Appendix C: Equation List

Equation List for BSIMSOI Built-In Potential Lowering Calculation

If SoiMod=0 (default), the model equation is identical to BSIMPD equation.

If SoiMod=1 (unified model for PD&FD) or SoiMod=2 (ideal FD), the following equations (FD module) are added on top of BSIMPD.

$$V_{bs0} = \frac{C_{Si}}{C_{Si} + C_{BOX}} \cdot \left(phi - \frac{qN_{ch}}{2\varepsilon_{Si}} \cdot T_{Si}{}^{2} + V_{nonideal} + \Delta V_{DIBL} \right) + \eta_e \frac{C_{BOX}}{C_{Si} + C_{BOX}} \cdot \left(V_{es} - V_{FBb} \right)$$

$$\text{where } C_{Si} = \frac{\varepsilon_{Si}}{T_{Si}}, C_{BOX} = \frac{\varepsilon_{OX}}{T_{BOX}}, C_{OX} = \frac{\varepsilon_{OX}}{T_{OX}}$$

$$\Delta V_{DIBL} = D_{vbd0} \left(\exp\left(-D_{vbd1} \frac{L_{eff}}{2l} \right) + 2\exp\left(-D_{vbd1} \frac{L_{eff}}{l} \right) \right) \cdot \left(V_{bi} - 2\Phi_B \right)$$

$$\eta_e = K_{1b} - K_{2b} \cdot \left(exp\left(-D_{k2b} \frac{L_{eff}}{2l} \right) + 2\,exp\left(-D_{k2b} \frac{L_{eff}}{l} \right) \right)$$

$$phi = phi_{ON} - \frac{C_{OX}}{C_{OX} + \left(C_{Si}{}^{-1} + C_{BOX}{}^{-1} \right)^{-1}} \cdot N_{OFF,FD} V_t \cdot ln\left(1 + exp\left(\frac{V_{th,FD} - V_{gs\_eff} - V_{OFF,FD}}{N_{OFF,FD} V_t} \right) \right)$$

$$phi_{ON} = 2\Phi_B + V_t\, ln\left(1 + \frac{V_{gsteff.FD}\left(V_{gsteff,FD} + 2K1\sqrt{2\Phi_B} \right)}{MoinFD \cdot K1 \cdot V_t{}^{2}} \right),$$

$$V_{gsteff,FD} = N_{OFF,FD} V_t \cdot ln\left(1 + exp\left(\frac{V_{gs\_eff} - V_{th,FD} - V_{OFF,FD}}{N_{OFF,FD} V_t} \right) \right)$$

Here Nch is the channel doping concentration. V_{FBb} is the backgate flatband voltage. $V_{th,FD}$ is the threshold voltage at V_{bs}=V_{bs0}(phi=2Φ_B). V_t is thermal voltage. K1 is the body effect coefficient.

If SoiMod=1, the lower bound of V_{bs} (SPICE solution) is set to V_{bs0}. If SoiMod=2, V_{bs} is pinned at V_{bs0}. Notice that there is no body node and body leakage/charge calculation in SoiMod=2.

The zero field body potential that will determine the transistor threshold voltage, V_{bsmos}, is then calculated by

$$\begin{aligned} V_{bsmos} &= V_{bs} - \frac{C_{Si}}{2qN_{ch}T_{Si}}\left(V_{bs0}\left(T_{OX} \to \infty\right) - V_{bs}\right)^2 \quad \text{if } V_{bs} \le V_{bs0}\left(T_{OX} \to \infty\right) \\ &= V_{bs} \quad \text{else} \end{aligned}$$

The subsequent clamping of V_{bsmos} will use the same equation that utilized in BSIMPD.

Equation List for BSIMPD IV

Body Voltages

V_{bsh} is equal to the V_{bs} bounded between (V_{bsc}, ϕ_{s1}). V_{bsh} is used in V_{th} and A_{bulk} calculation

$$T_1 = V_{bsc} + 0.5\left[V_{bs} - V_{bsc} - \delta + \sqrt{(V_{bs} - V_{bsc} - \delta)^2 - 4\delta V_{bsc}}\right],\ V_{bsc} = -5V$$

$$V_{bsh} = \phi_{s1} - 0.5\left[\phi_{s1} - T_1 - \delta + \sqrt{(\phi_{s1} - T_1 - \delta)^2 + 4\delta T_1}\right],\ \phi_{s1} = 1.5V$$

V_{bsh} is further limited to $0.95\phi_s$ to give V_{bseff}.

$$V_{bseff} = \phi_{s0} - 0.5\left[\phi_{s0} - V_{bsh} - \delta + \sqrt{\left(\phi_{s0} - V_{bsh} - \delta\right)^2 + 4\delta V_{bsh}}\right],\ \phi_{s0} = 0.95\phi_s$$

Effective Channel Length and Width

$$dW' = W_{\text{int}} + \frac{W_l}{L^{W_{\ln}}} + \frac{W_w}{W^{W_{wn}}} + \frac{W_{wl}}{L^{W_{\ln}} W^{W_{wn}}}$$

$$dW = dW' + dW_g V_{gsteff} + dW_b\left(\sqrt{\Phi_s - V_{bseff}} - \sqrt{\Phi_s}\right)$$

$$dL = L_{\text{int}} + \frac{L_l}{L^{L_{\ln}}} + \frac{L_w}{W^{L_{wn}}} + \frac{L_{wl}}{L^{L_{\ln}} W^{L_{wn}}}$$

