APPENDIX B: Equation List

B.1 I-V Model

B.1.1 Threshold Voltage

$$
\begin{aligned}
V_{th} &= V_{th0ox} + K_{1ox} \cdot \sqrt{\Phi_s - V_{bseff}} - K_{2ox} V_{bseff} \\
&+ K_{1ox}\left(\sqrt{1+\frac{Nlx}{L_{eff}}} - 1\right)\sqrt{\Phi_s} + \left(K_3 + K_{3b} V_{bseff}\right)\frac{T_{ox}}{W_{eff}' + W_0}\Phi_s \\
&- D_{VT0w}\left(\exp\left(-D_{VT1w}\frac{W_{eff}' L_{eff}}{2l_{tw}}\right) + 2\exp\left(-D_{VT1w}\frac{W_{eff}' L_{eff}}{l_{tw}}\right)\right)\left(V_{bi} - \Phi_s\right) \\
&- D_{VT0}\left(\exp\left(-D_{VT1}\frac{L_{eff}}{2l_t}\right) + 2\exp\left(-D_{VT1}\frac{L_{eff}}{l_t}\right)\right)\left(V_{bi} - \Phi_s\right) \\
&- \left(\exp\left(-D_{sub}\frac{L_{eff}}{2l_{to}}\right) + 2\exp\left(-D_{sub}\frac{L_{eff}}{l_{to}}\right)\right)\left(E_{tao} + E_{tab} V_{bseff}\right) V_{ds}
\end{aligned}
$$

$$V_{th0ox} = V_{th0} - K_1 \cdot \sqrt{\Phi_s}$$

$$K_{1ox} = K_1 \cdot \frac{T_{ox}}{T_{oxm}}$$

$$K_{2ox} = K_2 \cdot \frac{T_{ox}}{T_{oxm}}$$

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

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

$$l_{to} = \sqrt{\varepsilon_{si} X_{dep0} / C_{ox}}$$

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

$$X_{dep0} = \sqrt{\frac{2\varepsilon_{si}\Phi_s}{qN_{ch}}}$$

$$V_{bseff} = V_{bc} + 0.5[V_{bs} - V_{bc} - \delta_1 + \sqrt{(V_{bs} - V_{bc} - \delta_1)^2 - 4\delta_1 V_{bc}}\ ] \qquad (\delta 1 = 0.001)$$

$$V_{bc} = 0.9\left(\Phi_s - \frac{K_1^{\,2}}{4K_2^{\,2}}\right)$$

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

B.1.2 Effective (V_{gs}-V_{th})

$$V_{gsteff} = \frac{2\, n\, v_t \ln\left[1 + \exp(\frac{V_{gs} - V_{th}}{2\, n\, v_t})\right]}{1 + 2\, n\ \ C_{OX}\sqrt{\frac{2\Phi_s}{q\varepsilon_{si} N_{ch}}}\exp(-\frac{V_{gs} - V_{th} - 2V_{off}}{2\, n\, v_t})}$$

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

$$C_d = \frac{\varepsilon_{si}}{X_{dep}}$$

B.1.3 Mobility

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

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

B.1.4 Drain Saturation Voltage

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

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

$$a = A_{bulk}{}^2 W_{eff} v_{sat} C_{ox} R_{DS} + \left(\frac{1}{\lambda} - 1\right) A_{bulk}$$

$$b = -\left((V_{gsteff} + 2v_t)\left(\frac{2}{\lambda} - 1\right) + A_{bulk} E_{sat} L_{eff} + 3A_{bulk}(V_{gsteff} + 2v_t) W_{eff} v_{sat} C_{ox} R_{DS} \right)$$

$$c = (V_{gsteff} + 2v_t) E_{sat} L_{eff} + 2(V_{gsteff} + 2v_t)^2 W_{eff} v_{sat} C_{ox} R_{DS}$$

