBULK + 0.24)TGAA^2 1e18}}{2(EGBULK + 0.24)TGAA^2 1e18} \tag{3.369}$$

$$U0_i = U0_i \frac{WGAA + U0ETAWSC \cdot TGAA}{WGAA + TGAA} \cdot min\left(\frac{1e4}{\mu_{t5} - U0EMSM2 \cdot 1e5 - 0.8208}, 1\right) \tag{3.370}$$

$$UD_i = UD_i + (UDTHIN - UD_i)\Big(max([UDTSAT - TGAA]1e9, 0)\Big)^{UDPTSC} \tag{3.371}$$

3.2 Terminal Voltages

Terminal Voltages and V_{dsx} Calculation

$$devsign = \begin{cases} 1 & \text{for NMOS} \\ -1 & \text{for PMOS} \end{cases} \tag{3.372}$$

$$V_{gs\_noswap} = devsign \cdot (V(`IntrinsicGate) - V(si)) \tag{3.373}$$

$$V_{ds\_noswap} = devsign \cdot (V(di) - V(si)) \tag{3.374}$$

$$V_{gd\_noswap} = devsign \cdot (V(`IntrinsicGate) - V(di)) \tag{3.375}$$

$$V_{es\_jct} = devsign \cdot (V(e) - V(si)) \tag{3.376}$$

$$V_{ed\_jct} = devsign \cdot (V(e) - V(di)) \tag{3.377}$$

$$V_{ge} = V(`IntrinsicGate) - V_e \tag{3.378}$$

$$sigvds = 1.0 \tag{3.379}$$

if $V_{ds\_noswap} < 0.0$ then

$$sigvds = -1.0 \tag{3.380}$$

$$V_{gs} = V_{gs\_noswap} - V_{ds\_noswap} \tag{3.381}$$

$$V_{ds} = -1.0 \cdot V_{ds\_noswap} \tag{3.382}$$

$$V_{es} = V_{ed\_jct} \tag{3.383}$$

else

$$V_{gs} = V_{gs\_noswap} \tag{3.384}$$

$$V_{ds} = V_{ds\_noswap} \tag{3.385}$$

$$V_{es} = V_{es\_jct} \tag{3.386}$$

end

$$V_{dsx} = \sqrt{V_{ds}^2 + 0.01} - 0.1 \tag{3.387}$$

In RDSMOD=1 a resistor is added to the intrinsic FET element topology between the intrinsic source and the extrinsic source and a resistor is added to the intrinsic FET element topology between the intrinsic drain and the extrinsic drain. The external source/drain nodes are still labeled s and d while the intrinsic source and intrinsic drain nodes are labeled si and di respectively.

$$V(si, s) = V_{si} - V_s \tag{3.388}$$

$$V(di, d) = V_{di} - V_d \tag{3.389}$$

3.3 Short Channel Effects

3.3.1 Weighting Function for forward and reverse modes

$$T0 = tanh\left(\frac{0.6 * q \cdot V_{ds}}{kT}\right) \qquad \text{Use un-swapped } V_{ds} \text{ here} \tag{3.390}$$

$$W_f = 0.5 + 0.5 \cdot T0 \tag{3.391}$$

$$W_r = 0.5 - 0.5 \cdot T0 \tag{3.392}$$

3.3.2 Asymmetric parameters

If $ASYMMOD = 1$ then

$$CDSCD_a = CDSCD[N] \cdot W_f + CDSCDR[N] \cdot W_r \tag{3.393}$$

$$ETA0_a = ETA0(T) \cdot W_f + ETA0R(T) \cdot W_r \tag{3.394}$$

$$PDIBL1_a = PDIBL1_i \cdot W_f + PDIBL1R_i \cdot W_r \tag{3.395}$$

$$PTWG_a = PTWG(T) \cdot W_f + PTWGR(T) \cdot W_r \tag{3.396}$$

$$VSAT1_a = VSAT1(T) \cdot W_f + VSAT1R(T) \cdot W_r \tag{3.397}$$

$$RSDR_a = RSDR(T) \cdot W_f + RSDRR(T) \cdot W_r \tag{3.398}$$

$$RDDR_a = RDDR(T) \cdot W_f + RDDRR(T) \cdot W_r \tag{3.399}$$

$$MEXP_a = MEXP(T) \cdot W_f + MEXPR(T) \cdot W_r \tag{3.400}$$

$$U0_a = U0(T) \cdot W_f + U0R(T) \cdot W_r \tag{3.401}$$

$$UA_a = UA(T) \cdot W_f + UAR(T) \cdot W_r \tag{3.402}$$

$$UC_a = UC(T) \cdot W_f + UCR(T) \cdot W_r \tag{3.403}$$

$$UD_a = UD(T) \cdot W_f + UDR(T) \cdot W_r \tag{3.404}$$

$$EU_a = EU(T) \cdot W_f + EUR(T) \cdot W_r \tag{3.405}$$

$$PDIBL2_a = PDIBL2_i \cdot W_f + PDIBL2R_i \cdot W_r \tag{3.406}$$

$$KSATIV_a = KSATIV_i \cdot W_f + KSATIVR_i \cdot W_r \tag{3.407}$$

$$DVTSHIFT_a = DVTSHIFT_i \cdot W_f + DVTSHIFTR_i \cdot W_r \tag{3.408}$$

$$CIT_a = CIT_i \cdot W_f + CITR_i \cdot W_r \tag{3.409}$$

Else

All above $PARAM_a = PARAM$ and reverse mode parameter PARAMR are ignored

3.3.3 Vth Roll-off, DIBL, and Subthreshold Slope Degradation

The DITS effect is taken into account through the parameter Θ_{DITS}. The threshold voltage takes this effect into account through the parameter $\Delta V_{th,DIBL}$. In the equations, shown below, Θ_{SW}, Θ_{SS}, Θ_{SCE}, Θ_{DIBL} and Θ_{DITS} are model parameters (as shown in Table 6.4) used/referred to in the code as THETA_SW, THETA_SS, THETA_SCE, THETA_DIBL and THETA_DITS, respectively.

$$\psi_{st} = 0.4 + PHIN_i + \phi_B \tag{3.410}$$

$$\Theta_{SW} = \frac{0.5}{cosh\left(DVT1SS_i \cdot \frac{L_{eff}}{\lambda}\right) - 1} \tag{3.411}$$

$$C_{dsc} = \Theta_{SW} \cdot (CDSC[N] + CDSCD_a \cdot V_{dsx}) \tag{3.412}$$

$$n = \begin{cases} \Theta_{SS} \cdot \left(1 + \frac{CIT_i + C_{dsc}}{(2C_{si}) \| C_{ox}}\right) & \text{if } GEOMOD \neq 3 \\ \Theta_{SS} \cdot \left(1 + \frac{CIT_i + C_{dsc}}{C_{ox}}\right) & \text{if } GEOMOD = 3 \end{cases} \tag{3.413}$$

$$\Theta_{SCE} = -\frac{0.5}{cosh\left(DVT1_i \cdot \frac{L_{eff}}{\lambda}\right) - 1} \tag{3.414}$$

$$\Delta V_{th,SCE} = \Theta_{SCE} \cdot DVT0_i \cdot (V_{bi} - \psi_{st}) \tag{3.415}$$

$$\Theta_{DIBL} = -\frac{0.5}{cosh\left(DSUB_i \cdot \frac{L_{eff}}{\lambda}\right) - 1} \tag{3.416}$$

$$\Theta_{DITS} = \frac{1.0}{max\Big(\Big(1.0 + DVTP2 \cdot \Big(cosh\left(DSUB_i \cdot \frac{L_{eff}}{\lambda}\right) - 2.0\Big)\Big), 1.0e-6\Big)} \tag{3.417}$$

$$\Delta V_{th,DIBL} = \Theta_{DIBL} ETA0_i \cdot (V_{dsx} + ETA1\sqrt{V_{dsx} + 0.01}) + DVTP0 \cdot \Theta_{DITS} \cdot (V_{dsx} + 0.01)^{DVTP1} \tag{3.418}$$

$$\Delta V_{th,RSCE} = K1RSCE_i \cdot \left[\sqrt{1 + \frac{LPE0_i}{L_{eff}}} - 1\right] \cdot \sqrt{\psi_{st}} \tag{3.419}$$

$$\Delta V_{th,all} = \Delta V_{th,SCE} + \Delta V_{th,DIBL} + \Delta V_{th,RSCE} + \Delta V_{th,temp} \tag{3.420}$$

$$V_{gsfb} = V_{gs} - \Delta\phi - \Delta V_{th,all} - DVTSHIFT \tag{3.421}$$

BSIM-CMG provides an option to use Θ_{SW}, Θ_{SS}, Θ_{DIBL} and Θ_{DITS} as model parameters directly. In (3.576), 0.01 is added to avoid 1/0 in the derivative at Vds=0 when DVTP1 <1.

3.4 Surface Potential Calculation

The surface potential calculations take Quantum-Mechanical (QM) effects into account. These QM effects become relevant for smaller fin thicknesses and are seen both in terms of higher band-gap due to size confinement (higher threshold voltage) as well as in terms of charge confinement (different charge distribution from the conventional semi-classical case, where the Poisson equation solution is sufficient to determine the charge distribution). Surface potentials at the source and drain ends are derived from Poisson's equation with a perturbation method [7] and computed using the Householder's cubic iteration method [8, 9]. Perturbation allows accurate modeling of finite body doping.

3.4.1 Quantum Mechanical Vt correction

Note: $QMFACTOR_i$ also serves as a switch here.

If $GEOMOD \neq 3$ then

$$E_0 = \frac{\hbar^2 \pi^2}{2m_x \cdot TFIN^2} \tag{3.422}$$

$$E_0' = \frac{\hbar^2 \pi^2}{2m_x' \cdot TFIN^2} \tag{3.423}$$

$$E_1 = 4E_0 \tag{3.424}$$

$$E_1' = 4E_0' \tag{3.425}$$

$$\gamma = 1 + \exp\left(\frac{E_0 - E_1}{kT}\right) + \frac{g' m_d'}{g m_d} \cdot \left[\exp\left(\frac{E_0 - E_0'}{kT}\right) + \exp\left(\frac{E_0 - E_1'}{kT}\right)\right] \tag{3.426}$$

$$\Delta V_{t,QM} = QMFACTOR_i \cdot \left[\frac{E_0}{q} - \frac{kT}{q} \ln\left(\frac{g \cdot m_d}{\pi \hbar^2 N_c} \cdot \frac{kT}{TFIN} \cdot \gamma\right)\right] \tag{3.427}$$

If $GEOMOD = 3$ then

$$E_{0,QM} = \frac{\hbar^2 (2.4048)^2}{2m_x \cdot R^2} \tag{3.428}$$

$$\Delta V_{t,QM} = QMFACTOR_i \cdot \frac{E_{0,QM}}{q} \tag{3.429}$$

3.4.2 Voltage Limiting for Accumulation

If $GEOMOD \neq 3$ then

$$T0 = -(\Delta V_{t,QM} + \left(\frac{nkT}{q}\right) ln\left(\frac{2 \cdot L_{eff} \cdot I_{min}}{\mu_0(T) \cdot W_{eff} \cdot nkT \cdot N_c \cdot TFIN}\right)) \tag{3.430}$$

$$T1 = V_{gsfb} + T0 + DELVTRAND \tag{3.431}$$

$$V_{gsfbeff} = \frac{1}{2}\left[T1 + \sqrt{(T1)^2 + 4 \times 10^{-8}}\right] - T0 \tag{3.432}$$

If $GEOMOD = 3$ then

$$T0 = -(\Delta V_{t,QM} + \left(\frac{nkT}{q}\right) ln\left(\frac{2 \cdot L_{eff} \cdot I_{min}}{\mu_0(T) \cdot W_{eff} \cdot nkT \cdot n_i \cdot R}\right)) \tag{3.433}$$

$$T1 = V_{gsfb} + T0 + n \cdot \phi_B + \frac{E_g}{2} + DELVTRAND \tag{3.434}$$

$$V_{gsfbeff} = \frac{1}{2}\left[T1 + \sqrt{(T1)^2 + 4 \times 10^{-8}}\right] - T0 - V_{t0} \tag{3.435}$$

Note: $V_{gsfbeff}$ limiting for a small V_{gs} and V_{ds} being swept from positive to negative values can sometimes result in discontinuities in terminal capacitances. Such issues if arise can be resolved by lowering the value of IMIN parameter.

3.4.3 Source Side Potential and Charge Calculation

The core model calculation at the source side is shown below:

$$qdep = \frac{qdep}{nVtm} \tag{3.436}$$

$$vch = 0.0 + \Delta V_{t,QM} \tag{3.437}$$

Here 0.0 refers to the quasi-fermi potential at the source side

If $BULKMOD \neq 0$ then

$$T1 = hypsmooth(2.0 \cdot \phi_B + vch - ves, 1.0) \tag{3.438}$$

$$T3 = (-\frac{K1\_t}{2.0 \cdot nVtm}) \cdot (\sqrt{T1} - \sqrt{2.0 \cdot \phi_B}) \tag{3.439}$$

$$T0 = -qdep - T3 + vth\_fixed\_factor\_sub + QMFACTOR \cdot (-qdep)^{\frac{2}{3}} \tag{3.440}$$

$$T1 = -qdep - T3 + vth\_fixed\_factor\_SI \tag{3.441}$$

For the terms vth_fixed_factor_sub and vth_fixed_factor_SI, please see the Verilog-A source code file (bsim-cmg_body.include)

If $BULKMOD$=0 then

$$T0 = -qdep + vth\_fixed\_factor\_sub + QMFACTOR \cdot (-qdep)^{\frac{2}{3}} \tag{3.442}$$

$$T1 = -qdep + vth\_fixed\_factor\_SI \tag{3.443}$$

$$T2 = (\frac{vgsbeff - v_{ch}}{nVtm}) \tag{3.444}$$

$$F0 = -T2 + T1 \tag{3.445}$$

$$T3 = 0.5 \cdot (T2 - T0) \tag{3.446}$$

$$qm = \exp(T3) \tag{3.447}$$

If (qm $> 10^{-7}$) then

$$T7 = ln(1 + qm) \tag{3.448}$$

$$qm = 2.0 \cdot (1.0 - \sqrt{1.0 + T7 \cdot T7}) \tag{3.449}$$

$$T8 = (qm \cdot alpha\_UFCM + qdep) \cdot rc \tag{3.450}$$

$$T4 = \frac{T8}{(\exp(T8) - T8 - 1.0)} \tag{3.451}$$

$$T5 = T8 \cdot T4 \tag{3.452}$$

$$e0 = F0 - qm + ln(-qm) + ln(T5) + QMFACTOR \cdot (-(qm + qdep))^{\frac{2}{3}} \tag{3.453}$$

$$e1 = -1 + \frac{1}{qm} + (\frac{2}{T8 - T4 - 1}) \cdot rc - \frac{2}{3} \cdot QMFACTOR \cdot (-(qm + qdep))^{\frac{-1}{3}} \tag{3.454}$$

$$e2 = \frac{-1}{qm \cdot qm} - \frac{2}{9} \cdot QMFACTOR \cdot (-(qm + qdep))^{\frac{-4}{3}} \tag{3.455}$$

$$qm = qm - (\frac{e0}{e1}) \cdot (1.0 + \frac{e2 \cdot e2}{2.0 \cdot e1 \cdot e1}) \tag{3.456}$$

$$T8 = (qm \cdot alpha\_UFCM + qdep) \cdot rc \tag{3.457}$$

$$T4 = \frac{T8}{\exp(T8) - T8 - 1.0} \tag{3.458}$$

$$T5 = T8 \cdot T4 \tag{3.459}$$

$$e0 = F0 - qm + ln(-qm) + ln(T5) + QMFACTOR \cdot (-(qm + qdep))^{\frac{2}{3}} \tag{3.460}$$

$$e1 = -1 + \frac{1}{qm} + (\frac{2}{T8 - T4 - 1}) \cdot rc - \frac{2}{3} \cdot QMFACTOR \cdot (-(qm + qdep))^{\frac{-1}{3}} \tag{3.461}$$

$$e2 = \frac{-1}{qm \cdot qm} - \frac{2}{9} \cdot QMFACTOR \cdot (-(qm + qdep))^{\frac{-4}{3}} \tag{3.462}$$

$$qm = qm - (\frac{e0}{e1}) \cdot (1.0 + \frac{e2 \cdot e2}{2.0 \cdot e1 \cdot e1}) \tag{3.463}$$

If (qm $\leq 10^{-7}$) then

$$qm = -qm \cdot qm \tag{3.464}$$

$$qis = -qm \cdot nVtm \tag{3.465}$$

$$\psi_s = V_{gsfbeff} - qis \tag{3.466}$$

$$E_{effs} = 10^{-8} \cdot \left(\frac{q_{bs} + \eta \cdot q_{is}}{\epsilon_{ratio} \cdot EOT}\right) \tag{3.467}$$

$$\tag{3.468}$$

3.4.4 GAAFET quantum subband model (Source side):

This module can be turned on with SUBBANDMOD=1 (0=off; default);

$$Q_{t,1} = \frac{V_{gsfb} - vch}{nVtm};\ Q_{t,2} = \frac{V_{gsfb} - vch - qe2}{nVtm};\ Q_{t,3} = \frac{V_{gsfb} - vch - qe3}{nVtm} \tag{3.469}$$

$$\begin{aligned} qnds1 &= qnd10[min(Q_{t,1},0)]^{d_1/2} exp\Big(Q_{t,1} - min(Q_{t,1},0)\Big) \\ qnds2 &= qnd20[min(Q_{t,2},0)]^{d_2/2} exp\Big(Q_{t,2} - min(Q_{t,2},0)\Big) \\ qnds3 &= qnd30[min(Q_{t,3},0)]^{d_3/2} exp\Big(Q_{t,3} - min(Q_{t,3},0)\Big) \end{aligned} \tag{3.470}$$

$$q_{is} = Nc_{3d} q_{is} + Nc_q(qnds1 + qnds2 + qnds3) \tag{3.471}$$

3.5 Drain Saturation Voltage

The drain saturation voltage model is calculated from the source-side charge (q_{is}). V_{dseff} is subsequently used to compute the drain-side charge (q_{id}).

3.5.1 Drain Saturation Voltage (V_{dsat}) Calculations

$$T1 = q_{ia} \tag{3.472}$$

$$D_{mobs} = \begin{cases} 1 + UA(T)\cdot(E_{effs})^{EU} + \dfrac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{T1}{1E-2/Cox}\right)\right)^{UCS(T)}} & \text{if } BULKMOD = 0 \\ 1 + (UA(T) + UC(T)\cdot V_{eseff})\cdot(E_{effs})^{EU} + \dfrac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{T1}{1E-2/Cox}\right)\right)^{UCS(T)}} & \text{if } BULKMOD = 1 \end{cases} \tag{3.473}$$

$$D_{mobs} = \frac{D_{mobs}}{U0MULT} \tag{3.474}$$

If $RDSMOD = 0$ then

$$R_{ds,s} = \frac{1}{(W_{eff0}(\mu m))^{WR_i}} \cdot \left(RDSWMIN(T) + \frac{RDSW(T)}{1 + PRWGS_i \cdot T1}\right) \tag{3.475}$$

else if $RDSMOD = 1$ then

$$R_{ds,s} = 0 \tag{3.476}$$

else if $RDSMOD = 2$ then

$$R_{ds,s} = RS_{geo} + RD_{geo} + \frac{1}{(W_{eff0}(\mu m))^{WR_i}} \cdot \left(RDSWMIN(T) + \frac{RDSW(T)}{1 + PRWGS_i \cdot T1}\right) \tag{3.477}$$

$$E_{sat} = \frac{2 \cdot VSAT(T)}{\mu_0(T)/D_{mobs}} \tag{3.478}$$

$$E_{satL} = E_{sat} \cdot L_{eff} \tag{3.479}$$

Here, RS_{geo} and RD_{geo} are geometry dependent (bias independent) part of source and drain resistances. In RDSMOD=2 they are included in $R_{ds,s}$ calculation and no extra node is created. See section 3.15 for details.

If $R_{ds,s} = 0$ then

$$V_{dsat} = \frac{E_{satL} \cdot KSATIV_i \cdot (V_{gsfbeff} - \psi_s + 2\frac{kT}{q})}{E_{satL} + KSATIV_i \cdot (V_{gsfbeff} - \psi_s + 2\frac{kT}{q})} \tag{3.480}$$

else

$$WVC_{ox} = W_{eff0} \cdot VSAT(T) \cdot C_{ox} \tag{3.481}$$

$$T_a = 2 \cdot WVC_{ox} \cdot R_{ds,s} \tag{3.482}$$

$$T_b = KSATIV_i \cdot (V_{gsfbeff} - \psi_s + 2\frac{kT}{q}) \cdot (1 + 3 \cdot WVC_{ox} \cdot R_{ds,s}) + E_{satL} \tag{3.483}$$

$$T_c = KSATIV_i \cdot (V_{gsfbeff} - \psi_s + 2\frac{kT}{q}) \times \left(E_{satL} + T_a \cdot KSATIV_i \cdot (V_{gsfbeff} - \psi_s + 2\frac{kT}{q})\right) \tag{3.484}$$

$$V_{dsat} = \frac{\left(T_b - \sqrt{T_b^2 - 2T_aT_c}\right)}{T_a} \tag{3.485}$$

$$V_{dseff} = \frac{V_{ds}}{\left(1 + \left(\frac{V_{ds}}{V_{dsat}}\right)^{MEXP(T)}\right)^{1/MEXP(T)}} \tag{3.486}$$

3.5.2 Drain Side Potential and Charge Calculations

The core model calculation at the drain side is shown below:

$$vch = V_{dseff} + \Delta V_{t,QM} \tag{3.487}$$

The drain-side surface potential is computed in the same way as the source-side potential in section 3.4.3 except that vch is given as shown in equation (3.310). Based on this core model calculation at the drain side, similar to the approach previously outlined to calculate q_{is}, q_{id} is calculated, based on which ψ_d is calculated.

3.5.3 GAAFET quantum subband model (Drain side):

This module can be turned on with SUBBANDMOD=1 (0=off; default);

$$Q_{t,1} = \frac{V_{gsfb} - vch}{nVtm};\ Q_{t,2} = \frac{V_{gsfb} - vch - qe2}{nVtm};\ Q_{t,3} = \frac{V_{gsfb} - vch - qe3}{nVtm} \tag{3.488}$$

$$qndd1 = qnd10[min(Q_{t,1}, 0)]^{d_1/2} exp\Big(Q_{t,1} - min(Q_{t,1}, 0)\Big)$$

$$qndd2 = qnd20[min(Q_{t,2}, 0)]^{d_2/2} exp\Big(Q_{t,2} - min(Q_{t,2}, 0)\Big)$$

$$qndd3 = qnd30[min(Q_{t,3}, 0)]^{d_3/2} exp\Big(Q_{t,3} - min(Q_{t,3}, 0)\Big) \tag{3.489}$$

$$q_{id} = Nc_{3d} q_{id} + Nc_q(qndd1 + qndd2 + qndd3) \tag{3.490}$$

3.6 Average Potential, Charge and Related Variables

$$\Delta\psi = \psi_d - \psi_s \tag{3.491}$$

$$q_{ba} = q_{bs} \tag{3.492}$$

$$\Delta q_i = q_{is} - q_{id} \tag{3.493}$$

$$q_{ia} = 0.5 \cdot (q_{is} + q_{id}) \tag{3.494}$$

$$q_{ba} = 0.5 \cdot (qb\_acc\_d + qb\_acc\_s) \tag{3.495}$$

$$q_{ia2} = 0.5 \cdot (q_{is} + q_{id}) + 0.5 \cdot CHARGEWF \cdot \left[1.0 - exp(V_{dseff}^2/6.25e-4)\right] \cdot \Delta q_i \tag{3.496}$$

3.7 Quantum Mechanical Effects

Effects that arise due to structural and electrical confinement in the multi-gate structures are dealt in this section. The threshold voltage shift arising due to bias-dependent ground state sub-band energy is already accounted for in the surface potential calculations. (See the section on 'Surface Potential Calculation'). The reduction in width and bias-dependence in effective oxide thickness due to the inversion charge centroid being away from the interface is taken care of here. The section is evaluated only if $QMTCENIV_i$ or $QMTCENCV_i$ is non-zero. While a single equation with parameters $ETAQM$, $QM0$ and $ALPHAQM$ govern the motion of charge centroid w.r.t. bias, two different quasi-switches are introduced here for the purpose of effective width calculation and effective oxide thickness calculation. $QMTCENIV_i$ uses the above expression to account for the effective width in $I-V$ calculations and $QMTCENCV_i$ uses the same expression for the effective width and effective oxide thickness for $C-V$ calculations. The pre-calculated factor MTcen is for the geometric dependence (on $TFIN/HFIN/R$) of the charge centroid in sub-threshold region.

3.7.1 Charge Centroid Calculation for Inversion

If $QMTCENCV_i > 0$ then

$$T4 = \frac{q_{ia} + ETAQM \cdot q_{ba}}{QM0} \tag{3.497}$$

$$T5 = 1 + T4^{PQM} \tag{3.498}$$

$$T_{cen} = \frac{T_{cen0}}{T5} \tag{3.499}$$

end

3.7.2 Effective Width Model

If $GEOMOD = 0$ then

$$W_{eff} = W_{eff0} \tag{3.500}$$

$$W_{eff,CV} = W_{eff,CV0} \tag{3.501}$$

If $GEOMOD = 1$ then

$$W_{eff} = W_{eff0} - 4 \cdot QMTCENIV_i \cdot T_{cen} \tag{3.502}$$

$$W_{eff,CV} = W_{eff,CV0} - 4 \cdot QMTCENCV_i \cdot T_{cen} \tag{3.503}$$

If $GEOMOD = 2$ then

$$W_{eff} = W_{eff0} - 8 \cdot QMTCENIV_i \cdot T_{cen} \tag{3.504}$$

$$W_{eff,CV} = W_{eff,CV0} - 8 \cdot QMTCENCV_i \cdot T_{cen} \tag{3.505}$$

If $GEOMOD = 3$ then

$$W_{eff} = W_{eff0} - 2\pi \cdot QMTCENIV_i \cdot T_{cen} \tag{3.506}$$

$$W_{eff,CV} = W_{eff,CV0} - 2\pi \cdot QMTCENCV_i \cdot T_{cen} \tag{3.507}$$

3.7.3 Effective Oxide Thickness / Effective Capacitance

If $QMTCENCV_i = 0$, then $C_{ox}/C_{ox,acc}$ (with $EOT/EOTACC$) will continue to be used for both $I-V$ and $C-V$. Else the following calculations yield a $C_{ox,eff}$ that shall be used for $C-V$ purposes.

However C_{ox} will continue to be used for $I-V$. For calculation of $C_{ox,eff}$, the physical oxide thickness, $TOXP$ scaled appropriately will be added to the inversion charge centroid, T_{cen} calculated above instead of using EOT.

If $QMTCENCV_i \neq 0$ then

$$C_{ox,eff} = \begin{cases} \frac{3.9\cdot\epsilon_0}{TOXP\frac{3.9}{EPSROX}+T_{cen}\cdot\frac{QMTCENCV_i}{\epsilon_{ratio}}} & GEOMOD \neq 3 \\ \frac{3.9\cdot\epsilon_0}{R\cdot\left[\frac{1}{\epsilon_{ratio}}\ln\left(\frac{R}{R-T_{cen}}\right)+\frac{3.9}{EPSROX}\ln\left(1+\frac{T_{oxp}}{R}\right)\right]} & GEOMOD = 3 \\ \end{cases} \tag{3.508}$$

3.7.4 Charge Centroid Calculation for Accumulation

$$T6 = 1 + \left(\frac{q_{i,acc}}{QM0ACC}\right)^{PQMACC} \tag{3.509}$$

$$C_{ox,acc} = \begin{cases} \frac{3.9\cdot\epsilon_0}{TOXP\frac{3.9}{EPSROX}+\frac{T_{cen0}}{T6}\cdot\frac{QMTCENCVA_i}{\epsilon_{ratio}}} & GEOMOD \neq 3 \\ \frac{3.9\cdot\epsilon_0}{R\cdot\left[\frac{1}{\epsilon_{ratio}}\ln\left(\frac{R}{R-T_{cen0}/T6}\right)+\frac{3.9}{EPSROX}\ln\left(1+\frac{T_{oxp}}{R}\right)\right]} & GEOMOD = 3 \end{cases} \tag{3.510}$$

If $QMTCENCV_i = 0$ then

$$C_{ox,eff} = C_{ox} \tag{3.511}$$

$$C_{ox,acc} = \frac{3.9\cdot\epsilon_0}{EOTACC} \tag{3.512}$$

else if $QMTCENCV_i > 0$ then

$$T4 = \frac{q_{ia}}{QM0} \tag{3.513}$$

$$T5 = 1 + T4^{PQM} \tag{3.514}$$

$$T_{cen} = \frac{T_{cen0}}{T5} \tag{3.515}$$

$$C_{ox,eff} = \frac{1}{\left(\frac{1}{\left(C_{ox}\cdot\frac{EOT}{TOXP}\right)} + \frac{T_{cen}\cdot QMTCENCV_i}{\epsilon_{sub}}\right)} \tag{3.516}$$

end

Here, $C_{ox,eff}$ is the effective oxide capacitance taking QM effects into account for $V_{gs} > V_{fb}$ and $C_{ox,acc}$ is the effective oxide capacitance taking QM effects into account for $V_{gs} < V_{fb}$.

3.8 Mobility degradation and series resistance

3.8.1 Mobility degradation

$$\eta = \begin{cases} \frac{1}{2} \cdot ETAMOB_t & \text{for NMOS} \\ \frac{1}{3} \cdot ETAMOB_t & \text{for PMOS} \end{cases} \tag{3.517}$$

$$E_{effa} = 10^{-8} \cdot \left(\frac{q_{ba} + \eta \cdot q_{ia2}}{\epsilon_{ratio} \cdot EOT} \right) \tag{3.518}$$

For CRYOMOD = 0

$$D_{mob} = \begin{cases} 1 + UA(T) \cdot (E_{effa})^{EU} + \frac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{q_{ia2}}{1E-2/Cox}\right)\right)^{UCS(T)}} & \text{BULKMOD=0} \\ 1 + (UA(T) + UC(T) \cdot V_{eseff}) \cdot (E_{effa})^{EU} + \frac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{q_{ia2}}{1E-2/Cox}\right)\right)^{UCS(T)}} & \text{BULKMOD=1} \end{cases} \tag{3.519}$$

For CRYOMOD $\neq$ 0

$$T1 = q_{is} \qquad\qquad T2 = q_{id} \tag{3.520}$$

$$D_{mob} = \begin{cases} 1 + UA(T) \cdot (E_{effa})^{EU} + \frac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{UDS_{eff}(T)\cdot T1+UDD_{eff}(T)\cdot T2}{1E-2/Cox}\cdot T3\right)\right)^{UCS(T)}} & \text{BULKMOD=0} \\ 1 + (UA(T) + UC(T) \cdot V_{eseff}) \cdot (E_{effa})^{EU} + \\ \frac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{UDS_{eff}(T)\cdot T1+UDD_{eff}(T)\cdot T2}{1E-2/Cox}\cdot T3\right)\right)^{UCS(T)}} & \text{BULKMOD=1} \end{cases}$$

where $T3 = 1 - \exp(-V_{dseff}^2/6.25 \times 10^{-4})$ is a factor to preserve Gummel symmetry.

(3.521)

To incorporate the impact of hot-carrier defects on mobility degradation and to model these effects before and after stress, two model parameters MUHC0 and MUHC1 are used as:

$$u0mult_v = U0MULT \cdot (1 - MUHC0 \cdot exp(-MUHC1 \cdot V_{dseff})) \tag{3.522}$$

$$D_{mob} = \frac{D_{mob}}{u0mult_v} \tag{3.523}$$

3.8.2 Series resistance

The source/drain series resistance is the sum of a bias-independent component and a bias-dependent component. They are described in detail in section 3.15. If RDSMOD=0 or RDSMOD=2 the resistance will affect the I_{ds} expressions through a degradation factor D_r.

3.9 Lateral Non-uniform Doping Model

Lateral non-uniform doping along the length of the channel leads to I-V and C-V displaying different threshold voltages. However the consistent surface potential based I-V and C-V model doesn't allow for the usage of different Vth values. A straight forward method would be to re-compute the surface potentials at the source and drain end twice for I-V and C-V separately breaking the consistency but at the expense of computation time. The below model has been introduced as a multiplicative factor to the drain current (I-V) to allow for that Vth shift. This model should be exercised after the C-V extraction step to match the Vth for the subthreshold region Id,lin-Vg curve. Parameter K0 is used to fit the subthresold region, while parameter K0SI and KOSISAT helps reclaim the fit in the strong inversion region.

$$M_{nud} = \exp\left(-\frac{K0(T)}{\left(max(0, K0SI(T) + K0SISAT(T) \cdot dqi \cdot dqi) \cdot q_{ia} + 2.0 \cdot \frac{nkT}{q}\right)}\right) \tag{3.524}$$

3.10 Body Effect Model

A word of CAUTION: The above Lateral non-uniform doping model or the Body Effect model are empirical and have their limits as to how much Vth shift can be achieved without distorting the I-V curve. Over usage could lead to negative g_m or negative g_{ds}. For ex: The Lateral non-uniform doping model could be used in combination with the mobility model to achieve high Vth shift between C-V and I-V curved to avoid any distortion of higher order derivatives.

The equations showing the determination of the bulk charge (qi_acc_for_QM) are provided next. This bulk charge is critical in terms of determination of the centroid of charge in the accumulation region.

If $BULKMOD \neq 0$ then

$$T9 = \frac{K1}{(2.0 \cdot nVtm)}\sqrt{Vtm} \tag{3.525}$$

$$T0 = \frac{T9}{2.0} \tag{3.526}$$

$$T2 = \frac{(vge - (\Delta\phi - Eg - Vtm + ln(\frac{NBODY_i}{Nc}) + DELVFBACC))}{Vtm} \tag{3.527}$$

where vge is the gate to substrate voltage.

The following equations calculate the accumulation charge and related quantities considering QM effects.