$$L_{eff} = L_{drawn} - 2dL$$

$$W_{eff} = W_{drawn} - N_{bc} dW_{bc} - (2 - N_{bc}) dW$$

$$W_{eff}' = W_{drawn} - N_{bc} dW_{bc} - (2 - N_{bc}) dW'$$

$$W_{diod} = \frac{W_{eff}'}{N_{seg}} + P_{dbcp}$$

$$W_{dios} = \frac{W_{eff}'}{N_{seg}} + P_{sbcp}$$

Threshold Voltage

$$V_{th} = V_{tho} + (K_{1ox} sqrtPhisExt - K_{1eff} \sqrt{\Phi_s}) \sqrt{1 + \frac{LPEB}{L_{eff}}} - K_{2ox} V_{bseff}$$
$$+ K_{1ox} (\sqrt{1 + \frac{LPE0}{L_{eff}}} - 1) \sqrt{\Phi_s} + (K_3 + K_{3b} V_{bseff}) \frac{T_{ox}}{W_{eff}' + W_o} \Phi_s$$
$$- D_{VT0w} (\exp(-D_{VT1w} \frac{W_{eff}' L_{eff}}{2 l_{tw}}) + 2 \exp(-D_{VT1w} \frac{W_{eff}' L_{eff}}{l_{tw}}))(V_{bi} - \Phi_s)$$
$$- D_{VT0} (\exp(-D_{VT1} \frac{L_{eff}}{2 l_t}) + 2 \exp(-D_{VT1} \frac{L_{eff}}{l_t}))(V_{bi} - \Phi_s)$$
$$- (\exp(-D_{sub} \frac{L_{eff}}{2 l_{to}}) + 2 \exp(-D_{sub} \frac{L_{eff}}{l_{to}}))(E_{tao} + E_{tab} V_{bseff}) V_{ds}$$
$$- n v_t \cdot \ln \left(\frac{L_{eff}}{L_{eff} + DVTP0 \cdot (1 + e^{-DVTP1 \cdot V_{DS}}} \right)$$

$$l_t = \sqrt{\varepsilon_{si} X_{dep} / C_{ox}} (1 + D_{VT2} V_{bseff})$$

$$sqrtPhisExt = \sqrt{\phi_s - V_{bseff}} + s \left(V_{bsh} - V_{bseff} \right), \quad s = -\frac{1}{2\sqrt{\phi_s - \phi_{s0}}}$$

$$K_{1eff} = K_1 \left(1 + \frac{K_{1w1}}{W_{eff}' + K_{1w2}} \right)$$

$$K_{1ox} = K_{1eff} \frac{TOX}{TOXM}$$

$$K_{2ox} = K_2 \frac{TOX}{TOXM}$$

$$l_{tw} = \sqrt{\varepsilon_{si}\ X_{dep} / C_{ox}}(1 + D_{VT2w}V_{bseff}) \qquad l_{to} = \sqrt{\varepsilon_{si} X_{dep0} / C_{ox}}$$

$$X_{dep} = \sqrt{\frac{2\varepsilon_{si}(\Phi_s - V_{bseff})}{qN_{ch}}} \qquad X_{dep0} = \sqrt{\frac{2\varepsilon_{si}\Phi_s}{qN_{ch}}}$$

$$V_{bi} = v_t \ln(\frac{N_{ch}N_{DS}}{n_i^{\ 2}})$$

Poly depletion effect

$$V_{poly} + \frac{1}{2} X_{poly}E_{poly} = \frac{qN_{gate}X^2{}_{poly}}{2\varepsilon_{si}}$$

$$\varepsilon_{ox}E_{ox} = \varepsilon_{si}E_{poly} = \sqrt{2q\varepsilon_{si}N_{gate}V_{poly}}$$

$$V_{gs} - V_{FB} - \phi_x = V_{poly} + V_{ox}$$

$$a(V_{gs} - V_{FB} - \phi_s - V_{poly})^2 - V_{poly} = 0$$

$$a = \frac{\varepsilon^2{}_{ox}}{2q\varepsilon_{si}N_{gate}T^2{}_{ox}}$$

$$V_{gs\_eff} = V_{FB} + \phi_s + \frac{q\varepsilon_{si}N_{gate}T^2{}_{ox}}{\varepsilon^2{}_{ox}}\left[\sqrt{1 + \frac{2\varepsilon^2_{ox}(V_{gs} - V_{FB} - \phi_s)}{q\varepsilon_{si}N_{gate}T^2{}_{ox}}} - 1\right]$$

Effective V_{gst} for all region (with Polysilicon Depletion Effect)

$$V_{gsteff} = \frac{nv_t \ln[1 + \exp(\frac{m^*(V_{gs\_eff} - Vth)}{nv_t})]}{m^* + nCox\sqrt{\frac{2\Phi_s}{q\varepsilon_{si}N_{dep}}} \exp(-\frac{(1-m^*)(V_{gs\_eff} - Vth) - Voff}{nv_t})}$$

$$m^* = 0.5 + \frac{\arctan(MINV)}{\pi}$$

$$n = 1 + N_{factor}\frac{\varepsilon_{si}/X_{dep}}{C_{ox}} + \frac{(C_{dsc} + C_{dscd}V_{ds} + C_{dscb}V_{bseff})\left[\exp(-D_{VT1}\frac{L_{eff}}{2l_t}) + 2\exp(-D_{VT1}\frac{L_{eff}}{l_t})\right]}{C_{ox}} + \frac{C_{it}}{C_{ox}}$$

Effective Bulk Charge Factor

$$A_{bulk} = 1 + \left(\frac{K_{1ox}\cdot\sqrt{1+LPEB/L_{eff}}}{2\sqrt{(\phi_s + Ketas) - \frac{V_{bsh}}{1+Keta\cdot V_{bsh}}}} \left(\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{T_{si}X_{dep}}} \left(1 - A_{gs}V_{gsteff}\left(\frac{L_{eff}}{L_{eff} + 2\sqrt{T_{si}X_{dep}}} \right)^2 \right) + \frac{B_0}{W'_{eff} + B_1} \right) \right)$$

$$A_{bulk0} = A_{bulk}\left(V_{gsteff} = 0\right)$$

Mobility and Saturation Velocity

For Mobmod=1

$$\mu_{eff} = \frac{\mu_o}{1 + (U_a + U_c V_{bseff})(\frac{V_{gsteff} + 2V_{th}}{T_{ox}}) + U_b(\frac{V_{gsteff} + 2V_{th}}{T_{ox}})^2}$$