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

For $R_{ds} = 0$ and $\lambda = 1$:

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

$$A_{bulk} = \left(1 + \frac{K_{1ox}}{2\sqrt{\Phi_s - V_{bseff}}} \left(\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} \left(1 - A_{gs} V_{gsteff} \left(\frac{L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} \right)^2 \right) + \frac{B_0}{W_{eff}' + B_1} \right) \right) \cdot \frac{1}{1 + Keta V_{bseff}}$$

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

B.1.5 Effective V_{ds}

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

B.1.6 Drain Current Expression

$$I_{ds} = \frac{I_{dso(Vdseff)}}{1 + \frac{R_{ds} I_{dso(Vdseff)}}{V_{dseff}}} \left(1 + \frac{V_{ds} - V_{dseff}}{V_A}\right)\left(1 + \frac{V_{ds} - V_{dseff}}{V_{ASCBE}}\right)$$

$$I_{dso} = \frac{W_{eff}\mu_{eff}C_{ox}V_{gsteff}(1 - A_{bulk}\frac{V_{dseff}}{2(V_{gsteff} + 2v_t)})V_{dseff}}{L_{eff}[1 + V_{dseff} / (E_{sat}L_{eff})]}$$

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

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

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

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

$$\frac{1}{V_{ASCBE}} = \frac{P_{scbe2}}{L_{eff}}\exp\left(\frac{-P_{scbe1}\, litl}{V_{ds} - V_{dseff}}\right)$$

$$V_{Asat} = \frac{E_{sat}L_{eff} + V_{dsat} + 2R_{DS}v_{sat}C_{ox}W_{eff}V_{gsteff}[1 - \frac{A_{bulk}V_{dsat}}{2(V_{gsteff} + 2v_t)}]}{2/\lambda - 1 + R_{DS}v_{sat}C_{ox}W_{eff}A_{bulk}}$$

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

B.1.7 Substrate Current

$$I_{sub} = \frac{\alpha_0 + \alpha_1 \cdot L_{eff}}{L_{eff}}\left(V_{ds} - V_{dseff}\right)\exp\left(-\frac{\beta_0}{V_{ds} - V_{dseff}}\right)\frac{I_{ds0}}{1 + \frac{R_{ds}I_{ds0}}{V_{dseff}}}\left(1 + \frac{V_{ds} - V_{dseff}}{V_A}\right)$$

B.1.8 Polysilicon Depletion Effect

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

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

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

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

$$a = \frac{\varepsilon_{ox}^{\ 2}}{2q\varepsilon_{si} N_{gate} T_{ox}^{\ 2}}$$

$$V_{gs\_eff} = V_{FB} + \Phi_s + \frac{q\varepsilon_{si} N_{gate} T_{ox}^{\ 2}}{\varepsilon_{ox}^{\ 2}} \left(\sqrt{1 + \frac{2\varepsilon_{ox}^{\ 2}\left(V_{gs} - V_{FB} - \Phi_s\right)}{q\varepsilon_{si} N_{gate} T_{ox}^{\ 2}}} - 1 \right)$$

B.1.9 Effective Channel Length and Width

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

$$W_{eff} = W_{drawn} - 2dW$$

$$W_{eff}' = W_{drawn} - 2dW'$$

$$dW = dW' + dW_g V_{gsteff} + dW_b\left(\sqrt{\Phi_s - V_{bseff}} - \sqrt{\Phi_s}\right)$$
$$dW' = W_{\text{int}} + \frac{W_l}{L^{W\ln}} + \frac{W_w}{W^{Wwn}} + \frac{W_{wl}}{L^{W\ln}W^{Wwn}}$$