If $(T2 \cdot Vtm) > (\phi_B + T9 \cdot \sqrt{\phi_B \cdot Vtm})$ then

$$T1 = \sqrt{T2 - 1.0 + T0 \cdot T0} - T0 \tag{3.528}$$

$$T10 = 1.0 + T1 \cdot T1 \tag{3.529}$$

end else

$$T3 = 0.5 \cdot T2 - 3.0 \cdot (1.0 + \frac{T9}{\sqrt{2.0}}) \tag{3.530}$$

$$T10 = T3 + \sqrt{T3 \cdot T3 + 6 \cdot T2} \tag{3.531}$$

If $T2 < 0.0$ then

$$T4 = \frac{(T2 - T10)}{T9} \tag{3.532}$$

$$T10 = -ln(1.0 - T10 + T4 \cdot T4) \tag{3.533}$$

else

$$T11 = \exp(-T10) \tag{3.534}$$

$$T4 = \sqrt{T2 - 1.0 + T11 + T0 \cdot T0} - T0 \tag{3.535}$$

$$T10 = 1.0 - T11 + T4 \cdot T4 \tag{3.536}$$

end

end

$$T6 = \exp(-T10) - 1.0 \tag{3.537}$$

$$T7 = \sqrt{T6 + T10} \tag{3.538}$$

If $T10 > 10^{-15}$ then

$$e0 = -(T2 - T10) + T9 \cdot T7 \tag{3.539}$$

$$e1 = 1.0 - T9 \cdot 0.5 \cdot \frac{T6}{T7} \tag{3.540}$$

$$T8 = T10 - \frac{e0}{e1} \tag{3.541}$$

$$T11 = \exp(-T8) - 1.0 \tag{3.542}$$

$$T12 = \sqrt{T11 + T8} \tag{3.543}$$

$$qb\_acc\_s = -T9 + T12 \cdot Vtm \tag{3.544}$$

end else

If $T10 < -10^{-15}$ then

$$e0 = -(T2 - T10) - T9 \cdot T7 \tag{3.545}$$

$$e1 = 1.0 + T9 \cdot 0.5 \cdot \frac{T6}{T7} \tag{3.546}$$

$$T8 = T10 - \frac{e0}{e1} \tag{3.547}$$

$$T12 = T9 \cdot \sqrt{\exp(-T8) + T8 - 1.0} \tag{3.548}$$

end else

$$T12 = 0.0 \tag{3.549}$$

$$T8 = 0.0 \tag{3.550}$$

end

$$qb\_acc\_s = T12 \cdot Vtm \tag{3.551}$$

end

$$qi\_acc\_for\_QM = T9 \cdot \exp(\frac{-T8}{2}) \cdot Vtm \tag{3.552}$$

$$qb\_acc\_d = qb\_acc\_s \tag{3.553}$$

$$psipclamp = 0.5 \cdot (T8 + 1.0 + \sqrt{(T8 - 1.0) \cdot (T8 - 1.0) + 0.25 \cdot 2.0 \cdot 2.0}) \tag{3.554}$$

$$sqrtpsip = \sqrt{psiclamp} \tag{3.555}$$

$$nq = 1.0 + \frac{T9}{sqrtpsip} \tag{3.556}$$

3.11 Output Conductance

3.11.1 Channel Length Modulation

$$T1 = q_{ia} \tag{3.557}$$

$$\frac{1}{C_{clm}} = \begin{cases} PCLM_i + PCLMG_i \cdot T1 & \text{for } PCLMG_i \geq 0 \\ \frac{1}{\frac{1}{PCLM_i} - PCLMG_i \cdot T1} & \text{for } PCLMG_i < 0 \end{cases} \tag{3.558}$$

$$M_{clm} = 1 + \frac{1}{C_{clm}} \ln \left[1 + \frac{V_{ds} - V_{dseff}}{V_{dsat} + E_{satL}} \cdot C_{clm} \right] \tag{3.559}$$

3.11.2 Output Conductance due to DIBL

$$T1 = q_{ia} \tag{3.560}$$

$$PVAGfactor = \begin{cases} 1 + PVAG_i \cdot \frac{T1}{E_{sat} L_{eff}} & \text{for } PVAG_i > 0 \\ \frac{1}{1 - PVAG_i \cdot \frac{T1}{E_{sat} L_{eff}}} & \text{for } PVAG_i \leq 0 \end{cases} \tag{3.561}$$

$$\theta_{rout} = \frac{0.5 \cdot PDIBL1_a}{cosh\left(DROUT_i \cdot \frac{L_{eff}}{\lambda}\right) - 1} + PDIBL2_i \tag{3.562}$$

$$V_{ADIBL} = \frac{T1 + 2kT/q}{\theta_{rout}} \cdot \left(1 - \frac{V_{dsat}}{V_{dsat} + T1 + 2kT/q}\right) \cdot PVAGfactor \tag{3.563}$$

$$M_{oc} = \left(1 + \frac{V_{ds} - V_{dseff}}{V_{ADIBL}}\right) \cdot M_{clm} \tag{3.564}$$

M_{oc} is multiplied to I_{ds} in the final drain current expression.

3.12 Velocity Saturation

3.12.1 Current Degradation Due to Velocity Saturation

The following formulation models the current degradation factor due to velocity saturation in the linear region. It is adopted from the BSIM5 model [10, 11].

$$E_{sat1} = \frac{2 \cdot VSAT1_a \cdot D_{mob}}{\mu_0(T)} \tag{3.565}$$

$$\delta_{vsat} = DELTAVSAT_i \tag{3.566}$$

$$D_{vsat} = \frac{1 + \left(\delta_{vsat} + \left(\frac{\Delta q_i}{E_{sat1} L_{eff}}\right)^{PSAT(L)}\right)^{\frac{1}{PSAT(L)}}}{1 + (\delta_{vsat})^{\frac{1}{PSAT(L)}}} + \frac{1}{2} \cdot PTWG_a \cdot q_{ia} \cdot \Delta q_i^2 \tag{3.567}$$

3.12.2 Non-Saturation Effect

Some devices do not exhibit prominent or abrupt velocity saturation. The parameters A1 and A2 are used to tune this non-saturation effect to better the $I_{d,sat}$ or $g_{m,sat}$ fitting.

$$T0 = max\left[\left(A1(T) + \frac{A2(T)}{q_{ia} + 2.0 \cdot \frac{nkT}{q}}\right) \cdot \Delta q_i^2, -1\right] \tag{3.568}$$

$$N_{sat} = \frac{1 + \sqrt{1 + T0}}{2} \tag{3.569}$$

$$D_{vsat} = D_{vsat} \cdot N_{sat} \tag{3.570}$$

3.13 Drain Current Model

$$\eta_{iv} = \frac{q_0}{q_0 + q_{ia}} \tag{3.571}$$

$$T2 = (2 - \eta_{iv}) \cdot \frac{nkT}{q} \tag{3.572}$$

$$\frac{i_{ds0}}{\Delta q_i} = T1 + T2 \tag{3.573}$$

$$i_{ds0} = \frac{i_{ds0}}{\Delta q_i} \cdot \Delta q_i \tag{3.574}$$

$$I_{ds} = IDS0MULT \cdot \mu_0(T) \cdot C_{ox} \cdot \frac{W_{eff}}{L_{eff}} \cdot i_{ds0} \cdot \frac{M_{oc} M_{ob} M_{nud}}{D_{mob} \cdot D_r \cdot D_{vsat}} \times NFIN_{total} \tag{3.575}$$

3.14 Intrinsic Capacitance Model

In BSIM-CMG both the intrinsic capacitances and parasitic capacitances are modeled. In this section we describe the formulation of intrinsic capacitances. The formulation of parasitic capacitances will be described in section 3.15

To ensure charge conservation, terminal charges instead of branch capacitances are used as state variables. The terminal charges Q_g, Q_b, Q_s, and Q_d are the charges associated with the gate, bulk, source, and drain terminals, respectively. Please refer to [12] for details of the terminal charge derivation.

3.14.1 DIBL

For $CVMOD = 1$

$$\Delta V_{th,DIBLCV} = \Theta_{DIBL} ETA0CV_i \cdot V_{dsx} + DVTP0 \cdot \Theta_{DITS} \cdot (V_{dsx} + 0.01)^{DVTP1} \tag{3.576}$$

$$\tag{3.577}$$

3.14.2 Mobility

$$\eta_{cv} = \begin{cases} \frac{1}{2} & \text{for NMOS} \\ \frac{1}{3} & \text{for PMOS} \end{cases} \tag{3.578}$$

$$E_{effa,cv} = \begin{cases} 10^{-8} \cdot \left(\frac{q_{ba}+\eta_{cv}\cdot q_{ia}}{\epsilon_{ratio}\cdot EOT}\right) & \text{for CVMOD=0} \\ 10^{-8} \cdot \left(\frac{q_{ba}+\eta_{cv}\cdot q_{ia,cv}}{\epsilon_{ratio}\cdot EOT}\right) & \text{for CVMOD=1} \end{cases} \tag{3.579}$$

$$D_{mob,cv} = \begin{cases} 1 + UA(T) \cdot (E_{effa,cv})^{EU} + \frac{UD(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{q_{ia}}{q_{ba}}\right)\right)^{UCS(T)}} & \text{for CVMOD=0} \\ 1 + UACV(T) \cdot (E_{effa,cv})^{EU} + \frac{UDCV(T)}{\left(\frac{1}{2}\cdot\left(1+\frac{q_{ia,cv}}{q_{ba}}\right)\right)^{UCS(T)}} & \text{for CVMOD=1} \end{cases} \tag{3.580}$$

$$D_{mob,CV} = \frac{D_{mob,cv}}{U0MULT} \tag{3.581}$$

3.14.3 Velocity Saturation

$$E_{satCV} = \begin{cases} \frac{2\cdot VSATCV(T)\cdot D_{mob,CV}}{\mu_0(T)} & \text{for CVMOD=0} \\ \frac{2\cdot VSATCV(T)\cdot D_{mob,CV}}{\mu_{0,cv}(T)} & \text{for CVMOD=0} \end{cases} \tag{3.582}$$

$$E_{satCVL} = E_{satCV} L_{effCV} \tag{3.583}$$

$$D_{vsat,CV} = \begin{cases} \frac{1+\left(\delta_{vsatcv}+\left(\frac{\Delta q_i}{E_{satCVL}}\right)^{PSATCV(L)}\right)^{\frac{1}{PSATCV(L)}}}{1+(\delta_{vsatcv})^{\frac{1}{PSATCV(L)}}} & \text{for CVMOD=0} \\ \frac{\left(1+\left(\delta_{vsatcv}+\left(\frac{\Delta q_{i,cv}}{E_{satCVL}}\right)^{PSATCV(L)}\right)^{\frac{1}{PSATCV(L)}}\right)\cdot ASAT}{1+(\delta_{vsatcv})^{\frac{1}{PSATCV(L)}}} & \text{for CVMOD=1} \end{cases} \tag{3.584}$$

3.14.4 Channel Length Modulation

Channel length modulation causes an effective reduction of the intrinsic capacitance at high drain bias. This reduction factor is modeled by $M_{clm,CV}$:

$$M_{clm,CV} = 1 + \frac{1}{PCLMCV} \ln\left[1 + \frac{V_{ds} - V_{dseff}}{Vdsat + E_{satCVL}} \cdot PCLMCV\right] \quad (3.585)$$

3.14.5 Accumulation Charge

Note: This section is still subject to verification and may be changed or removed in future versions. The calculation for accumulation region charge are performed if BULKMOD is set to 1, i.e. for a bulk-substrate device only. This introduces a computational effort equal to the calculation of surface potential on the source side. For calculation of accumulation region charge, the device is treated as intrinsically doped i.e. $NBODY_i{=}n_i$. However additional flexibility is introduced through a separate effective oxide thickness (EOTACC) and a separate Flatband voltage value (through DELVFBACC) for the accumulation side calculations. Full bias-dependent calculations are carried out to evaluate accumulation charge.

3.14.6 Surface Potential Evaluation

For $GEMOD \neq 3$, the simplified surface potential calculation is used with $V_{gsfbeff,acc}$, $F_{1,acc}$ and $r1_{acc}$ calculated above together with $r2 = 0$, $V_{ch} = 0$. Then the normalized charge is evaluated the following way...

$$q_{i,acc} = V_{gsfbeff,acc} - \frac{2kT}{q}\left[\ln(\beta) - \ln\left(\cos(\beta)\right) + F_{1,acc}\right] \quad (3.586)$$

Similarly for $GEMOD = 3$, the surface potential calculations are performed with $V_{gsfbeff,acc}$ and $r1_{acc}$, with $r2$ and V_{ch} both set to 0. The normalized charge in this case is give by,

$$q_{i,acc} = q_{0,acc} \cdot g \quad (3.587)$$

It may be noted here that qi,acc = 0 if BULKMOD =0.

3.14.7 Terminal Charges

$$T11 = \frac{(2.0 \cdot qia + nVtm)}{DvsatCV} \tag{3.588}$$

$$qg = qia + \frac{dqi \cdot dqi}{6 \cdot T11} \tag{3.589}$$

$$qd = 0.5 \cdot (qia - (\frac{dqi}{6.0}) \cdot (1.0 - (\frac{dqi}{T11}) \cdot (1 + \frac{dqi}{(5 \cdot T11)}))) \tag{3.590}$$

$$inv\_MclmCV = \frac{1.0}{M_{clm,CV}} \tag{3.591}$$

$$qg = inv\_MclmCV \cdot qg + (M_{clm,CV} - 1.0) \cdot qid \tag{3.592}$$

$$qd = inv\_MclmCV \cdot inv\_MclmCV \cdot qd + 0.5 \cdot (M_{clm,CV} - inv\_MclmCV) \cdot qid \tag{3.593}$$

$$\tag{3.594}$$

$$qs = -qg - qd \tag{3.595}$$

$$T6 = NFIN_{total} \cdot WeffCV \cdot LeffCV \cdot coxeff \tag{3.596}$$

$$qg = T6 \cdot qg \tag{3.597}$$

$$qd = T6 \cdot qd \tag{3.598}$$

$$qs = T6 \cdot qs \tag{3.599}$$

$$qinv = qg \tag{3.600}$$

If $BULKMOD \neq 0$ then

$$T1 = NFIN_{total} \cdot WeffCV \cdot LeffCV\_acc \cdot cox\_acc \tag{3.601}$$

$$T7 = qi\_acc\_for\_QM \tag{3.602}$$

$$T10 = T7 \cdot T1 \tag{3.603}$$

$$qg\_acc = -T10 \tag{3.604}$$

$$qb\_acc = T10 \tag{3.605}$$

$$T1 = NFIN_{total} \cdot WeffCV \cdot LeffCV \cdot cox \tag{3.606}$$

$$T2 = qb\_acc\_s - qi\_acc\_for\_QM \tag{3.607}$$

$$T10 = T1 \cdot T2 \tag{3.608}$$

$$qg\_acc = qg\_acc - T10 \tag{3.609}$$

$$qb\_acc = qb\_acc + T10 \tag{3.610}$$

$$T1 = NFIN_{total} \cdot WeffCV \cdot LeffCV \cdot cox \tag{3.611}$$

$$T2 = (nq - 1.0) \cdot 0.5 \cdot (qia + \frac{dqi \cdot dqi}{6 \cdot T11}) \tag{3.612}$$

$$T10 = T1 \cdot T2 \tag{3.613}$$

$$qg\_acc = qg\_acc - T10 \tag{3.614}$$

$$qb\_acc = qb\_acc + T10 \tag{3.615}$$

$$Q_{g,intrinsic} = NFIN_{total} \cdot C_{ox,eff} \cdot W_{eff,CV} \cdot L_{eff,CV} \cdot (q_g) \tag{3.616}$$

$$Q_{d,intrinsic} = NFIN_{total} \cdot C_{ox,eff} \cdot W_{eff,CV} \cdot L_{eff,CV} \cdot (-q_d) \tag{3.617}$$

$$Q_{b,intrinsic} = NFIN_{total} \cdot C_{ox} \cdot W_{eff,CV} \cdot L_{eff,CV} \cdot (-q_b) \tag{3.618}$$

$$Q_{s,intrinsic} = -Q_{g,intrinsic} - Q_{d,intrinsic} - Q_{b,intrinsic} \tag{3.619}$$

$$Q_{g,acc} = NFIN_{total} \cdot C_{ox,acc} \cdot W_{eff,CV0} \cdot L_{eff,CV,acc} \cdot (-q_{i,acc}) \tag{3.620}$$

$$Q_{b,acc} = NFIN_{total} \cdot C_{ox,acc} \cdot W_{eff,CV0} \cdot L_{eff,CV,acc} \cdot (-q_{i,acc}) \tag{3.621}$$

3.15 Parasitic resistances and capacitance models

In this section we will describe the models for parasitic resistances and capacitances in BSIM-CMG.

BSIM-CMG models the parasitic source/drain resistance in two components: a bias dependent extension resistance and a bias independent diffusion resistance. Parasitic gate resistance is modeled as well.

The parasitic capacitance model in BSIM-CMG includes a bias-indepedent fringe capacitance, a bias-dependent overlap capacitance, and substrate capacitances. In the case of MuGFETs on SOI, the substrate capacitances are from source/drain/gate to the substrate through the buried oxide. For MuGFETs on bulk substrate, an additional junction capacitor is modeled, which we will describe along with the junction current model in section 3.20.

3.15.1 Parasitic Resistance Model

The total parasitic resistance at the source/drain terminal consists of two parts: (a) Bias independent and (b) Bias dependent. BSIM-CMG offers three different options to model parasitic resistance with variations on the way the bias dependent and bias independent parts of the parasitic resistance are handled, . These options can be exercised by the switch $RDSMOD$ as described below:

(a)RDSMOD=0: Bias dependent part of parasitic resistance is internal to the model, while bias independent part is external to the model. Additional nodes are created. This is same as BSIM3 model.

(b)RDSMOD=1: Both bias dependent and bias independent parts of parasitic resistances are external to the model. The bias-dependent extension resistance model is adopted from BSIM4 [13]. Similar to BSIM4, this option in BSIM-CMG 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.

(c)RDSMOD=2: Both bias dependent and bias independent parts of parasitic resistances are internal to the model. This option assumes symmetric source/drain resistances. No additional nodes are created in this option.

The expressions for source/drain series resistances are as follows:

$\underline{RDSMOD = 0}$ **(Internal bias dependent, external bias independent)**

$$R_{source} = R_{s,geo} \tag{3.622}$$

$$R_{drain} = R_{d,geo} \tag{3.623}$$

$$R_{ds} = \frac{1}{NFIN_{total} \times Weff0^{WR_i}} \cdot \left(RDSWMIN(T) + \frac{RDSW(T)}{1 + PRWGS_i \cdot q_{ia}} \right) \tag{3.624}$$

$$D_r = 1.0 + NFIN_{total} \times \mu_0(T) \cdot C_{ox} \cdot \frac{W_{eff}}{L_{eff}} \cdot \frac{i_{ds0}}{\Delta q_i} \cdot \frac{R_{ds}}{D_{vsat} \cdot D_{mob}} \tag{3.625}$$

D_r goes into the denominator of the final I_{ds} expression.

<u>$RDSMOD = 1$</u> **(External)**

$$V_{gs,eff} = \frac{1}{2}\left[V_{gs1} - V_{fbsd} + \sqrt{(V_{gs1} - V_{fbsd})^2 + 0.1}\right] \tag{3.626}$$

$$V_{gd,eff} = \frac{1}{2}\left[V_{gd1} - V_{fbsd} + \sqrt{(V_{gd1} - V_{fbsd})^2 + 0.1}\right] \tag{3.627}$$

$$V_{si1,s,eff} = \sqrt{V(si1,s)^2 + 1.0E-6} \tag{3.628}$$

$$R_{sw} = \frac{RSW(T)\cdot(1 + RSDR_a \cdot V_{si,s,eff}^{PRSDR})}{1 + PRWGS_i \cdot V_{gs,eff}} \tag{3.629}$$

$$V_{di1,d,eff} = \sqrt{V(di1,d)^2 + 1.0E-6} \tag{3.630}$$

$$R_{dw} = \frac{RDW(T)\cdot(1 + RDDR_a \cdot V_{di1,d,eff}^{PRDDR})}{1 + PRWGD_i \cdot V_{gd,eff}} \tag{3.631}$$

$$R_{source} = \frac{1}{Weff0^{WR_i}\cdot NFIN_{total}}\cdot(RSWMIN(T) + R_{sw}) + R_{s,geo} \tag{3.632}$$

$$R_{drain} = \frac{1}{Weff0^{WR_i}\cdot NFIN_{total}}\cdot(RDWMIN(T) + R_{dw}) + R_{d,geo} \tag{3.633}$$

$$D_r = 1.0 \tag{3.634}$$

<u>$RDSMOD = 2$</u> **(Internal bias independent and bias dependent)**

$$R_{source} = 0.0 \tag{3.635}$$

$$R_{drain} = 0.0 \tag{3.636}$$

$$R_{ds} = R_{s,geo} + R_{d,geo} + \frac{1}{NFIN_{total}\times Weff0^{WR_i}}\cdot\left(RDSWMIN(T) + \frac{RDSW(T)}{1 + PRWGS_i\cdot q_{ia}}\right) \tag{3.637}$$

$$D_r = 1.0 + NFIN_{total}\times\mu_0(T)\cdot C_{ox}\cdot\frac{W_{eff}}{L_{eff}}\cdot\frac{i_{ds0}}{\Delta q_i}\cdot\frac{R_{ds}}{D_{vsat}\cdot D_{mob}}$$

$R_{s,geo}$ and $R_{d,geo}$ are the source and drain diffusion resistances, which we will describe as follows.

3.15.2 Velocity saturation effect in drain/source resistances

This model only works for $RDSMOD = 1$. At high current levels, the charge carriers in drain/source resistances may undergo velocity saturation. To this end, two resistances $R_{vs,d}$ and $R_{vs,s}$ are added at the drain and source sides, and expressed as follows.

Drain side

$$R_{vs,d} = R_{0d}\left[1 + \left(\frac{\delta_{vs,rd}^{\frac{1}{MVSRSD}} \cdot |V_{di1,di}|}{V_{sat,rd}}\right)^{MVSRSD}\right]^{\frac{1}{MVSRSD}} \tag{3.638}$$

$$R_{0d} = RDLCW \cdot rdstempvs(T) \cdot \frac{1}{NFINtotal \cdot Weff0^{WR}} \tag{3.639}$$

$$rdstempvs = 1 + PRTVSRSD \cdot (T - T_{nom}) \tag{3.640}$$

$$\delta_{vs,rd} = \frac{|V_{di1,di}|^{4-MVSRSD}}{|V_{di1,di}|^{4-MVSRSD} + VSRDFACTOR \cdot V_{sat,rd}^{4-MVSRSD}} \tag{3.641}$$

Modeling of gate bias dependency:

$$T1 = qis - PTWG1VSRSD \tag{3.642}$$

$$T2 = 10 \cdot PSATXVSRSD \cdot T1/(10 \cdot PSATXVSRSD + T1) \tag{3.643}$$

$$VSATRSD(T) = VSATRSD \cdot (1 - ATVSRSD \cdot (T - T_{nom})) \tag{3.644}$$

$$VSATRSD_{eff} = VSATRSD(T) \cdot (1 + PTWGVSRSD \cdot T2) \tag{3.645}$$

$$T0 = 1 + GAVSRD * (|V(di1, di)| - RDVDS) \tag{3.646}$$

$$I_{sat,rd} = q \cdot NVSRD \cdot Weff0 \cdot NFINtotal \cdot VSATRSD_{eff} \cdot T0 \tag{3.647}$$

$$V_{sat,rd} = R_{0d} \cdot I_{sat,rd} \tag{3.648}$$

Source side

$$R_{vs,s} = R_{0s}\left[1 + \left(\frac{\delta_{vs,rs}^{\frac{1}{MVSRSD}} \cdot |V_{si,si1}|}{V_{sat,rs}}\right)^{MVSRSD}\right]^{\frac{1}{MVSRSD}} \tag{3.649}$$

$$R_{0s} = RSLCW \cdot rdstempvs(T) \cdot \frac{1}{NFINtotal \cdot Weff0^{WR}} \tag{3.650}$$

$$\delta_{vs,rs} = \frac{|V_{si,si1}|^{4-MVSRSD}}{|V_{si,si1}|^{4-MVSRSD} + VSRSFACTOR \cdot V_{sat,rs}^{4-MVSRSD}} \tag{3.651}$$

$$I_{sat,rs} = q \cdot NVSRS \cdot Weff0 \cdot NFINtotal \cdot VSATRSD_{eff} \tag{3.652}$$

$$V_{sat,rs} = R_{0s} \cdot I_{sat,rs} \tag{3.653}$$

3.15.3 Diffusion resistance

BSIM-CMG offers two models for the source/drain diffusion resistance, selected by a parameter $RGEOMOD$.

3.15.3.1 Sheet resistance model

If $RGEOMOD = 0$, the resistance will be simply calculated as the sheet resistance ($RSHS$,$RSHD$) times the number of squares (NRS,NRD):

$\underline{RGEOMOD = 0}$ (**sheet resistance model**)

$$R_{s,geo} = NRS \cdot RSHS \tag{3.654}$$

$$R_{d,geo} = NRD \cdot RSHD \tag{3.655}$$

3.15.3.2 Diffusion resistance model for variability modeling

If $RGEOMOD = 1$, a diffusion resistance model for variability modeling will be invoked. The physically-derived model captures the complex dependences of resistance on the geometry of FinFETs.

$RGEOMOD = 1$ is derived based on the FinFET structure (single-fin or multi-fin with merged source/drain). Figure 1 shows the cross section of a double-gate FinFET with raised source/drain (RSD) along the source-drain direction. L_g (gate length) and $TOXP$ (physical oxide thickness, not shown in Fig. 1) are calculated in section 3.1. A hard mask with thickness $TMASK$ often exists on top of the fin. If $TMASK = 0$, the model will assume there is no hard mask and the dielectric thickness on top of the fin is $TOXP$ (triple-gate FinFET). In the figure, LSP is the spacer thickness, $LRSD$ is the length of the raised source/drain, $HFIN$ is the fin height, $TGATE$ is the gate height, and $HEPI$ is the height of the epitaxial silicon above the fin. These parameters are specified by the user.

The resistivity of the raised source/drain can be specified with the parameter $RHORSD$. If $RHORSD$ is not given the resistivity is calculated using the following expressions [14]:

$$\mu_{MAX} = \begin{cases} 1417 & \text{for NMOS} \\ 470.5 & \text{for PMOS} \end{cases} \tag{3.656}$$

$$\mu_{rsd} = \begin{cases} 52.2 + \frac{\mu_{MAX}-52.2}{1+\left(\frac{NSD}{9.68\times10^{22}m^{-3}}\right)^{0.680}} - \frac{43.4}{1+\left(\frac{3.41\times10^{26}m^{-3}}{NSD}\right)^{2.0}}\, cm^2/V-s & \text{for NMOS} \\ 44.9 + \frac{\mu_{MAX}-44.9}{1+\left(\frac{NSD}{2.23\times10^{23}m^{-3}}\right)^{0.719}} - \frac{29.0}{1+\left(\frac{6.10\times10^{26}m^{-3}}{NSD}\right)^{2.0}}\, cm^2/V-s & \text{for PMOS} \end{cases} \tag{3.657}$$

$$\rho_{RSD} = \frac{1}{q\, NSD\, \mu_{RSD}} \tag{3.658}$$

where NSD is the active doping concentration of the raised source/drain.

The diffusion resistance includes two components: the spreading resistance due to current spreading from the extension region into the raised source/drain (R_{sp}) and the resistance of the raised source/drain region (R_{con}).

The spreading resistance, R_{sp} is derived by assuming the current spreads at a constant angle θ_{RSP} in the raised source/drain. Comparison with numerical simulation shows that θ_{RSP} is around 55 degrees. The

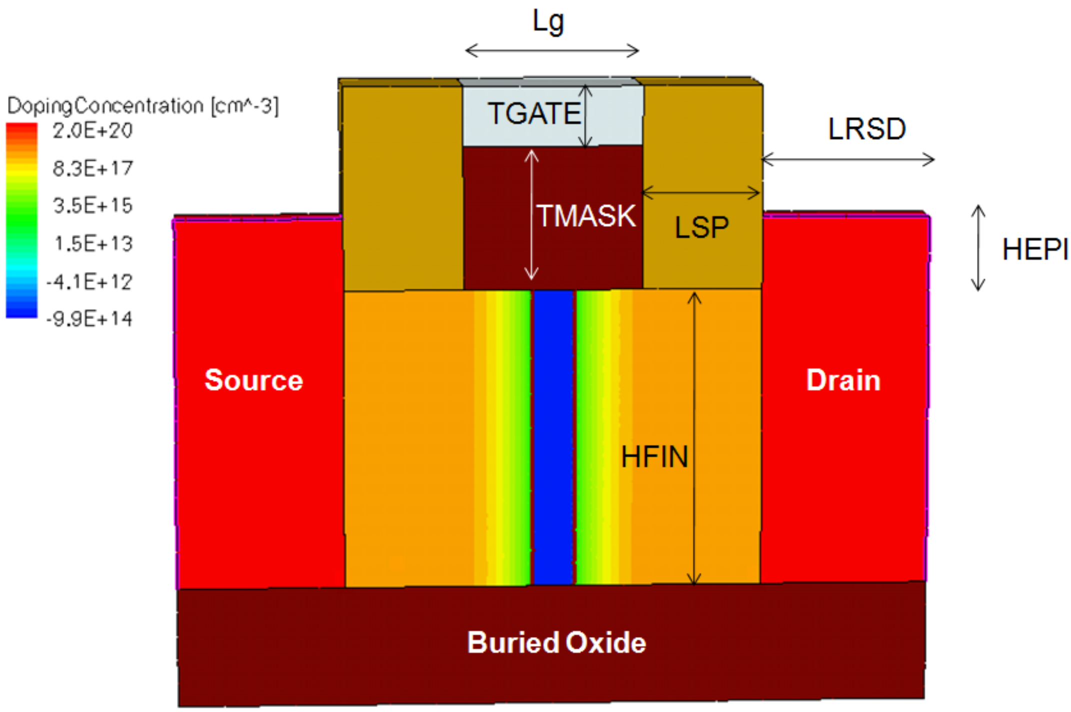

Figure 1: Cross section of a raised source/drain double-gate FinFET and symbol definition

spreading resistance is given as a function of the cross sectional area of the raised source/drain (A_{rsd}) and the effective fin area (A_{fin}):

$$R_{sp} = \frac{\rho_{RSD} \cdot cot(\theta_{rsp})}{\sqrt{\pi} \cdot NFIN} \cdot \left[\frac{1}{\sqrt{A_{fin}}} - \frac{2}{\sqrt{A_{rsd}}} + \sqrt{\frac{A_{fin}}{A_{rsd}^2}} \right] \tag{3.659}$$

A_{fin} is given by

$$A_{fin} = \begin{cases} HFIN \times TFIN & \text{for } HEPI \geq 0 \\ (HFIN + HEPI) \times TFIN & \text{for } HEPI < 0 \end{cases} \tag{3.660}$$

Here $HEPI < 0$ is the case where silicidation removes part of the silicon, forming a recessed source/drain (Fig. 2).

The raised source drain cross sectional area (A_{rsd}) is given by

$$A_{rsd} = \begin{cases} FPITCH \cdot HFIN + \Big[TFIN + \\ \quad (FPITCH - TFIN) \cdot CRATIO \Big] \cdot HEPI & \text{for } HEPI \geq 0 \\ FPITCH \cdot (HFIN + HEPI) & \text{for } HEPI < 0 \end{cases} \tag{3.661}$$

Figure 2: Lithography-defined FinFET with a smaller source/drain height compared to the fin height (silicide not shown).

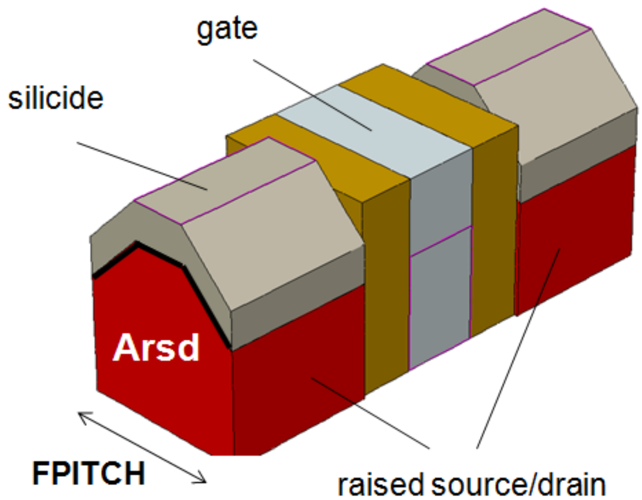

Figure 3: FinFET with non-rectangular epi and top silicide

In the above formula, we have assumed a rectangular geometry for negative $HEPI$ (Fig. 2) and the cross sectional area is simply the fin pitch times the final height of the source/drain. For positive $HEPI$, we have considered a RSD formed by selective epitaxial growth, in which case the RSD may not be rectangular (e.g. Fig. 3). In calculating the cross sectional area, we take into account the non-rectangular corner through the parameter $CRATIO$. $CRATIO$ is defined as the ratio of corner area filled with silicon to the total corner area. In the example given in Fig. 4, $CRATIO$ is 0.5.

The calculation of the contact resistance (R_{con}) is based on the transmission line model [15]. R_{con} is

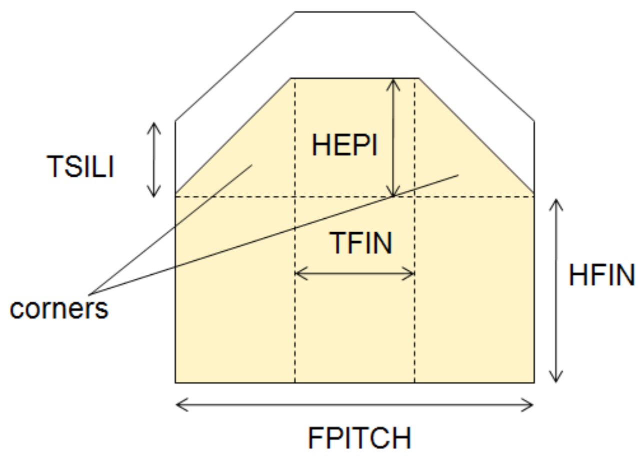

Figure 4: 2-D cross section of a FinFET with non-rectangular epi and top silicide

expressed as a function of the total area ($A_{rsd,total}$) and the total perimeter ($P_{rsd,total}$):

$$R_{rsd,TML} = \frac{\rho_{RSD} \cdot l_t}{A_{rsd,total}} \cdot \frac{\cosh(\alpha) + \eta \cdot \sinh(\alpha)}{\sinh(\alpha) + \cdot \cosh(\alpha)} \tag{3.662}$$

$$\alpha = \frac{LRSD}{l_t} \tag{3.663}$$

$$l_t = \sqrt{\frac{RHOC \cdot A_{rsd,total}}{\rho_{RSD} \cdot P_{rsd,total}}} \tag{3.664}$$

where RHOC is the contact resistivity at the silicide/silicon interface.

The total area and perimeter are given by

$$A_{rsd,total} = A_{rsd} \times NFIN + ARSDEND \tag{3.665}$$

$$P_{rsd,total} = (FPITCH + DELTAPRSD) \times NFIN + PRSDEND \tag{3.666}$$

$DELTAPRSD$ is the per-fin increase in perimeter due to non-rectangular raised source/drains. $ARSDEND$ and $PRSDEND$ are introduced to model the additional cross-sectional area and the additional perimeter, respectively, at the two ends of a multi-fin FinFET.

$SDTERM = 1$ indicates the source/drain are terminated with silicide (Fig. 5), while $SDTERM = 0$ indicates they are not. η is given by

$$\eta = \begin{cases} \frac{\rho_{RSD} \cdot l_t}{RHOC} & SDTERM = 1 \\ 0.0 & SDTERM = 0 \end{cases} \tag{3.667}$$

In the case of the recessed source/drain, a side component of the contact resistance must be modeled as

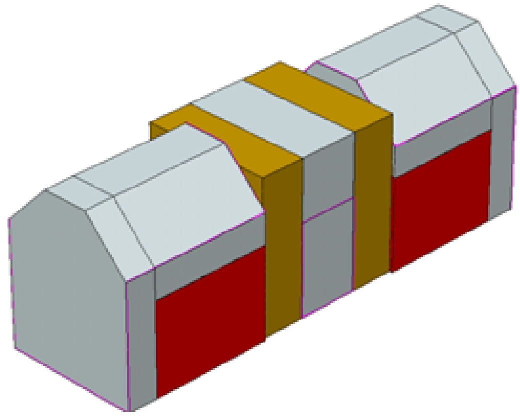

Figure 5: FinFET with a non-rectangular epi and silicide on top and two ends.

well. It is given by

$$R_{rsd,side} = \frac{RHOC}{NFIN \cdot (-HEPI) \cdot TFIN} \tag{3.668}$$

Finally, the total diffusion resistance is given by

$$R_{s,geo} = R_{d,geo} = \frac{R_{rsd}}{NF} \cdot \Big[RGEOA + RGEOB \times TFIN + \tag{3.669}$$

$$RGEOC \times FPITCH + RGEOD \times LRSD + RGEOE \times HEPI\Big]$$

where

$$R_{rsd} = \begin{cases} R_{rsd,TML} + R_{sp} & \text{for } HEPI \geq 0 \\ \frac{(R_{rsd,TML}+R_{sp})\times R_{rsd,side}}{(R_{rsd,TML}+R_{sp})+R_{rsd,side}} & \text{for } HEPI < 0 \end{cases} \tag{3.670}$$

Fitting parameters RGEOA, RGEOB, RGEOC, RGEOD and RGEOE are introduced for fitting flexibility.