For Mobmod=2

$$\mu_{eff} = \frac{\mu_o}{1 + (U_a + U_c V_{bseff})(\frac{V_{gsteff}}{T_{ox}}) + U_b(\frac{V_{gsteff}}{T_{ox}})^2}$$

For Mobmod=3

$$\mu_{eff} = \frac{\mu_0}{1 + [U_a(\frac{V_{gstef} + 2V_{th}}{T_{ox}}) + U_b(\frac{V_{gsteff} + 2V_{th}}{T_{ox}})^2](1 + U_c V_{bseff})}$$

Drain Saturation Voltage

For R_{ds}>0 or $\lambda \neq 1$:

$$V_{dsat} = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

$$a = A_{bulk}{}^2 W_{eff} \nu_{sat} C_{ox} R_{ds} + (\frac{1}{\lambda} - 1) A_{bulk}$$

$$b = -\left[(V_{gsteff} + 2\nu_t)(\frac{2}{\lambda} - 1) + A_{bulk} E_{sat} L_{eff} + 3A_{bulk}(V_{gsteff} + 2\nu_t) W_{eff} \nu_{sat} C_{ox} R_{ds} \right]$$

$$c = (V_{gsteff} + 2\nu_t) E_{sat} L_{eff} + 2(V_{gsteff} + 2\nu_t)^2 W_{eff} \nu_{sat} C_{ox} R_{ds}$$

$$\lambda = A_1 V_{gsteff} + A_2$$

For R_{ds}=0, λ=1:

$$V_{dsat} = \frac{E_{sat} L_{eff} (V_{gsteff} + 2\nu_t)}{A_{bulk} E_{sat} L_{eff} + (V_{gsteff} + 2\nu_t)}$$

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

V_{dseff}

$$V_{dseff} = V_{dsat} - \frac{1}{2}\left[V_{dsat} - V_{ds} - \delta + \sqrt{(V_{dsat} - V_{ds} - \delta)^2 + 4\delta V_{dsat}} \right]$$

Drain current expression

$$I_{ds,MOSFET} = \frac{1}{N_{seg}} \frac{I_{ds0}(V_{dseff})}{1 + \frac{R_{ds} I_{dso}(V_{dseff})}{V_{dseff}}} (1 + \frac{V_{ds} - V_{dseff}}{V_A})$$

$$\beta = \mu_{eff} C_{ox} \frac{W_{eff}}{L_{eff}}$$

$$I_{dso} = \frac{\beta V_{gsteff}\left(1 - A_{bulk}\frac{V_{dseff}}{2\left(V_{gsteff} + 2\nu_t\right)}\right)V_{dseff}}{1 + \frac{V_{dseff}}{E_{sat}L_{eff}}}$$

$$V_A = V_{Asat} + \left(1 + \frac{P_{vag}V_{gsteff}}{E_{sat}L_{eff}}\right)\left(\frac{1}{V_{ACLM}} + \frac{1}{V_{ADIBLC}}\right)^{-1}$$

$$V_{ACLM} = \frac{A_{bulk}E_{sat}L_{eff} + V_{gsteff}}{P_{clm}A_{bulk}E_{sat}litl}(V_{ds} - V_{dseff})$$

$$V_{ADIBLC} = \frac{(V_{gsteff} + 2\nu_t)}{\theta_{rout}(1 + P_{DIBLCB}V_{bseff})}\left(1 - \frac{A_{bulk}V_{dsat}}{A_{bulk}V_{dsat} + 2\nu_t}\right)$$

$$\theta_{rout} = P_{DIBLC1}\left[\exp\left(-D_{ROUT}\frac{L_{eff}}{2l_{t0}}\right) + 2\exp\left(-D_{ROUT}\frac{L_{eff}}{l_{t0}}\right)\right] + P_{DIBLC2}$$

$$V_{Asat} = \frac{E_{sat}L_{eff} + V_{dsat} + 2R_{ds}\nu_{sat}C_{ox}W_{eff}V_{gsteff}\left[1 - \frac{A_{bulk}V_{dsat}}{2(V_{gsteff} + 2\nu_t)}\right]}{2/\lambda - 1 + R_{ds}\nu_{sat}C_{ox}W_{eff}A_{bulk}}$$

$$litl = \sqrt{\frac{\varepsilon_{si}T_{ox}T_{Si}}{\varepsilon_{ox}}}$$

Drain/Source Resistance

• ***rdsMod*** = 0 (Internal *Rds*(V))

$$R_{ds} = R_{dsw}\frac{1 + P_{rwg}V_{gsteff} + P_{rwb}\left(\sqrt{\phi_s - V_{bseff}} - \sqrt{\phi_s}\right)}{\left(10^6 W'_{eff}\right)^{Wr}}$$

• ***rdsMod*** = 1 (External *Rd*(V) and *Rs*(V))

$$R_d(V) = \frac{RDWMIN + RDW \cdot \left[-PRWB \cdot V_{bd} + \frac{1}{1 + PRWG \cdot (V_{gd} - V_{fbsd})} \right]}{\left(1e6 \cdot W_{eff}\right)^{WR} \cdot NF}$$

$$R_s(V) = \frac{RSWMIN + RSW \cdot \left[-PRWB \cdot V_{bs} + \frac{1}{1 + PRWG \cdot (V_{gs} - V_{fbsd})} \right]}{\left(1e6 \cdot W_{eff}\right)^{WR} \cdot NF}$$

where $V_{fbsd} = \frac{k_B T}{q} \ln\left(\frac{N_{gate}}{10^{20}}\right)$ for NGATE larger than 0, otherwise $V_{fbsd} = 0$.