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

B.1.10Source/Drain Resistance

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

B.1.11Temperature Effects

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

$$\mu_{o(T)} = \mu_{o(Tnorm)}\left(\frac{T}{T_{norm}}\right)^{\mu_{te}}$$

$$v_{sat(T)} = v_{sat(Tnorm)} - A_T(T / T_{norm} - 1)$$

$$R_{dsw(T)} = R_{dsw(T_{norm})} + \mathrm{P}_{\mathrm{r}\,t}\left(\frac{T}{T_{norm}} - 1\right)$$

$$U_{a(T)} = U_{a(Tnorm)} + U_{a1}(T / T_{norm} - 1)$$

$$U_{b(T)} = U_{b(Tnorm)} + U_{b1}(T / T_{norm} - 1)$$

$$U_{c(T)} = U_{c(Tnorm)} + U_{c1}(T / T_{norm} - 1)$$

B.2 Capacitance Model Equations

B.2.1 Dimension Dependence

$$\mathrm{L}_{\mathrm{active}} = \mathrm{L}_{\mathrm{drawn}} - 2\delta\mathrm{L}_{\mathrm{eff}}$$

$$\mathrm{W}_{\mathrm{active}} = \mathrm{W}_{\mathrm{drawn}} - 2\delta\mathrm{W}_{\mathrm{eff}}$$

$$\delta L_{eff} = DLC + \frac{Llc}{L^{L\ln}} + \frac{Lwc}{W^{Lwn}} + \frac{Lwlc}{L^{L\ln} W^{Lwn}}$$

$$\delta W_{eff} = DWC + \frac{Wlc}{L^{W\ln}} + \frac{Wwc}{W^{Wwn}} + \frac{Wwlc}{L^{W\ln} W^{Wwn}}$$

B.2.2 Overlap Capacitance

B.2.2.1 Source Overlap Capacitance

(1) for capMod = 0

$$\frac{Q_{overlap,s}}{W_{active}} = \mathrm{CGS0}V_{gs}$$

(2) for capMod = 1

If $V_{gs} < 0$

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

Else

$$\frac{Q_{overlap,s}}{W_{active}} = (CGS0 + CKAPPA \cdot CGS1) \cdot V_{gs}$$

(3) for capMod = 2

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

$$V_{gs,overlap} = \frac{1}{2}\left(V_{gs} + \delta_1 - \sqrt{(V_{gs} + \delta_1)^2 + 4\delta_1}\right), \quad \delta_1 = 0.02$$

B.2.2.2 Drain Overlap Capacitance

(1) for capMod = 0

$$\frac{Q_{overlap,d}}{W_{active}} = \mathrm{CGD0}V_{gd}$$

(2) for capMod = 1

If $V_{gd} < 0$

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

Else

$$\frac{Q_{overlap,d}}{W_{active}} = \left(CGD0 + CKAPPA \cdot CGD1\right) \cdot V_{gd}$$

(3) for capMod = 2

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

$$V_{gd,overlap} = \frac{1}{2}\left(V_{gd} + \delta_1 - \sqrt{\left(V_{gd} + \delta_1\right)^2 + 4\delta_1}\right), \quad \delta_1 = 0.02$$

B.2.2.3 Gate Overlap Charge

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

B.2.3 Instrinsic Charges

(1) **capMod = 0**

a. Accumulation region ($V_{gs} < V_{fbcv} + V_{bs}$)

$$Q_g = W_{active} L_{active} C_{ox} \left(V_{gs} - V_{bs} - V_{fbcv}\right)$$

$$Q_{sub} = -Q_g$$

$$Q_{inv} = 0$$

b. Subthreshold region ($V_{gs} < V_{th}$)

$$Q_{sub0} = -W_{active} L_{active} C_{ox} \cdot \frac{K_{1ox}{}^2}{2} \left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{fbcv} - V_{bs}\right)}{K_{1ox}{}^2}} \right)$$

$$Q_g = -Q_b$$

$$Q_{inv} = 0$$

c. Strong inversion ($V_{gs} > V_{th}$)