3.15.4 Gate electrode resistance model

The gate electrode resistance model can be switched on by setting $RGATEMOD = 1$. This introduces an internal node "ge". The gate electrode resistor (R_{geltd}) is placed between the external "g" node and the internal "ge" node.

The gate electrode resistance model takes into account the number of gate contacts, $NGCON$. $NGCON = 1$ indicates single-sided contact; $NGCON = 2$ indicates double-sided contact. R_{geltd} is given by

$$Rgeltd = \begin{cases} \frac{RGEXT+RGFIN\cdot NFIN/3}{NF} & \text{for } NGCON = 1 \\ \frac{RGEXT/2+RGFIN\cdot NFIN/12}{NF} & \text{for } NGCON = 2 \end{cases} \tag{3.671}$$

3.15.5 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 BSIM-CMG is adopted from BSIM4 [13] for $CGEOMOD = 0$ and $CGEOMOD = 2$.

The overlap charge is given by:

$$\frac{Q_{gs,ov}}{NFIN_{total} \cdot WeffCV} = CGSO \cdot V_{gs} +$$

$$CGSL \cdot \left[V_{gs} - V_{fbsd} - V_{gs,overlap} - \frac{CKAPPAS}{2} \left(\sqrt{1 - \frac{4V_{gs,overlap}}{CKAPPAS}} - 1 \right) \right] \tag{3.672}$$

$$\frac{Q_{gd,ov}}{NFIN_{total} \cdot WeffCV} = CGDO \cdot V_{gd} +$$

$$CGDL \cdot \left[V_{gd} - V_{fbsd} - V_{gd,overlap} - \frac{CKAPPAD}{2} \left(\sqrt{1 - \frac{4V_{gd,overlap}}{CKAPPAD}} - 1 \right) \right] \tag{3.673}$$

$$V_{gs,overlap} = \frac{1}{2} \left[V_{gs} - V_{fbsd} + \delta_1 - \sqrt{(V_{gs} - V_{fbsd} + \delta_1)^2 + 4\delta_1} \right] \tag{3.674}$$

$$V_{gd,overlap} = \frac{1}{2} \left[V_{gd} - V_{fbsd} + \delta_1 - \sqrt{(V_{gd} - V_{fbsd} + \delta_1)^2 + 4\delta_1} \right] \tag{3.675}$$

$$\delta_1 = 0.02V \tag{3.676}$$

For $CGEOMOD = 1$, the overlap capacitors are bias-independent, as we will discuss in the end of this section.

3.15.6 Substrate parasitics

In multi-gate devices such as the FinFET, there is capacitive coupling from the source/drain to the substrate through the buried oxide. This component is modeled in BSIM-CMG and is given by:

$$C_{sbox} = C_{box} \cdot ASEO + C_{box,sw} \cdot (PSEO - FPITCH * NFIN_{total}) \tag{3.677}$$

$$C_{dbox} = C_{box} \cdot ADEO + C_{box,sw} \cdot (PDEO - FPITCH * NFIN_{total}) \tag{3.678}$$

where the side component per width is [16]

$$C_{box,sw} = CSDESW \cdot \ln \left(1 + \frac{HFIN}{EOTBOX} \right) \tag{3.679}$$

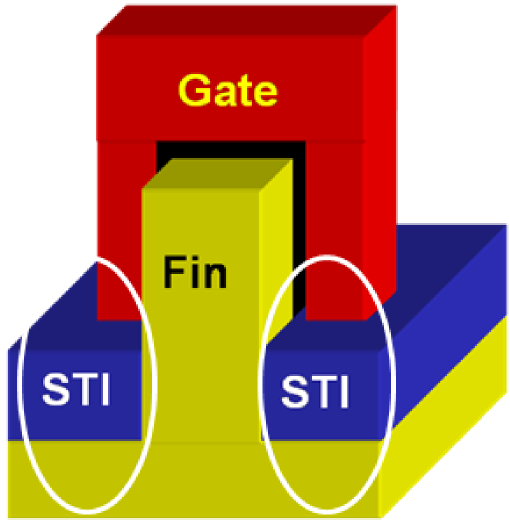

Figure 6: Illustration of the direct gate to substrate overlap region in the FinFET.

There is also direct capacitive coupling from the gate to the substrate in FinFETs (Fig. 6). Following BSIM4[13] this component is given by

$$C_{ge,overlap} = (CGBO \cdot NF \cdot NGCON + CGBN \cdot NFIN_{total}) \cdot (L + XL) \tag{3.680}$$

C_{sbox}, C_{dbox} and $C_{ge,overlap}$ are all linear capacitors.

3.15.7 Fringe capacitances and capacitance model selectors

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.

BSIM-CMG offers 3 models for the outer fringe capacitance, selected by $CGEOMOD$:

I. For $\underline{CGEOMOD = 0}$, the fringe and overlap capacitances are proportional to the number of fins and the effective width. The fringe capacitances is given by:

$\underline{CGEOMOD = 0}$

$$C_{gs,fr} = NFIN_{total} \cdot W_{eff,CV0} \cdot CFS_i \tag{3.681}$$

$$C_{gd,fr} = NFIN_{total} \cdot W_{eff,CV0} \cdot CFD_i \tag{3.682}$$

Fig. 7 illustrates the parasitic resistance and capacitance network used for $CGEOMOD = 0$.

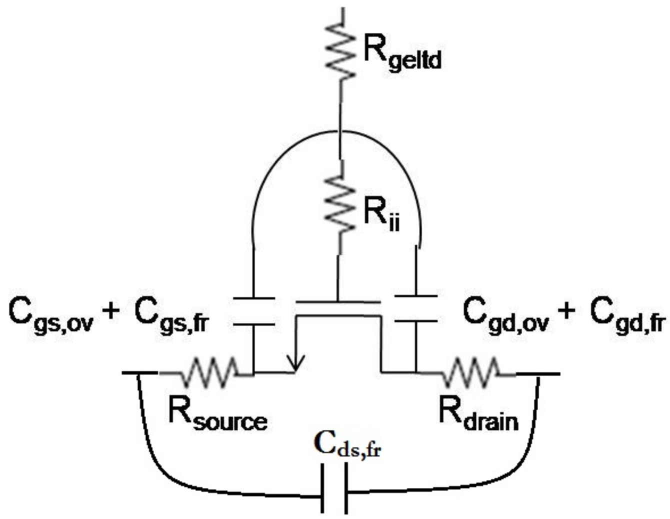

Figure 7: R-C network for CGEOMOD=0, NQSMOD=1, and RGATEMOD=1. If NQSMOD or RGATEMOD is 0, then the corresponding resistances become 0 and the nodes collapse.

II. In some multi-gate applications the parasitic capacitances are not directly proportional to the width of the device. BSIM-CMG offers $\underline{CGEOMOD = 1}$ so that the fringe and overlap capacitance values can be directly specified without assuming any width dependencies. The simple expressions for fringe and overlap capacitances in $CGEOMOD = 1$ are:

$\underline{CGEOMOD = 1}$

$$C_{gs,ov} = COVS_i \tag{3.683}$$

$$C_{gd,ov} = COVD_i \tag{3.684}$$

$$C_{gs,fr} = CGSP \tag{3.685}$$

$$C_{gd,fr} = CGDP \tag{3.686}$$

NOTE) The switch CGEO1SW can be used to enable the parameters *COVS*, *COVD*, *CGSP*, and *CGDP* to be in F per fin, per gate-finger, per unit channel width.

The parasitic resistance and capacitance network for $CGEOMOD = 1$ is illustrated in Fig. 8.

III. If $\underline{CGEOMOD = 2}$, an outer fringe capacitance model for variability modeling which address the complex dependencies on the FinFET geometry will be invoked. $RGEOMOD = 1$ and $CGEOMOD = 2$ share the same set of input parameters and can be used at the same time. Both models are derived based on the FinFET structure (single-fin or multi-fin with merged source/drain).

In $CGEOMOD = 2$ the fringe capacitance is partitioned into a top component, a corner component and a side component (Fig. 9). The top and side components are calculated based on a 2-D fringe capacitance model, which has been derived and calibrated to numerical simulation in [17]. The corner component is calculated

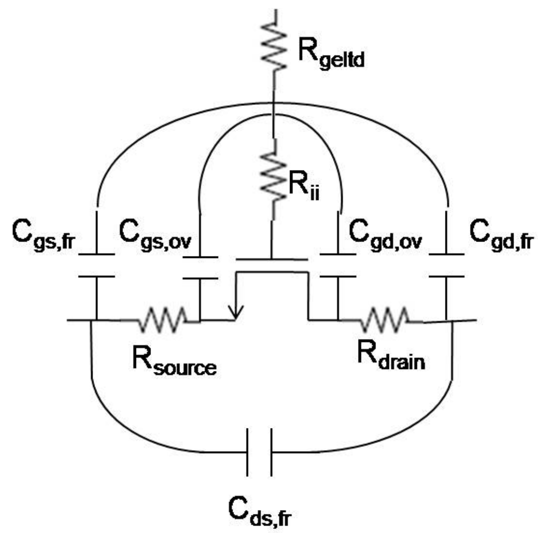

Figure 8: R-C network for CGEOMOD=1, NQSMOD=1, and RGATEMOD=1. If NQSMOD or RGATEMOD is 0, then the corresponding resistances become 0 and the nodes collapse.

based on the formula of parallel plate capacitors.

$$C_{fr,top} = C_{fringe,2D}(H_g, H_{rsd}, LRSD) \times TFIN \times NFIN \tag{3.687}$$

$$C_{fr,side} = 2 \times C_{fringe,2D}(W_g, T_{rsd}, LRSD) \times HFIN \times NFIN \tag{3.688}$$

$$C_{corner} = \frac{\epsilon_{sp}}{LSP} \cdot [A_{corner} \times NFIN + ARSDEND + ASILIEND] \tag{3.689}$$

where

$$H_g = TGATE + TMASK \tag{3.690}$$

$$T_{rsd} = \frac{1}{2}(FPITCH - TFIN) \tag{3.691}$$

$$W_g = T_{rsd} - TOXP \tag{3.692}$$

$$H_{rsd} = HEPI + TSILI \tag{3.693}$$

ARSDEND and ASILIEND are the additional area of silicon and silicide, respectively, at the two ends of a multi-fin FinFET.

The three components are summed up to give the total fringe capacitance. Several fitting parameters are added to aid fitting. The final expression is:

$\underline{CGEOMOD = 2}$

$$C_{fr,geo} = (C_{corner} + C_{fr,top} + CGEOE \cdot C_{fr,side}) \times NF \times [CGEOA + CGEOB \cdot TFIN + CGEOC \cdot FPITCH + CGEOD \cdot LRSD] \tag{3.694}$$

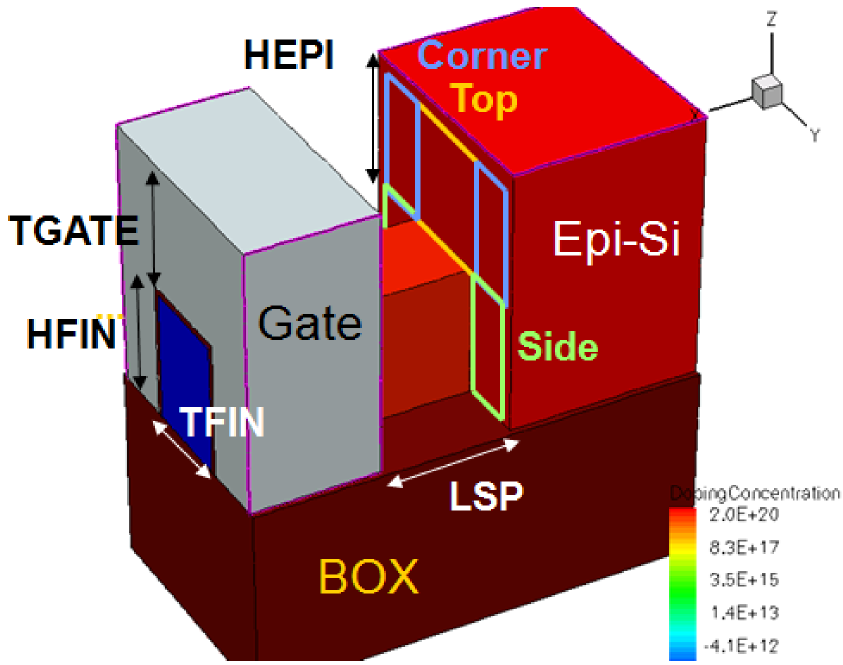

Figure 9: Illustration of top, corner and side components of the outer fringe capacitance

For the case of $TMASK > 0$ the fringe capacitances are calculated a little differently, since the 2D model is valid only for a thin T_{ox}. C_{corner} is set to 0. $C_{fr,top}$ is proportional to $FPITCH$ and is given by

$$C_{fr,top} = \left\{ 3.467 \times 10^{-11} \cdot \ln \left(\frac{EPSRSP \cdot 10^{-7}}{3.9 \cdot LSP} \right) + 0.942 \cdot H_{rsd} \cdot \frac{\epsilon_{sp}}{LSP} \right\} \cdot ([TFIN + (FPITCH - TFIN) \cdot CRATIO] \cdot NFIN \tag{3.695}$$

The R-C network has the same topology as $CGEOMOD = 0$.

IV. $\underline{CGEOMOD = 3}$ turns the fringe capacitance model for Gate-All-Around FETs (GAAFETs). This module is an extension of $CGEOMOD = 2$ and is designed specifically for multiple stacked GAA channels in a single fin.

In $CGEOMOD = 3$ the fringe capacitance is partitioned into a top component, corner components, side components and intermediate components between two GAA bodies; while also including the parasitic finfet component (Fig. 10). The top, intermediate and side components are calculated based on a 2-D fringe capacitance model, which has been derived and calibrated to numerical simulation in [17]. The corner component is

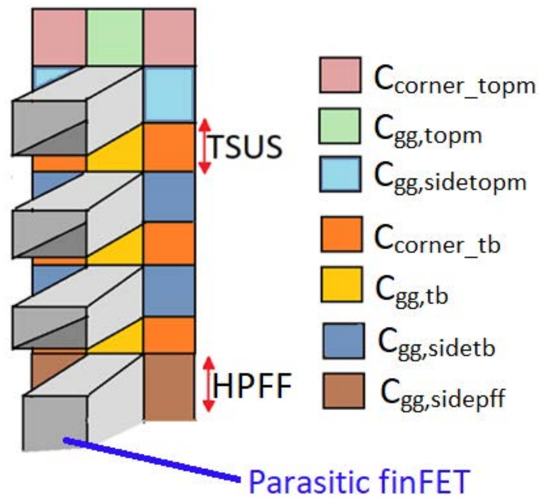

Figure 10: Illustration of top, corner and side components of the outer fringe capacitance for GAAFETs

calculated based on the formula of parallel plate capacitors.

$$C_{gg,topm} = C_{fringe,2D}(H_g, H_{rsd}, WGAA) \tag{3.696}$$

$$C_{gg,tb} = 2 \times C_{fringe,2D}(TGATE, Hrsd2, WGAA) \tag{3.697}$$

$$C_{gg,sidetopm} = C_{fringe,2D}(W_g, T_{rsd}, TGAA) \tag{3.698}$$

$$C_{gg,sidetb} = C_{fringe,2D}(W_g, T_{rsd}, TGAA) \tag{3.699}$$

$$C_{gg,sidepff} = C_{fringe,2D}(W_g, T_{rsd}, HPFF) \tag{3.700}$$

$$C_{corner} = \frac{\epsilon_{sp}}{LSP} \cdot [(A_{corner,topm} + 2NGAA \cdot A_{corner,tb})NFIN + ARSDEND + ASILIEND] \tag{3.701}$$

where

$$H_g = TGATE + TMASK \tag{3.702}$$

$$T_{rsd} = \frac{1}{2}(FPITCH - WGAA) \tag{3.703}$$

$$W_g = T_{rsd} - TOXP \tag{3.704}$$

$$H_{rsd} = HEPI + TSILI \tag{3.705}$$

$$Hrsd2 = \frac{1}{2}TSUS \tag{3.706}$$

ARSDEND and ASILIEND are the additional area of silicon and silicide, respectively, at the two ends of a multi-fin FinFET.

The components are summed up to give the total fringe capacitance. Several fitting parameters are added to aid fitting. The final expression is:

$$\underline{CGEOMOD = 3}$$

$$C_{fr,geo} = \Big(C_{corner} + (C_{gg,topm} + 2 \cdot NGAA \cdot C_{gg,tb})NFIN$$

$$+ 2 \cdot CGEOE[C_{gg,sidetopm} + (NGAA - 1)C_{gg,sidetb} + C_{gg,sidepff}]NFIN\Big)NF \times \tag{3.707}$$

$$[CGEOA + CGEOB \cdot WGAA + CGEOC \cdot FPITCH + CGEOD \cdot LRSD] \tag{3.708}$$

For the case of $TMASK > 0$ the fringe capacitances are calculated a little differently, since the 2D model is valid only for a thin T_{ox}. C_{corner} is set to 0. $C_{fr,top}$ is proportional to $FPITCH$ and is given by

$$C_{fr,top} = \left\{ 3.467 \times 10^{-11} \cdot \ln\left(\frac{EPSRSP \cdot 10^{-7}}{3.9 \cdot LSP}\right) + 0.942 \cdot H_{rsd} \cdot \frac{\epsilon_{sp}}{LSP} \right\}$$

$$\cdot ([TFIN + (FPITCH - TFIN) \cdot CRATIO] \cdot NFIN \tag{3.709}$$

The R-C network has the same topology as $CGEOMOD = 0$.
And finally,

$$\underline{CGEOMOD = 0/1/2/3}$$

$$C_{ds,fr} = CDSP$$

3.16 Impact Ionization and GIDL/GISL Model

3.16.1 Impact Ionization Current

Iii can be switched off by setting $IIMOD = 0$

$$\underline{\text{Case: } IIMOD = 1} \tag{3.710}$$

$$I_{ii} = \frac{ALPHA0(T) + ALPHA1(T) \cdot L_{eff}}{L_{eff}} (V_{ds} - V_{dseff}) \cdot e^{\frac{BETA0(T)}{V_{ds} - V_{dseff}}} \cdot I_{ds} \tag{3.711}$$

Case: $IIMOD = 2$

$$I_{ii} = \frac{ALPHAII0(T) + ALPHAII1(T) \cdot L_{eff}}{L_{eff}} \cdot I_{ds} \cdot exp\left(\frac{V_{diff}}{BETAII2_i + BETAII1_i V_{diff} + BETAII0_i V_{diff}^2}\right) \tag{3.712}$$

$$V_{diff} = V_{ds} - V_{dsatii} \tag{3.713}$$

$$V_{dsatii} = V_{gsStep} \cdot \left(1 - \frac{LII_i}{L_{eff}}\right) \tag{3.714}$$

$$V_{gsStep} = \left(\frac{ESATII_i L_{eff}}{1 + ESATII_i L_{eff}}\right)\left(\frac{1}{1 + SII1_i V_{gsfbeff}} + SII2_i\right)\left(\frac{SII0(T) \cdot V_{gsfbeff}}{1 + SIID_i V_{ds}}\right) \tag{3.715}$$

3.16.2 Gate-Induced-Drain/Source-Leakage Current

GIDL/GISL are calculated only for $GIDLMOD \neq 1$

$$T0 = AGIDL_i \cdot W_{eff0} \cdot \left(\frac{V_{ds} - V_{gs} - EGIDL_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGIDL_i} \times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGIDL(T)}{V_{ds} - V_{gs} - EGIDL_i + V_{fbsd}}\right) \times NFIN_{total} \tag{3.716}$$

$$I_{gidl} = \begin{cases} T0 \cdot \frac{V_{de}^3}{CGIDL_i + V_{de}^3} & \text{for } BULKMOD = 1 \\ T0 \cdot V_{ds} & \text{for } BULKMOD = 0 \end{cases} \tag{3.717}$$

$$T1 = AGISL_i \cdot W_{eff0} \cdot \left(\frac{-V_{ds} - V_{gd} - EGISL_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGISL_i} \times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGISL(T)}{-V_{ds} - V_{gd} - EGISL_i + V_{fbsd}}\right) \times NFIN_{total} \tag{3.718}$$

$$I_{gisl} = \begin{cases} T1 \cdot \frac{V_{se}^3}{CGISL_i + V_{se}^3} & \text{for } BULKMOD = 1 \\ T1 \cdot V_{sd} & \text{for } BULKMOD = 0 \end{cases} \tag{3.719}$$

Note) For V_{de} or $V_{se} \leq 0$, GIDL/GISL current is zero.[18], where V_{de} and V_{se} are the drain to channel, source to channel voltages.

For $BULKMOD \neq 0$, and $GEOMOD$ =2 or 3 or 5, substrate parasitic GIDL/GISL components (I_{gidlb}/I_{gislb}) are calculated separately from the direct drain to source/source to drain GIDL/GISL components (I_{gidl}/I_{gisl}).

Parasitic substrate GIDL/GISL is enabled by $GIDLMOD = 2$.

$$T0 = AGIDLB_i \cdot W_{effB} \cdot \left(\frac{V_{ds} - V_{gs} - EGIDLB_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGIDLB_i} \tag{3.720}$$

$$\times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGIDLB(T)}{V_{ds} - V_{gs} - EGIDLB_i + V_{fbsd}}\right) \times NFIN_{total} \tag{3.721}$$

$$I_{gidlb} = T0 \cdot \frac{V_{de}^3}{CGIDLB_i + V_{de}^3} \tag{3.722}$$

$$T1 = AGISLB_i \cdot W_{effB} \cdot \left(\frac{V_{ds} - V_{gs} - EGISLB_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGISLB_i} \tag{3.723}$$

$$\times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGISLB(T)}{V_{ds} - V_{gs} - EGISLB_i + V_{fbsd}}\right) \times NFIN_{total} \tag{3.724}$$

$$I_{gislb} = T1 \cdot \frac{V_{de}^3}{CGISLB_i + V_{de}^3} \tag{3.725}$$

where

$$W_{effB} = \begin{cases} TFIN\_BASE & \text{for } GEOMOD = 2 \\ D & \text{for } GEOMOD = 3 \\ WGAA & \text{for } GEOMOD = 5 \end{cases} \tag{3.726}$$

$GIDLMOD = 3$ is introduced to model trap assisted tunneling (TAT) in addition to the band to band tunneling.

$$T0 = AGIDL_i \cdot W_{eff0} \cdot \left(\frac{V_{ds} - V_{gs} - EGIDL_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGIDL_i}$$

$$\times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGIDL(T)}{V_{ds} - V_{gs} - EGIDL_i + V_{fbsd}}\right) \times NFIN_{total} \tag{3.727}$$

$$T1 = ATATD_i \cdot W_{eff0} \cdot n_i \times NFIN_{total}$$

$$\times \exp\left(\frac{BTATD_i \cdot (V_{ds} - V_{gs})^2 - CTATD(T) \cdot (V_{ds} - V_{gs}) - DTATD_i + V_{fbsd}}{V_{tm}}\right) \tag{3.728}$$

$$I_{gidl} = \begin{cases} (T0 + T1) \cdot \frac{V_{de}^3}{CGIDL_i + V_{de}^3} & \text{for } BULKMOD = 1 \\ (T0 + T1) \cdot V_{ds} & \text{for } BULKMOD = 0 \end{cases} \tag{3.729}$$

$$T0 = AGISL_i \cdot W_{eff0} \cdot \left(\frac{-V_{ds} - V_{gd} - EGISL_i + V_{fbsd}}{\epsilon_{ratio} \cdot EOT}\right)^{PGISL_i}$$
$$\times \exp\left(-\frac{\epsilon_{ratio} \cdot EOT \cdot BGISL(T)}{-V_{ds} - V_{gd} - EGISL_i + V_{fbsd}}\right) \times NFIN_{total} \quad (3.730)$$
$$T1 = ATATS_i \cdot W_{eff0} \cdot n_i \times NFIN_{total}$$
$$\times \exp\left(\frac{BTATS_i \cdot (-V_{ds} - V_{gd})^2 - CTATS(T) \cdot (-V_{ds} - V_{gd}) - DTATS_i + V_{fbsd}}{V_{tm}}\right) \quad (3.731)$$
$$I_{gisl} = \begin{cases} (T0 + T1) \cdot \frac{V_{se}^3}{CGISL_i + V_{se}^3} & \text{for } BULKMOD = 1 \\ (T0 + T1) \cdot V_{sd} & \text{for } BULKMOD = 0 \end{cases} \quad (3.732)$$

The parasitic substrate GIDL/GISL component in $GIDLMOD = 3$ is the same as in $GIDLMOD = 2$.

3.17 Gate Tunneling Current

$$T_{ox,ratio} = \frac{1}{TOXG^2} \cdot \left(\frac{TOXREF}{TOXG}\right)^{NTOX_i} \quad (3.733)$$

3.17.1 Gate to body current

I_{gbinv} and I_{gbacc} calculated only if $IGBMOD = 1$

$$A = 3.75956 \times 10^{-7} \quad (3.734)$$
$$B = 9.82222 \times 10^{11} \quad (3.735)$$
$$T1 = q_{ia} \quad (3.736)$$
$$V_{aux,igbinv} = NIGBINV_i \cdot \frac{kT}{q} \cdot \ln\left(1 + \exp\left(\frac{T1 - EIGBINV_i}{NIGBINV_i \cdot kT/q}\right)\right) \quad (3.737)$$
$$I_{gbinv} = IGB0MULT \cdot W_{eff0} \cdot L_{eff} \cdot A \cdot T_{ox,ratio} \cdot V_{ge} \cdot V_{aux,igbinv} \cdot Igtemp \cdot NFIN_{total}$$
$$\times \exp\left(-B \cdot TOXG \cdot (AIGBINV(T) - BIGBINV_i \cdot T1) \cdot (1 + CIGBINV_i \cdot T1)\right) \quad (3.738)$$

$$A = 4.97232 \times 10^{-7} \tag{3.739}$$

$$B = 7.45669 \times 10^{11} \tag{3.740}$$

$$V_{fbzb} = \Delta\phi - E_g/2 - \phi_B \tag{3.741}$$

$$T0 = V_{fbzb} - V_{ge} \tag{3.742}$$

$$T1 = T0 - 0.02; \tag{3.743}$$

$$V_{aux,igbacc} = NIGBACC_i \cdot \frac{kT}{q} \cdot \ln\left(1 + \exp\left(\frac{T0}{NIGBACC_i \cdot kT/q}\right)\right) \tag{3.744}$$

$$V_{oxacc} = \begin{cases} q_{i,acc} & \text{for} \quad \text{BULKMOD=1} \\ 0.5 \cdot [T1 + \sqrt{(T1)^2 - 0.08 \cdot V_{fbzb}}] & \text{for } BULKMOD \neq 1 \text{ and } V_{fbzb} \leq 0 \\ 0.5 \cdot [T1 + \sqrt{(T1)^2 + 0.08 \cdot V_{fbzb}}] & \text{for } BULKMOD \neq 1 \text{ and } V_{fbzb} > 0 \end{cases} \tag{3.745}$$

$$I_{gbacc} = IGB0MULT \cdot W_{eff0} \cdot L_{eff} \cdot A \cdot T_{ox,ratio} \cdot V_{ge} \cdot V_{aux,igbacc} \cdot Igtemp \cdot NFIN_{total}$$
$$\times \exp\left(-B \cdot TOXG \cdot (AIGBACC(T) - BIGBACC_i \cdot V_{oxacc}) \cdot (1 + CIGBACC_i \cdot V_{oxacc})\right) \tag{3.746}$$

For BULKMOD=1, I_{gb} simply flows from the gate into the substrate. For BULKMOD=0, I_{gb} mostly flows into the source because the potential barrier for holes is lower at the source, which has a lower potential. To ensure continuity when V_{ds} switches sign, I_{gb} is partitioned into a source component, I_{gbs} and a drain component, I_{gbd} using a partition function:

$$I_{gbs} = (I_{gbinv} + I_{gbacc}) \cdot W_f \tag{3.747}$$

$$I_{gbd} = (I_{gbinv} + I_{gbacc}) \cdot W_r \tag{3.748}$$

W_f and W_r are defined in equations (3.216) and (3.217), respectively.

3.17.2 Gate to channel current

I_{gc} is calculated only for $IGCMOD = 1$

$$A = \begin{cases} 4.97232 \times 10^{-7} & \text{for} \quad \text{NMOS} \\ 3.42536 \times 10^{-7} & \text{for} \quad \text{PMOS} \end{cases} \tag{3.749}$$

$$B = \begin{cases} 7.45669 \times 10^{11} & \text{for} \quad \text{NMOS} \\ 1.16645 \times 10^{12} & \text{for} \quad \text{PMOS} \end{cases} \tag{3.750}$$

$$T1 = q_{ia} \qquad T0 = T1 \cdot (V_{ge} - 0.5 \cdot V_{dsx} + 0. \tag{3.751}$$

$$I_{gc0} = IGC0MULT \cdot W_{eff0} \cdot L_{eff} \cdot A \cdot T_{ox,ratio} \cdot Igtemp \cdot NFIN_{total} \cdot T0$$

$$\times \exp\left(-B \cdot TOXG \cdot (AIGC(T) - BIGC_i \cdot T1) \cdot (1 + CIGC_i \cdot T1)\right) \tag{3.752}$$

$$V_{dseffx} = \sqrt{V_{dseff}^2 + 0.01} - 0.1 \tag{3.753}$$

$$I_{gcs} = I_{gc0} \cdot \frac{PIGCD_i \cdot V_{dseffx} + \exp(PIGCD_i \cdot V_{dseffx}) - 1.0 + 1.0E - 4}{PIGCD_i^2 \cdot V_{dseffx}^2 + 2.0E - 4} \tag{3.754}$$

$$I_{gcd} = I_{gc0} \cdot \frac{1.0 - (PIGCD_i \cdot V_{dseffx} + 1.0)\exp(-PIGCD_i \cdot V_{dseffx}) + 1.0E - 4}{PIGCD_i^2 \cdot V_{dseffx}^2 + 2.0E - 4} \tag{3.755}$$

3.17.3 Gate to source/drain current

I_{gs}, I_{gd} are calculated only for $IGCMOD = 1$

$$A = \begin{cases} 4.97232 \times 10^{-7} & \text{for NMOS} \\ 3.42536 \times 10^{-7} & \text{for PMOS} \end{cases} \tag{3.756}$$

$$B = \begin{cases} 7.45669 \times 10^{11} & \text{for NMOS} \\ 1.16645 \times 10^{12} & \text{for PMOS} \end{cases} \tag{3.757}$$

$$V'_{gs} = \sqrt{(V_{gs} - V_{fbsd})^2 + 10^{-4}} \tag{3.758}$$

$$V'_{gd} = \sqrt{(V_{gd} - V_{fbsd})^2 + 10^{-4}} \tag{3.759}$$

$$i_{gsd,mult} = Igtemp \cdot \frac{W_{eff0} \cdot A}{(TOXG \cdot POXEDGE_i)^2} \cdot \left(\frac{TOXREF}{TOXG \cdot POXEDGE_i}\right)^{NTOX_i} \tag{3.760}$$

$$I_{gs} = i_{gsd,mult} \cdot DLCIGS \cdot V_{gs} \cdot V'_{gs} \cdot NFIN_{total} \\ \times \exp\left(-B \cdot TOXG \cdot POXEDGE_i \cdot hypsmooth\left(AIGS(T) - BIGS_i \cdot V'_{gs}, 1e-6\right) \cdot \left(1 + CIGS_i \cdot V'_{gs}\right)\right) \tag{3.761}$$

$$I_{gd} = i_{gsd,mult} \cdot DLCIGD \cdot V_{gd} \cdot V'_{gd} \cdot NFIN_{total} \\ \times \exp\left(-B \cdot TOXG \cdot POXEDGE_i \cdot hypsmooth\left(AIGD(T) - BIGD_i \cdot V'_{gd}, 1e-6\right) \cdot \left(1 + CIGD_i \cdot V'_{gd}\right)\right) \tag{3.762}$$

3.18 Non Quasi-static Models

This version offers three different Non quasi-static (NQS) models. Each of these can be turned on/off using the NQSMOD switch. Setting $NQSMOD = 0$ turns off all NQS models and switches to plain quasi-static calculations.

3.18.1 Gate Resistance Model ($NQSMOD = 1$)

NQS effects for $NQSMOD = 1$ is modeled through an effective intrinsic input resistance, R_{ii} [19, 20]. This would introduce a gate node in between the intrinsic gate and the physical gate electrode resistance (RGATEMOD). This node collapses to the intrinsic gate if the user turns off this model.

$$I_{dovVds} = \mu_0(T) C_{ox} \frac{W_{eff}}{L_{eff}} \cdot \frac{i_{ds0}}{\Delta q_i} \cdot \frac{M_{oc}}{D_{vsat} D_{mob} D_r} \tag{3.763}$$

$$\frac{1}{R_{ii}} = NF \cdot NFIN \cdot XRCRG1_i \cdot \left(I_{dovVds} + XRCRG2 \cdot \frac{\mu_{eff} C_{oxe} W_{eff} kT}{q L_{eff}}\right) \tag{3.764}$$

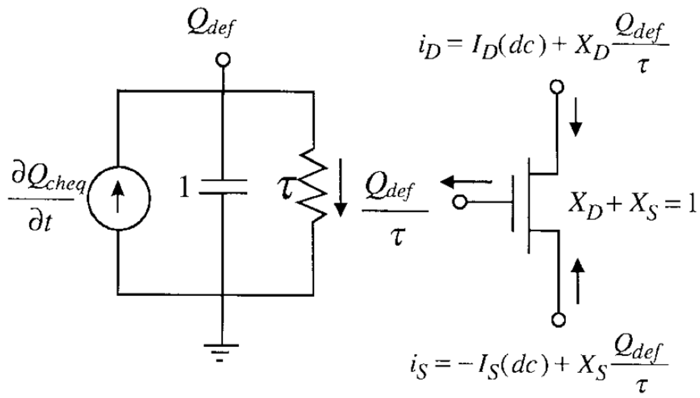

Figure 11: R-C network for calculating deficient charge Q_{def} and the instantaneous charge, Q_{def}/τ is used in place of the quasi-static charges. [21]

3.18.2 Charge Deficit Model ($NQSMOD = 2$)

The charge-deficit model from BSIM4 has been adopted here [13]. Based on a relaxation time approach, the deficient charge (equilibrium quasi-static charge minus the instantaneous channel charge) is kept track through a R-C sub-circuit [21]. An extra node whose voltage is equal to the deficient charge is introduced for this purpose. The instantaneous channel charge that is obtained from the self-consistent solution of the MOSFET and R-C sub-circuit is then split between the source and drain using a partition ratio ($X_{d,part}$) calculated from the quasi-static charges. A capacitance of 1 Farad is used for this purpose, while the resistance is give by the inverse of the relaxation time constant, $1/\tau$.

$$X_{d,part} = -\frac{qd}{qg} \tag{3.765}$$

$$I_{dovVds} = \mu_0(T) C_{ox} \frac{W_{eff}}{L_{eff}} \cdot \frac{i_{ds0}}{\Delta q_i} \cdot \frac{M_{oc}}{D_{vsat} D_{mob} D_r} \tag{3.766}$$

$$\frac{1}{R_{ii}} = NF \cdot NFIN \cdot XRCRG1_i \cdot \left(I_{dovVds} + XRCRG2 \cdot \frac{\mu_{eff} C_{oxe} W_{eff} kT}{q L_{eff}} \right) \tag{3.767}$$

$$\frac{1}{\tau} = \frac{1}{R_{ii} \cdot C_{ox} \cdot W_{eff} \cdot L_{eff}} \tag{3.768}$$

3.19 Generation-recombination Component

$$
\begin{aligned}
I_{ds,gen} &= HFIN \cdot TFIN \cdot (L_{eff} - LINTIGEN) \cdot (AIGEN_i \cdot V_{ds} + BIGEN_i \cdot V_{ds}^3) \\
&\cdot \exp\left[\frac{qE_g}{NTGEN_i \cdot kT}\left(\frac{T}{TNOM} - 1\right)\right] \times NFIN_{total}
\end{aligned} \tag{3.769}
$$

3.20 Junction Current and capacitances

The junction current and capacitances are only calculated for bulk multi-gate devices ($BULKMOD = 1$).