Impact Ionization Current

$$I_{ii} = \alpha_0 (I_{ds,MOSFET} + F_{bjtii} I_c) \exp\left(\frac{V_{diff}}{\beta_2 + \beta_1 V_{diff} + \beta_0 V_{diff}{}^2} \right)$$

$$V_{diff} = V_{ds} - V_{dsatii}$$

$$V_{dsatii} = VgsStep + \left[V_{dsatii0} \left(1 + T_{ii} \left(\frac{T}{T_{nom}} - 1 \right) \right) - \frac{L_{ii}}{L_{eff}} \right]$$

$$VgsStep = \left(\frac{E_{satii} L_{eff}}{1 + E_{satii} L_{eff}} \right) \left(\frac{1}{1 + S_{ii1} V_{gsteff}} + S_{ii2} \right) \left(\frac{S_{ii0} V_{gst}}{1 + S_{iid} V_{ds}} \right)$$

Gate-Induced-Drain-Leakage (GIDL)

$$\boldsymbol{I_{GIDL} = AGIDL \cdot W_{diod} \cdot Nf \cdot \frac{V_{ds} - V_{gse} - EGIDL}{3 \cdot T_{oxe}} \cdot \exp\left(-\frac{3 \cdot T_{oxe} \cdot BGIDL}{V_{ds} - V_{gse} - EGIDL} \right) \cdot \frac{V_{db}^3}{CGIDL + V_{db}^3}}$$

Oxide tunneling current

In inversion,

$$J_{gb} = A\frac{V_{gb}V_{aux}}{T_{ox}^2}\left(\frac{\mathrm{T_{oxref}}}{T_{oxqm}}\right)^{\mathrm{N_{tox}}} exp\left(\frac{-B(\alpha_{\mathrm{gb1}} - \beta_{\mathrm{gb1}}|V_{ox}|)T_{ox}}{1 - |V_{ox}|/\mathrm{V_{gb1}}}\right)$$

$$V_{aux} = \mathrm{V_{EVB}}\, ln\left(1 + exp\left(\frac{|V_{ox}| - \varphi_{\mathrm{g}}}{\mathrm{V_{EVB}}}\right)\right)$$

$$A = \frac{q^3}{8\pi h\phi_b}$$

$$B = \frac{8\pi\sqrt{2m_{ox}}\phi_b^{3/2}}{3hq}$$

$$\phi_b = 4.2eV$$

$$m_{ox} = 0.3m_0$$

In accumulation,

$$J_{gb} = A\frac{V_{gb}V_{aux}}{T_{ox}^2}\left(\frac{\mathrm{T_{oxref}}}{T_{oxqm}}\right)^{\mathrm{N_{tox}}} exp\left(\frac{-B(\alpha_{\mathrm{gb2}} - \beta_{\mathrm{gb2}}|V_{ox}|)T_{ox}}{1 - |V_{ox}|/\mathrm{V_{gb2}}}\right)$$

$$V_{aux} = \mathrm{V_{ECB}}V_t\, ln\left(1 + exp\left(-\frac{V_{gb} - V_{fb}}{\mathrm{V_{ECB}}}\right)\right)$$

$$A = \frac{q^3}{8\pi h\phi_b}$$

$$B = \frac{8\pi\sqrt{2m_{ox}}\phi_b^{3/2}}{3hq}$$

$$\phi_b = 3.1eV$$

$$m_{ox} = 0.4m_0$$

Body contact current

$$R_{bp} = \left(R_{body}\frac{W_{eff}'/N_{seg}}{L_{eff}}\right) \| \left(R_{halo}\frac{W_{eff}'/N_{seg}}{2}\right),\ R_{bodyext} = R_{bsh}N_{rb}$$

For 4-T device, $I_{bp} = 0$

For 5-T device,

$$I_{bp} = \frac{V_{bp}}{R_{bp} + R_{bodyext}}$$

Diode and BJT currents

Bipolar Transport Factor

$$\alpha_{bjt} = \exp\left[-0.5\left(\frac{L_{eff}}{L_n}\right)^2\right]$$

Body-to-Source/drain diffusion

$$\boldsymbol{I_{bs1} = W_{dios} T_{si} j_{difs} \left(\exp\left(\frac{V_{bs}}{n_{diode} V_t}\right) - 1\right)}$$

$$\boldsymbol{I_{bd1} = W_{diod} T_{si} j_{difd} \left(\exp\left(\frac{V_{bd}}{n_{dioded} V_t}\right) - 1\right)}$$

Recombination/trap-assisted tunneling current in depletion region

$$\boldsymbol{I_{bs2} = W_{dios} T_{si} j_{recs} \left(\exp\left(\frac{V_{bs}}{0.026 n_{recf}}\right) - \exp\left(\frac{V_{sb}}{0.026 n_{recr}} \frac{V_{rec0}}{V_{rec0} + V_{sb}}\right)\right)}$$

$$\boldsymbol{I_{bd2} = W_{diod} T_{si} j_{recd} \left(\exp\left(\frac{V_{bd}}{0.026 n_{recfd}}\right) - \exp\left(\frac{V_{db}}{0.026 n_{recrd}} \frac{V_{rec0d}}{V_{rec0d} + V_{db}}\right)\right)}$$

Reversed bias tunneling leakage

$$\boldsymbol{I_{bs4} = W_{dios} T_{si} j_{tuns} \left(1 - \exp\left(\frac{V_{sb}}{0.026 n_{tun}} \frac{V_{tun0}}{V_{tun0} + V_{sb}}\right)\right)}$$

$$\boldsymbol{I_{bd4} = W_{diod} T_{si} j_{tund} \left(1 - \exp\left(\frac{V_{db}}{0.026 n_{tund}} \frac{V_{tun0d}}{V_{tun0d} + V_{db}}\right)\right)}$$