$$V_{dsat,cv} = \frac{V_{gs} - V_{th}}{A_{bulk}'}$$

$$A_{bulk}' = A_{bulk0}\left(1 + \left(\frac{CLC}{Leff}\right)^{CLE}\right)$$

$$A_{bulk0} = \left(1 + \frac{K_{1ox}}{2\sqrt{\Phi_s - V_{bseff}}}\left(\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} + \frac{B_0}{W_{eff}' + B_1}\right)\right) \cdot \frac{1}{1 + KetaV_{bseff}}$$

$$V_{th} = V_{fbcv} + \Phi_s + K_{1ox}\sqrt{\Phi_s - V_{bseff}}$$

(i) 50/50 Charge partition

If $V_{ds} < V_{dsat}$

$$Q_g = C_{ox} W_{active} L_{active}\left(V_{gs} - V_{fbcv} - \Phi_s - \frac{V_{ds}}{2} + \frac{A_{bulk}' V_{ds}^{\,2}}{12\left(V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2}\right)}\right)$$

$$Q_{inv} = -W_{active} L_{active} C_{ox} [V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2} + \frac{A_{bulk}'^2 V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_b = W_{active} L_{active} C_{ox} [V_{fb} - V_{th} + \Phi_s + \frac{(1 - A_{bulk}')V_{ds}}{2} - \frac{(1 - A_{bulk}')A_{bulk}' V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_s = Q_d = 0.5 Q_{inv} = -W_{active} L_{active} C_{ox} [V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2} + \frac{A_{bulk}'^2 V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

otherwise

$$Q_g = W_{active} L_{active} C_{ox} (V_{gs} - V_{fb} - \Phi_s - \frac{V_{dsat}}{3})$$

$$Q_s = Q_d = -\frac{1}{3} W_{active} L_{active} C_{ox} (V_{gs} - V_{th})$$

$$Q_b = -W_{active} L_{active} C_{ox} (V_{fb} + \Phi_s - V_{th} + \frac{(1 - A_{bulk}')V_{dsat}}{3})$$

(ii) 40/60 channel-charge Partition

if ($V_{ds} < V_{dsat}$)

$$Q_g = C_{ox} W_{active} L_{active} [V_{gs} - V_{fb} - \Phi_s - \frac{V_{ds}}{2} + \frac{A_{bulk}' V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2})}]$$

$$Q_{inv} = -W_{active} L_{active} C_{ox} [V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2} + \frac{A_{bulk}'^2 V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_b = W_{active} L_{active} C_{ox} [V_{fb} - V_{th} + \Phi_s + \frac{(1 - A_{bulk}') V_{ds}}{2} - \frac{(1 - A_{bulk}') A_{bulk}' V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_d = -W_{active} L_{active} C_{ox}$$
$$\left[\frac{V_{gs} - V_{th}}{2} - \frac{A_{bulk}'}{2} V_{ds} + \frac{A_{bulk}' V_{ds} [\frac{(V_{gs} - V_{th})^2}{6} - \frac{A_{bulk}' V_{ds} (V_{gs} - V_{th})}{8} + \frac{(A_{bulk}' V_{ds})^2}{40}}{(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})^2} \right]$$

$$Q_s = -(Q_g + Q_b + Q_d)$$

otherwise

$$Q_g = W_{active} L_{active} C_{ox} (V_{gs} - V_{fb} - \Phi_s - \frac{V_{dsat}}{3})$$

$$Q_d = -\frac{4}{15} W_{active} L_{active} C_{ox} (V_{gs} - V_{th})$$

$$Q_s = -(Q_g + Q_b + Q_d)$$

$$Q_b = -W_{active} L_{active} C_{ox} (V_{fb} + \Phi_s - V_{th} + \frac{(1 - A_{bulk}')V_{dsat}}{3})$$