3.20.1 Source side junction current

Bias Independent Calculations

The bias independent source side junction current, I_{sbs}, is determined as shown below:

$$I_{sbs} = ASEJ \cdot J_{ss}(T) + PSEJ \cdot J_{sws}(T) + TFIN \cdot NFIN_{total} \cdot J_{swgs}(T) \tag{3.770}$$

$$NV_{tms} = \frac{kT}{q} \cdot NJS \tag{3.771}$$

$$XExpBVS = exp\left(-\frac{BVS}{NV_{tms}}\right) \cdot XJBVS \tag{3.772}$$

$$T_b = 1 + \frac{IJTHSFWD}{I_{sbs}} - XExpBVS \tag{3.773}$$

$$V_{jsmFwd} = NV_{tms} \cdot ln\left(\frac{T_b + \sqrt{T_b^2 + 4 \cdot XExpBVS}}{2}\right) \tag{3.774}$$

$$T_0 = exp\left(\frac{V_{jsmFwd}}{NV_{tms}}\right) \tag{3.775}$$

$$IV_{jsmFwd} = I_{sbs}\left(T_0 - \frac{XExpBVS}{T_o} + XExpBVS - 1\right) \tag{3.776}$$

$$S_{slpFwd} = \frac{I_{sbs}}{NV_{tms}} \cdot \left(T_0 + \frac{XExpBVS}{T_0}\right) \tag{3.777}$$

$$V_{jsmRev} = -BVS - NV_{tms} \cdot ln\left(\frac{\frac{IJTHSREV}{I_{sbs}} - 1}{XJBVS}\right) \tag{3.778}$$

$$T_1 = XJBVS \cdot exp\left(-\frac{BVS + V_{jsmRev}}{NV_{tms}}\right) \tag{3.779}$$

$$IV_{jsmRev} = I_{sbs} \cdot (1 + T_1) \tag{3.780}$$

$$S_{slpRev} = -I_{sbs} \cdot \frac{T_1}{NV_{tms}} \tag{3.781}$$

Bias Dependent Calculations

The bias dependent source side junction current, I_{es}, is determined as shown below:

$$\text{If } V_{es} < V_{jsmRev} \tag{3.782}$$

$$I_{es} = \left(exp\left(\frac{V_{es}}{NV_{tms}}\right) - 1\right) \cdot (IV_{jsmRev} + S_{slpRev}(V_{es} - V_{jsmRev})) \tag{3.783}$$

Else If $V_{jsmRev} \leq V_{es} \leq V_{jsmFwd}$

$$I_{es} = I_{sbs} \cdot \left(exp\left(\frac{V_{es}}{NV_{tms}}\right) + XExpBVS - 1 - XJBVS \cdot exp\left(-\frac{BVS + V_{es}}{NV_{tms}}\right)\right) \tag{3.784}$$

Else $V_{es} > V_{jsmFwd}$

$$I_{es} = IV_{jsmFwd} + S_{slpFwd}(V_{es} - V_{jsmFwd}) \tag{3.785}$$

Including Source Side Junction Tunneling Current

$$I_{es1} = ASEJ \cdot J_{tss}(T) \times \left(exp\left(\frac{-V_{es}/(k \cdot TNOM/q)/NJTS(T) \times VTSS}{max(VTSS - V_{es}, VTSS \cdot 1.0E - 3)}\right) - 1\right) \tag{3.786}$$

$$I_{es2} = PSEJ \cdot J_{tssws}(T) \times \left(exp\left(\frac{-V_{es}/(k \cdot TNOM/q)/NJTSSW(T) \times VTSSWS}{max(VTSSWS - V_{es}, VTSSWS \cdot 1.0E - 3)}\right) - 1\right) \tag{3.787}$$

$$I_{es3} = TFIN \cdot NFIN_{total} \cdot J_{tsswgs}(T) \times \left(exp\left(\frac{-V_{es}/(k \cdot TNOM/q)/NJTSSWG(T) \times VTSSWGS}{max(VTSSWGS - V_{es}, VTSSWGS \cdot 1.0E - 3)}\right) - 1\right) \tag{3.788}$$

Including Drain Side Junction Tunneling Current

$$I_{es} = I_{es} - (I_{es1} + I_{es2} + I_{es3}) \tag{3.789}$$

3.20.2 Drain side junction current

Bias Independent Calculations

The bias independent drain side junction current , I_{sbd}, is determined as shown below:

$$I_{sbd} = ADEJ \cdot J_{sd}(T) + PDEJ \cdot J_{swd}(T) + TFIN \cdot NFIN_{total} \cdot J_{swgd}(T) \tag{3.790}$$

$$NV_{tmd} = \frac{kT}{q} \cdot NJD \tag{3.791}$$

$$XExpBVD = exp\left(-\frac{BVD}{NV_{tmd}}\right) \cdot XJBVD \tag{3.792}$$

$$T_b = 1 + \frac{IJTHDFWD}{I_{sbd}} - XExpBVD \tag{3.793}$$

$$V_{jdmFwd} = NV_{tmd} \cdot ln\left(\frac{T_b + \sqrt{T_b^2 + 4 \cdot XExpBVD}}{2}\right) \tag{3.794}$$

$$T_0 = exp\left(\frac{V_{jdmFwd}}{NV_{tmd}}\right) \tag{3.795}$$

$$IV_{jdmFwd} = I_{sbd}\left(T_0 - \frac{XExpBVD}{T_o} + XExpBVD - 1\right) \tag{3.796}$$

$$D_{slpFwd} = \frac{I_{sbd}}{NV_{tmd}} \cdot \left(T_0 + \frac{XExpBVD}{T_0}\right) \tag{3.797}$$

$$V_{jdmRev} = -BVD - NV_{tmd} \cdot ln\left(\frac{\frac{IJTHDREV}{I_{sbd}} - 1}{XJBVD}\right) \tag{3.798}$$

$$T_1 = XJBVD \cdot exp\left(-\frac{BVD + V_{jdmRev}}{NV_{tmd}}\right) \tag{3.799}$$

$$IV_{jdmRev} = I_{sbd} \cdot (1 + T_1) \tag{3.800}$$

$$D_{slpRev} = -I_{sbd} \cdot \frac{T_1}{NV_{tmd}} \tag{3.801}$$

Bias Dependent Calculations

The bias dependent source side junction current, I_{ed}, is determined as shown below:

If $V_{ed} < V_{jdmRev}$

$$I_{ed} = \left(exp\left(\frac{V_{ed}}{NV_{tmd}}\right) - 1\right) \cdot (IV_{jdmRev} + D_{slpRev}(V_{ed} - V_{jdmRev})) \tag{3.802}$$

Else If $V_{jdmRev} \le V_{ed} \le V_{jdmFwd}$

$$I_{ed} = I_{sbd} \cdot \left(exp\left(\frac{V_{ed}}{NV_{tmd}}\right) + XExpBVD - 1 - XJBVD \cdot exp\left(-\frac{BVD + V_{ed}}{NV_{tmd}}\right)\right) \tag{3.803}$$

Else $V_{ed} > V_{jdmFwd}$

$$I_{ed} = IV_{jdmFwd} + D_{slpFwd}(V_{ed} - V_{jdmFwd}) \tag{3.804}$$

Including Drain Side Junction Tunneling Current

$$I_{ed1} = ADEJ \cdot J_{tsd}(T) \times \left(exp\left(\frac{-V_{ed}/(k \cdot TNOM/q)/NJTSD(T) \times VTSD}{max(VTSD - V_{ed}, VTSD \cdot 1.0E-3)} \right) - 1 \right) \tag{3.805}$$

$$I_{ed2} = PDEJ \cdot J_{tsswd}(T) \times \left(exp\left(\frac{-V_{ed}/(k \cdot TNOM/q)/NJTSSWD(T) \times VTSSWD}{max(VTSSWD - V_{es}, VTSSWD \cdot 1.0E-3)} \right) - 1 \right) \tag{3.806}$$

$$I_{ed3} = TFIN \cdot NFIN_{total} \cdot J_{tsswgd}(T) \times \left(exp\left(\frac{-V_{ed}/(k \cdot TNOM/q)/NJTSSWGD(T) \times VTSSWGD}{max(VTSSWGD - V_{ed}, VTSSWGD \cdot 1.0E-3)} \right) - 1 \right) \tag{3.807}$$

Including Drain Side Junction Tunneling Current

$$I_{ed} = I_{ed} - (I_{ed1} + I_{ed2} + I_{ed3}) \tag{3.808}$$

3.20.3 Source side junction capacitance

Bias Independent Calculations

$$C_{zbs} = CJS(T) \cdot ASEJ \tag{3.809}$$

$$C_{zbssw} = CJSWS(T) \cdot PSEJ \tag{3.810}$$

$$C_{zbsswg} = CJSWGS(T) \cdot TFIN \cdot NFIN_{total} \tag{3.811}$$

Bias Dependent Calculations

$$Q_{es1} = \begin{cases} C_{zbs} \cdot PBS(T) \cdot \frac{1-\left(1-\frac{V_{es}}{PBS(T)}\right)^{1-MJS}}{1-MJS} & V_{es} > 0 \\ V_{es} \cdot C_{zbs} + V_{es}^2 \cdot \frac{MJS \cdot C_{zbs}}{2 \cdot PBS(T)} & V_{es} \leq 0 \end{cases} \tag{3.812}$$

$$Q_{es2} = \begin{cases} C_{zbssw} \cdot PBSWS(T) \cdot \frac{1-\left(1-\frac{V_{es}}{PBSWS(T)}\right)^{1-MJSWS}}{1-MJSWS} & V_{es} > 0 \\ V_{es} \cdot C_{zbssw} + V_{es}^2 \cdot \frac{MJSWS \cdot C_{zbssw}}{2 \cdot PBSWS(T)} & V_{es} \leq 0 \end{cases} \tag{3.813}$$

$$Q_{es3} = \begin{cases} C_{zbsswg} \cdot PBSWGS(T) \cdot \frac{1-\left(1-\frac{V_{es}}{PBSWGS(T)}\right)^{1-MJSWGS}}{1-MJSWGS} & V_{es} > 0 \\ V_{es} \cdot C_{zbsswg} + V_{es}^2 \cdot \frac{MJSWGS \cdot C_{zbsswg}}{2 \cdot PBSWGS(T)} & V_{es} \leq 0 \end{cases} \tag{3.814}$$

$$Q_{es} = Q_{es1} + Q_{es2} + Q_{es3} \tag{3.815}$$

3.20.4 Two-Step Source side junction capacitance

In some cases, the depletion edge in the channel/ substrate edge might transition into a region with a different doping (for ex. in a NMOS device: [n^+ (source) , p_1 (channel/substrate) , p_2 (substrate)], where p_1 and p_2 are regions with different doping levels). The following could be used to capture such a situation. In what follows, V_{escn} (< 0) can be interpreted as the transition voltage at which the depletion region switches from p_1 to p_2 region. It is calculated assuming parameters SJxxx (proportionality constant for second region) and MJxxx2 (gradient of second region's doping) are given, to give a continuous charge and capacitance.

For $V_{es} < V_{esc1}$

$$Q_{es1} = C_{zbs} \cdot \left(PBS(T) \cdot \frac{1 - \left(1 - \frac{V_{esc1}}{PBS(T)}\right)^{1-MJS}}{1 - MJS} + SJS \cdot Pbs2 \cdot \frac{1 - \left(1 - \frac{V_{es} - V_{esc1}}{Pbs2}\right)^{1-MJS2}}{1 - MJS2} \right) \tag{3.816}$$

Else use the Q_{es1} of single junction above for $V_{es} > V_{esc1}$ where,

$$V_{esc1} = PBS(T) \cdot \left(1 - \left(\frac{1}{SJS} \right)^{\frac{1}{MJS}} \right) \tag{3.817}$$

$$Pbs2 = \frac{PBS(T) \cdot SJS \cdot MJS2}{MJS \cdot \left(1 - \frac{V_{esc1}}{PBS(T)}\right)^{-1-MJS}} \tag{3.818}$$

For $V_{es} < V_{esc2}$

$$\begin{aligned} Q_{es2} = {} & C_{zbssw} \cdot PBSWS(T) \cdot \frac{1 - \left(1 - \frac{V_{esc2}}{PBSWS(T)}\right)^{1-MJSWS}}{1 - MJSWS} \\ & + C_{zbssw} \cdot SJSWS \cdot Pbsws2 \cdot \frac{1 - \left(1 - \frac{V_{es} - V_{esc2}}{Pbsws2}\right)^{1-MJSWS2}}{1 - MJSWS2} \end{aligned} \tag{3.819}$$

Else use the Q_{es2} of single junction above for $V_{es} > V_{esc2}$ where,

$$V_{esc2} = PBSWS(T) \cdot \left(1 - \left(\frac{1}{SJSWS} \right)^{\frac{1}{MJSWS}} \right) \tag{3.820}$$

$$Pbsws2 = \frac{PBSWS(T) \cdot SJSWS \cdot MJSWS2}{MJSWS \cdot \left(1 - \frac{V_{esc2}}{PBSWS(T)}\right)^{-1-MJSWS}} \tag{3.821}$$

For $V_{es} < V_{esc3}$

$$Q_{es3} = C_{zbsswg} \cdot PBSWGS(T) \cdot \frac{1 - \left(1 - \frac{V_{esc3}}{PBSWGS(T)}\right)^{1-MJSWGS}}{1 - MJSWGS} + C_{zbsswg} \cdot SJSWGS \cdot Pbswgs2 \cdot \frac{1 - \left(1 - \frac{V_{es}-V_{esc3}}{Pbswgs2}\right)^{1-MJSWGS2}}{1 - MJSWGS2} \tag{3.822}$$

Else use the Q_{es3} of single junction above for $V_{es} > V_{esc3}$ where,

$$V_{esc3} = PBSWGS(T) \cdot \left(1 - \left(\frac{1}{SJSWGS}\right)^{\frac{1}{MJSWGS}}\right) \tag{3.823}$$

$$Pbswgs2 = \frac{PBSWGS(T) \cdot SJSWGS \cdot MJSWGS2}{MJSWGS \cdot \left(1 - \frac{V_{esc3}}{PBSWGS(T)}\right)^{-1-MJSWGS}} \tag{3.824}$$

3.20.5 Drain side junction capacitance

Bias Independent Calculations

$$C_{zbd} = CJD(T) \cdot ADEJ \tag{3.825}$$

$$C_{zbdsw} = CJSWD(T) \cdot PDEJ \tag{3.826}$$

$$C_{zbdswg} = CJSWGD(T) \cdot TFIN \cdot NFIN_{total} \tag{3.827}$$

Bias Dependent Calculations

$$Q_{ed1} = \begin{cases} C_{zbd} \cdot PBD(T) \cdot \frac{1-\left(1-\frac{V_{ed}}{PBD(T)}\right)^{1-MJD}}{1-MJD} & V_{ed} > 0 \\ V_{ed} \cdot C_{zbd} + V_{ed}^2 \cdot \frac{MJD \cdot C_{zbd}}{2 \cdot PBD(T)} & V_{ed} \leq 0 \end{cases} \tag{3.828}$$

$$Q_{ed2} = \begin{cases} C_{zbdsw} \cdot PBSWD(T) \cdot \frac{1-\left(1-\frac{V_{ed}}{PBSWD1(T)}\right)^{1-MJSWD}}{1-MJSWD} & V_{ed} > 0 \\ V_{ed} \cdot C_{zbdsw} + V_{ed}^2 \cdot \frac{MJSWD \cdot C_{zbdsw}}{2 \cdot PBSWD(T)} & V_{ed} \leq 0 \end{cases} \tag{3.829}$$

$$Q_{ed3} = \begin{cases} C_{zbdswg} \cdot PBSWGD(T) \cdot \frac{1-\left(1-\frac{V_{ed}}{PBSWGD(T)}\right)^{1-MJSWGD}}{1-MJSWGD} & V_{ed} > 0 \\ V_{ed} \cdot C_{zbdswg} + V_{ed}^2 \cdot \frac{MJSWGD \cdot C_{zbdswg}}{2 \cdot PBSWGD(T)} & V_{ed} \leq 0 \end{cases} \tag{3.830}$$

$$Q_{ed} = Q_{ed1} + Q_{ed2} + Q_{ed3} \tag{3.831}$$

3.20.6 Two-Step Drain side junction capacitance

Refer to the description made for the source side.

For $V_{ed} < V_{edc1}$

$$Q_{ed1} = C_{zbd} \cdot \left(PBD(T) \cdot \frac{1 - \left(1 - \frac{V_{edc1}}{PBD(T)}\right)^{1-MJD}}{1 - MJD} + SJD \cdot Pbd2 \cdot \frac{1 - \left(1 - \frac{V_{ed} - V_{edc1}}{Pbd2}\right)^{1-MJD2}}{1 - MJD2} \right) \tag{3.832}$$

Else use the Q_{ed1} of single junction above for $V_{ed} > V_{edc1}$ where,

$$V_{edc1} = PBD(T) \cdot \left(1 - \left(\frac{1}{SJD} \right)^{\frac{1}{MJD}} \right) \tag{3.833}$$

$$Pbd2 = \frac{PBD(T) \cdot SJD \cdot MJD2}{MJD \cdot \left(1 - \frac{V_{edc1}}{PBD(T)}\right)^{-1-MJD}} \tag{3.834}$$

For $V_{ed} < V_{edc2}$

$$\begin{aligned} Q_{ed2} = C_{zbdsw} \cdot PBSWD(T) \cdot \frac{1 - \left(1 - \frac{V_{edc2}}{PBSWD(T)}\right)^{1-MJSWD}}{1 - MJSWD} \\ + C_{zbdsw} \cdot SJSWD \cdot Pbswd2 \cdot \frac{1 - \left(1 - \frac{V_{ed} - V_{edc2}}{Pbswd2}\right)^{1-MJSWD2}}{1 - MJSWD2} \end{aligned} \tag{3.835}$$

Else use the Q_{ed2} of single junction above for $V_{ed} > V_{edc2}$ where,

$$V_{edc2} = PBSWD(T) \cdot \left(1 - \left(\frac{1}{SJSWD} \right)^{\frac{1}{MJSWD}} \right) \tag{3.836}$$

$$Pbswd2 = \frac{PBSWD(T) \cdot SJSWD \cdot MJSWD2}{MJSWD \cdot \left(1 - \frac{V_{edc2}}{PBSWD(T)}\right)^{-1-MJSWD}} \tag{3.837}$$

For $V_{ed} < V_{edc3}$

$$\begin{aligned} Q_{ed3} = C_{zbdswg} \cdot PBSWGD(T) \cdot \frac{1 - \left(1 - \frac{V_{edc3}}{PBSWGD(T)}\right)^{1-MJSWGD}}{1 - MJSWGD} \\ + C_{zbdswg} \cdot SJSWGD \cdot Pbswgd2 \cdot \frac{1 - \left(1 - \frac{V_{ed} - V_{edc3}}{Pbswgd2}\right)^{1-MJSWGD2}}{1 - MJSWGD2} \end{aligned} \tag{3.838}$$

Else use the Q_{ed3} of single junction above for $V_{ed} > V_{edc3}$ where,

$$V_{edc3} = PBSWGD(T) \cdot \left(1 - \left(\frac{1}{SJSWGD} \right)^{\frac{1}{MJSWGD}} \right) \tag{3.839}$$

$$Pbswgd2 = \frac{PBSWGD(T) \cdot SJSWGD \cdot MJSWGD2}{MJSWGD \cdot \left(1 - \frac{V_{edc3}}{PBSWGD(T)}\right)^{-1-MJSWGD}} \tag{3.840}$$

3.21 Self-heating model

The self-heating effect is modeled using an R-C network approach (based on BSIM-SOI [16]), as illustrated in Fig. 12. The voltage at the temperature node (T) denotes the change in temperature due to self-heating and is accounted for in all temperature-dependence calculations in the model.

3.21.1 Thermal resistance and capacitance calculations

The thermal resistance (R_{th}) and capacitance (C_{th}) are modified from BSIMSOI to capture the fin pitch ($FPITCH$) dependence.

$$NFINtotal = NF \cdot NFIN \tag{3.841}$$

$$\frac{1}{R_{th}} = G_{th} = \frac{(WTH0 \cdot NF^{BSHEXP} + ASH \cdot FPITCH \cdot NFINtotal^{ASHEXP})}{RTH0} \tag{3.842}$$

$$C_{th} = CTH0 \cdot (WTH0 \cdot NF^{BSHEXP} + ASH \cdot FPITCH \cdot NFINtotal^{ASHEXP}) \tag{3.843}$$

When ASHEXP =1, BSHEXP = 1, the expressions for R_{th} and C_{th} are backward compatible with BSIM CMG 108.0.

When GEOMOD=5, thermal resistance (R_{th}) and capacitance (C_{th}) are defined as:

$$\frac{1}{R_{th}} = G_{th} = \frac{(WTH0 \cdot NF^{BSHEXP} + ASH \cdot FPITCH \cdot NFINtotal^{ASHEXP})}{RTH0} + \frac{(CSH \cdot WGAA \cdot NF \cdot NGAA^{CSHEXP})}{RTH0} \tag{3.844}$$

$$C_{th} = CTH0 \cdot (WTH0 \cdot NF^{BSHEXP} + ASH \cdot FPITCH \cdot NFINtotal^{ASHEXP} + CSH \cdot WGAA \cdot NF \cdot NGAA^{CSHEXP}) \tag{3.845}$$

3.22 Noise Models

Noise models in BSIM-CMG are based on BSIM4 [13]. Table 1 lists the origin of each noise model:

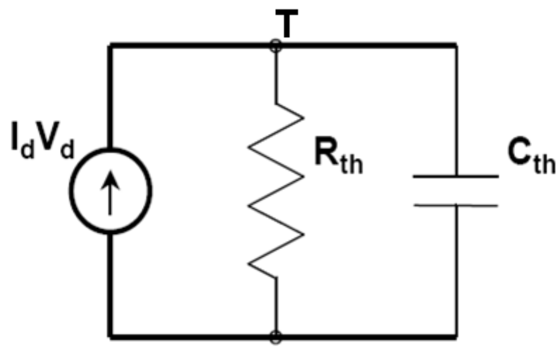

Figure 12: R-C network for self-heating calculation [16]

Model in BSIM-CMG 112.0.0	Origin
Flicker noise model (FNMOD=0)	BSIM4 Unified Model (FNOIMOD=1)
Flicker noise model (FNMOD=1)	Advanced nodes [22]
Thermal noise (TNOIMOD = 0)	BSIM4 TNOIMOD=0
Thermal noise (TNOIMOD = 1)	BSIM4 TNOIMOD=2
Gate current shot noise	BSIM4 gate current noise
Noise associated with parasitic resistances	BSIM4 parasitic resistance noise

Table 1: Origin of noise models in BSIM-CMG

3.22.1 Flicker noise model

$$E_{sat,noi} = \frac{2VSAT_i}{\mu_{eff}} \tag{3.846}$$

$$L_{eff,noi} = L_{eff} - 2 \cdot LINTNOI \tag{3.847}$$

$$\Delta L_{clm} = l \cdot \ln\left[\frac{1}{E_{sat,noi}} \cdot \left(\frac{V_{ds} - V_{dseff}}{l} + EM\right)\right] \tag{3.848}$$

$$N_0 = \frac{C_{oxe} \cdot q_{is}}{q} \tag{3.849}$$

$$N_l = \frac{C_{oxe} \cdot q_{id}}{q} \tag{3.850}$$

$$N^* = \frac{kT}{q^2}\left(C_{oxe} + CIT_i\right) \tag{3.851}$$

When FNMOD=1, [22]

$$NOIA_{eff} = Max\left[1, \left(\frac{\frac{NOIA2}{NOIA}}{1 + \left(\frac{qia2}{QSREF}\right)^{MPOWER}}\right)\right] NOIA \tag{3.852}$$

The Max[·] function is implemented using $Max(x, y) = 0.5(x + y + \sqrt{(x-y)^2 + SMOOTH^2/4})$, where $SMOOTH$ is a smoothing parameter. When FNMOD=0,

$$NOIA_{eff} = NOIA \tag{3.853}$$

The flicker noise is calculated as

$$FN1 = NOIA_{eff} \cdot \ln\left(\frac{N_0 + N^*}{N_l + N^*}\right) + NOIB \cdot (N_0 - N_l) + \frac{NOIC}{2}(N_0^2 - N_l^2) \tag{3.854}$$

$$FN2 = \frac{NOIA_{eff} + NOIB \cdot N_l + NOIC \cdot N_l^2}{(N_l + N^*)^2} \tag{3.855}$$

$$S_{si} = \frac{kTq^2\mu_{eff}I_{ds}}{C_{oxe}L_{eff,noi}^2 f^{EF} \cdot 10^{10}} \cdot FN1 + \frac{kTI_{ds}^2\Delta L_{clm}}{W_{eff} \cdot NFIN_{total} \cdot L_{eff,noi}^2 f^{EF} \cdot 10^{10}} \cdot FN2 \tag{3.856}$$

$$S_{wi} = \frac{NOIA_{eff} \cdot kT \cdot I_{ds}^2}{W_{eff} \cdot NFIN_{total} \cdot L_{eff,noi} f^{EF} \cdot 10^{10} \cdot N^{*2}} \tag{3.857}$$

$$S_{id,flicker} = \frac{S_{wi}S_{si}}{S_{wi} + S_{si}} \tag{3.858}$$

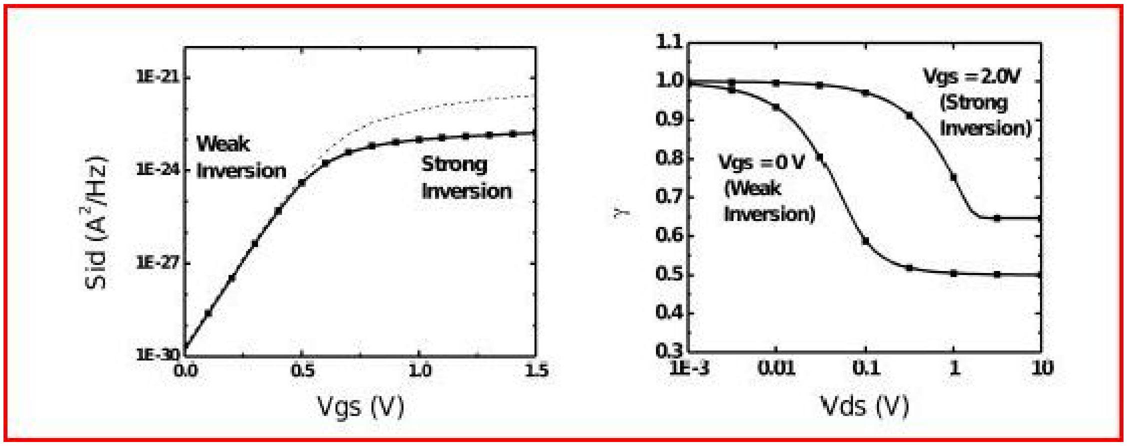

Figure 13: TNOIMOD=1 shows good physical behavior at high and low Vds from sub-threshold to strong inversion regions.

3.22.2 Thermal noise model ($TNOIMOD = 0$)

$$Q_{inv} = |Q_{s,intrinsic} + Q_{d,intrinsic}| \times NFIN_{total} \tag{3.859}$$

$$\overline{i_d^2} = \begin{cases} NTNOI \cdot \frac{4kT\Delta f}{R_{ds} + \frac{L_{eff}^2}{\mu_{eff} Q_{inv}}} & \text{if RDSMOD} = 0 \text{ or } 2 \\ NTNOI \cdot \frac{4kT\Delta f}{L_{eff}^2} \cdot \mu_{eff} Q_{inv} & \text{if RDSMOD} = 1 \end{cases} \tag{3.860}$$

3.22.3 Thermal Noise Model ($TNOIMOD = 1$)

TNOIMOD=1 is a correlated thermal noise model where both drain and gate noise are implemented as current sources in this thermal noise model. The correlation between two sources is independently controllable and can be tuned using RNOIC parameter. The BSIM4.8 correlated model noise was adapted for use with a surface potential core.

3.22.4 Gate current shot noise

$$\overline{i_{gs}^2} = 2q(I_{gcs} + I_{gs}) \tag{3.861}$$

$$\overline{i_{gd}^2} = 2q(I_{gcd} + I_{gd}) \tag{3.862}$$

$$\overline{i_{gb}^2} = 2qI_{gbinv} \tag{3.863}$$

3.22.5 Resistor noise

The noise associated with each parasitic resistors in BSIM-CMG are calculated

If $RDSMOD \neq 2$ then

$$\frac{\overline{i_{RS}^2}}{\Delta f} = 4kT \cdot \frac{1}{R_{source}} \tag{3.864}$$

$$\frac{\overline{i_{RD}^2}}{\Delta f} = 4kT \cdot \frac{1}{R_{drain}} \tag{3.865}$$

If $RDSMOD = 1$ then

$$\frac{\overline{i_{R_{vs,s}}^2}}{\Delta f} = 4kT \cdot \frac{1}{R_{vs,s}} \tag{3.866}$$

$$\frac{\overline{i_{R_{vs,d}}^2}}{\Delta f} = 4kT \cdot \frac{1}{R_{vs,d}} \tag{3.867}$$

If $RGATEMOD = 1$ then

$$\frac{\overline{i_{RG}^2}}{\Delta f} = 4kT \cdot \frac{1}{R_{geltd}} \tag{3.868}$$

3.23 Threshold Voltage

A simple analytical threshold voltage V_{th} definition for GEOMOD=0, 1, and 2 was derived and implemented as operating point info in BSIM-CMG106.1.0beta2. For a long channel device, V_{th} is defined as the value of V_g at which the drift and diffusion components of the source to drain current at the source side are equal. Based on this definition, it can be shown that at $V_g = V_{th}$, the charge at source side is given by [23]

$$Q_{is} = C_{ox} \cdot \frac{kT}{q}. \tag{3.869}$$

Next, the surface potential at the source is [approximately] calculated from the charges as follows ([7], ch. 3, p.66)

$$\psi_s \approx \frac{kT}{q} ln \left[\frac{Q_{is}\left(Q_{is} + 2Q_{bulk} + 5C_{si}\frac{kT}{q}\right)}{2qn_i e_{sub}\frac{kT}{q}} \right] + \phi_B + \Delta V_{t,QM}. \tag{3.870}$$

The Gauss law demands that at the source side

$$V_g = V_{fb} + \psi_s + \frac{Q_{is} + Q_{bs}}{C_{ox}}. \tag{3.871}$$

Substituting (3.869) and (3.870) in (3.871) results in the following expression for V_{th} for a long channel device:

$$V_{th0} = V_{fb} + \frac{kT}{q} ln \left[\frac{C_{ox}\frac{kT}{q}\left(C_{ox}\frac{kT}{q} + 2Q_{bulk} + 5C_{si}\frac{kT}{q}\right)}{2qn_i\epsilon_{sub}\frac{kT}{q}} \right] + \phi_B + \Delta V_{t,QM} + \frac{kT}{q} + q_{bs}. \tag{3.872}$$

Corrections due to threshold voltage roll-off, DIBL, reverse short channel effect, and temperature are added accordingly:

$$V_{th} = V_{th0} + \Delta V_{th,all}. \tag{3.873}$$

3.24 Equivalent Circuit

In BSIM-CMG, we define current sources and charge flows inside the nodes of D (drain), G (gate), S (source), and E (substrate) to represent DC and AC behavior according to the FinFET physics. Parasitic resistances and parasitic capacitances are added between the nodes to accurately describe the undesired effects in a real process. Parasitic and real device effects are modularized in BSIM-CMG to give users flexibility in data fitting and debugging. They are independently controlled by the MOD parameters. Table 2 gives descriptions of their functions and controlled components. In the following sections, we show typical DC and AC equivalent circuits for FinFETs on bulk substrate (BULKMOD = 1) and FinFETs on SOI substrate (BULKMOD= 0).

Parameter	Function	Controlled Components
RGATEMOD	Parasitics	Rg: parasitic gate resistance
RDSMOD	Parasitics	Rd: parasitic drain resistance Rs: parasitic source resistance
NQSMOD	Non-quasi static	Rii: Intrinsic input resistance
IGCMOD	Gate leakage	Igs: gate-to-source tunneling current Igd: gate-to-drain tunneling current Igcs: gate-to-channel tunneling current at source side Igcd: gate-to-channel tunneling current at drain side
IGBMOD	Gate leakage	For BULKMOD = 1, Igbinv: gate-to-substrate tunneling current at inversion Igbacc: gate-to-substrate tunneling current at accumulation For BULKMOD = 0, Igbs: (Igbinv + Igbacc) at source side Igbd: (Igbinv + Igbacc) at drain side
GIDLMOD	GIDL leakage	Igidl: gate-induced drain lowering current Igisl: gate-induced source lowering current
IIMOD	Impact ionization	Iii: impact ionization current

Table 2: MOD Parameters

3.24.1 FinFETs on Bulk Substrate (BULKMOD = 1)

Table 3 shows the allowed and disallowed values of the MOD parameters. With different combinations of MOD parameters, there are many versions of DC or AC equivalent circuits available. For example, Fig. 14 shows one of the most complex cases of DC equivalent circuit for BULKMOD = 1. If RGATEMOD = 1, a parasitic gate resistor (Rg) is added between the G node and the internal gate node (Gi). This is true when NQSMOD = 0. If NQSMOD = 1, an intrinsic input resistor (Rii)

Parameter	Component	MOD=0	MOD=1	MOD=2
RGATEMOD	Rg	Not included	Included	RGATEMOD = 2 is not allowed
RDSMOD	Rd,Rs	Included	Included	Not included
NQSMOD	Rii	Not included	Included	Charge decit model
IGCMOD	Igs, Igd, Igcs, Igcd	Not included	Included	IGCMOD = 2 is not allowed
IGBMOD	Igbinv, Igbacc	Not included	Included	IGBMOD = 2 is not allowed
GIDLMOD	Igidl, Igisl	Not included	Included	GIDLMOD = 2 is not allowed
IIMOD	Iii	Not included	Included	Included

Table 3: MOD parameters for Fig. (14) to Fig. (18)

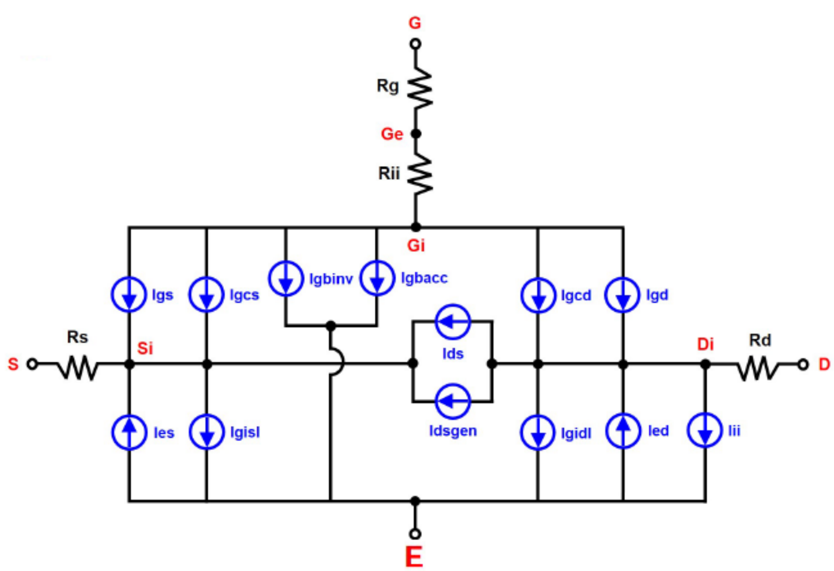

Figure 14: DC equivalent circuit with BULKMOD = 1. Other MOD parameters: RGATEMOD = 1, RDSMOD = 1, NQSMOD = 1, IGCMOD = 1, IGBMOD = 1, GIDLMOD = 1, and IIMOD = 1.