Recombination current in neutral body

$$\boldsymbol{I_{bs3} = (1 - \alpha_{bjt}) I_{en} \left[\exp\left(\frac{V_{bs}}{n_{diode} V_t}\right) - 1\right] \frac{1}{\sqrt{E_{hli} + 1}}}$$

$$\boldsymbol{I_{bd3} = (1 - \alpha_{bjt}) I_{en} \left[\exp\left(\frac{V_{bd}}{n_{dioded} V_t}\right) - 1\right] \frac{1}{\sqrt{E_{hlid} + 1}}}$$

$$I_{ens} = \frac{W_{eff}^{'}}{N_{seg}} T_{si} j_{sbjt} \left[L_{bjt0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right]^{N_{bjt}}$$

$$I_{end} = \frac{W_{eff}^{'}}{N_{seg}} T_{si} j_{dbjt} \left[L_{bjt0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right]^{N_{bjt}}$$

$$E_{hlis} = A_{hli\_eff} \left[\exp\left(\frac{V_{bs}}{n_{diode} V_t} \right) - 1 \right]$$

$$E_{hlid} = A_{hli\_eff} \left[\exp\left(\frac{V_{bd}}{n_{dioded} V_t} \right) - 1 \right]$$

$$A_{hlis\_eff} = A_{hli} \exp\left[\frac{-E_g(300K)}{n_{diode} V_t} X_{bjt} \left(1 - \frac{T}{T_{nom}} \right) \right]$$

$$A_{hlid\_eff} = A_{hlid} \exp\left[\frac{-E_g(300K)}{n_{dioded} V_t} X_{bjt} \left(1 - \frac{T}{T_{nom}} \right) \right]$$

BJT collector current

$$I_c = \alpha_{bjt} I_{en} \left\{ \exp\left[\frac{V_{bs}}{n_{diodes} V_t} \right] - \exp\left[\frac{V_{bd}}{n_{dioded} V_t} \right] \right\} \frac{1}{E_{2nd}}$$

$$E_{2nd} = \frac{E_{ely} + \sqrt{E_{ely}^{\ 2} + 4E_{hli}}}{2}$$

$$E_{ely} = 1 + \frac{V_{bs} + V_{bd}}{V_{Abjt} + A_{ely} L_{eff}}$$

$$E_{hli} = E_{hlis} + E_{hlid}$$

Total body-source/drain current

$$I_{bs} = I_{bs1} + I_{bs2} + I_{bs3} + I_{bs4}$$

$$I_{bd} = I_{bd1} + I_{bd2} + I_{bd3} + I_{bd4}$$

Total body current

$$I_{ii} + I_{dgidl} + I_{sgidl} + I_{gb} - I_{bs} - I_{bd} - I_{bp} = 0$$

Temperature effects

$$V_{th(T)} = V_{th(Tnom)} + (K_{T1} + K_{t1l} / L_{eff} + K_{T2} V_{bseff})(T / T_{nom} - 1)$$

$$\mu_{o(T)} = \mu_{o(Tnom)} (\frac{T}{T_{nom}})^{\mu te} , \quad \nu_{sat(T)} = \nu_{sat(Tnom)} - A_T (T / T_{nom} - 1)$$

$$R_{dsw(T)} = R_{dsw(} T_{nom)} + P_{rt} (\frac{T}{T_{nom}} - 1)$$

$$U_{a(T)} = U_{a(Tnom)} + U_{a1} (T / T_{nom} - 1)$$

$$U_{b(T)} = U_{b(Tnom)} + U_{b1} (T / T_{nom} - 1)$$

$$U_{c(T)} = U_{c(Tnom)} + U_{c1} (T / T_{nom} - 1)$$

$$\boldsymbol{R_{th}} = \frac{\boldsymbol{R_{th0}}}{\left(\boldsymbol{W'_{eff}} + \boldsymbol{W_{th0}}\right) / \boldsymbol{N_{seg}}} , \quad \boldsymbol{C_{th}} = \boldsymbol{C_{th0}} \frac{\boldsymbol{W'_{eff}} + \boldsymbol{W_{th0}}}{\boldsymbol{N_{seg}}}$$

$$\boldsymbol{j_{sbjt}} = \boldsymbol{i_{sbjt}} \,\mathbf{exp}\left[\frac{-\boldsymbol{E_g}(300\boldsymbol{K})}{\boldsymbol{n_{diode}} \boldsymbol{V_t}} \boldsymbol{X_{bjt}} \left(1 - \frac{\boldsymbol{T}}{\boldsymbol{T_{nom}}}\right)\right]$$

$$j_{dbjt} = i_{dbjt} \exp\left[\frac{-E_g (300K)}{n_{dioded} V_t} X_{bjt} \left(1 - \frac{T}{T_{nom}}\right)\right]$$

$$\boldsymbol{j_{sdif}} = \boldsymbol{i_{sdif}} \,\mathbf{exp}\left[\frac{-\boldsymbol{E_g}(300\boldsymbol{K})}{\boldsymbol{n_{diode}} \boldsymbol{V_t}} \boldsymbol{X_{dif}} \left(1 - \frac{\boldsymbol{T}}{\boldsymbol{T_{nom}}}\right)\right]$$

$$\boldsymbol{j_{ddif}} = \boldsymbol{i_{ddif}} \,\mathbf{exp}\left[\frac{-\boldsymbol{E_g}(300\boldsymbol{K})}{\boldsymbol{n_{dioded}} \boldsymbol{V_t}} \boldsymbol{X_{difd}} \left(1 - \frac{\boldsymbol{T}}{\boldsymbol{T_{nom}}}\right)\right]$$

$$\boldsymbol{j_{srec}} = \boldsymbol{i_{srec}} \,\mathbf{exp}\left[\frac{-\boldsymbol{E_g}(300\boldsymbol{K})}{\boldsymbol{n_{recf0}} \boldsymbol{V_t}} \boldsymbol{X_{rec}} \left(1 - \frac{\boldsymbol{T}}{\boldsymbol{T_{nom}}}\right)\right]$$

$$j_{drec} = i_{drec} \exp\left[\frac{-E_g(300K)}{n_{recf0d} V_t} X_{recd}\left(1 - \frac{T}{T_{nom}}\right)\right]$$

$$j_{stun} = i_{stun} \exp\left[X_{tun}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

$$j_{dtun} = i_{dtun} \exp\left[X_{tund}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

$$n_{recfs} = n_{recf0}\left[1 + nt_{recf}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

$$n_{recfd} = n_{recf0d}\left[1 + nt_{recf}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

$$n_{recrs} = n_{recr0}\left[1 + nt_{recr}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

$$n_{recrd} = n_{recr0d}\left[1 + nt_{recr}\left(\frac{T}{T_{nom}} - 1\right)\right]$$

E_g is the energy gap energy.