(iii) 0/100 Channel-charge Partition

if $V_{ds} < V_{dsat}$

$$Q_g = C_{ox} W_{active} L_{active} [V_{gs} - V_{fb} - \Phi_s - \frac{V_{ds}}{2} + \frac{A_{bulk}' V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2})}]$$

$$Q_{inv} = -W_{active} L_{active} C_{ox} [V_{gs} - V_{th} - \frac{A_{bulk}' V_{ds}}{2} + \frac{A_{bulk}'^2 V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_b = W_{active} L_{active} C_{ox} [V_{fb} - V_{th} + \Phi_s + \frac{(1 - A_{bulk}')V_{ds}}{2} - \frac{(1 - A_{bulk}')A_{bulk}' V_{ds}^2}{12(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})}]$$

$$Q_d = -W_{active} L_{active} C_{ox} \left[\frac{V_{gs} - V_{th}}{2} + \frac{A_{bulk}'}{4} V_{ds} - \frac{(A_{bulk}' V_{ds})^2}{24(V_{gs} - V_{th} - \frac{A_{bulk}'}{2} V_{ds})} \right]$$

$$Q_s = -(Q_g + Q_b + Q_d)$$

otherwise

$$Q_g = W_{active} L_{active} C_{ox}(V_{gs} - V_{fb} - \Phi_s - \frac{V_{dsat}}{3})$$

$$Q_b = -W_{active} L_{active} C_{ox}(V_{fb} + \Phi_s - V_{th} + \frac{(1 - A_{bulk}')V_{dsat}}{3})$$

$$Q_d = 0$$

$$Qs = -(Q_g + Q_b)$$

(2) **capMod = 1**

The flat-band voltage V_{fb} is calculated from

$$V_{fb} = V_{th} - \Phi_s - K_{1ox} \sqrt{\Phi_s - V_{bseff}}$$

where the bias dependences of V_{th} given in Section B.1.1 are not considered in calculating V_{fb} for capMod = 1.

if ($V_{gs} < V_{fb} + V_{bs} + V_{gsteffcv}$)

$$Q_{g1} = -W_{active} L_{active} C_{ox} \left(V_{gs} - Vfb - V_{bs} - V_{gsteffcv} \right)$$

else

$$Q_{g1} = W_{active} L_{active} C_{ox} \cdot \frac{K_{1ox}{}^2}{2} \left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{fb} - V_{gsteff,CV} - V_{bseff}\right)}{K_{1ox}{}^2}} \right)$$

$$Q_{b1} = -Q_{g1}$$

$$V_{dsat,cv} = \frac{V_{gsteffcv}}{A_{bulk}{}'}$$

$$\mathrm{A_{bulk}}' = \mathrm{A_{bulk0}} \left(1 + \left(\frac{CLC}{\mathrm{L_{eff}}} \right)^{CLE} \right)$$

$$A_{bulk0} = \left(1 + \frac{K_{1ox}}{2\sqrt{\Phi_s - V_{bseff}}} \left(\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} + \frac{B_0}{W_{eff}' + B_1} \right) \right) \cdot \frac{1}{1 + KetaV_{bseff}}$$

$$V_{gsteff,cv} = noff \cdot nv_t \ln\left(1+\exp\left(\frac{V_{gs}-V_{th}-voffcv}{noff \cdot nv_t}\right)\right)$$

if (V_{ds} <=V_{dsat})

$$Q_g = Q_{g1} + W_{active}L_{active}C_{ox}\left(V_{gsteff\,cv} - \frac{V_{ds}}{2} + \frac{A_{bulk}'V_{ds}^{2}}{12\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{ds}\right)}\right)$$

$$Q_b = Q_{b1} + W_{active}L_{active}C_{ox}\left(\frac{1-A_{bulk}'}{2}V_{ds} - \frac{\left(1-A_{bulk}'\right)A_{bulk}'V_{ds}^{2}}{12\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{ds}\right)}\right)$$