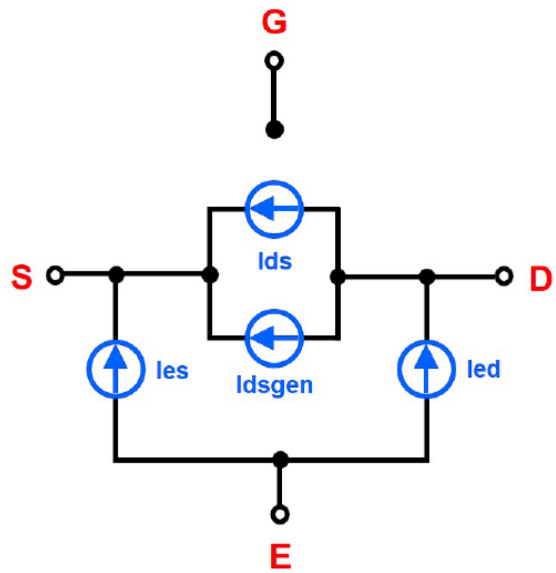

Figure 15: DC equivalent circuit for BULKMOD = 1. Other MOD parameters: RGATEMOD = 0, RDSMOD = 2, NQSMOD = 0, IGCMOD = 0, IGBMOD = 0, GIDLMOD = 0, and IIMOD = 0.

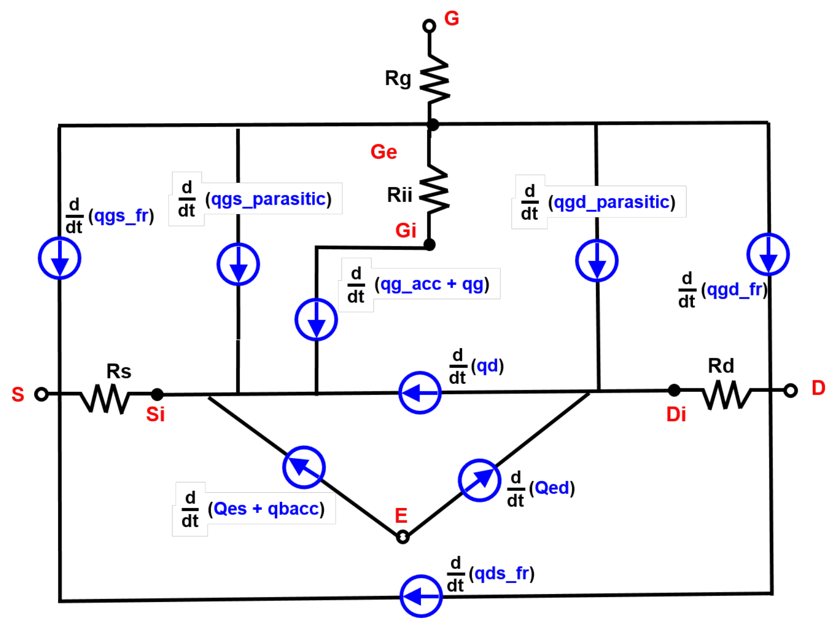

Figure 16: AC equivalent circuit for BULKMOD = 1. Other MOD parameters: CGEOMOD = 1, NQSMOD = 1.

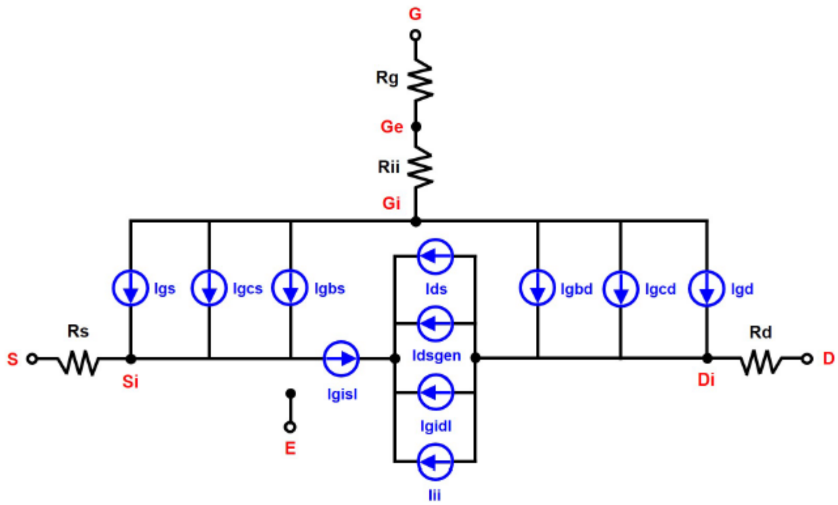

Figure 17: DC equivalent circuit with BULKMOD = 0. All DC MOD switches are turned on as in Table 2.

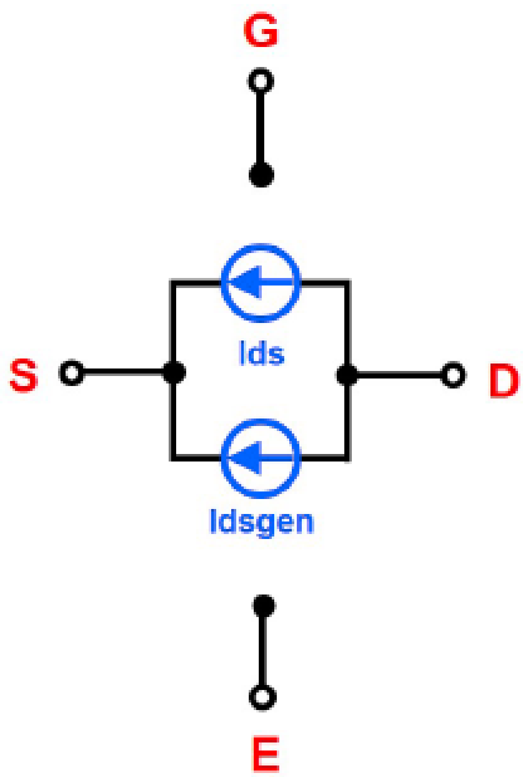

Figure 18: DC equivalent circuit for BULKMOD = 0. Other MOD parameters: RGATEMOD = 0, RDSMOD = 2, NQSMOD = 0, IGCMOD = 0, IGBMOD = 0, GIDLMOD = 0, and IIMOD = 0.

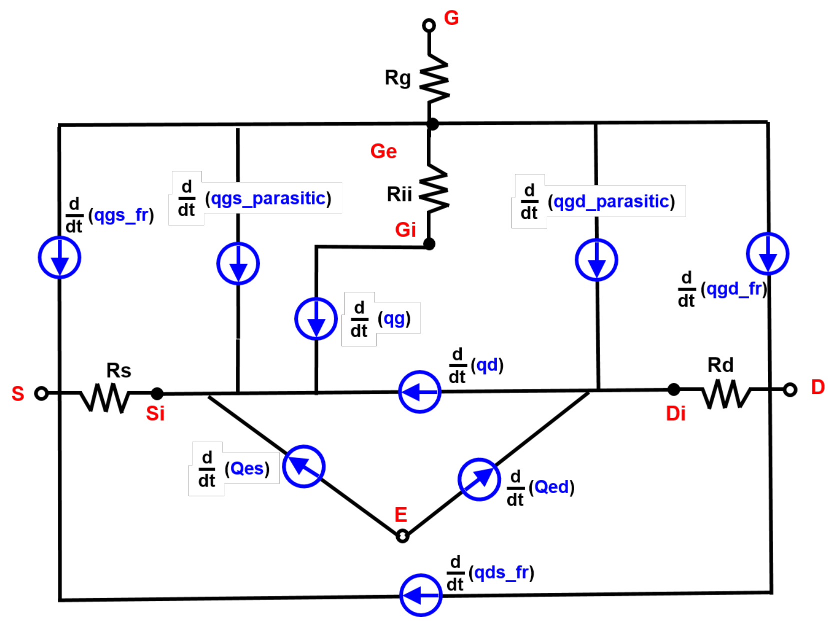

Figure 19: AC equivalent circuit with BULKMOD = 0. Other MOD parameters: CGEOMOD = 0, NQSMOD = 0.

is inserted between the Gi node and the gate edge node (Ge), pushing Rg to be between the G node and the Ge node. If RDSMOD = 0 or RDSMOD = 1, a parasitic drain resistor (Rd) is added between the D node and the internal drain node (Di). Likewise, a parasitic source resistor (Rs) is added between the S node and the internal source node (Si). Other current sources in the figure include: Ies (the source-to-substrate junction current), Ied (the drain-to-substrate junction current), and Idsgen (the generation-combination current). Fig. 15 shows the simplest case of DC equivalent circuit for BULKMOD = 1. Note that all other MOD parameters are zero except RDSMOD = 2. Although not realistic in its physical nature, this reduction is useful in model debugging. Fig. 16 shows one of the most complex cases of AC equivalent circuit for BULKMOD = 1.

3.24.2 FinFETs on SOI Substrate (BULKMOD = 0)

Due to the SOI substrate, there is no current flow through the E node. Refer to Fig. 17 for one of the most complex cases of DC equivalent circuit for BULKMOD = 0. For debugging purpose, Fig. 18 is the simplest case of DC equivalent circuit for BULKMOD = 0. Fig. 19 shows one of the most complex cases of AC equivalent circuit for BULKMOD = 0.

3.24.3 Noise Equivalent Circuit

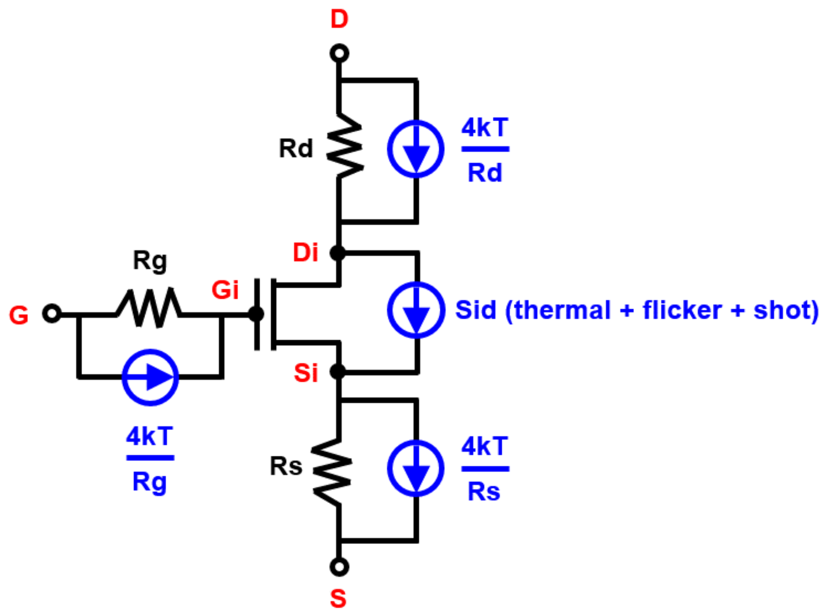

Figure 20: Noise equivalent circuit.

4 Parameter Extraction Procedure

4.1 Global Parameter Extraction

4.1.1 Basic Device Parameter List

The objective of this procedure is to find one global set of parameters for BSIM-CMG to fit experimental data for devices with channel length ranging from short to long dimensions.

Some parameters are measured or specified by user, and need not be extracted, such as those given in Table 4.

Parameter Name	Description
EOT	Gate oxide thickness
HFIN	Fin Height
TFIN	Fin Thickness
L	Fin Length Drawn
NFIN	Number of Fins
NF	Number of Fingers in parallel
NBODY	Channel Doping Concentration
BULKMOD	0: SOI 1: bulk
GIDLMOD	0: off 1: on 2: on with parasitic substrate component for GEOMOD = 2, 3 or 5
GEOMOD	0: double gate 1: triple gate 2: quadruple gate 3: cylindrical gate 4: unified model
	5: gate-all-around FET model
RDSMOD	0: internal bias dependent, external bias independent 1: external 2: Internal
TYPE	-1: PMOS 1:NMOS
NGATE	0: metal gate > 0: Poly Gate doping

Table 4: Examples of parameters that are measured or specified by the user

Parameters that are going to be extracted are divided into two categories. Category One parameters are presented as the coefficients in a set of length dependent intermediate quantities. These intermediate quantities are introduced to facilitate the extraction procedure. To keep the procedure simple, these quantities are not visible to the end user. Category Two parameters don't appear in these intermediate quantities.

The length dependent intermediate quantities, 9 in total, are summarized in Table 5.

Group	Parameters
Group 1	U0[L], ΔL[L], UA[L], UD[L], RDSW[L] [Relates to Mobility and R_{series}]
Group 2	VSAT[L], VSAT1[L], PTWG[L] [Relates to Velocity Saturation]
Group 3	MEXP[L] [Relates to Smoothing Functions]

Table 5: Classification of Length dependent parameters

Category Two parameters which don't appear in the length dependent functions are:

PHIG, CIT, EU, ETAMOB, DVT0, DVT1, CDSC, DVT2, ETA0, DSUB, CDSCD, AGIDL, BGIDL, EGIDL, VTL, XN, LC,MM, PCLM, PDIBL1, PDIBL2, DROUT, PVAG, etc

Since Category One parameters can only manifest themselves by first yielding the 9 length dependent

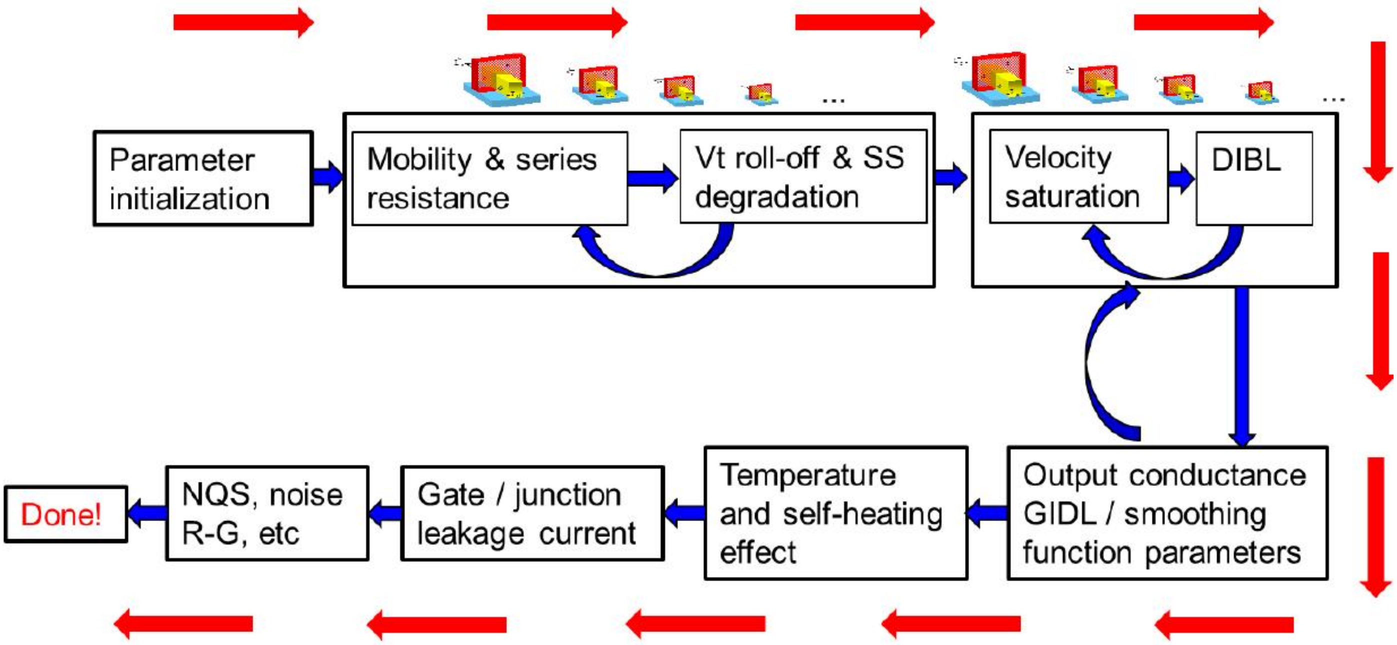

Figure 21: Extraction Flow Chart

intermediate quantities, determining the value of these intermediate quantities is inevitable if we want to extract them. Category Two parameters, however, can be extracted from experimental data directly.

Now we start extracting all the global parameters in both categories.

The extraction procedure can be divided into 8 stages:

- Parameter initialization
- Linear region: Step 1-6
- Saturation region: Step 7-11
- GIDL and Output Conductance: Step 12-13
- Smoothing between linear and saturation regions: Step 14
- Parameters for temperature effect and self-heating effect: Step 15
- Gate / Junction leakage current : Step 16
- Other important physical effects : Step 17

See the extraction overview flow chart for details.

4.2 Parameter Initialization

- Determine $V_{th}(L)$ by strong inversion region data using maximum slope extrapolation algorithm.
- Plot $\frac{V_d(\sim 0.05V)}{I_d(V_g,L)}$v.s.$L$ for different

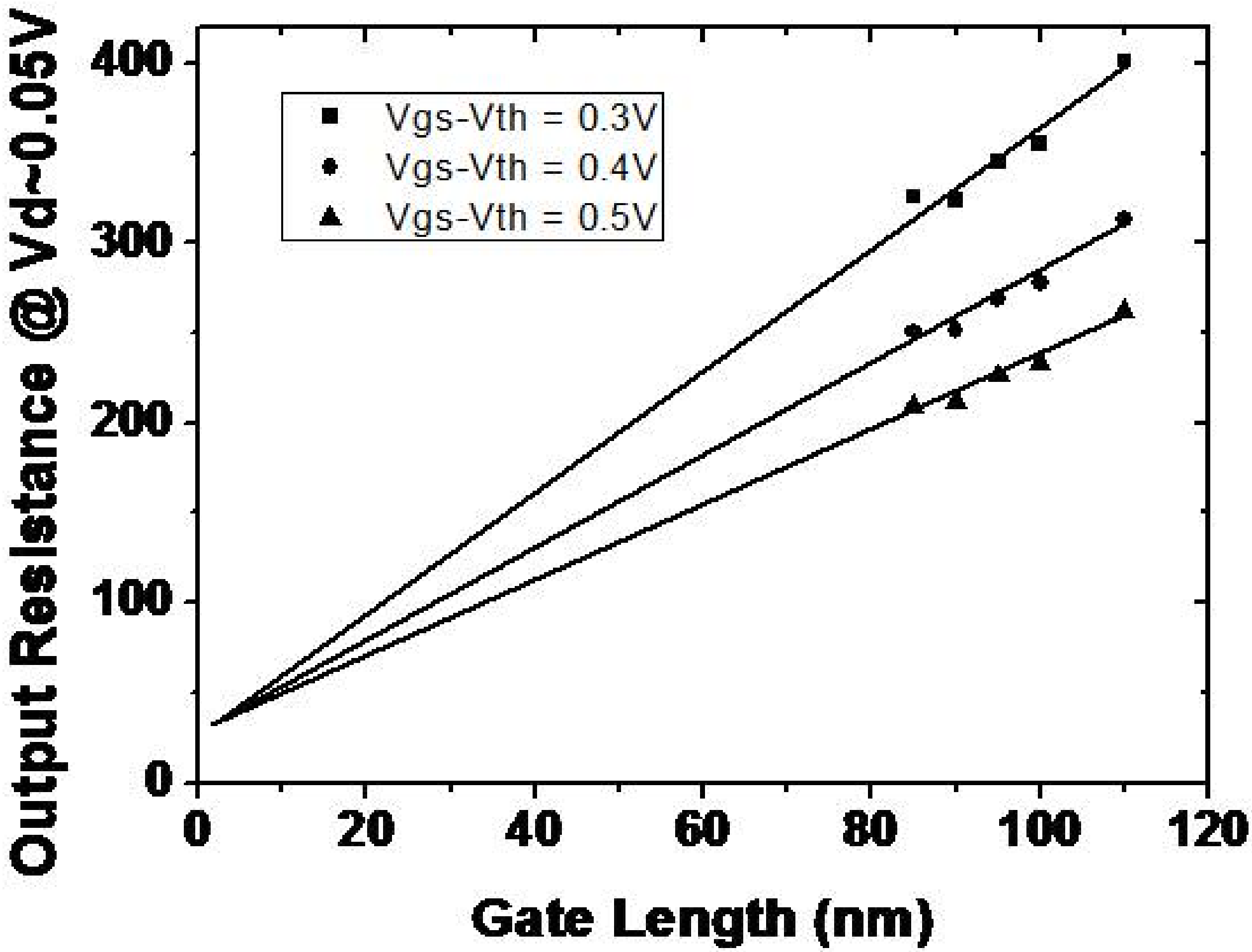

Figure 22: Initialize ΔL and R_{series}

- Make linear fitting to the curve set above, extrapolate each straight line and find the intersection (ΔL ,R_{series}), Initialize LINT = $\frac{\Delta L}{2}$, RDSW = R_{series} as shown in the Fig. 22.
- Use Constant-Current method to extract $V_{th}(L)$ by using sub-threshold region data.
- Plot $\Delta V_{th}(L)$v.s.@$V_d \sim 0.05V$ and V_{dd} respectively. Extract short channel effect(SCE) and Reverse SCE parameters DVT0, DVT1, ETA0, DSUB, K1RSCE, LPE0 as shown in Figure 23 left.
- Plot $2.3n(L) \times \frac{kT}{q}$v.s.$L$@$V_d \sim 0.05V$ and V_{dd}. Extract CDSC, CDSCD, DVT2 as shown in Figure 23 right.
- Set all other parameters in Category One and Two as default value as the manual shows.

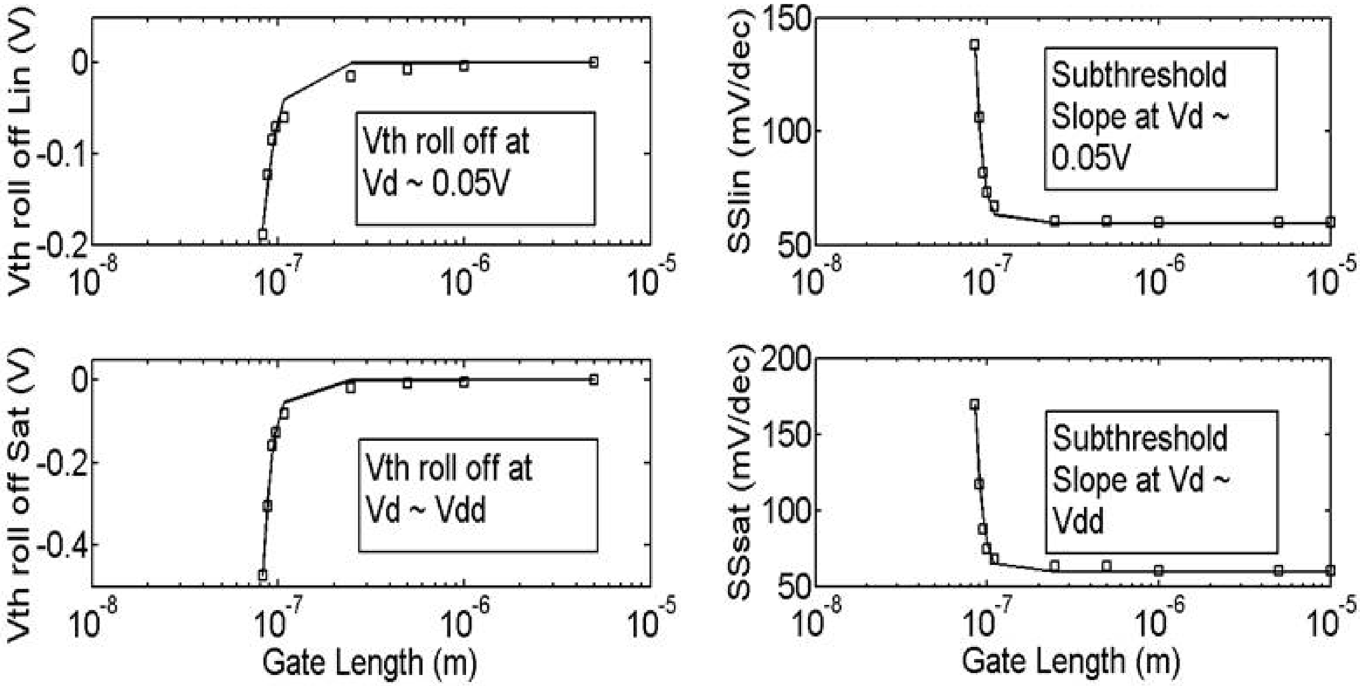

Figure 23: Initialize SCE and RSCE Parameters

4.3 Linear region

Step 1: Extract work function, interface charge and mobility model parameters for long gate length. [Note: Larger length is better, as it will minimize the short channel effect and emphasize carrier mobility, work function and interface charge related parameters.]

Extracted Parameters	Device & Experimental Data	Extraction Methodology
PHIG, CIT	A long device I_d v.s. V_g @ $V_d \sim 0.05V$	Observe sub-threshold region offset and slope.
$U0_0$, UA_0, UD_0, EU, ETAMOB	A long device I_d v.s. V_g @ $V_d \sim 0.05V$	Observe strong inversion region Idlin and $G_m lin$.

Step 2: Refine Vth roll-off, DIBL and SS degradation parameters.

Extracted Parameters	Device & Experimental Data	Extraction Methodology
DVT0, DVT1, CDSC, DVT2	Both short and medium devices I_d v.s. V_g @ $V_d \sim 0.05V$	Observe sub-threshold region of all devices in the same plot. Optimize DVT0, DVT1, CDSC, DVT2.

Note: need not very accurate fitting because mobility, series resistance parameters are not determined yet.

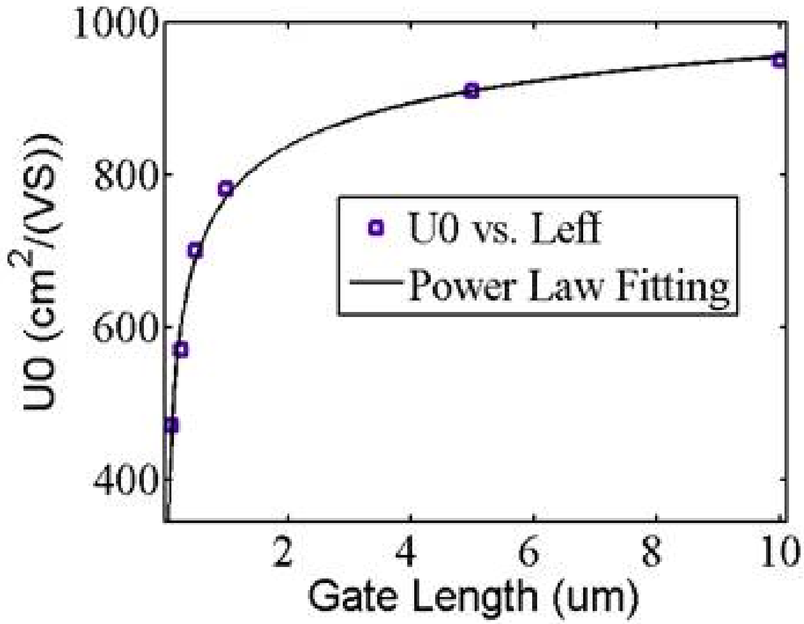

Figure 24: Fit low field electron mobility with L_g

Step 3: Extract low field mobility U0[L] for long and medium gate lengths.

So far, we have good fit with data in sub-threshold regions from long to short channel devices, and strong inversion for long channel devices. We need good fit for strong inversion in medium and short channel devices.

In linear region, current is to the first order, governed by low field mobility. So we start by tuning low field mobility values.

In short channel devices series resistance, coulombic scattering and enhanced mobility degradation effects are pronounced. To avoid the influence of these effects, long and medium channel length devices are selected to especially extract low field mobility parameters.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
UP,LPA	Long and medium devices I_d v.s. V_g @ $V_d \sim 0.05V$ $U_0[L] = U0_0 \times (1 - UP \times L_{eff}^{-LPA})$	Observe strong inversion region Idlin and $G_m lin$, extract U0[L] to get UP,LP. i.e. for each L_i, find Y_i corresponding to L_i, fit (L_i,Y_i) by Eq(1) to extract UP,LP). Refer to Figure 24 for instance.

Step 4: Extract mobility model and series resistance parameters for short gate lengths.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
$Param_0$,AParam, BParam,LINT, LL,LLN	Short and medium devices I_d v.s. V_g @ $V_d \sim 0.05V$	a. Observe strong inversion region $I_d lin$ and $G_m lin$. Similar to Step 3, find values of UA[L], UD[L], RDSW[L] and $DeltaL[L]$ that gives good fit to experimental data, varying them simultaneously. UA_0,UD_0 are provided from Step 1 and RDSW0, LINT are provided from parameter Initialization. b. Variation of each parameter with respect to L should be kept minimal with smooth continuous trend. c. From the length dependence of UA[L], UD[L], RDSW[L] and ΔL[L], find AUA, BUA; AUD,BUD; ARDSW, BRDSW; LL, LLN .

Note: Step 3 parameters are extracted from long and medium channel lengths, whereas, Step 4 involves short and medium channel lengths. As in Step 4 'exponential' corrections are particularly pronounced for small L (short channel). Its Taylor expansion when L_{eff} is medium can give appropriate modifications when power functions alone don't fit very well for medium lengths. Thus, the extracted parameters remain valid for all channel lengths to bring forth the intended length dependence in effect.

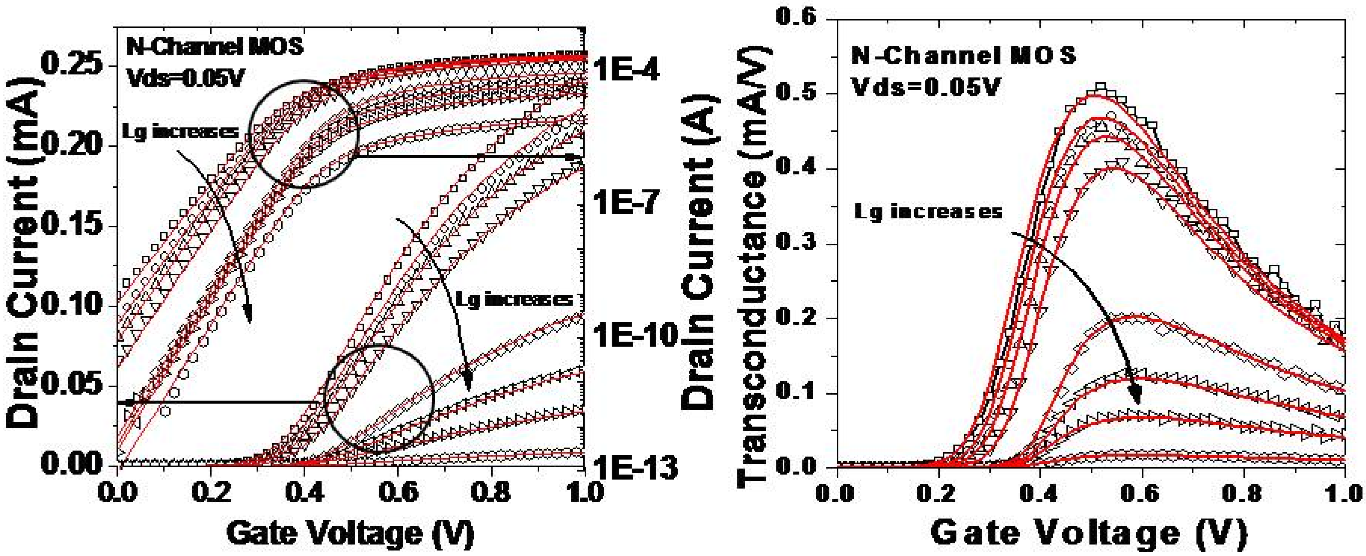

Figure 25: I_d vs V_g and G_m vs V_g @ $V_d\sim$ 0.05V

Step 5: Refine geometry scaling parameters for mobility degradation parameters.

Refined Parameters	**Device & Experimental Data**	**Extraction Methodology**
AUA,AUD,ARDSW,LL	Short and medium devices I_d v.s. V_g @ $V_d \sim 0.05V$	Observe strong inversion region of all devices in the same plot; optimize AUA, AUD, ARDSW, LL.

Step 6: Refine all Group 1 scaling parameters.

Further optimize the parameters by repeating step 5 and 2. If not getting good fitting, tune LLN, BUA, BUD, BRDSW. If still not good, tune other parameters in Group 1 as appropriate. Iteration ends in step 5 and then proceeds to step 7. A sample fitting result up till this step is shown in Figure 25.

4.4 Saturation region

Step 7: Refine DIBL parameters.

Extracted Parameters	Device & Experimental Data	Extraction Methodology
ETA0, DSUB, CDSCD	Short and long devices I_d v.s. V_g @ $V_d \sim V_{dd}$	Observe sub-threshold region of all devices in the same plot. Optimze ETA0, DSUB, CDSCD.

Note: need not very accurate fitting because velocity saturation, smoothing function and output conductance parameters are not determined yet.

Step 8: Extract velocity saturation parameters for long and medium gate lengths

Extracted Parameters	Device & Experimental Data	Extraction Methodology
$VSAT_0$, $VSAT1_0$, $PTWG_0$, $KSATIV_0$, $MEXP_0$	long device and medium devices I_d v.s. V_g @ $V_d \sim V_{dd}$	Observe strong inversion region $I_d sat$, $G_m sat$, $I_d V_d$.

Note: long channel alone is not enough to accurately extract velocity saturation parameters.

Step 9: Extract velocity saturation parameters for short and medium gate lengths

Extracted Parameters	Device & Experimental Data	Extraction Methodology
AVSAT, AVSAT1, APTWG, BVSAT, BVSAT1, BPTWG	short and medium devices I_d v.s. V_g @ $V_d \sim V_{dd}$	a. Observe strong inversion region of $I_d sat$ and $G_m sat$. Find VSAT1[L_i]=X_i, VSAT[L_i]=Y_i, PTWG[L_i]=Z_i to fit data. b. Extract AVSAT1, BVSAT1 from (L_i, X_i); AVSAT,BVSAT from (L_i, Y_i); APTWG, BPTWG from (L_i, Z_i).

Step 10: Refine geometry scaling parameters for velocity saturation, over the range from short to long channel devices.

Refined Parameters	Device & Experimental Data	Extraction Methodology
AVSAT, AVSAT1, APTWG	medium and short devices I_d v.s. V_g @ $V_d \sim V_{dd}$	Observe strong inversion region of all devices in the same plot. Optimize AVSAT, AVSAT1, APTWG.