Equation List for BSIMPD CV

Dimension Dependence

$$\delta W_{eff} = DWC + \frac{W_{lc}}{L^{W_{ln}}} + \frac{W_{wc}}{W^{W_{wn}}} + \frac{W_{wlc}}{L^{W_{ln}} W^{W_{wn}}}$$

$$\delta L_{eff} = DLC + \frac{L_{lc}}{L^{L_{\ln}}} + \frac{L_{wc}}{W^{L_{wn}}} + \frac{L_{wlc}}{L^{L_{\ln}} W^{L_{wn}}}$$

$$L_{active} = L_{drawn} - 2\delta L_{eff}$$

$$L_{activeB} = L_{active} - DLCB$$

$$L_{activeBG} = L_{activeB} + 2\delta L_{bg}$$

$$W_{active} = W_{drawn} - N_{bc} dW_{bc} - (2 - N_{bc})\delta W_{eff}$$

$$W_{diosCV} = \frac{W_{active}}{N_{seg}} + P_{sbcp}$$

$$W_{diodCV} = \frac{W_{active}}{N_{seg}} + P_{dbcp}$$

Charge Conservation

$$Q_{Bf} = Q_{acc} + Q_{sub0} + Q_{subs}$$

$$Q_{inv} = Q_{inv,s} + Q_{inv,d}$$

$$Q_g = -\left(Q_{inv} + Q_{Bf}\right)$$

$$Q_b = Q_{Bf} - Q_e + Q_{js} + Q_{jd}$$

$$Q_s = Q_{inv,s} - Q_{js}$$

$$Q_d = Q_{inv,d} - Q_{jd}$$

$$Q_g + Q_e + Q_b + Q_s + Q_d = 0$$

Intrinsic Charges

(1) capMod = 2

Front Gate Body Charge

Accumulation Charge

$$V_{FBeff} = V_{fb} - 0.5\left(\left(V_{fb} - V_{gb} - \delta\right) + \sqrt{\left(V_{fb} - V_{gb} - \delta\right)^2 + \delta^2}\right)$$

where $V_{gb} = V_{gs} - V_{bseff}$

$$V_{fb} = V_{th} - \phi_s - K_{1eff}\sqrt{\phi_s - V_{bseff}} + delvt$$

$$V_{gsteffCV} = nv_t \ln\left(1 + \exp\left[\frac{V_{gs} - V_{th}}{nv_t}\right] \cdot \exp\left[-\frac{delvt}{nv_t}\right]\right)$$

$$Q_{acc} = -F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)C_{ox}(V_{FBeff} - V_{fb})$$

Gate Induced Depletion Charge

$$Q_{sub0} = -F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)C_{ox}\frac{K_{1eff}{}^2}{2}\left(-1 + \sqrt{1 + \frac{4(V_{gs} - V_{FBeff} - V_{gsteffCV} - V_{bseff})}{K_{1eff}{}^2}}\right)$$

Drain Induced Depletion Charge

$$V_{dsatCV} = V_{gsteffCV} / A_{bulkCV}\ ,\ A_{bulkCV} = A_{bulk0}\left[1 + \left(\frac{CLC}{L_{activeB}}\right)^{CLE}\right]$$

$$V_{dsCV} = V_{dsatCV} - \frac{1}{2}(V_{dsatCV} - V_{ds} - \delta + \sqrt{(V_{dsatCV} - V_{ds} - \delta)^2 + 4\delta\, V_{dsatCV}})$$

$$Q_{subs} = F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)K_{1eff}C_{ox}\left(A_{bulkCV} - 1\right)\left[\frac{V_{dsCV}}{2} - \frac{A_{bulkCV}V_{dsCV}^2}{12\left(V_{gsteffCV} - A_{bulkCV}V_{dsCV}/2\right)}\right]$$

Back Gate Body Charge

$$Q_e = k_{b1} F_{body} \left(\frac{W_{active} L_{activeBG}}{N_{seg}} + A_{ebcp} \right) C_{box} \left(V_{es} - V_{fbb} - V_{bseff} \right)$$

Inversion Charge

$$V_{cveff} = V_{dsat,CV} - 0.5\left(V_4 + \sqrt{V_4^2 + 4\delta_4 V_{dsat,CV}} \right) where V_4 = V_{dsat,CV} - V_{ds} - \delta_4 ; \delta_4 = 0.02$$

$$Q_{inv} = -\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{ox} \left(\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2} V_{cveff} \right) + \frac{A_{bulkCV}{}^2 V_{cveff}{}^2}{12\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2} V_{cveff} \right)} \right)$$

50/50 Charge Partition

$$Q_{inv,s} = Q_{inv,.d} = 0.5 Q_{inv}$$

40/60 Charge Partition

$$Q_{inv,s} = -\frac{\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{ox}}{2\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2} V_{cvefff} \right)^2} \left(V_{gsteffCV}{}^3 - \frac{4}{3} V_{gsteffCV}{}^2 \left(A_{bulkCV} V_{cveff} \right) + \frac{2}{3} V_{gsteff} \left(A_{bulkCV} V_{cveff} \right)^2 - \frac{2}{15} \left(A_{bulkCV} V_{cveff} \right)^3 \right)$$

$$Q_{inv,d} = -\frac{\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{ox}}{2\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2} V_{cvefff} \right)^2} \left(V_{gsteffCV}{}^3 - \frac{5}{3} V_{gsteffCV}{}^2 \left(A_{bulkCV} V_{cveff} \right) + V_{gsteff} \left(A_{bulkCV} V_{cveff} \right)^2 - \frac{1}{5} \left(A_{bulkCV} V_{cveff} \right)^3 \right)$$

0/100 Charge Partition

$$Q_{inv,s} = -\frac{W_{active}L_{active} + A_{gbcp}}{N_{seg}} C_{ox} \left(\frac{V_{gsteffCV}}{2} + \frac{A_{bulkCV}V_{cveff}}{4} - \frac{\left(A_{bulkCV}V_{cveff}\right)^2}{24\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2}V_{cveff}\right)} \right)$$

$$Q_{inv,d} = -\frac{W_{active}L_{active} + A_{gbcp}}{N_{seg}} C_{ox} \left(\frac{V_{gsteffCV}}{2} - \frac{3A_{bulkCV}V_{cveff}}{4} + \frac{\left(A_{bulkCV}V_{cveff}\right)^2}{8\left(V_{gsteffCV} - \frac{A_{bulkCV}}{2}V_{cveff}\right)} \right)$$

(2) capMod = 3 (Charge-Thickness Model)

capMod = 3 only supports zero-bias flat band voltage, which is calculated from bias-independent threshold voltage. This is different from capMod = 2. For the finite thickness (X_{DC}) formulation, refer to Chapter 4 of BSIM3v3.2 Users's Manual.