(i) 50/50 Channel-charge Partition

$$Q_s = Q_d = -\frac{W_{active}L_{active}C_{ox}}{2}\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{ds} + \frac{A_{bulk}'^{2}V_{ds}^{2}}{12\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{ds}\right)}\right)$$

(ii) 40/60 Channel-charge partition

$$Q_s = -\frac{W_{active} L_{active} C_{ox}}{2\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2} V_{ds}\right)^2}$$
$$\left(V_{gsteffcv}{}^3 - \frac{4}{3} V_{gstefcvf}{}^2 \left(A_{bulk}' V_{ds}\right) + \frac{2}{3} V_{gsteffcv} \left(A_{bulk}' V_{ds}\right)^2 - \frac{2}{15} \left(A_{bulk}' V_{ds}\right)^3\right)$$

$$Q_d = -(Q_g + Q_b + Q_s)$$

(iii) 0/100 Channel-charge Partition

$$Q_s = -W_{active} L_{active} C_{ox} \left(\frac{V_{gstefcv}}{2} + \frac{A_{bulk}' V_{ds}}{4} - \frac{\left(A_{bulk}' V_{ds}\right)^2}{24\left(V_{gsteffcv} - \frac{A_{bulk}'}{2} V_{ds}\right)} \right)$$

$$Q_d = -(Q_g + Q_b + Q_s)$$

if ($V_{ds} > V_{dsat}$)

$$Q_g = Q_{g1} + W_{active} L_{active} C_{ox} \left(V_{gsteff\,cv} - \frac{V_{dsat}}{3} \right)$$

$$Q_b = Q_{b1} - W_{active} L_{active} C_{ox} \frac{\left(V_{gsteffcv} - V_{dsat}\right)}{3}$$

(i) 50/50 Channel-charge Partition

$$Q_s = Q_d = -\frac{W_{active} L_{active} C_{ox}}{3} V_{gsteff}{}_{cv}$$

(ii) 40/60 Channel-charge Partition

$$Q_s = -\frac{2W_{active} L_{active} C_{ox}}{5} V_{gsteffcv}$$

$$Q_d = -(Q_g + Q_b + Q_s)$$

(iii) 0/100 Channel-charge Partition

$$Q_s = -W_{active} L_{active} C_{ox} \frac{2V_{gstefcv}}{3}$$

$$Q_d = -(Q_g + Q_b + Q_s)$$

(3) **capMod = 2**

The flat-band voltage V_{fb} is calculated from

$$vfb = V_{th} - \Phi_s - K_{1ox} \sqrt{\Phi_s - V_{bseff}}$$

where the bias dependences of V_{th} given in Section B.1.1 are not considered in calculating V_{fb} for capMod = 2.

$$Q_g = -\left(Q_{inv} + Q_{acc} + Q_{sub0} + \delta Q_{sub}\right)$$

$$Q_b = Q_{acc} + Q_{sub0} + \delta Q_{sub}$$

$$Q_{inv} = Q_s + Q_d$$

$$V_{FBeff} = vfb - 0.5\left\{V_3 + \sqrt{V_3^{\,2} + 4\delta_3 vfb}\right\} \quad where \quad V_3 = vfb - V_{gb} - \delta_3; \quad \delta_3 = 0.02$$

$$Q_{acc} = -W_{active} L_{active} C_{ox}\left(V_{FBeff} - vfb\right)$$

$$Q_{sub0} = -W_{active} L_{active} C_{ox} \cdot \frac{K_{1ox}^{\;2}}{2}\left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{FBeff} - V_{gsteff,CV} - V_{bseff}\right)}{K_{1ox}^{\;2}}}\right)$$

$$V_{dsat,cv} = \frac{V_{gsteff,cv}}{A_{bulk}'}$$

$$A_{bulk}' = A_{bulk0}\left(1 + \left(\frac{CLC}{L_{active}}\right)^{CLE}\right)$$

$$A_{bulk0} = \left(1 + \frac{K_{1ox}}{2\sqrt{\Phi_s - V_{bseff}}}\left(\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} + \frac{B_0}{W_{eff}' + B_1}\right)\right) \cdot \frac{1}{1 + KetaV_{bseff}}$$

$$V_{gsteff,cv} = noff \cdot nv_t \ln\left(1 + \exp\left(\frac{V_{gs} - V_{th} - voffcv}{noff \cdot nv_t}\right)\right)$$