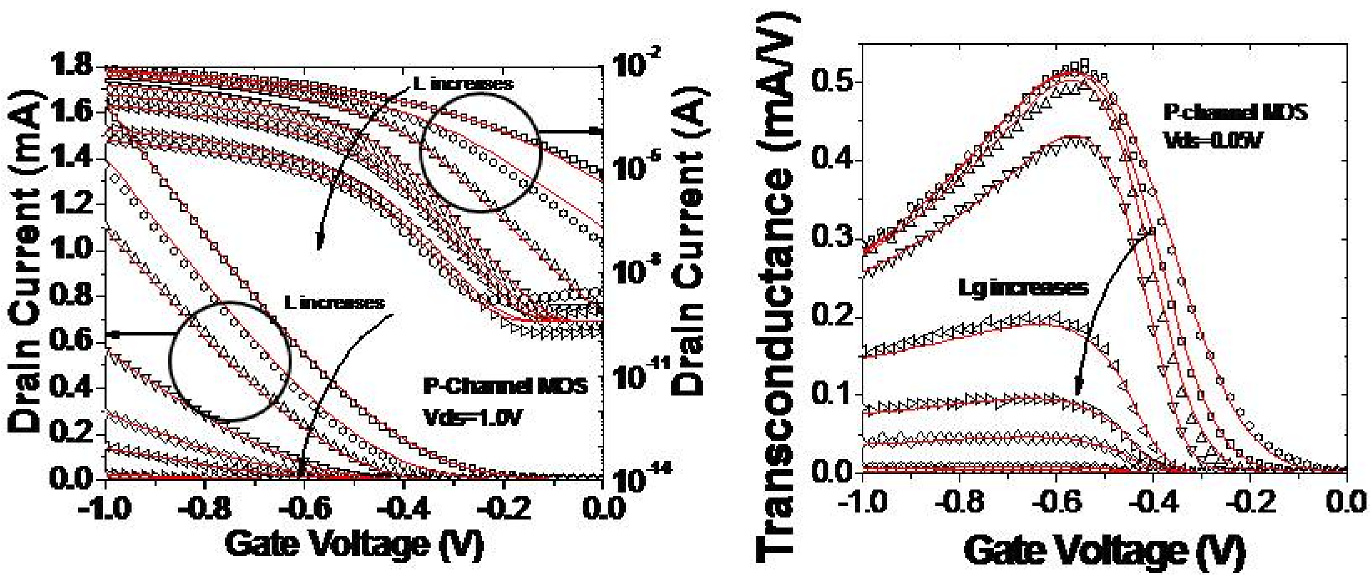

Figure 26: I_d vs V_g and G_m vs V_g @ $V_d \sim V_{dd}$

Step 11: Refine Group 2 scaling parameters.

Further refine the geometry scaling parameters by repeating step 10 and 7. If not getting good fitting, tune BVSAT, BVSAT1, BPTWG. If still not good, tune other parameters in Group 2 as appropriate. Iteration ends in step 10 and then proceeds to step 13. A sample fitting result up till this step is shown in Figure 26.

4.5 Other Parameters representing important physical effects

Step 12: Extract GIDL current model parameters.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
AGIDL, BGIDL, EGIDL	long and short devices I_d v.s. V_d @ different V_g	Observe sub-threshold region I_d v.s. V_g @ $V_d \sim V_{dd}$ & R_{out} v.s. V_d @ $V_g \sim 0V$.

Step 13: Extract output conductance parameters.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
MEXP[L], PCLM, PDIBL1, PDIBL2, DROUT, PVAG	Long and short devices I_d v.s. V_d @ differentV_g	Observe strong inversion region I_d v.s.V_d & G_d v.s.V_d @ different V_g.

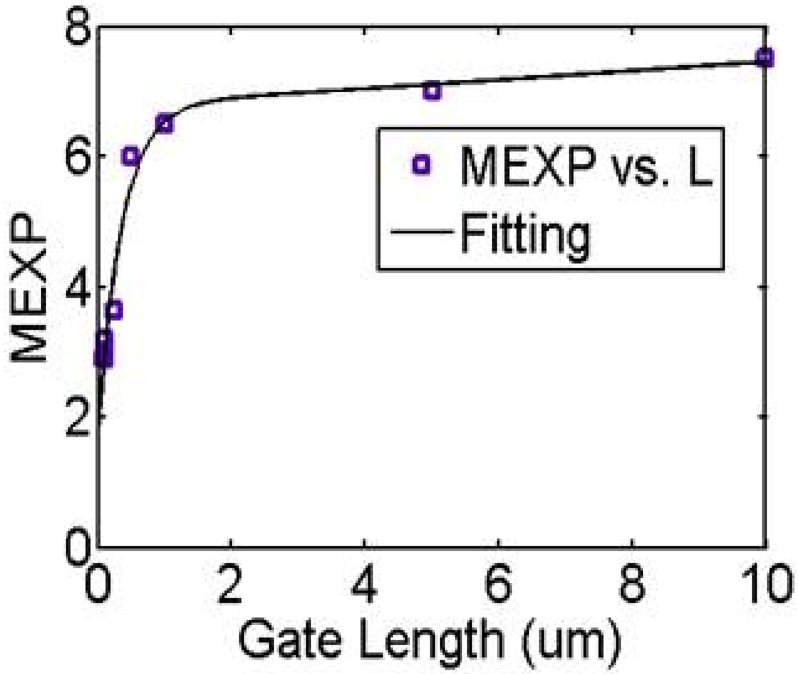

Figure 27: MEXP vs L_g

4.6 Smoothing between Linear and Saturation regions

Step 14: Extract geometry scaling parameters for smoothing function parameter.

Extracted Parameters	Device & Experimental Data	Extraction Methodgology
$MEXP_0$, AMEXP, BMEXP	MEXP[L] v.s. L from Step 14, i.e. (L_i,X_i)	Observe data trend; extract AMEXP and BMEXP. An example is shown in Figure 27.

A sample global fitting result for L_g=90 nm N-Channel MOS is shown in Figure 28 as below.

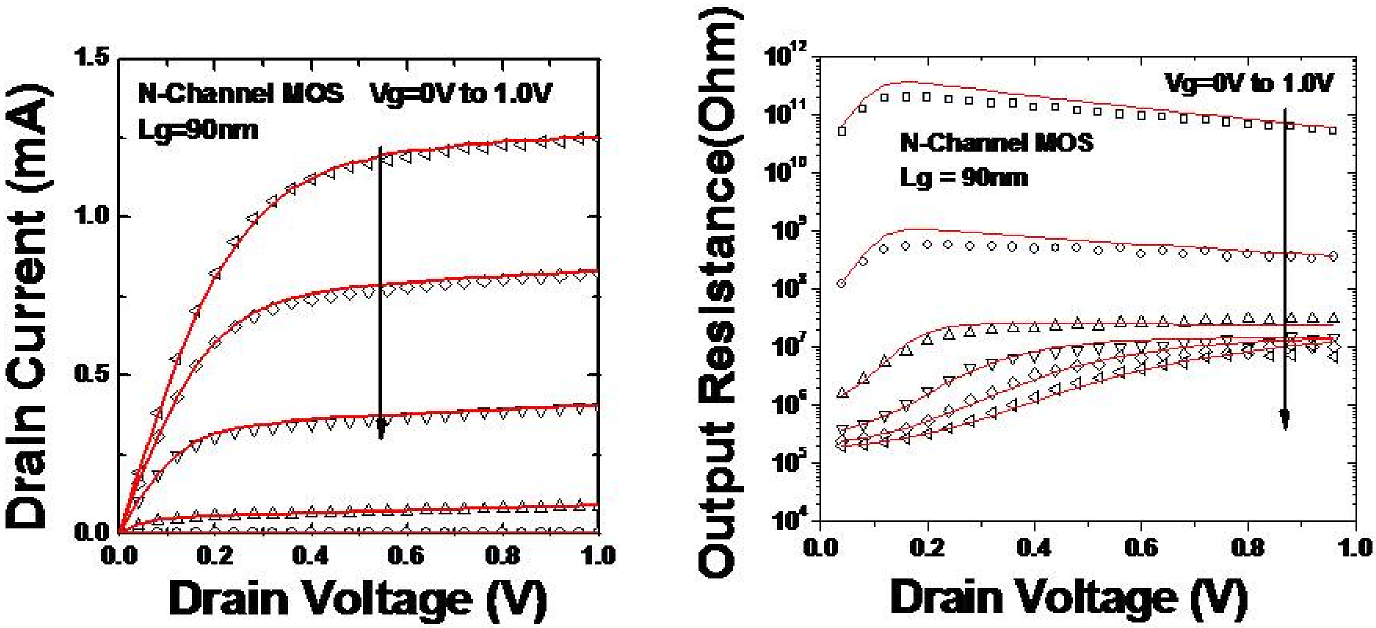

Figure 28: I_d vs V_d and R_{out} vs V_d

4.7 Other Effects

Step 15: Temperature and Self-Heating Effects.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
Thermal resistance (RTH0) and capacitances (CTH0) for the self-heating model and etc.	I_{ds} v.s. V_{gs} @ V_d V_{dd} under different temperatures.	Observe data trend and tune RTH0, CTH0, TNOM, TBGASUB, TBGBSUB, etc.

Step 16: Gate / Junction leakage current

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
Gate tunneling current and junction current parameters.	I_{gb} v.s. V_{gs} @ V_d $0V$.	Observe data trend and tune NIGBINV, AIGBINV, BIGBINV, CIGBINV, EIGBINV, AS, PS1, PS2, NJS, IJTHSFWD, BVS, XJBVS, AD, PD1, PD2, NJD, IJTHDFWD, BVD, XJBVD, etc.

Step 17: Advanced Feature

Extracted Parameters	Device & Experimental Data	Extraction Methodology
Non quasi static effect, noise model, poly depletion, generation recombination etc.	S-parameters, noise figure, CV measurement, etc.	Extract XRCRG1, XRCRG2, NOIA, NOIB, NOIC, FN1, FN2, AIGEN, BIGEN, etc.

5 Local parameter extraction for $CV - IV$

This procedure shows how to extract parameters for IV and CV fittings for device with a particular channel length. The procedure can be followed for both long and short channel devices for local fitting. In the future we plan to expand this section to include the global parameter extraction for the CV part, as done for the IV part in the previous section.

The complete $CV - IV$ fitting procedure consists of 7 steps. The procedure starts with fitting $C_{gg} - V_{gs}$ data at low V_{ds} (50mV) to extract PHIG, EOT and quantum mechanical effects related parameters. These parameters are used to fit IV data at low V_{ds} (50mV) to extract sub-threshold IV and mobility related parameters. The extracted parameters are utilized to fit the IV data at high V_{ds} (1V), to extract parameters related to V_{th} shift due to DIBL, V_{ds} dependence of sub-threshold slope, and velocity saturation. In the next step, $I_{ds} - V_{ds}$ data at various V_{gs} are fitted to extract parameters related to DIBL, Output conductance and CLM.

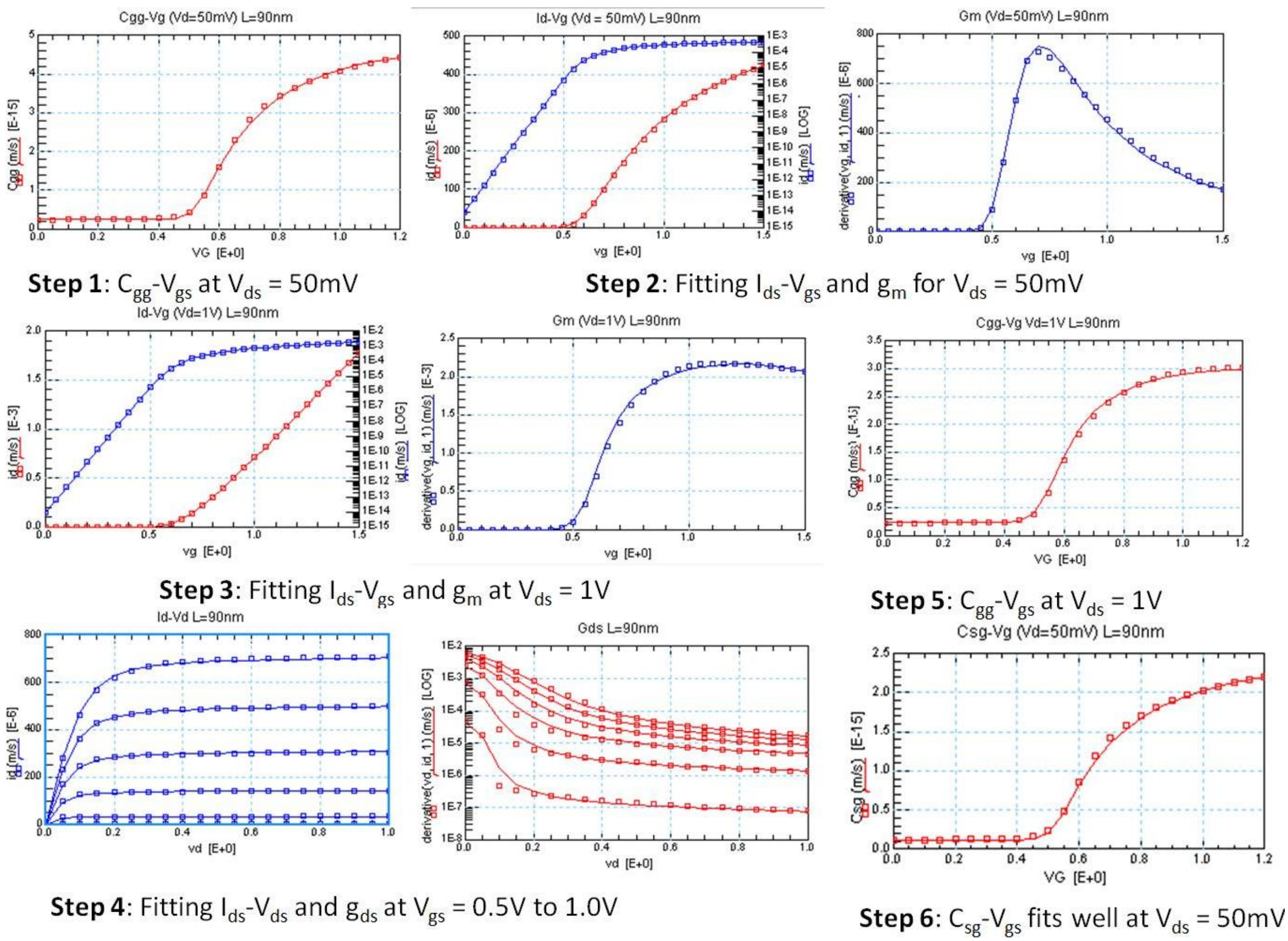

Figure 29: Fitting results from a self-consistent IV-CV Extraction

Since the saturation parameters are already extracted in step 3, we can use $C_{gg} - V_{gs}$ data at high V_{ds} (1V) to extract parameters related to CLM for the CV part. All 7 steps are summarized in the following table with description of the data used, bias conditions and list of extracted parameters with which part of data they affect.

CV-IV procedure applicable for devices with any channel length

Step	Data Used	Bias	Parameters extracted (Quantities influenced)
0	-	-	Initialize process and model control parameters such as TYPE, HFIN, TFIN, FPITCH, NFIN, NF, ASEO, ADEO, L, XL, LINT, DLC, GEOMOD etc.
1	$C_{gg} - V_{gs}$	$V_{ds} = 50mV$	PHIG (V_{fb}/V_{th}), EOT, QMTCENCV (Capacitance value at high V_{gs}) QM0, ETAQM, CFS, CFD (Parasitic capacitance params as needed)
2	$I_{ds} - V_{gs}, g_m$	$V_{ds} = 50mV$	CDSC (Sub-threshold slope), U0 (Low field mobility), UA, EU, ETAMOB (sharpness of g_m curve)
3	$I_{ds} - V_{gs}, g_m$	$V_{ds} = 1V$	CDSCD (V_{ds} dependence of Sub-threshold slope), ETA0, DSUB (V_{th} shift due to DIBL at high V_{ds}), VSAT, KSATIV (I_{ds}, g_m at moderate V_{gs}), VSAT1 (Saturation current at high V_{gs}), PTWG (g_m at high V_{gs})
4	$I_{ds} - V_{ds}, g_{ds}$	Various V_{gs} (0-1V)	PCLMG, PCLM (I_{ds}, g_{ds} at high V_{ds}), MEXP, VSAT1 (optimize by looping between step 3 and 4)
5	$C_{gg} - V_{gs}$	$V_{ds} = 1V$	PCLMCV
6	$C_{sg} - V_{gs}$	$V_{ds} = 50mV$	Step 1 ensures good fit of C_{sg} at low V_{ds}
7	$C_{sg} - V_{gs}$	$V_{ds} = 50mV$	Under investigation

6 Cryogenic Parameter Extraction Procedure

Step 1. To enable cryogenic mode, select either of CRYOMOD = 1 or 2.
CRYOMOD = 1: Most physical cryogenic models
CRYOMOD = 2: Cryogenic models converge to CRYOMOD=0 models for T > 210 K

For a multiple temperature (T) fitting, the nominal temperature (TNOM) device characteristics are fitted first using the procedure given in section 5. Once, TNOM characteristics are fitted well, the temperature models in the cryogenic mode (1 or 2) can be used to fit the device characteristics for multiple temperatures down to the cryogenic temperature range.

6.1 Drain Current Fitting in Linear Region

Step 2. Subthreshold region fitting: In this step, the V_{GS} dependence of the drain current I_{DS} in low V_{GS} region is extracted.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
TLOW and DTLOW	I_{ds} v.s. V_{gs} @ $V_{ds} = 50mV$ @ multiple temperatures.	Observe Subthreshold swing (SS) @ different temperatures and tune TLOW and DTLOW to capture SS saturation.
TLOW1, KLOW1, DTLOW1	I_{ds} v.s. V_{gs} @ $V_{ds} = 50mV$ @ multiple temperatures.	Observe sub-threshold swing (SS) @ different temperatures in cryogenic range for a rise in SS with T reduction. Tune TLOW1, KLOW1, DTLOW1 to capture the SS rise if any.
TVTH, KT11, KT12, KT1	I_{ds} v.s. V_{gs} @ $V_{ds} = 50mV$ @ multiple temperatures.	Observe threshold voltage offset @ different temperatures and tune TVTH, KT11, KT12, KT1.

Notes:

- TLOW is used to extract the temperature at which SS saturates w.r.t temperature in the cryogenic range. DTLOW is used to smoothly transition to the SS saturation region @ low T from the usual SS behavior governed by the Boltzmann law ($\ln(10)kT/q$) @ high T. At very low temperatures, the SS may again start to rise with T and TLOW1 is the temperature below which this happens. DTLOW1 is used to capture the smoothness of this SS transition and KLOW1 is used to capture the rate at which the SS rises w.r.t T (assuming linear dependency on T).
- TVTH is approximately the temperature below which the V_{th} offset model ($\Delta V_{\mathrm{th,temp0}}$) becomes non-zero. KT11 is used to capture the extent of V_{th} offset required @ low T. KT12 is used for

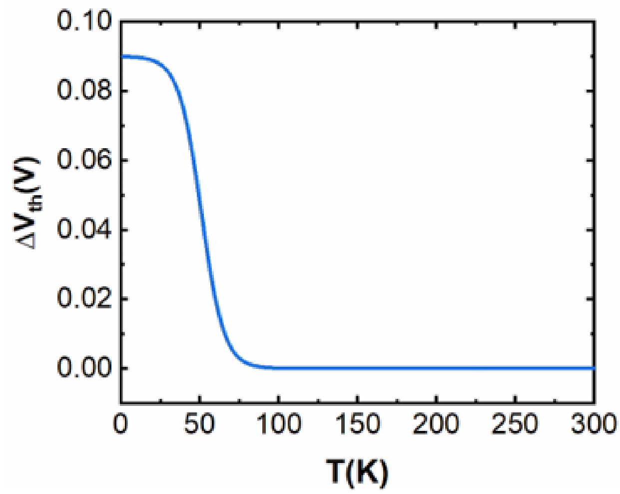

Figure 30: Threshold voltage offset ($\Delta V_{\text{th,temp0}}$) as a function of temperature.

smoothing out the transition between $\Delta V_{\text{th,temp0}}$ @ low T and high T. KT1 can be used to introduce a linear temperature dependency term in $\Delta V_{\text{th,temp0}}$ if needed. An example model simulation of $\Delta V_{\text{th,temp0}}$ is shown in Figure 30.

Step 3. Sub-threshold to above threshold transition region fitting: In this step, the V_{GS} dependence of the drain current I_{DS} in a low to intermediate V_{GS} region is extracted, especially, the increased V_{GS} dependence in subthreshold swing at cryogenic temperatures observed in cryogenic characteristics which we attribute to Coulomb scattering by trap centers [4].

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
UD1, UD2, UCSTE, UCSTE1, UDS, UDS1, UDD, UDD1	I_{ds} v.s. V_{gs} and g_m v.s. V_{gs} @ $V_{ds} = 50mV$ @ multiple temperatures.	Observe near V_t region of I_{Dlin} and g_{mlin} in log and linear scales @ different temperatures and tune UD1, UD2, UCSTE, UCSTE1, UDS, UDS1, UDD, UDD1.

Notes: The experimental cryogenic data suggests that the impact of Coulomb scattering is smaller at high V_{DS}, and therefore source and drain charge densities in the Coulomb mobility model require different weight factors (section 3.1.9 and [4]). UDS and UDS1 can be used to capture the temperature dependency of the weight factor UDS_{eff} assigned to the source charge density in Coulomb scattering model. Similarly, UDD and UDD1 capture the temperature dependency of the weight factor UDD_{eff} assigned to the drain charge density. These weight factors together can capture the V_{DS} dependence of Coulomb scattering at low temperatures. I_{DS} vs V_{GS} @ $V_{DS} = 50$ mV, can be used first to extract an approximate value of $UDS_{eff} + UDD_{eff}$ since $q_{is} \approx q_{id}$. I_{DS} vs V_{GS} @ $V_{DS} = V_{DD}$ can later be used to differentiate between values of UDS_{eff} and UDD_{eff} and the related parameters as explained in step 6.

Step 4. Strong inversion region fitting: In this step, the V_{GS} dependence of the drain current I_{DS} in intermediate to high V_{GS} region is extracted.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
UTE, UTE1, UA1, UA2, EU1, EMOBT, PRT, PRT1, TR0, SPRT	I_{ds}-V_{gs} and g_m- V_{gs} @ V_{ds} = $50mV$ @ multiple temperatures.	Observe strong inversion region of I_{Dlin} and g_{mlin} in linear scale @ different temperatures to extract these parameters and tune UTE, UTE1, UA1, UA2, EU1 and EMOBT (to capture phonon and surface roughness mobility temperature dependence) and PRT, PRT1, TR0, SPRT (to capture S/D resistance temperature dependence).

6.2 Drain Current Fitting in Saturation Region

Step 5. Temperature dependency of DIBL.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
TETA0	I_{ds}-V_{gs} @ $V_{ds} = V_{DD}$ @ different temperatures.	Observe threshold voltage offset of I_{Dsat} @ different T.

Step 6. Drain bias dependency of Coulomb scattering at low temperatures.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
UDS, UDS1	$I_{DS} - V_{GS}$ and $g_m - V_{GS}$ @ $V_{DS} = V_{DD}$ @ different temperatures.	At high V_{DS}, q_{id} becomes negligible. Observe near V_t region of $I_{DS} - V_{GS}$ and $g_m - V_{GS}$ @ $V_{DS} = V_{DD}$ in log and linear scales @ different temperatures to extract UDS and UDS1. Adjust UDD and UDD1 now such that the I_{Dlin} fitting done earlier in step 3 remains unaffected.

Step 7. Temperature dependency of velocity saturation model and CLM.

Extracted Parameters	**Device & Experimental Data**	**Extraction Methodology**
AT, AT2, KSATIV1, KSATIV2, PTWGT	$I_{DS}-V_{GS}$, g_m-V_{GS} @ $V_{DS}=V_{DD}$ @ different temperatures, and $I_{DS}-V_{DS}$ @ different V_{GS} for multiple temperatures.	Observe strong inversion region of $I_{DS}-V_{GS}$ and g_m-V_{GS} @ $V_{DS}=V_{DD}$ for multiple T as well as V_{dsat} and the saturation region of $I_{DS}-V_{DS}$ @ different V_{GS} for multiple T. Tune AT, AT2, and PTWGT for velocity saturation T dependence, and KSATIV1 and KSATIV2 for channel pinchoff effect T dependence.
PCLMT	$I_{DS}-V_{DS}$ @ different V_{GS} for multiple T.	Observe slope of the saturation region of $I_{DS}-V_{DS}$ @ different V_{GS} for multiple T and tune PCLMT.
TMEXP, TMEXP2	$I_{DS}-V_{DS}$ @ different V_{GS} for multiple T.	Observe linear to saturation transition region of $I_{DS}-V_{DS}$ @ different V_{GS} for multiple T and tune TMEXP and TMEXP2.

Example fittings of FinFET from room temperature down to cryogenic temperatures are shown in Figure 31.

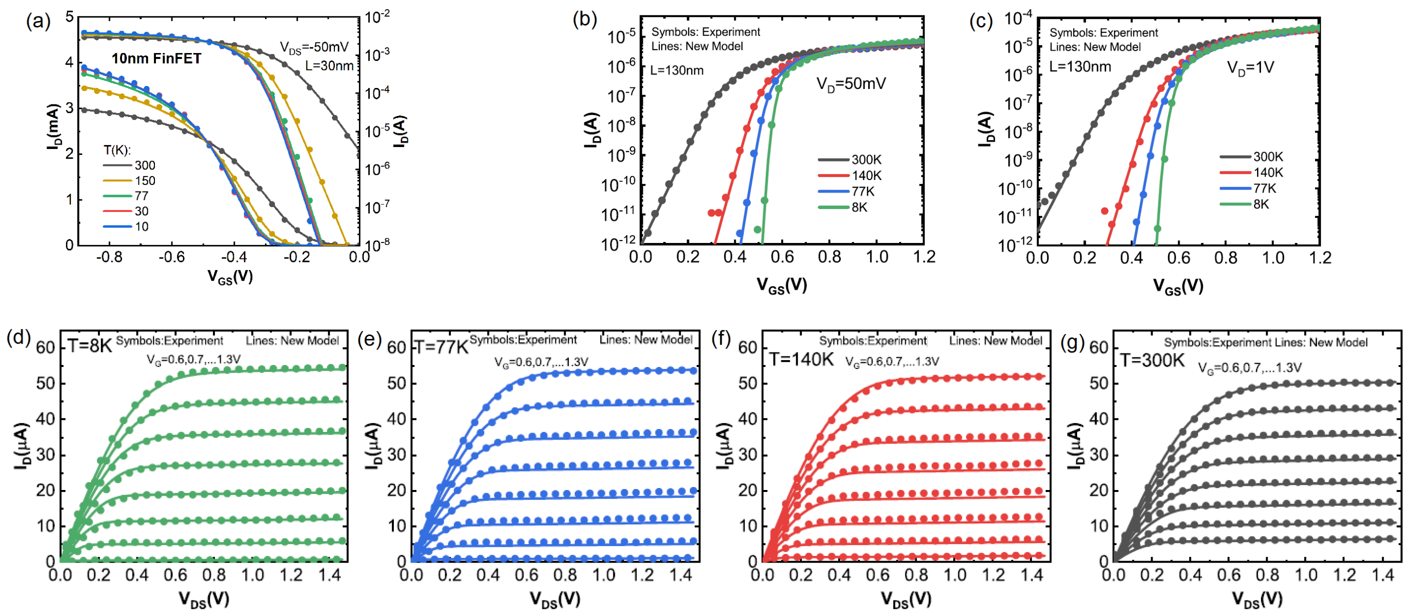

Figure 31: Cryogenic model fitting with experimental data for different temperatures. (a) model fitting for a 10nm p-FinFET technology device [24]. (b) to (g) model fitting for an n-FinFET device (L = 130 nm) [25]. Symbols: experimental data; Lines: BSIM-CMG cryogenic model [4].

7 Complete Parameter List

7.1 Both Model and Instance Parameters

The parameter types are based on user inputs and previous experience.
Note: Binnable parameters are marked as $^{(b)}$

Name	**Unit**	**Default**	**Min**	**Max**	**Description**
L	m	30e-9	1e-9	-	Designed gate length
D	m	40e-9	1e-9	-	Diameter of cylinder ($GEOMOD = 3$)
TFIN	m	15e-9	1e-9	-	Fin thickness
FPITCH	m	80e-9	TFIN	-	Fin pitch
NFIN	-	1	> 0	-	Number of fins per finger
NFINNOM	-	0	0	-	Nominal Number of fins per finger
NGCON	-	1	1	2	Number of gate contacts
ASEO	m^2	0	0	-	Source to substrate overlap area through oxide (all fingers)
ADEO	m^2	0	0	-	Drain to substrate overlap area through oxide (all fingers)

Name	Unit	Default	Min	Max	Description
PSEO	m	0	0	-	Perimeter of source to substrate overlap region through oxide (all fingers)
PDEO	m	0	0	-	Perimeter of drain to substrate overlap region through oxide (all fingers)
ASEJ	m^2	0	0	-	Source junction area (all fingers; for bulk MuGFETs, $BULKMOD = 1$)
ADEJ	m^2	0	0	-	Drain junction area (all fingers; for bulk MuGFETs, $BULKMOD = 1$)
PSEJ	m	0	0	-	Source junction perimeter (all fingers; for bulk MuGFETs, $BULKMOD = 1$)
PDEJ	m	0	0	-	Drain junction perimeter (all fingers; for bulk MuGFETs, $BULKMOD = 1$)
COVS$^{(b)}$	F *or* $F \cdot m^{-1}$ see CGEO1SW	0	0	-	Constant gate to source overlap capacitance (for $CGEOMOD = 1$)
COVD$^{(b)}$	F *or* $F \cdot m^{-1}$ see CGEO1SW	COVS	0	-	Constant gate to drain overlap capacitance (for $CGEOMOD = 1$)
CGSP	F *or* $F \cdot m^{-1}$ see CGEO1SW	0	0	-	Constant gate to source fringe capacitance (for $CGEOMOD = 1$)
CGDP	F *or* $F \cdot m^{-1}$ see CGEO1SW	0	0	-	Constant gate to drain fringe capacitance (for $CGEOMOD = 1$)
CDSP	F	0	0	-	Constant drain to source fringe capacitance
NRS	-	0	0	-	Number of source diffusion squares (for $RGEOMOD = 0$)
NRD	-	0	0	-	Number of drain diffusion squares (for $RGEOMOD = 0$)
LRSD	m	L	0	-	Length of the source/drain
XL$^{(b)}$	m	0	-	-	L offset for channel length due to mask/etch effect
XW$^{(b)}$	m	0	-	-	W offset for GAA channel width due to mask/etch effect (GEOMOD=5)
TGAA	m	5e-9	0	-	Thickness of individual GAA bodies (GEOMOD=5)
TSUS	m	2e-9	0	-	Separation between GAA bodies (GEOMOD=5)
HPFF	m	5e-9	0	-	Fin height of parasitic FinFET (CGEOMOD=3)
WGAA	m	6e-9	0	-	Width of GAA body (GEOMOD=5)
DWS1	m	0	-	0	Total width correction for first GAA body (GEOMOD=5)

Name	Unit	Default	Min	Max	Description
DWS2	m	DWS1	-	0	Total width correction for second GAA body (GEOMOD=5)
DWS3	m	DWS1	-	0	Total width correction for third GAA body (GEOMOD=5)
DACH1	m^2	0	-	0	Total area correction for first GAA body (GEOMOD=5)
DACH2	m^2	DACH1	-	0	Total area correction for second GAA body (GEOMOD=5)
DACH3	m^2	DACH1	-	0	Total area correction for third GAA body (GEOMOD=5)
NGAA	-	1	1	3	Number of GAA bodies per fin (GEOMOD=5)
SUBBANDMOD	-	0	0	1	Switch for GAAFET quantumsubband model (0=off; 1=on)
MOBSCMOD	-	0	0	1	Switch for GAAFET geometry dependent mobility model (0=off; 1=on)

7.2 Pure Instance Parameters

Name	Unit	Default	Min	Max	Description
NF	-	1	1	-	Number of fingers

7.3 Model Controllers and Process Parameters

Note: Binnable parameters are marked as $^{(b)}$

Name	Unit	Default	Min	Max	Description
TYPE	-	NMOS	PMOS	NMOS	NMOS=1, PMOS=-1
BULKMOD	-	0	0	1	Substrate model selector. 0 = multi-gate on SOI substrate, 1 = multi-gate on bulk substrate.
GEOMOD	-	1	0	6	Structure selector; 0 = double gate, 1 = triple gate, 2 = quadruple gate, 3 = cylindrical gate, 4 = unified model, 5 = gate-all-around FET model, 6 = single gate

Name	Unit	Default	Min	Max	Description
GEO1SW	-	0	0	1	For CGEOMOD=1 only, GEO1SW=1 enables the parameters COVS, COVD, CGSP, and CGDP to be in F per fin, per gate-finger, per unit channel width
RDSMOD	-	0	0	1	Bias-dependent, source/drain extension resistance model selector 0 = internal bias dependent, 1 = external, 2=internal
ASYMMOD	-	0	0	1	Asymmetric I-V model selector 0 = turn off, reverse mode parameters ignored, 1 = turn on
IGCMOD	-	0	0	1	Model selector for Igc, Igs and Igd; 1=turn on, 0=turn off
IGBMOD	-	0	0	1	Model selector for Igb; 1=turn on, 0=turn off
GIDLMOD	-	0	0	2	GIDL/GISL current switcher; 0=turn off, 1=turn on GIDL/GISL, 2=turn on GIDL/GISL with parasitic substrate component for GEOMOD = 2, 3 or 5 and BULKMOD≠0
CVMOD	-	0	0	1	Capacitance mode selector; 0= Consistent I-V and C-V, 1= Decoupled I-V and C-V
IIMOD	-	0	0	2	Impact ionization model switch; 0 = OFF, 1 = BSIM4 based, 2 = BSIMSOI based
NQSMOD	-	0	0	1	NQS gate resistor and gi node switcher; 1=turn on, 0=turn off
SHMOD	-	0	0	1	Self-heating and T node switcher; 1=turn on, 0=turn off
RGATEMOD	-	0	0	1	Gate electrode resistor and ge node switcher ; 1=turn on, 0=turn off
RSUBMOD	-	0	0	1	Substrate resistor network and ex node switcher ; 1=turn on, 0=turn off
RGEOMOD	-	0	0	1	Bias independent parasitic resistance model selector (see sec. 3.15)
CGEOMOD	-	0	0	2	Parasitic capacitance model selector (see sec. 3.15)
TEMPMOD	-	0	0	1	Temperature dependence model selector

Name	Unit	Default	Min	Max	Description
CRYOMOD	-	0	0	2	Cryogenic model selector: 0:same as BSIMCMG 111.1.0, 1 = most physical cryogenic models, 2 = cryogenic expressions converge to BSIMCMG 111.1.0 for T > 210 K (-63.15 °C)
FNMOD	-	0	0	1	Flicker noise model selector: 0 = same as BSIM-CMG111.0.0, 1 = improved 1/f model
TNOIMOD	-	0	0	1	Thermal noise model selector, 0 = charge-based, 1 = correlated noise model
SH_WARN	-	0	0	1	Warning on Self-Heating Network being disabled, 0 = Warning turned off, 1 = Warning turned on
IGCLAMP	-	1	0	1	Igs/Igd clamp selector, default value '1', 0 = Igs/Igd clamps turned off, 1 = Igs/Igd clamps turned on
LINT$^{(b)}$	m	0.0	-	-	Length reduction parameter (dopant diffusion effect)
LL	$m^{(LLN+1)}$	0.0	-	-	Length reduction parameter (dopant diffusion effect)
LLN	-	1.0	-	-	Length reduction parameter (dopant diffusion effect)
DLC	m	0.0	-	-	Length reduction parameter for CV (dopant diffusion effect)
DLCACC	m	0.0	-	-	Length reduction parameter for CV in accumulation region ($BULKMOD = 1$)
LLC	$m^{(LLN+1)}$	0.0	-	-	Length reduction parameter for CV (dopant diffusion effect)
DLBIN$^{(b)}$	m	0.0	-	-	Length reduction parameter for binning
EOT	m	1.0e-9	1e-10	-	SiO_2 equivalent gate dielectric thickness (including inversion layer thickness)
TOXP	m	1.2e-9	1e-10	-	Physical oxide thickness
EOTBOX	m	140e-9	1e-9	-	SiO_2 equivalent buried oxide thickness (including substrate depletion)
HFIN	m	30e-9	1e-9	-	Fin height