<u>Front Gate Body Charge</u>

Accumulation Charge

$$V_{FBeff} = V_{fb} - 0.5\left(\left(V_{fb} - V_{gb} - \delta\right) + \sqrt{\left(V_{fb} - V_{gb} - \delta\right)^2 + \delta^2} \right)$$

where $V_{gb} = V_{gs} - V_{bseff}$

$$V_{fb} = V_{th} - \phi_s - K_{1eff}\sqrt{\phi_s - V_{bseff}}$$

$$Q_{acc} = -F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)C_{oxeff}V_{gbacc}$$

$$V_{gbacc} = 0.5\left(V_0 + \sqrt{V_0^2 + 4\delta V_{fb}}\right)$$

$$V_0 = V_{fb} + V_{bseff} - V_{gs} - \delta$$

$$C_{oxeff} = \frac{C_{ox}C_{cen}}{C_{ox} + C_{cen}}$$

$$C_{cen} = \varepsilon_{Si} / X_{DC}$$

Gate Induced Depletion Charge

$$Q_{sub0} = -F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)C_{oxeff}\frac{K_{1eff}{}^2}{2}\left(-1 + \sqrt{1 + \frac{4(V_{gs} - V_{FBeff} - V_{gsteffCV} - V_{bseff})}{K_{1eff}{}^2}}\right)$$

Drain Induced Depletion Charge

$$V_{dsatCV} = \left(V_{gsteffCV} - \Phi_\delta\right) / A_{bulkCV}$$

$$\Phi_\delta = \Phi_s - 2\Phi_B = v_t \ln\left[1 + \frac{V_{gsteffCV}\left(V_{gstefCV} + 2K_{1eff}\sqrt{2\Phi_B}\right)}{moinK_{1eff}v_t^2}\right]$$

$$V_{dsCV} = V_{dsatCV} - \frac{1}{2}(V_{dsatCV} - V_{ds} - \delta + \sqrt{(V_{dsatCV} - V_{ds} - \delta)^2 + 4\delta V_{dsatCV}})$$

$$Q_{subs} = F_{body}\left(\frac{W_{active}L_{activeB}}{N_{seg}} + A_{gbcp}\right)K_{1eff}C_{oxeff}\left(A_{bulkCV} - 1\right)\left[\frac{V_{dsCV}}{2} - \frac{A_{bulkCV}V_{dsCV}^2}{12\left(V_{gsteffCV} - \Phi_\delta - A_{bulkCV}V_{dsCV}/2\right)}\right]$$

Back Gate Body Charge

$$Q_e = k_{b1} F_{body} \left(\frac{W_{active} L_{activeBG}}{N_{seg}} + A_{ebcp} \right) C_{box} \left(V_{es} - V_{fbb} - V_{bseff} \right)$$

Inversion Charge

$$V_{cveff} = V_{dsat,CV} - 0.5 \left(V_4 + \sqrt{V_4^2 + 4\delta_4 V_{dsat,CV}} \right) where V_4 = V_{dsat,CV} - V_{ds} - \delta_4 ; \delta_4 = 0.02$$

$$Q_{inv} = -\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{oxeff} \left(\left(V_{gsteffCV} - \Phi_\delta - \frac{A_{bulkCV}}{2} V_{cveff} \right) + \frac{A_{bulkCV}{}^2 V_{cveff}{}^2}{12 \left(V_{gsteffCV} - \Phi_\delta - \frac{A_{bulkCV}}{2} V_{cveff} \right)} \right)$$

50/50 Charge Partition

$$Q_{inv,s} = Q_{inv,.d} = 0.5 Q_{inv}$$

40/60 Charge Partition

$$Q_{inv,s} = -\frac{\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{oxeff}}{2 \left(V_{gsteffCV} - \Phi_\delta - \frac{A_{bulkCV}}{2} V_{cvefff} \right)^2} \left(\left(V_{gsteffCV} - \Phi_\delta \right)^3 - \frac{4}{3} \left(V_{gsteffCV} - \Phi_\delta \right)^2 \left(A_{bulkCV} V_{cveff} \right) + \frac{2}{3} \left(V_{gsteff} - \Phi_\delta \right) \left(A_{bulkCV} V_{cveff} \right)^2 - \frac{2}{15} \left(A_{bulkCV} V_{cveff} \right)^3 \right)$$

$$Q_{inv,d} = -\frac{\left(\frac{W_{active} L_{active}}{N_{seg}} + A_{gbcp} \right) C_{oxef}}{2 \left(V_{gsteffCV} - \Phi_\delta - \frac{A_{bulkCV}}{2} V_{cvefff} \right)^2} \left(\left(V_{gsteffCV} - \Phi_\delta \right)^3 - \frac{5}{3} \left(V_{gsteffCV} - \Phi_\delta \right)^2 \left(A_{bulkCV} V_{cveff} \right) + \left(V_{gstefCVf} - \Phi_\delta \right) \left(A_{bulkCV} V_{cveff} \right)^2 - \frac{1}{5} \left(A_{bulkCV} V_{cveff} \right)^3 \right)$$