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

$$Q_{inv} = -W_{active} L_{active} C_{ox}\left(\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{cveff}\right) + \frac{A_{bulk}'^2 V_{cveff}^2}{12\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{cveff}\right)}\right)$$

$$\delta Q_{sub} = W_{active} L_{active} C_{ox}\left(\frac{1 - A_{bulk}'}{2}V_{cveff} - \frac{(1 - A_{bulk}')A_{bulk}' V_{cveff}^2}{12\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{cveff}\right)}\right)$$

B.2.3.1 50/50 Charge partition

$$Q_s = Q_d = 0.5Q_{inv} = -\frac{W_{active}L_{active}C_{ox}}{2}\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{cveff} + \frac{A_{bulk}'^2 V_{cveff}^2}{12\left(V_{gsteffcv} - \frac{A_{bulk}}{2}V_{cveff}\right)}\right)$$

B.2.3.2 40/60 Channel-charge Partition

$$Q_s = -\frac{W_{active}L_{active}C_{ox}}{2\left(V_{gsteff\,cv} - \frac{A_{bulk}'}{2}V_{cveff}\right)^2}\left(V_{gsteffcv}^{\;3} - \frac{4}{3}V_{gsteffc}^{\;2}\left(A_{bulk}'V_{cveff}\right) + \frac{2}{3}V_{gsteff}\left(A_{bulk}'V_{cveff}\right)^2 - \frac{2}{15}\left(A_{bulk}'V_{cveff}\right)^3\right)$$

$$Q_d = -\frac{W_{active}L_{active}C_{ox}}{2\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{cveff}\right)^2}\left(V_{gsteffcv}^{\;3} - \frac{5}{3}V_{gsteffc}^{\;2}\left(A_{bulk}'V_{cveff}\right) + V_{gsteff\,cv}\left(A_{bulk}'V_{cveff}\right)^2 - \frac{1}{5}\left(A_{bulk}'V_{cveff}\right)^3\right)$$

B.2.3.3 0/100 Charge Partition

$$Q_s = -W_{active}L_{active}C_{ox}\left(\frac{V_{gsteffcv}}{2} + \frac{A_{bulk}'V_{cveff}}{4} - \frac{\left(A_{bulk}'V_{cveff}\right)^2}{24\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{cveff}\right)}\right)$$

$$Q_d = -W_{active}L_{active}C_{ox}\left(\frac{V_{gsteffcv}}{2} - \frac{3A_{bulk}'V_{cveff}}{4} + \frac{\left(A_{bulk}'V_{cveff}\right)^2}{8\left(V_{gsteffcv} - \frac{A_{bulk}'}{2}V_{cveff}\right)}\right)$$

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

capMod = 3 also uses the bias-independent V_{th} to calculate V_{fb} as in capMod = 1 and 2.

$$vfb = V_{th} - \Phi_s - K_{1ox}\sqrt{\Phi_s - V_{bseff}}$$

For the finite charge thickness (X_{DC}) formulations, refer to Chapter 4.

$$Q_{acc} = WLC_{oxeff} \cdot V_{gbacc}$$

$$V_{gbacc} = \frac{1}{2} \cdot \left[V_0 + \sqrt{V_0^2 + 4\delta_3 V_{fb}}\right]$$

$$V_0 = V_{fb} + V_{bseff} - V_{gs} - \delta_3$$

$$V_{FBeff} = vfb - 0.5\left\{V_3 + \sqrt{V_3^{\,2} + 4\delta_3 vfb}\right\} \quad where \quad V_3 = vfb - V_{gb} - \delta_3; \quad \delta_3 = 0.02$$