Name	Unit	Default	Min	Max	Description
FECH	-	1.0	0	-	End-channel factor, for different orientaion/shape (Mobility difference between the side channel and the top channel is handled by this parameter)
DELTAW	m	0.0	-	-	Reduction of effective width due to shape of fin
FECHCV	-	1.0	0	-	CV end-channel factor, for different orientaion/shape
DELTAWCV	m	0.0	-	-	CV reduction of effective width due to shape of fin
DWBIN$^{(b)}$	m	0.0	-	-	GAA width reduction parameter for binning (GEOMOD = 5)
DWCACC$^{(b)}$	m	0.0	-	-	GAA width reduction parameter for CV in accumulation region (GEOMOD = 5 and BULKMOD = 1)
NBODY$^{(b)}$	m^{-3}	1e22	-	-	Channel (body) doping concentration
NBODYN1	-	0	-0.08	-	NFIN dependence of NBODY
NBODYN2	-	1e5	1e-5	-	NFIN dependence of NBODY
NSD	m^{-3}	2e26	2e25	1e27	S/D doping concentration
PHIG$^{(b)}$	eV	4.61	0	-	Gate workfunction
PHIGL	eVm^{-1}	0	-	-	Length dependence of gate workfunction
PHIGLT	m^{-1}	0.0	-	-	Coupled NFIN and Length dependence of Gate workfunction
PHIGN1	-	0	-0.08	-	NFIN dependence of PHIG
PHIGN2	-	1e5	1e-5	-	NFIN dependence of PHIG
EPSROX	-	3.9	1	-	Relative dielectric constant of the gate insulator
EPSRSUB	-	11.9	1	-	Relative dielectric constant of the channel material
EASUB	eV	4.05	0	-	Electron affinity of the substrate material
NI0SUB	m^{-3}	1.1e16	-	-	Intrinsic carrier concentration of channel at 300.15K
BG0SUB	eV	1.12	-	-	Band gap of the channel material at 300.15K
NC0SUB	m^{-3}	2.86e25	-	-	Conduction band density of states at 300.15K
NGATE$^{(b)}$	m^{-3}	0	-	-	Parameter for Poly Gate doping. Set $NGATE = 0$ for metal gates

Name	Unit	Default	Min	Max	Description
IMIN	Am^{-2}	1e-15	0.0	-	Parameter for voltage clamping for inversion region calc. in accumulation

7.4 Basic Model Parameters

Note: Binnable parameters are marked as $^{(b)}$

Name	Unit	Default	Min	Max	Description
CIT$^{(b)}$	$F \cdot m^{-2}$	0.0	-	-	Parameter for interface trap
CDSC$^{(b)}$	$F \cdot m^{-2}$	7e-3	0.0	-	Coupling capacitance between S/D and channel
CDSCN1	-	0	-0.08	-	NFIN dependence of CDSC
CDSCN2	-	1e5	-	-	NFIN dependence of CDSC. It cannot be 0.
CDSCD$^{(b)}$	$F \cdot m^{-2}$	7e-3	0.0	-	Drain-bias sensitivity of CDSC
CDSCDN1	-	0	-0.08	-	NFIN dependence of CDSCD
CDSCDN2	-	1e5	1e-5	-	NFIN dependence of CDSCD
CDSCDR$^{(b)}$	$F \cdot m^{-2}$	CDSCD	0.0	-	Reverse-mode drain-bias sensitivity
CDSCDRN1	-	CDSCDN1	-0.08	-	NFIN dependence of CDSCDR
CDSCDRN2	-	CDSCDN2	1e-5	-	NFIN dependence of CDSCDR
DVT0$^{(b)}$	-	0.0	0.0	-	SCE coefficient
DVT1$^{(b)}$	-	0.60	> 0	-	SCE exponent coefficient
DVT1SS$^{(b)}$	-	DVT1	> 0	-	Subthreshold Swing exponent coefficient
PHIN$^{(b)}$	V	0.05	-	-	Nonuniform vertical doping effect on surface potential
ETA0$^{(b)}$	-	0.60	0.0	-	DIBL coefficient
ETA1$^{(b)}$	-	0.00	-	-	DIBL coefficient for low gate overdrive
ETA0LT	m^{-1}	0.0	-	-	Coupled NFIN and Length dependence of ETA0
ETA0N1	-	0	-0.08	-	NFIN dependence of ETA0
ETA0N2	-	0	1e-5	-	NFIN dependence of ETA0
ETA0CV$^{(b)}$	-	ETA0	0.0	-	DIBL coefficient for C-V
ETA0LTCV	m^{-1}	0.0	ETA0LT	-	Coupled NFIN and Length dependence of ETA0CV
ETA0N1CV	-	ETA0N1	-0.08	-	NFIN dependence of ETA0CV
ETA0N2CV	-	ETA0N2	1e-5	-	NFIN dependence of ETA0CV
DSUB$^{(b)}$	-	1.06	> 0	-	DIBL exponent coefficient
DVTP0$^{(b)}$	-	0	-	-	Coefficient for Drain-Induced Vth Shift (DITS)
DVTP1$^{(b)}$	-	0	-	-	DITS exponent coefficient
K1RSCE$^{(b)}$	$V^{1/2}$	0.0	-	-	Prefactor for reverse short channel effect

Name	Unit	Default	Min	Max	Description
LPE0$^{(b)}$	m	5e-9	$-L_{eff}$	-	Equivalent length of pocket region at zero bias
K0$^{(b)}$	V	-		-	Lateral NUD parameter
K0SI$^{(b)}$	-	1.0	>0	-	Correction factor for strong inversion/ g_m
DVTSHIFT$^{(b)}$	V	0.0	-	-	Additional Vth shift handle
PHIBE$^{(b)}$	V	0.7	0.2	1.2	Body-effect voltage parameter
K1$^{(b)}$	$V^{1/2}$	0.0	0.0	-	Body-effect coefficient for subthreshold region
QMFACTOR$^{(b)}$	-	0.0	-	-	Prefactor for QM V_{th} shift correction
QMTCENCV$^{(b)}$	-	0.0	-	-	Prefactor/switch for QM effective width and oxide thickness correction for CV
QMTCENCVA$^{(b)}$	-	0.0	-	-	Prefactor/switch for QM effective width and oxide thickness correction for accumulation region CV
ETAQM	-	0.54	-	-	Body-charge coefficient for QM charge centroid
QM0	V	1e-3	>0	-	Normalization parameter for QM charge centroid (inversion)
PQM$^{(b)}$	-	0.66	-	-	Fitting parameter for QM charge centroid (inversion)
PQML	m^{-1}	0.0	-	-	Length dependence of PQM
QM0ACC	V	1e-3	>0	-	Normalization parameter for QM charge centroid (accumulation)
PQMACC	-	0.66	-	-	Fitting parameter for QM charge centroid (accumulation)
VSAT$^{(b)}$	$m \cdot s^{-1}$	85000	-	-	Saturation velocity for the saturation region
VSATN1	-	0	-0.08	-	NFIN dependence of VSAT
VSATN2	-	1e5	1e-5	-	NFIN dependence of VSAT
VSAT1$^{(b)}$	$m \cdot s^{-1}$	VSAT	-	-	Saturation velocity for the linear region in forward mode
VSAT1N1	-	0	-0.08	-	NFIN dependence of VSAT1
VSAT1N2	-	1e5	1e-5	-	NFIN dependence of VSAT1
VSAT1R$^{(b)}$	$m \cdot s^{-1}$	VSAT1	-	-	Saturation velocity for the linear region in reverse mode
VSAT1RN1	-	VSAT1N1	-0.08	-	NFIN dependence of VSAT1R
VSAT1RN2	-	VSAT1N2	1e-5	-	NFIN dependence of VSAT1R

Name	Unit	Default	Min	Max	Description
DELTAVSAT$^{(b)}$	-	1.0	0.01	-	Velocity saturation parameter in the linear region
PSAT$^{(b)}$	-	2.0	2.0	-	Exponent for field for velocity saturation
KSATIV$^{(b)}$	-	1.0	-	-	Parameter for long channel Vdsat
VSATCV$^{(b)}$	$m \cdot s^{-1}$	VSAT	-	-	Saturation velocity for the capacitance model
DELTAVSATCV$^{(b)}$	-	DELTAVSAT	0.01	-	Velocity saturation parameter in the linear region for the capacitance model
ASAT$^{(b)}$	-	1	-	-	Velocity saturation fitting parameter for CV
PSATCV$^{(b)}$	-	PSAT	2.0	-	Exponent for field for velocity saturation for the capacitance model
MEXP$^{(b)}$	-	4	2	-	Smoothing function factor for Vdsat
MEXPR$^{(b)}$	-	MEXP	2	-	Reverse-mode smoothing function factor for Vdsat
PTWG$^{(b)}$	V^{-2}	0.0	-	-	Correction factor for velocity saturation in forward mode
PTWGR$^{(b)}$	V^{-2}	PTWG	-	-	Correction factor for velocity saturation in reverse mode
A1$^{(b)}$	V^{-2}	0.0	-	-	Non-saturation effect parameter in strong inversion region
A2$^{(b)}$	V^{-1}	0.0	-	-	Non-saturation effect parameter in moderate inversion region
U0$^{(b)}$	m^2/Vs	3e-2	-	-	Low field mobility
U0LT	$/m$	0.0	-	-	Coupled NFIN and Length dependence of U0
U0N1	-	0	-0.08	-	NFIN dependence of U0
U0N2	-	1e5	1e-5	-	NFIN dependence of U0
U0CV$^{(b)}$	m^2/Vs	U0	-	-	Low field mobility for CVMOD=1
U0LTCV	$/m$	U0LT	-	-	Coupled NFIN and Length dependence of U0CV
U0N1CV	-	U01	-0.08	-	NFIN dependence of U0CV
U0N2CV	-	U0N2	1e-5	-	NFIN dependence of U0CV
CHARGEWF	-	0	-1	1	Average channel charge weighting (sampling) factor, +1 : source-side, 0 : middle, -1 : drain-side
ETAMOB$^{(b)}$	-	2.0	-	-	Effective field parameter
UP$^{(b)}$	μm^{LPA}	0.0	-	-	Mobility L coefficient

Name	Unit	Default	Min	Max	Description
LPA	-	1.0	-	-	Mobility L power coefficient
UA$^{(b)}$	$(cmMV^{-1})^{EU}$	0.3	> 0.0	-	Phonon / surface roughness scattering parameter
UACV$^{(b)}$	$(cmMV^{-1})^{EU}$	UA	> 0.0	-	Phonon / surface roughness scattering parameter for CVMOD=1
UC$^{(b)}$	$(10^{-6}cmMV^{-2})^{EU}$	0.0	-	-	Body effect coefficient for mobility (BULKMOD=1)
UCCV$^{(b)}$	$(10^{-6}cmMV^{-2})^{EU}$	UC	-	-	Body effect coefficient for mobility (BULKMOD=1 and CVMOD=1)
EU$^{(b)}$	$cmMV^{-1}$	2.5	> 0.0	-	Phonon / surface roughness scattering parameter
UD$^{(b)}$	$cmMV^{-1}$	0.0	> 0.0	-	Columbic scattering parameter
UDCV$^{(b)}$	$cmMV^{-1}$	UDCV	> 0.0	-	Columbic scattering parameter for CV-MOD=1
UCS$^{(b)}$	-	1.0	> 0.0	-	Columbic scattering parameter
UCS$^{(b)}$	-	1.0	> 0.0	-	Columbic scattering parameter
UDS$^{(b)}$	-	2.0e-5	-	-	Weight factor correction for source side charge density in Coulomb scattering (CRYOMOD $\neq$ 0)
UDD$^{(b)}$	-	-2.0e-5	-	-	Weight factor correction for drain side charge density in Coulomb scattering (CRYOMOD $\neq$ 0)
MUHC0	-	0.0	0.0	1.0	Coefficient for hot-carrier induced mobility degradation
MUHC1	-	0.0	0.0	3.0	Exponential coefficient for hot-carrier induced mobility degradation
ETAMOBTHIN	-	ETAMOB	-	-	Effective field parameter for thin GAA bodies (MOBSCMOD=1)
ETAMOBTNI	m	7.5e-9	0	-	Critical TGAA for non-ideality (MOB-SCMOD=1)
ETAMOBIR	nm	0.1	0	-	Ideality parameter (MOBSCMOD=1)
UATHIN	$(cmMV^{-1})^{EU}$	UA	-	-	Phonon/surface-roughness scattering parameter for thin GAA bodies (MOBSCMOD=1)
UATSAT	m	9e-9	0	-	Critical TGAA for UA saturation (MOBSCMOD=1)
UARTSC	$(nm)^{-1}$	0.09	0	-	Rate of UA decay with TGAA scaling (MOBSCMOD=1)
UATNI	m	6.4e-9	0	-	Critical TGAA for non-ideality (MOB-SCMOD=1)

Name	Unit	Default	Min	Max	Description
UAIR	nm	0.2	0	-	Ideality parameter (MOBSCMOD=1)
EUTHIN	$cmMV^{-1}$	EU	-	-	Phonon/surface-roughness scattering parameter for thin GAA bodies (MOBSCMOD=1)
EUPTSC	-	3.5	0	-	Exponent for TGAA scaling of EU (MOBSCMOD=1)
EUTNI	m	6e-9	0	-	Critical TGAA for non-ideality (MOBSCMOD=1)
EUIR	nm	0.2	0	-	Ideality parameter (MOBSCMOD=1)
UDTHIN	$cmMV^{-1}$	UD	-	-	Coulomb-scattering parameter for thin GAA bodies (MOBSCMOD=1)
UDTSAT	m	8.1e9	0	-	Critical TGAA for UD saturation (MOBSCMOD=1)
UDPTSC	-	1.3	0	-	Exponent for TGAA scaling of UD (MOBSCMOD=1)
U0ETAWSC	-	1.5	0	-	Ratio of primary carrier low-field mobilities: $\frac{U0_{sidewall}}{U0_{surface}}$ (MOBSCMOD=1)
EGBULK	eV	1.1	0	-	Bulk band-gap (MOBSCMOD=1)
U0EMSM1	$meV(nm)^2$	26.6	0	-	Parameter for effective mass scaling (MOBSCMOD=1)
U0EMSM2	-	4	-	-	Parameter for effective mass scaling (MOBSCMOD=1)
PCLM$^{(b)}$	-	0.013	> 0.0	-	Channel Length Modulation (CLM) parameter
PCLMG$^{(b)}$	-	0	-	-	Gate bias dependent parameter for channel Length Modulation (CLM)
RDSWMIN	$\Omega \cdot \mu m^{WR}$	0.0	0.0	-	$RDSMOD = 0$ S/D extension resistance per unit width at high V_{gs}
RDSW$^{(b)}$	$\Omega \cdot \mu m^{WR}$	100	0.0	-	$RDSMOD = 0$ zero bias S/D extension resistance per unit width
RSWMIN	$\Omega \cdot \mu m^{WR}$	0.0	0.0	-	$RDSMOD = 1$ source extension resistance per unit width at high V_{gs}
RSW$^{(b)}$	$\Omega \cdot \mu m^{WR}$	50	0.0	-	$RDSMOD = 1$ zero bias source extension resistance per unit width
RDWMIN	$\Omega \cdot \mu m^{WR}$	0.0	0.0	-	$RDSMOD = 1$ drain extension resistance per unit width at high V_{gs}
RDW$^{(b)}$	$\Omega \cdot \mu m^{WR}$	50	0.0	-	$RDSMOD = 1$ zero bias drain extension resistance per unit width
RSDR	V^{-PRSDR}	0.0	0.0	-	$RDSMOD = 1$ source side drift resistance parameter in forward mode

Name	Unit	Default	Min	Max	Description
RSDRR	V^{-PRSDR}	RSDR	0.0	-	$RDSMOD = 1$ source side drift resistance parameter in reverse mode
RDDR	V^{-PRDDR}	RSDR	0.0	-	$RDSMOD = 1$ drain side drift resistance parameter in forward mode
RSDRR	V^{-PRDDR}	RDDR	0.0	-	$RDSMOD = 1$ drain side drift resistance parameter in reverse mode
PRWGS$^{(b)}$	V^{-1}	0.0	0.0	-	Source side quasi-saturation parameter
PRWGD$^{(b)}$	V^{-1}	PRWGS	0.0	-	Drain side quasi-saturation parameter
PRSDR	-	1.0	0.0	-	$RDSMOD = 1$ drain side drift resistance parameter in forward mode
PRDDR	-	PRSDR	0.0	-	$RDSMOD = 1$ drain side drift resistance parameter in reverse mode
WR$^{(b)}$	-	1.0	-	-	W dependence parameter of S/D extension resistance
RDLCW	$\Omega \cdot \mu m^{WR}$	0.0	0.0	-	Resistance of the Drain region at Low Current
RSLCW	$\Omega \cdot \mu m^{WR}$	0.0	0.0	-	Resistance of the Source region at Low Current
NVSRD	m^{-2}	5.0e16	> 0	-	Charge density in the drain region
NVSRS	m^{-2}	NVSRD	> 0	-	Charge density in the source region
VSATRSD	m/s	1.0e5	> 0	-	Saturation velocity in S/D region
PTWGVSRSD	V^{-1}	0.0	0.0	-	VSATRSD variation with gate bias
PTWG1VSRSD	V	0.0	0.0	-	VSATRSD variation with gate bias
PSATXVSRSD	V	60.0	0.0	-	Fine tuning of PTWGVSRSD effect
MVSRSD	-	1.0	0.0	-	Non-linear resistance parameter in S/D velocity saturation model
VSRDFACTOR	-	1.0e-3	1.0e-4	1.0	Parameter for δ_{vsrd} tuning
VSRSFACTOR	-	1.0e-3	1.0e-4	1.0	Parameter for δ_{vsrs} tuning
RDVDS	V	8.0	-	-	Parameter for $I_{sat,rd}$ variation with drain voltage
GAVSRD	V^{-1}	0.0	0.0	-	Parameter for $I_{sat,rd}$ variation with drain voltage
RGEXT	Ω	0.0	0.0	-	Effective gate electrode external resistance (Experimental)
RGFIN	Ω	1.0e-3	1.0e-3	-	Effective gate electrode resistance per fin per finger
GBMIN	Ω^{-1}	1e-12	0	-	Minimum substrate conductance
RBPB	Ω	50	1.0e-3	-	Substrate network: resistance between e and ex nodes

Name	Unit	Default	Min	Max	Description
RBSB	Ω	50	1.0e-3	-	Substrate network: resistance between *se* and *ex* nodes
RBDB	Ω	50	1.0e-3	-	Substrate network: resistance between *de* and *ex* nodes
RBPS	Ω	50	1.0e-3	-	Substrate network: resistance between *se* and *e* nodes
RBPD	Ω	50	1.0e-3	-	Substrate network: resistance between *de* and *e* nodes
RSHS	Ω	0.0	0.0	-	Source-side sheet resistance
RSHD	Ω	RSHS	0.0	-	Drain-side sheet resistance
PDIBL1$^{(b)}$	-	1.30	0.0	-	Parameter for DIBL effect on Rout in forward mode
PDIBL1R$^{(b)}$	-	PDIBL1	0.0	-	Parameter for DIBL effect on Rout in reverse mode
PDIBL2$^{(b)}$	-	2e-4	0.0	-	Parameter for DIBL effect on Rout
DROUT$^{(b)}$	-	1.06	> 0.0	-	L dependence of DIBL effect on Rout
PVAG$^{(b)}$	-	1.0	-	-	V_{gs} dependence on early voltage
TOXREF	m	1.2e-9	> 0.0	-	Nominal gate oxide thickness for Gate tunneling current
TOXG	m	TOXP	> 0.0	-	Oxide thickness for gate current model
NTOX$^{(b)}$	-	1.0	-	-	Exponent for gate oxide ratio
AIGBINV$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}$	1.11e-2	-	-	Parameter for Igb in inversion
BIGBINV$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}V^{-1}$	9.49e-4	-	-	Parameter for Igb in inversion
CIGBINV$^{(b)}$	V^{-1}	6.00e-3	-	-	Parameter for Igb in inversion
EIGBINV$^{(b)}$	V	1.1	-	-	Parameter for Igb in inversion
NIGBINV$^{(b)}$	-	3.0	> 0.0	-	Parameter for Igb in inversion
AIGBACC$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}$	1.36e-2	-	-	Parameter for Igb in accumulation
BIGBACC$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}V^{-1}$	1.71e-3	-	-	Parameter for Igb in accumulation
CIGBACC$^{(b)}$	V^{-1}	7.5e-2	-	-	Parameter for Igb in accumulation
NIGBACC$^{(b)}$	-	1.0	> 0.0	-	Parameter for Igb in accumulation
AIGC$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}$	1.36e-2	-	-	Parameter for Igc in inversion
BIGC$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}V^{-1}$	1.71e-3	-	-	Parameter for Igc in inversion
CIGC$^{(b)}$	V^{-1}	0.075	-	-	Parameter for Igc in inversion
PIGCD$^{(b)}$	-	1.0	> 0.0	-	V_{ds} dependence of Igcs and Igcd
DLCIGS	m	0.0	-	-	Delta L for Igs model.
AIGS$^{(b)}$	$(Fs^2g^{-1})0.5 * m^{-1}$	1.36e-2	-	-	Parameter for Igs in inversion
BIGS$^{(b)}$	$(Fs^2g^{-1})0.5 * m^{-1}V^{-1}$	1.71e-3	-	-	Parameter for Igs in inversion
CIGS$^{(b)}$	V^{-1}	0.075	-	-	Parameter for Igs in inversion

Name	**Unit**	**Default**	**Min**	**Max**	**Description**
DLCIGD	m	DLCIGS	-	-	Delta L for Igd model.
AIGD[b]	$(Fs^2g^{-1})0.5 * m^{-1}$	AIGS	-	-	Parameter for Igd in inversion
BIGD[b]	$(Fs^2g^{-1})0.5 * m^{-1}V^{-1}$	BIGS	-	-	Parameter for Igd in inversion
CIGD[b]	V^{-1}	CIGS	-	-	Parameter for Igd in inversion
VFBSD	V	0.0	-	-	Flat band voltage for S/D region
VFBSDCV	V	VFBSD	-	-	Flat band voltage for S/D region for C-V calculations
POXEDGE [b]	-	1	> 0.0	-	Factor for the gate edge Tox
AGIDL[b]	Ω^{-1}	6.055e-12	-	-	Pre-exponetial coeff. for GIDL
BGIDL[b]	Vm^{-1}	0.3e9	-	-	Exponential coeff. for GIDL
CGIDL[b]	V^3	0.2	-	-	Parameter for body bias effect of GIDL
EGIDL[b]	V	0.2	-	-	Band bending parameter for GIDL
PGIDL[b]	-	1.0	-	-	Exponent of electric field for GIDL
AGISL[b]	Ω^{-1}	AIGDL	-	-	Pre-exponetial coeff for GISL.
BGISL[b]	Vm^{-1}	BGIDL	-	-	Exponential coeff. for GISL
CGISL[b]	V^3	CGIDL	-	-	Parameter for body bias effect of GISL
EGISL[b]	V	EGIDL	-	-	Band bending parameter for GISL
PGISL[b]	-	PGIDL	-	-	Exponent of electric field for GISL
AGIDLB[b]	Ω^{-1}	6.055e-12	-	-	Pre-exponetial coeff. for parasitic substrate GIDL (GIDLMOD=2 or 3)
BGIDLB[b]	Vm^{-1}	0.3e9	-	-	Exponential coeff. for parasitic substrate GIDL (GIDLMOD=2 or 3)
CGIDLB[b]	V^3	0.2	-	-	Parameter for body bias effect of parasitic substrate GIDL (GIDLMOD=2 or 3)
EGIDLB[b]	V	0.2	-	-	Band bending parameter for parasitic substrate GIDL (GIDLMOD=2 or 3)
PGIDLB[b]	-	1.0	-	-	Exponent of electric field for parasitic substrate GIDL (GIDLMOD=2 or 3)
AGISLB[b]	Ω^{-1}	AIGDLB	-	-	Pre-exponetial coeff. for parasitic substrate GISL (GIDLMOD=2 or 3)
BGISLB[b]	Vm^{-1}	BGIDLB	-	-	Exponential coeff. for parasitic substrate GISL (GIDLMOD=2 or 3)
CGISLB[b]	V^3	CGIDLB	-	-	Parameter for body bias effect of parasitic substrate GISL (GIDLMOD=2 or 3)
EGISLB[b]	V	EGIDLB	-	-	Band bending parameter for parasitic substrate GISL (GIDLMOD=2 or 3)

Name	Unit	Default	Min	Max	Description
PGISLB$^{(b)}$	-	PGIDLB	-	-	Exponent of electric field for parasitic substrate GISL (GIDLMOD=2 or 3)
ATATD$^{(b)}$	$A \cdot m^2$	1.0e-27	-	-	Pre-exponetial coeff. for TAT GIDL (GIDLMOD=3)
BTATD$^{(b)}$	V^{-1}	6.3e-5	-	-	Field correction parameter for TAT GIDL (GIDLMOD=3)
CTATD$^{(b)}$	$-$	0.215	-	-	Field correction parameter for TAT GIDL (GIDLMOD=3)
DTATD$^{(b)}$	V	0.382	-	-	Field correction parameter for TAT GIDL (GIDLMOD=3)
ATATS$^{(b)}$	$A \cdot m^2$	ATATD	-	-	Pre-exponetial coeff. for TAT GISL (GIDLMOD=3)
BTATS$^{(b)}$	V^{-1}	BTATD	-	-	Field correction parameter for TAT GISL (GIDLMOD=3)
CTATS$^{(b)}$	$-$	CTATD	-	-	Field correction parameter for TAT GISL (GIDLMOD=3)
DTATS$^{(b)}$	V	DTATD	-	-	Field correction parameter for TAT GISL (GIDLMOD=3)
ALPHA0$^{(b)}$	$m \cdot V^{-1}$	0.0	-	-	First parameter of Iii (IIMOD=1)
ALPHA1 $^{(b)}$	V^{-1}	0.0	-	-	L scaling parameter of Iii (IIMOD=1)
ALPHAII0$^{(b)}$	$m \cdot V^{-1}$	0.0	-	-	First parameter of Iii (IIMOD=2)
ALPHAII1 $^{(b)}$	V^{-1}	0.0	-	-	L scaling parameter of Iii (IIMOD=2)
BETA0$^{(b)}$	V^{-1}	0.0	-	-	Vds dependent paramter of Iii (IIMOD=1)
BETAII0$^{(b)}$	V^{-1}	0.0	-	-	Vds dependent paramter of Iii (IIMOD=2)
BETAII1$^{(b)}$	-	0.0	-	-	Vds dependent paramter of Iii (IIMOD=2)
BETAII2$^{(b)}$	V	0.1	-	-	Vds dependent paramter of Iii (IIMOD=2)
ESATII$^{(b)}$	Vm^{-1}	1.0e7	-	-	Saturation channel E-Field for Iii (IIMOD=2)
LII$^{(b)}$	Vm	0.5e-9	-	-	Channel length dependent parameter of Iii (IIMOD=2)
SII0$^{(b)}$	V^{-1}	0.5	-	-	Vgs dependent paramter of Iii (IIMOD=2)
SII1$^{(b)}$	-	0.1	-	-	Vgs dependent paramter of Iii (IIMOD=2)
SII2$^{(b)}$	V	0.0	-	-	Vgs dependent paramter of Iii (IIMOD=2)

Name	Unit	Default	Min	Max	Description
SIID$^{(b)}$	V	0.0	-	-	Vds dependent paramter of Iii (IIMOD=2)
EOTACC	m	EOT	1e-10	-	SiO_2 equivalent gate dielectric thickness for accumulation region
DELVFBACC	V	0.0	-	-	Additional V_{fb} shift required for accumulation region
PCLMCV$^{(b)}$	-	PCLM	> 0.0	-	Channel Length Modulation (CLM) parameter for the capacitance model
CFS$^{(b)}$	$F \cdot m^{-1}$	2.5e-11	-	-	Source-side outer fringe cap (for $CGEOMOD = 0$)
CFD$^{(b)}$	$F \cdot m^{-1}$	CFS	-	-	Drain-side outer fringe cap (for $CGEOMOD = 0$)
CGSO	$F \cdot m^{-1}$	calculated	0.0	-	Non LDD region source-gate overlap capacitance per unit channel width (for $CGEOMOD = 0, 2$)
CGDO	$F \cdot m^{-1}$	calculated	0.0	-	Non LDD region drain-gate overlap capacitance per unit channel width (for $CGEOMOD = 0, 2$)
CGSL$^{(b)}$	$F \cdot m^{-1}$	0	-	-	Overlap capacitance between gate and lightly-doped source region (for $CGEOMOD = 0, 2$ and 3)
CGDL$^{(b)}$	$F \cdot m^{-1}$	CGSL	-	-	Overlap capacitance between gate and lightly-doped drain region (for $CGEOMOD = 0, 2$ and 3)
CKAPPAS$^{(b)}$	V	0.6	-	-	Coefficient of bias-dependent overlap capacitance for the source side (for $CGEOMOD = 0, 2$ and 3)
CKAPPAD$^{(b)}$	V	CKAPPAS	-	-	Coefficient of bias-dependent overlap capacitance for the drain side (for $CGEOMOD = 0, 2$ and 3)
CGBO	$F \cdot m^{-1}$	0	0.0	-	Gate-substrate overlap capacitance per unit channel length per finger per gate contact
CGBN	$F \cdot m^{-1}$	0	0.0	-	Gate-substrate overlap capacitance per unit channel length per finger per fin
CSDESW	$F \cdot m^{-1}$	0	0.0	-	Source/drain sidewall fringing capacitance per unit length
CJS	$F \cdot m^{-2}$	0.0005	0.0	-	Unit area source-side junction capacitance at zero bias

Name	Unit	Default	Min	Max	Description
CJD	$F \cdot m^{-2}$	CJS	0.0	-	Unit area drain-side junction capacitance at zero bias
CJSWS	$F \cdot m^{-1}$	5.0e-10	0.0	-	Unit length sidewall junction capacitance at zero bias (source-side)
CJSWD	$F \cdot m^{-1}$	CJSWS	0.0	-	Unit length sidewall junction capacitance at zero bias (drain-side)
CJSWGS	$F \cdot m^{-1}$	0.0	0.0	-	Unit length gate sidewall junction capacitance at zero bias (source-side)
CJSWGD	$F \cdot m^{-1}$	CJSWGS	0.0	-	Unit length gate sidewall junction capacitance at zero bias (drain-side)
PBS	V	1.0	0.01	-	Bottom junction built-in potential (source-side)
PBD	V	PBS	0.01	-	Bottom junction built-in potential (drain-side)
PBSWS	V	1.0	0.01	-	Isolation-edge sidewall junction built-in potential (source-side)
PBSWD	V	PBSWS	0.01	-	Isolation-edge sidewall junction built-in potential (drain-side)
PBSWGS	V	PBSWS	0.01	-	Gate-edge sidewall junction built-in potential (source-side)
PBSWGD	V	PBSWGS	0.01	-	Gate-edge sidewall junction built-in potential (drain-side)
MJS	-	0.5	> 0	-	Source bottom junction capacitance grading coefficient
MJD	-	MJS	> 0	-	Drain bottom junction capacitance grading coefficient
MJSWS	-	0.33	> 0	-	Isolation-edge sidewall junction capacitance grading coefficient (source-side)
MJSWD	-	MJSWS	> 0	-	Isolation-edge sidewall junction capacitance grading coefficient (drain-side)
MJSWGS	-	MJSWS	> 0	-	Gate-edge sidewall junction capacitance grading coefficient (source-side)
MJSWGD	-	MJSWGS	> 0	-	Gate-edge sidewall junction capacitance grading coefficient (drain-side)
SJS	-	0.0	0.0	-	Constant for source-side two-step second junction capacitance
SJD	-	SJS	0.0	-	Constant for drain-side two-step second junction capacitance
SJSWS	-	0.0	0.0	-	Constant for sidewall two-step second junction capacitance (source-side)

Name	Unit	Default	Min	Max	Description
SJSWD	-	SJSWS	0.0	-	Constant for sidewall two-step second junction capacitance (drain-side)
SJSWGS	-	0.0	0.0	-	Constant for gate sidewall two-step second junction capacitance (source-side)
SJSWGD	-	SJSWGS	0.0	-	Constant for gate sidewall two-step second junction capacitance (drain-side)
MJS2	-	0.125	-	-	Source bottom two-step second junction capacitance grading coefficient
MJD2	-	MJS2	-	-	Drain bottom two-step second junction capacitance grading coefficient
MJSWS2	-	0.083	-	-	Isolation-edge sidewall two-step second junction capacitance grading coefficient (source-side)
MJSWD2	-	MJSWS2	-	-	Isolation-edge sidewall two-step second junction capacitance grading coefficient (drain-side)
MJSWGS2	-	MJSWS2	-	-	Gate-edge sidewall two-step second junction capacitance grading coefficient (source-side)
MJSWGD2	-	MJSWGS2	-	-	Gate-edge sidewall two-step second junction capacitance grading coefficient (drain-side)
JSS	Am^{-2}	1.0e-4	0.0	-	Bottom source junction reverse saturation current density
JSD	Am^{-2}	JSS	0.0	-	Bottom drain junction reverse saturation current density
JSWS	Am^{-1}	0	0.0	-	Unit length reverse saturation current for isolation-edge source sidewall junction
JSWD	Am^{-1}	JSWS	0.0	-	Unit length reverse saturation current for isolation-edge drain sidewall junction
JSWGS	Am^{-1}	0	0.0	-	Unit length reverse saturation current for gate-edge source sidewall junction
JSWGD	Am^{-1}	JSWGS	0.0	-	Unit length reverse saturation current for gate-edge drain sidewall junction
JTSS	Am^{-2}	0	0.0	-	Bottom source junction trap-assisted saturation current density
JTSD	Am^{-2}	JTSS	0.0	-	Bottom drain junction trap-assisted saturation current density