0/100 Charge Partition

$$Q_{inv,s} = -\frac{W_{active}L_{active} + A_{gbcp}}{N_{seg}} C_{oxeff} \left(\frac{V_{gsteffCV} - \Phi_{\delta}}{2} + \frac{A_{bulkCV}V_{cveff}}{4} - \frac{\left(A_{bulkCV}V_{cveff}\right)^2}{24\left(V_{gsteffCV} - \Phi_{\delta} - \frac{A_{bulkCV}}{2}V_{cveff}\right)} \right)$$

$$Q_{inv,d} = -\frac{W_{active}L_{active} + A_{gbcp}}{N_{seg}} C_{oxeff} \left(\frac{V_{gsteffCV} - \Phi_{\delta}}{2} - \frac{3A_{bulkCV}V_{cveff}}{4} + \frac{\left(A_{bulkCV}V_{cveff}\right)^2}{8\left(V_{gsteffCV} - \Phi_{\delta} - \frac{A_{bulkCV}}{2}V_{cveff}\right)} \right)$$

Overlap Capacitance

Source Overlap Charge

$$V_{gs\_overlap} = \frac{1}{2}\left\{\left(V_{gs} + \delta\right) + \sqrt{\left(V_{gs} + \delta\right)^2 + 4\delta}\right\}$$

$$\frac{Q_{overlap,s}}{W_{diosCV}} = CGS0 \cdot V_{gs} + CGS1\left\{V_{gs} - V_{gs\_overlap} + \frac{CKAPPA}{2}\left(-1 + \sqrt{1 + \frac{4V_{gs\_overlap}}{CKAPPA}}\right)\right\}$$

Drain Overlap Charge

$$V_{gd\_overlap} = \frac{1}{2}\left\{\left(V_{gd} + \delta\right) + \sqrt{\left(V_{gd} + \delta\right)^2 + 4\delta}\right\}$$

$$\frac{Q_{overlap,d}}{W_{diodCV}} = CGD0 \cdot V_{gd} + CGD1\left\{V_{gd} - V_{gd\_overlap} + \frac{CKAPPA}{2}\left(-1 + \sqrt{1 + \frac{4V_{gd\_overlap}}{CKAPPA}}\right)\right\}$$

Gate Overlap Charge

$$Q_{overlap,g} = -\left(Q_{overlap,s} + Q_{overlap,d}\right)$$

Source/Drain Junction Charge

For $\mathbf{V_{bs}}$ < $0.95\phi_s$

$$Q_{jswg} = Q_{bsdep} + Q_{bsdif}$$

else

$$Q_{jswg} = C_{bsdep}(0.95\phi_s)\left(V_{bs} - 0.95\phi_s\right) + Q_{bsdif}$$

For $\mathbf{V_{bd}}$ < $0.95\phi_s$

$$Q_{jdwg} = Q_{bddep} + Q_{bddif}$$

else

$$Q_{jdwg} = C_{bddep}\left(0.95\phi_s\right)\left(V_{bd} - 0.95\phi_s\right) + Q_{bddif}$$

where

$$Q_{bsdep} = W_{dioCV} C_{jswgs} \frac{T_{si}}{10^{-7}} \frac{P_{bswgs}}{1 - M_{jswgs}} \left[1 - \left(1 - \frac{V_{bs}}{P_{bswgs}}\right)^{1 - M_{jswgs}}\right]$$

$$Q_{bddep} = W_{dioCV} C_{jswgd} \frac{T_{si}}{10^{-7}} \frac{P_{bswgd}}{1 - M_{jswgd}} \left[1 - \left(1 - \frac{V_{bd}}{P_{bswgd}}\right)^{1 - M_{jswgd}}\right]$$

$$\boldsymbol{C_{jswgs} = C_{jswgs0}\left[1 + t_{cjswgs}\left(T - T_{nom}\right)\right]}$$
$$\boldsymbol{C_{jswgd} = C_{jswgd0}\left[1 + t_{cjswgd}\left(T - T_{nom}\right)\right]}$$
$$\boldsymbol{P_{bswgs} = P_{bswgs0} - t_{pbswgs}\left(T - T_{nom}\right)}$$
$$\boldsymbol{P_{bswgd} = P_{bswgd0} - t_{pbswgd}\left(T - T_{nom}\right)}$$

$$Q_{bsdif} = \tau \frac{W_{eff}'}{N_{seg}} T_{si} J_{sbjt} \left[1 + L_{dif0} \left(L_{bj0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right)^{N_{dif}} \right] \left[\exp\left(\frac{V_{bs}}{n_{dios} V_t} \right) - 1 \right] \frac{1}{\sqrt{E_{hlis} + 1}}$$

$$Q_{bddif} = \tau \frac{W_{eff}'}{N_{seg}} T_{si} J_{dbjt} \left[1 + L_{dif0} \left(L_{bj0} \left(\frac{1}{L_{eff}} + \frac{1}{L_n} \right) \right)^{N_{dif}} \right] \left[\exp\left(\frac{V_{bd}}{n_{diod} V_t} \right) - 1 \right] \frac{1}{\sqrt{E_{hlid} + 1}}$$

Extrinsic Capacitance

Bottom S/D to Substrate Capacitance (per unit area)

$$C_{esb} = \begin{cases} C_{box} & \text{if} \quad V_{s/d,e} < V_{sdfb} \\ C_{box} - \dfrac{1}{A_{sd}} \left(C_{box} - C_{min} \right) \left(\dfrac{V_{s/d,e} - V_{sdfb}}{V_{sdth} - V_{sdfb}} \right)^2 & \text{elseif} \quad V_{s/d,e} < V_{sdfb} + A_{sd} \left(V_{sdth} - V_{sdfb} \right) \\ C_{min} + \dfrac{1}{1 - A_{sd}} \left(C_{box} - C_{min} \right) \left(\dfrac{V_{s/d,e} - V_{sdth}}{V_{sdth} - V_{sdfb}} \right)^2 & \text{elseif} \quad V_{s/d,e} < V_{sdth} \\ C_{min} & \text{else} \end{cases}$$

Sidewall S/D to Substrate Capacitance (per unit length)

$$C_{s/d,esw} = C_{sdesw} \log\left(1 + \frac{T_{si}}{T_{box}} \right)$$