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

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

$$\Phi_\delta = \Phi_s - 2\Phi_B = v_t \ln\left(\frac{V_{gsteffCV} \cdot (V_{gsteffCV} + 2K_{1ox}\sqrt{2\Phi_B}}{moin \cdot K_{1ox}{}^2 v_t} \right)$$

$$Q_{sub0} = -WLC_{oxeff} \cdot \frac{K_{1ox}{}^2}{2} \cdot \left[-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{FBeff} - V_{bseffs} - V_{gsteff,cv}\right)}{K_{1ox}{}^2}} \right]$$

$$V_{cveff} = V_{dsat} - \frac{1}{2} \cdot \left(V_1 + \sqrt{V_1{}^2 + 4\delta_3 V_{dsat}} \right)$$

$$V_1 = V_{dsat} - V_{ds} - \delta_3$$

$$V_{dsat} = \frac{V_{gsteff,cv} - \varphi_\delta}{A_{bulk}'}$$

$$Q_{inv} = -WLC_{oxeff} \cdot \left[V_{gsteff,cv} - \varphi_\delta - \frac{1}{2} A_{bulk}' V_{cveff} + \frac{A_{bulk}'^2 V_{cveff}^2}{12 \cdot \left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)} \right]$$

$$\delta Q_{sub} = WLC_{oxeff} \cdot \left[\frac{1 - A_{bulk}'}{2} V_{cveff} - \frac{(1 - A_{bulk}') \cdot A_{bulk}' V_{cveff}^2}{12 \cdot \left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)} \right]$$

(i) 50/50 Charge Partition

$$Q_S = Q_D = \frac{1}{2} Q_{inv} = -\frac{WLC_{oxeff}}{2} \left[V_{gsteff,cv} - \varphi_\delta - \frac{1}{2} A_{bulk}' V_{cveff} + \frac{A_{bulk}'^2 V_{cveff}^2}{12 \cdot \left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)} \right]$$

(ii) 40/60 Charge Partition

$$Q_S = -\frac{WLC_{oxeff}}{2\left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)^2} \left[(V_{gsteff,cv} - \varphi_\delta)^3 - \frac{4}{3} (V_{gsteff,cv} - \varphi_\delta)^2 A_{bulk}' V_{cveff} + \frac{2}{3} (V_{gsteff,cv} - \varphi_\delta)(A_{bulk}' V_{cveff})^2 - \frac{2}{15} (A_{bulk}' V_{cveff})^3 \right]$$

$$Q_D = -\frac{WLC_{oxeff}}{2\left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)^2} \left[(V_{gsteff,cv} - \varphi_\delta)^3 - \frac{5}{3} (V_{gsteff,cv} - \varphi_\delta)^2 A_{bulk}' V_{cveff} + (V_{gsteff,cv} - \varphi_\delta)(A_{bulk}' V_{cveff})^2 - \frac{1}{5} (A_{bulk}' V_{cveff})^3 \right]$$

(iii) 0/100 Charge Partition

$$Q_S = -\frac{WLC_{oxeff}}{2} \cdot \left[V_{gsteff,cv} - \varphi_\delta + \frac{1}{2} A_{bulk}' V_{cveff} - \frac{A_{bulk}'^2 V_{cveff}^2}{12 \cdot \left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{cveff} / 2 \right)} \right]$$

$$Q_D = -\frac{WLC_{oxeff}}{2} \cdot \left[V_{gsteff,cv} - \varphi_\delta - \frac{3}{2} A_{bulk}' V_{cveff} + \frac{A_{bulk}'^2 V_{cveff}^2}{4 \cdot \left(V_{gsteff,cv} - \varphi_\delta - A_{bulk}' V_{dveff} / 2 \right)} \right]$$