Name	Unit	Default	Min	Max	Description
JTSSWS	Am^{-1}	0	0.0	-	Unit length trap-assisted saturation current for isolation-edge source sidewall junction
JTSSWD	Am^{-1}	JTSSWS	0.0	-	Unit length trap-assisted saturation current for isolation-edge drain sidewall junction
JTSSWGS	Am^{-1}	0	0.0	-	Unit length trap-assisted saturation current for gate-edge source sidewall junction
JTSSWGD	Am^{-1}	JTSSWGS	0.0	-	Unit length trap-assisted saturation current for gate-edge drain sidewall junction
JTWEFF	m	0	0.0	-	Trap assisted tunneling current width dependence
NJS	-	1.0	0.0	-	Source junction emission coefficient
NJD	-	NJS	0.0	-	Drain junction emission coefficient
NJTS	-	20	0.0	-	Non-ideality factor for JTSS
NJTSD	-	NJTS	0.0	-	Non-ideality factor for JTSD
NJTSSW	-	20	0.0	-	Non-ideality factor for JTSSWS
NJTSSWD	-	NJTSSW	0.0	-	Non-ideality factor for JTSSWD
NJTSSWG	-	20	0.0	-	Non-ideality factor for JTSSWGS
NJTSSWGD	-	NJTSSWG	0.0	-	Non-ideality factor for JTSSWGD
VTSS	V	10	0.0	-	Bottom source junction trap-assisted current voltage dependent parameter
VTSD	V	VTSS	0.0	-	Bottom drain junction trap-assisted current voltage dependent parameter
VTSSWS	V	10	0.0	-	Unit length trap-assisted current voltage dependent parameter for sidewall source junction
VTSSWD	V	VTSSWS	0.0	-	Unit length trap-assisted current voltage dependent parameter for sidewall drain junction
VTSSWGS	V	10	0.0	-	Unit length trap-assisted current voltage dependent parameter for gate-edge sidewall source junction
VTSSWGD	V	VTSSWGS	0.0	-	Unit length trap-assisted current voltage dependent parameter for gate-edge sidewall drain junction
IJTHSFWD	A	0.1	$10I_{sbs}$	-	Forward source diode breakdown limiting current

Name	Unit	Default	Min	Max	Description
IJTHDFWD	A	IJTHSFWD	$10I_{sbd}$	-	Forward drain diode breakdown limiting current
IJTHSREV	A	0.1	$10I_{sbs}$	-	Reverse source diode breakdown limiting current
IJTHDREV	A	IJTHSREV	$10I_{sbd}$	-	Reverse drain diode breakdown limiting current
BVS	V	10.0	-	-	Source diode breakdown voltage
BVD	V	BVS	-	-	Drain diode breakdown voltage
XJBVS	-	1.0	-	-	Fitting parameter for source diode breakdown current. XJBVS cannot be 0.
XJBVD	-	XJBVS	-	-	Fitting parameter for source diode breakdown current. XJBVD cannot be 0.
LINTIGEN	m	0.0	-	$L_{eff}/2$	L_{int} offset for R/G current
NTGEN$^{(b)}$	-	1.0	> 0.0	-	Parameter for R/G current (Experimental)
AIGEN$^{(b)}$	$m^{-3}V^{-1}$	0.0	-	-	Parameter for R/G current (Experimental)
BIGEN$^{(b)}$	$m^{-3}V^{-3}$	0.0	-	-	Parameter for R/G current (Experimental)
XRCRG1$^{(b)}$	-	12.0	0.0 or $\geq 10^{-3}$	-	Parameter for non quasi-static gate resistance (NQSMOD=1) and NQSMOD=2
XRCRG2$^{(b)}$	-	1.0	-	-	Parameter for non quasi-static gate resistance (NQSMOD=1) and NQSMOD=2
EF	-	1.0	> 0.0	2.0	Flicker noise frequency exponent
LINTNOI	m	0.0	-	$L_{eff}/2$	L_{int} offset for flicker noise calculation
EM	Vm^{-1}	4.1e7	-	-	Flicker noise parameter
NOIA	$eV^{-1}s^{1-EF}m^{-3}$	6.250e39	-	-	Flicker noise parameter
NOIA2$^{(b)}$	$eV^{-1}s^{1-EF}m^{-3}$	NOIA	>0	-	Flicker noise parameter for FNMOD=1
QSREF$^{(b)}$	-	0.05	>0	-	Charge at threshold condition: Flicker noise parameter for FNMOD=1
MPOWER$^{(b)}$	-	1.2	>0	-	Sub-threshold to strong-inversion transition slope parameter: Flicker noise parameter for FNMOD=1
SMOOTH	-	2	>0	-	Smoothing parameter: Flicker noise parameter for FNMOD=1
NOIB	$eV^{-1}s^{1-EF}m^{-1}$	3.125e24	-	-	Flicker noise parameter

Name	Unit	Default	Min	Max	Description
NOIC	$eV^{-1}s^{1-EF}m$	8.750e7	-	-	Flicker noise parameter
NTNOI	-	1.0	0.0	-	Thermal noise parameter
RNOIA	-	0.577	-	-	Thermal noise parameter
RNOIB	-	0.37	-	-	Thermal noise parameter
TNOIA	m^{-1}	1.5	0.0	-	Thermal noise parameter
TNOIB	m^{-1}	3.5	0.0	-	Thermal noise parameter
RNOIK	-	0	0.0	-	Empirical parameter for Sid level at low Ids
TNOIK	m^{-1}	0	-	-	Empirical parameter for Leff trend of Sid at low Ids
TNOIK2		0.1	0.0	-	Empirical parameter for Leff trend of Sid at low Ids
NVTM	V	nkT/q	0	-	If provided NVTM will override nkT/q calculated in the model
THETASCE	-	Θ_{SCE}	-	-	If provided THETASCE will override Θ_{SCE} (see 3.414) calculated in the model
THETASW	-	Θ_{SW}	-	-	If provided THETASW will override Θ_{SW} (see 3.411) calculated in the model
THETADIBL	-	Θ_{DIBL}	-	-	If provided THETADIBL will override Θ_{DIBL} (see 3.416) calculated in the model
TFIN_BASE	m	0	0	inf	Base Body (Fin) thickness, for Trapezoidal Triple Gate
TFIN_TOP	m	0	0	-	Top Body (Fin) thickness, for Trapezoidal Triple Gate
ACH_UFCM	m^2	1	-	-	Area of the Channel for the Unified Model
CINS_UFCM	$F \cdot m^{-1}$	1	-	-	Insulator Capacitance for the Unified Model
W_UFCM	m	1	-	-	Effective Channel Width for the Unified Model
ALPHA_UFCM	-	$\frac{1}{1.8}$	-	-	Mobile charge scaling term taking QM effects into account
DIM1H	-	3.0	1.0	3.0	Maximum dimension for first subband for cross-section scaling (SUBBANDMOD=1)
DIMENSION1	-	2.0	1.0	3.0	Dimension for first subband (SUBBANDMOD=1)

Name	**Unit**	**Default**	**Min**	**Max**	**Description**
DIM2H	-	3.0	1.0	3.0	Maximum dimension for second subband for cross-section scaling (SUBBANDMOD=1)
DIMENSION2	-	2.6	1.0	3.0	Dimension for second subband (SUBBANDMOD=1)
DIM3H	-	3	1	3	Maximum dimension for third subband for cross-section scaling (SUBBANDMOD=1)
DIMENSION3	-	2.6	1.0	3.0	Dimension for third subband (SUBBANDMOD=1)
WGAANOM	m	8e-9	0.0	-	Nominal WGAA (SUBBANDMOD=1)
WDIM0	m	9.5e-9	0.0	-	WGAA at which dimension change happens (SUBBANDMOD=1)
WDIMR	nm	0.1	0.0	-	Rate of dimension change with WGAA scaling (SUBBANDMOD=1)
WSSP0	m	WDIM0	0.0	-	WGAA around which SSP change happens (SUBBANDMOD=1)
WSSPR	nm	WDIMR	0.0	-	Rate of SSP change with WGAA scaling (SUBBANDMOD=1)
SSP1$^{(b)}$	-	14.0	0.0	-	Subband smoothing parameter for first subband (WGAA¡WSSP0) (SUBBANDMOD=1)
SSP2$^{(b)}$	-	24.0	0.0	-	Subband smoothing parameter for second subband (WGAA¡WSSP0) (SUBBANDMOD=1)
SSP3$^{(b)}$	-	24.0	0.0	-	Subband smoothing parameter for third subband (WGAA¡WSSP0) (SUBBANDMOD=1)
DSSP1$^{(b)}$	-	2.0	0.0	-	Change in SSP1 with WGAA scaling (WGAA¿WSSP0) (SUBBANDMOD=1)
DSSP2$^{(b)}$	-	0.0	0.0	-	Change in SSP2 with WGAA scaling (WGAA¿WSSP0) (SUBBANDMOD=1)
DSSP3$^{(b)}$	-	0.0	0.0	-	Change in SSP3 with WGAA scaling (WGAA¿WSSP0) (SUBBANDMOD=1)
E2NOM$^{(b)}$	eV	0.139	0.0	-	Second subband energy for WGAANOM (SUBBANDMOD=1)

Name	Unit	Default	Min	Max	Description
E3NOM$^{(b)}$	eV	2.0	0.0	-	Third subband energy for WGAANOM (SUBBANDMOD=1)
MFE2	-	1.0	-	-	Rate of change in seconf subband energy with cross-section scaling (SUBBANDMOD=1)
MFE3	-	1.0	-	-	Rate of change in third subband energy with cross-section scaling (SUBBANDMOD=1)
WSFE2	-	1.0	0.0	-	WGAA scaling factor for second subband energy (SUBBANDMOD=1)
WSFE3	-	1.0	0.0	-	WGAA scaling factor for third subband energy (SUBBANDMOD=1)
TSRE2	-	1.8	0.0	-	TGAA scaling for second subband energy (SUBBANDMOD=1)
TDWSE2	-	1.0	0.0	-	TGAA dependence of WGAA scaling for second subband energy (SUBBANDMOD=1)
TSRE3	-	0.67	0.0	-	TGAA scaling for third subband energy (SUBBANDMOD=1)
TDWSE3	-	0.23	0.0	-	TGAA dependence of WGAA scaling for third subband energy (SUBBANDMOD=1)
MFQ1NOM$^{(b)}$	-	11.2	0.0	-	Scaling factor for first subband charge for WGAANOM (SUBBANDMOD=1)
MFQ2NOM$^{(b)}$	-	8.02	0.0	-	Scaling factor for second subband charge for WGAANOM (SUBBANDMOD=1)
MFQ3NOM$^{(b)}$	-	6.18	0.0	-	Scaling factor for third subband charge for WGAANOM (SUBBANDMOD=1)
MFQ1	-	1.0	-	-	Rate of change in first subband charge with cross-section scaling (SUBBANDMOD=1)
MFQ2	-	1.0	-	-	Rate of change in second subband charge with cross-section scaling (SUBBANDMOD=1)
MFQ3	-	1.0	-	-	Rate of change in third subband charge with cross-section scaling (SUBBANDMOD=1)
WSFQ1	-	1.0	0.0	-	WGAA scaling factor for first subband charge (SUBBANDMOD=1)

Name	Unit	Default	Min	Max	Description
WSFQ2	-	1.0	0.0	-	WGAA scaling factor for second subband charge (SUBBANDMOD=1)
WSFQ3	-	1.0	0.0	-	WGAA scaling factor for third subband charge (SUBBANDMOD=1)
TSRQ1	-	1.1	0.0	-	TGAA scaling for first subband charge (SUBBANDMOD=1)
TDWSQ1	-	2.4	0.0	-	TGAA dependence of WGAA scaling for first subband charge (SUBBANDMOD=1)
TSRQ2	-	2.0	0.0	-	TGAA scaling for second subband charge (SUBBANDMOD=1)
TDWSQ2	-	2.0	0.0	-	TGAA dependence of WGAA scaling for second subband charge (SUBBANDMOD=1)
TSRQ3	-	6.0	0.0	-	TGAA scaling for third subband charge (SUBBANDMOD=1)
TDWSQ3	-	2.4	0.0	-	TGAA dependence of WGAA scaling for third subband charge (SUBBANDMOD=1)

7.5 Parameters for geometry-dependent parasitics

The parameters listed in this section are for RGEOMOD = 1 and CGEOMOD = 2.

Name	Unit	Default	Min	Max	Description
HEPI	m	10e-9	-	-	Height of the raised source/drain on top of the fin
TSILI	m	10e-9	-	-	Thickness of the silicide on top of the raised source/drain
RHOC	Ωm^2	1e-12	1e-18	10e-9	Contact resistivity at the silicon/silicide interface
RHORSD	Ωm	calculated	0	-	Average resistivity of silicon in the raised source/drain region
CRATIO	-	0.5	0	1	Ratio of the corner area filled with silicon to the total corner area
DELTAPRSD	m	0.0	-FPITCH	-	Change in silicon/silicide interface length due to non-rectangular epi
SDTERM	-	0	0	1	Indicator of whether the source/drain are terminated with silicide
LSP	m	0.2(L+XL)	> 0	-	Thickness of the gate sidewall spacer
EPSRSP	-	3.9	1	-	Relative dielectric constant of the gate sidewall spacer material
TGATE	m	30e-9	0	-	Gate height on top of the hard mask
TMASK	m	30e-9	0	-	Height of the hard mask on top of the fin
ASILIEND	m^2	0	0	-	Extra silicide cross sectional area at the two ends of the FinFET
ARSDEND	m^2	0	0	-	Extra raised source/drain cross sectional area at the two ends of the FinFET
PRSDEND	m	0	0	-	Extra silicon/silicide interface perimeter at the two ends of the FinFET
NSDE	m^{-3}	2e25	$1e25$	$1e26$	Active doping concentration at the channel edge
RGEOA	-	1.0	-	-	Fitting parameter for RGEOMOD=1
RGEOB	m^{-1}	0	-	-	Fitting parameter for RGEOMOD=1
RGEOC	m^{-1}	0	-	-	Fitting parameter for RGEOMOD=1
RGEOD	m^{-1}	0	-	-	Fitting parameter for RGEOMOD=1
RGEOE	m^{-1}	0	-	-	Fitting parameter for RGEOMOD=1
CGEOA	-	1.0	-	-	Fitting parameter for CGEOMOD=2 and 3

Name	Unit	Default	Min	Max	Description
CGEOB	m^{-1}	0	-	-	Fitting parameter for CGEOMOD=2 and 3
CGEOC	m^{-1}	0	-	-	Fitting parameter for CGEOMOD=2 and 3
CGEOD	m^{-1}	0	-	-	Fitting parameter for CGEOMOD=2 and 3
CGEOE	-	1.0	-	-	Fitting parameter for CGEOMOD=2 and 3

7.6 Parameters for Temperature Dependence and Self-heating

Note: Binnable parameters are marked as $^{(b)}$

Name	Unit	Default	Min	Max	Description
TNOM	^oC	27	-273.15	-	Temperature at which the model is extracted (in Celsius)
TBGASUB	eVK^{-1}	7.02e-4	-	-	Bandgap Temperature Coefficient
TBGBSUB	K	1108.0	-	-	Bandgap Temperature Coefficient
KT1$^{(b)}$	V	0.0	-	-	V_{th} Temperature Coefficient
KT1L	Vm	0.0	-	-	V_{th} Temperature Coefficient
KT11	V	0.01	-	-	V_{th} temperature coefficient (CRYOMOD $\neq$ 0)
KT12	K^{-1}	0.1	-	-	V_{th} temperature coefficient (CRYOMOD $\neq$ 0)
TVTH	K	40.0	-	-	Transition temperature in V_{th} temperature model (CRYOMOD $\neq$ 0)
TSS$^{(b)}$	K^{-1}	0.0	-	-	Subthreshold Swing Temperature Coefficient
TLOW	K	50.0	0.0	-	Transition temperature of SS at low temperatures (CRYOMOD $\neq$ 0)
DTLOW	K	1.0	> 0	-	Smoothing parameter for TLOW (CRYOMOD $\neq$ 0)
TLOW1	K	0.0	0.0	-	Transition temperature of SS at low temperatures (CRYOMOD $\neq$ 0)
DTLOW1	K	1.0e-3	> 0	-	Smoothing parameter for TLOW1 (CRYOMOD $\neq$ 0)
KLOW1	-	0.0	0.0	-	Slope magnitude of effective low temperature below TLOW1 (CRYOMOD $\neq$ 0)
TETA0	K^{-1}	0.0	-	-	Temperature dependence of DIBL coefficient
TETA0R	K^{-1}	0.0	-	-	Temperature dependence of Reverse-mode DIBL coefficient
UTE$^{(b)}$	-	0.0	-	-	Mobility Temperature Coefficient
UTL$^{(b)}$	-	-1.5e-3	-	-	Mobility Temperature Coefficient
UTE1$^{(b)}$	-	-0.4	-	-	Mobility Temperature Coefficient for U0 (CRYOMOD $\neq$ 0)
EMOBT$^{(b)}$	-	0.0	-	-	Temperature Coefficient of ETAMOB
UA1$^{(b)}$	-	1.032e-3	-	-	Mobility Temperature Coefficient for UA

Name	Unit	Default	Min	Max	Description
UA2$^{(b)}$	-	-0.04	-	-	Mobility Temperature Coefficient for UA (CRYOMOD $\neq$ 0)
UC1$^{(b)}$	-	0.056e-9	-	-	Mobility Temperature Coefficient for UC
UD1$^{(b)}$	-	0.0	-	-	Mobility Temperature Coefficient
UD2$^{(b)}$	-	-0.04	-	-	Mobility Temperature Coefficient for UD (CRYOMOD $\neq$ 0)
UCSTE$^{(b)}$	-	-4.775e-3	-	-	Mobility Temperature Coefficient
UCSTE1$^{(b)}$	-	-0.04	-	-	Mobility Temperature Coefficient for UCS (CRYOMOD $\neq$ 0)
UDS1$^{(b)}$	-	-10	-	-	Mobility Temperature Coefficient for UDS (CRYOMOD $\neq$ 0)
UDD1$^{(b)}$	-	-10	-	-	Mobility Temperature Coefficient for UDD (CRYOMOD $\neq$ 0)
AT$^{(b)}$	K^{-1}	-0.00156	-	-	Saturation Velocity Temperature Coefficient
AT2	K^{-2}	2.0e-6	-	-	Saturation Velocity Temperature Coefficient (CRYOMOD $\neq$ 0)
ATCV$^{(b)}$	K^{-1}	AT	-	-	Saturation Velocity Temperature Coefficient for C-V
AT2CV$^{(b)}$	K^{-2}	AT2	-	-	Saturation Velocity Temperature Coefficient for C-V (CRYOMOD $\neq$ 0)
ATVSRSD$^{(b)}$	K^{-1}	0	-	-	Saturation Velocity Temperature Coefficient for source/drain resistance
KSATIVT1	K^{-1}	-2.0e-4	-	-	Temperature Coefficient for KSATIV (CRYOMOD $\neq$ 0)
KSATIVT2	K^{-2}	-2.0e-7	-	-	Temperature Coefficient for KSATIV (CRYOMOD $\neq$ 0)
PCLMT	$1/K$	-2.0e-5	-	-	PCLM Temperature Coefficient
A11$^{(b)}$	$V^{-2}K^{-1}$	0.0	-	-	Temperature dependence of non-saturation effect parameter for strong inversion region
A21$^{(b)}$	$V^{-1}K^{-1}$	0.0	-	-	Temperature dependence of non-saturation effect parameter for moderate inversion region
K01$^{(b)}$	VK^{-1}	0.0	-	-	Temperature dependence of K0
K0SI1$^{(b)}$	K^{-1}	0.0	-	-	Temperature dependence of K0SI
K11$^{(b)}$	$V^{1/2}K^{-1}$	0.0	-	-	Temperature dependence of K1
TMEXP$^{(b)}$	K^{-1}	0.0	-	-	Temperature Coefficient for V_{dseff} smoothing

Name	Unit	Default	Min	Max	Description
TMEXPR$^{(b)}$	K^{-1}	TMEXP	-	-	Reverse-mode Temperature Coefficient for V_{dseff} smoothing
TMEXP2	K^{-2}	-4.0e-6	-	-	Temperature Coefficient for V_{dseff} smoothing (CRYOMOD $\neq 0$)
PTWGT$^{(b)}$	K^{-1}	0.004	-	-	PTWG Temperature Coefficient
PRT$^{(b)}$	K^{-1}	0.001	-	-	Series resistance temperature Coefficient
PRTVSRSD$^{(b)}$	K^{-1}	0.001	-	-	Temperature coefficient of resistance in S/D velocity saturation model
PRT1$^{(b)}$	K^{-1}	4.0e-4	-	-	Series resistance temperature coefficient at low temperatures (CRYOMOD $\neq 0$)
TR0$^{(b)}$	K	170.0	-	-	Corner temperature in dual-slope temperature model of series resistance (CRYOMOD $\neq 0$)
SPRT$^{(b)}$	-	0.01	-	-	Smoothing parameter for TR0 (CRYOMOD $\neq 0$)
TRSDR$^{(b)}$	K^{-1}	0.0	-	-	Source side drift resistance Temperature Coefficient
TRDDR$^{(b)}$	K^{-1}	TRSDR	-	-	Drain side drift resistance Temperature Coefficient
IIT$^{(b)}$	-	-0.5	-	-	Impact Ionization Temperature Coefficient (IIMOD=1)
TII$^{(b)}$	-	0.0	-	-	Impact Ionization Temperature Coefficient (IIMOD=2)
ALPHA01$^{(b)}$	$m \cdot V^{-1}K^{-1}$	0.0	-	-	Temperature dependence of ALPHA0
ALPHA11 $^{(b)}$	$V^{-1}K^{-1}$	0.0	-	-	Temperature dependence of ALPHA1
ALPHAII01$^{(b)}$	$m \cdot V^{-1}K^{-1}$	0.0	-	-	Temperature dependence of ALPHAII0
ALPHAII11 $^{(b)}$	$V^{-1}K^{-1}$	0.0	-	-	Temperature dependence of ALPHAII1
TGIDL$^{(b)}$	K^{-1}	-0.003	-	-	GISL/GIDL Temperature Coefficient
IGT$^{(b)}$	-	2.5	-	-	Gate Current Temperature Coefficient
AIGBINV1$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}K^{-1}$	0.0	-	-	Temperature dependence of AIGBINV
AIGBACC1$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}K^{-1}$	0.0	-	-	Temperature dependence of AIGBACC
AIGC1$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}K^{-1}$	0.0	-	-	Temperature dependence of AIGC
AIGS1$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}K^{-1}$	0.0	-	-	Temperature dependence of AIGS
AIGD1$^{(b)}$	$(Fs^2g^{-1})^{0.5}m^{-1}K^{-1}$	0.0	-	-	Temperature dependence of AIGD
TCJ	K^{-1}	0.0	-	-	Temperature coefficient for CJS/CJD
TCJSW	K^{-1}	0.0	-	-	Temperature coefficient for CJSWS/CJSWD

Name	Unit	Default	Min	Max	Description
TCJSWG	K^{-1}	0.0	-	-	Temperature coefficient for CJSWGS/CJSWGD
TPB	K^{-1}	0.0	-	-	Temperature coefficient for PBS/PBD
TPBSW	K^{-1}	0.0	-	-	Temperature coefficient for PBSWS/PBSWD
TPBSWG	K^{-1}	0.0	-	-	Temperature coefficient for PBSWGS/PBSWGD
XTIS	-	3.0	-	-	Source junction current temperature exponent
XTID	-	XTIS	-	-	Drain junction current temperature exponent
XTSS	-	0.02	-	-	Power dependence of JTSS on temperature
XTSD	-	XTSS	-	-	Power dependence of JTSD on temperature
XTSSWS	-	0.02	-	-	Power dependence of JTSSWS on temperature
XTSSWD	-	XTSSWS	-	-	Power dependence of JTSSWD on temperature
XTSSWGS	-	0.02	-	-	Power dependence of JTSSWGS on temperature
XTSSWGD	-	XTSSWGS	-	-	Power dependence of JTSSWGD on temperature
TNJTS	-	0.0	-	-	Temperature coefficient for NJTS
TNJTSD	-	TNJTS	-	-	Temperature coefficient for NJTSD
TNJTSSW	-	0.0	-	-	Temperature coefficient for NJTSSW
TNJTSSWD	-	TNJTSSW	-	-	Temperature coefficient for NJTSSWD
TNJTSSWG	-	0.0	-	-	Temperature coefficient for NJTSSWG
TNJTSSWGD	-	TNJTSSWG	-	-	Temperature coefficient for NJTSSWGD
RTH0	$\Omega m \cdot K \cdot W^{-1}$	0.01	0.0	-	Thermal resistance for self-heating calculation
CTH0	$Ws(m \cdot K)^{-1}$	1.0e-5	0.0	-	Thermal capacitance for self-heating calculation
WTH0	m	0.0	0.0	-	Width-dependence coefficient for self-heating calculation
ASHEXP	-	1.0	0.0	-	Exponent to tune RTH dependence of NFINTOTAL
BSHEXP	-	1.0	0.0	-	Exponent to tune RTH dependence of NF

Name	Unit	Default	Min	Max	Description
CSHEXP	-	1.0	0.0	-	Exponent to tune RTH dependence of NGAA
ASH	-	1.0	0.0	-	Coefficient to tune RTH dependence of NGAA
CSH	-	1.0	0.0	-	Coefficient to tune RTH dependence of NGAA

7.7 Parameters for Variability Modeling

A set of parameters causing variability in device behavior are identified. Users can associate appropriate variability function as appropriate. The list is open to modification with users feedbacks and suggestions. Other than DELVTRAND, UOMULT and IDS0MULT, the parameters listed here were already introduced previously as either instance parameters or model parameters. All of the following parameters should be elevated to instance parameter status if required for variability modeling or should be delegated to a model parameter status (unless introduced before as an instance parameter). **Note: parameters already introduced as instance parameters are marked: $^{(i)}$ and model parameters are marked: $^{(mod)}$**

Name	Unit	Default	Min	Max	Description
DTEMP	K	0.0	-	-	Device temperature shift handle
DELVTRAND	V	0.0	-	-	Threshold voltage shift handle
U0MULT	-	1.0	> 0	-	Multiplier to mobility (or more precisely divides D_{mob},D_{mobs})
IDS0MULT	-	1.0	0.0	-	Multiplier to source-drain channel current
IGB0MULT	-	1.0	0.0	-	Multiplier to gate-body current
IGC0MULT	-	1.0	0.0	-	Multiplier to gate-channel current
TFIN$^{(i)}$	m	15e-9	1e-9	-	Body (fin) thickness
FPITCH$^{(i)}$	m	80e-9	TFIN	-	Fin Pitch
XL$^{(mod)}$	m	0	-	-	L offset for channel length due to mask/etch effect
NBODY$^{(mod)}$	m^{-3}	1e22	-	-	Channel (body) doping concentration
EOT$^{(mod)}$	m	1.0e-9	1e-10	-	SiO_2 equivalent gate dielectric thickness (including inversion layer thickness)
TOXP$^{(mod)}$	m	1.2e-9	1e-10	-	Physical oxide thickness
RSHS$^{(mod)}$	Ω	0.0	0.0	-	Source-side sheet resistance
RSHD$^{(mod)}$	Ω	RSHS	0.0	-	Drain-side sheet resistance
RHOC$^{(mod)}$	Ωm^2	1e-12	1e-18	$1e-9$	Contact resistivity at the silicon/silicide interface
RHORSD$^{(mod)}$	Ωm	1	0	-	Average resistivity of silicon in the raised source/drain region

8 Model Parameter Output

8.1 Built-in Model Operating Point Outputs

8.1.1 Output variables when Verilog-A is compiled with __INFO__ enabled

Name	**Unit**	**Description**	**Equation**
WEFF	m	Effective width for I-V	(3.22)
LEFF	m	Effective length for I-V	(3.12)
WEFFCV	m	Effective width for C-V	(3.21)
LEFFCV	m	Effective length for C-V	(3.14)
IDS	A	Drain-to-source current	(3.575)
IDEFF	A	Total current flowing out of drain	
ISEFF	A	Total current flowing out of source	
IGTOT	A	total current flowing out of gate	
IDSGEN	A	Generation-recombination current	(3.769)
III	A	Impact ionization current	(4.92, 4.93)
IGS	A	Gate-to-source tunneling current	(3.761)
IGD	A	Gate-to-drain tunneling current	(3.762)
IGCS	A	Gate-to-channel tunneling current to source	(3.754
IGCD	A	Gate-to-channel tunneling current to drain	(3.755)
IGBS	A	Gate-to-body tunneling current to source	(3.747)
IGBD	A	Gate-to-body tunneling current to drain	(3.748)
IGIDL	A	Gate-induced drain leakage at drain side	(3.499)
IGISL	A	Gate-induced drain leakage at source side	(3.501)
IJSB	A	Source-to-substrate current	(3.808)
IJDB	A	Drain-to-substrate current	(3.789)
ISUB	A	Total current flowing out of substrate	
BETA	AV^{-2}	Drain current pre-factor per fin per finger	
VTH	V	Analytic threshold voltage	(3.873)
VDSSAT	V	Drain-source saturation voltage	(3.485)
VDSEFF	V	Effective drain-source saturation voltage	(3.486)
VFB	V	Flatband voltage	(3.192), (3.193)
GM	S	$\partial I_{ds}/\partial V_{gs}$	
GDS	S	$\partial I_{ds}/\partial V_{ds}$	
GMBS	S	$\partial I_{ds}/\partial V_{bs}$	
QGI	C	Intrinsic gate charge	
QDI	C	Intrinsic drain charge	

Name	Unit	Description	Equation
QSI	C	Intrinsic source charge	
QBI	C	Intrinsic body charge	
QG	C	Total gate charge	
QD	C	Total drain charge	
QS	C	Total source charge	
QB	C	Total body charge	
CGGI	F	$\partial Q_{g,intrinsic}/\partial V_g$	
CGSI	F	$\partial Q_{g,intrinsic}/\partial V_s$	
CGDI	F	$\partial Q_{g,intrinsic}/\partial V_d$	
CGEI	F	$\partial Q_{g,intrinsic}/\partial V_e$	
CDGI	F	$\partial Q_{d,intrinsic}/\partial V_g$	
CDDI	F	$\partial Q_{d,intrinsic}/\partial V_d$	
CDSI	F	$\partial Q_{d,intrinsic}/\partial V_s$	
CDEI	F	$\partial Q_{d,intrinsic}/\partial V_e$	
CSGI	F	$\partial Q_{s,intrinsic}/\partial V_g$	
CSDI	F	$\partial Q_{s,intrinsic}/\partial V_d$	
CSSI	F	$\partial Q_{s,intrinsic}/\partial V_s$	
CSEI	F	$\partial Q_{s,intrinsic}/\partial V_e$	
CEGI	F	$\partial Q_{e,intrinsic}/\partial V_g$	
CEDI	F	$\partial Q_{e,intrinsic}/\partial V_d$	
CESI	F	$\partial Q_{e,intrinsic}/\partial V_s$	
CEEI	F	$\partial Q_{e,intrinsic}/\partial V_e$	
CGG	F	$\partial Q_{g,total}/\partial V_g$	
CGS	F	$\partial Q_{g,total}/\partial V_s$	
CGD	F	$\partial Q_{g,total}/\partial V_d$	
CGE	F	$\partial Q_{g,total}/\partial V_e$	
CDG	F	$\partial Q_{d,total}/\partial V_g$	
CDD	F	$\partial Q_{d,total}/\partial V_d$	
CDS	F	$\partial Q_{d,total}/\partial V_s$	
CDE	F	$\partial Q_{d,total}/\partial V_e$	
CSG	F	$\partial Q_{s,total}/\partial V_g$	
CSD	F	$\partial Q_{s,total}/\partial V_d$	
CSS	F	$\partial Q_{s,total}/\partial V_s$	
CSE	F	$\partial Q_{s,total}/\partial V_e$	
CEG	F	$\partial Q_{e,total}/\partial V_g$	
CED	F	$\partial Q_{e,total}/\partial V_d$	
CES	F	$\partial Q_{e,total}/\partial V_s$	
CEE	F	$\partial Q_{e,total}/\partial V_e$	
CGSEXT	F	Gate-source overlap and outer fringing capacitance	

Name	Unit	Description	Equation
CGDEXT	F	Gate-drain overlap and outer fringing capacitance	
CGBOV	F	Gate-body overlap capacitance	
CJST	F	Junction and overlap capacitance at source side	
CJDT	F	Junction and overlap capacitance at drain side	
RSGEO	F	External bias-independent source resistance	(3.459), (3.474)
RDGEO	F	External bias-independent drain resistance	(3.460), (3.474)
CFGEO	F	Geometric parasitic capacitance for CGEOMOD = 1	(3.499)
T_TOTAL_K	K	Device temperature including self-heating	
T_TOTAL_C	C	Device temperature including self-heating	
T_DELTA_SH	C or K	Temperature rise due to self-heating	

8.1.2 Output variables when Verilog-A is compiled with __INFO__ and __DEBUG__ enabled

Name	Unit	Description	Equation
IGBACC	A	Accumulation component of I_{gb}	(3.523)
IGBINV	A	Inversion component of I_{gb}	(3.515)
DIDSDVG	S	$\partial I_{ds}/\partial V_g$	
DIDSDVS	S	$\partial I_{ds}/\partial V_s$	
DIDSDVD	S	$\partial I_{ds}/\partial V_d$	
DIGSDVG	S	$\partial I_{gs}/\partial V_g$	
DIGSDVS	S	$\partial I_{gs}/\partial V_s$	
DIGSDVD	S	$\partial I_{gs}/\partial V_d$	
DIGDDVG	S	$\partial I_{gd}/\partial V_g$	
DIGDDVS	S	$\partial I_{gd}/\partial V_s$	
DIGDDVD	S	$\partial I_{gd}/\partial V_d$	
DIIIDVG	S	$\partial I_{ii}/\partial V_g$	
DIIIDVS	S	$\partial I_{ii}/\partial V_s$	
DIIIDVD	S	$\partial I_{ii}/\partial V_d$	
DIGIDLDVG	S	$\partial I_{gidl}/\partial V_g$	
DIGIDLDVS	S	$\partial I_{gidl}/\partial V_s$	
DIGIDLDVD	S	$\partial I_{gidl}/\partial V_d$	
DIGISLDVG	S	$\partial I_{gisl}/\partial V_g$	
DIGISLDVS	S	$\partial I_{gisl}/\partial V_s$	
DIGISLDVD	S	$\partial I_{gisl}/\partial V_d$	
ITH	$A \cdot V$	Thermal subcircuit current	
DITHDVG	S	$\partial I_{TH}/\partial V_g$	
DITHDVS	S	$\partial I_{TH}/\partial V_s$	

Name	Unit	Description	Equation
DITHDVD	S	$\partial I_{TH}/\partial V_d$	

8.1.3 Output variables when Verilog-A is compiled with __INFO__ and __DEBUG__ and __SHMOD__ enabled

Name	Unit	Description	Equation
CGT	F	$\partial Q_g/\partial V_{thermal}$	
CST	F	$\partial Q_s/\partial V_{thermal}$	
CDT	F	$\partial Q_d/\partial V_{thermal}$	
DIDSDVTH	S	$\partial I_{ds}/\partial V_{thermal}$	
DIGSDVTH	S	$\partial I_{gs}/\partial V_{thermal}$	
DIGDDVTH	S	$\partial I_{gd}/\partial V_{thermal}$	
DIIIDVTH	S	$\partial I_{ii}/\partial V_{thermal}$	
DIGIDLDVTH	S	$\partial I_{gidl}/\partial V_{thermal}$	
DIGISLDVTH	S	$\partial I_{gisl}/\partial V_{thermal}$	
DITHDVTH	A	$\partial I_{thermal}/\partial V_{thermal}$	

9 History of BSIM-CMG Models

- BSIM-CMG 106.0.0 was officially released on 3/1/2012. BSIM-CMG 106.0.0 was the first standard model for FinFETs.
- BSIM-CMG 106.1.0 was officially released on 9/11/2012.
- BSIM-CMG 107.0.0 was officially released on 7/12/2013.
- BSIM-CMG 108.0.0 was officially released on 8/22/2014.
- BSIM-CMG 109.0.0 was officially released on 11/19/2015.
- BSIM-CMG 110.0.0 was officially released on 1/1/2016.
- BSIM-CMG 111.0.0 was officially released on 9/12/2019.
- BSIM-CMG 111.1.0 was officially released on 01/14/2021.
- BSIM-CMG 111.2.0 was officially released on 04/15/2022.
- BSIM-CMG 111.2.1 was officially released on 06/06/2022.

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