APPENDIX B: Equation List

B.1 I-V Model

B.1.1 Threshold Voltage

$$
\begin{aligned}
V_{th} = {} & V_{tho} + K_1(\sqrt{\Phi_s - V_{bseff}} - \sqrt{\Phi_s}) - K_2 V_{bseff} \\
& + K_1\left(\sqrt{1 + \frac{N_{LX}}{L_{eff}}} - 1\right)\sqrt{\Phi_s} + (K_3 + K_{3b}V_{bseff})\frac{T_{OX}}{W_{eff}{}' + W_0}\Phi_s \\
& - D_{VT0w}\left(exp(-D_{VT1w}\frac{W_{eff}{}'L_{eff}}{2l_{tw}}) + 2exp(-D_{VT1w}\frac{W_{eff}{}'L_{eff}}{l_{tw}})\right)(V_{bi} - \Phi_s) \\
& - D_{VT0}\left(exp(-D_{VT1}\frac{L_{eff}}{2l_t}) + 2exp(-D_{VT1}\frac{L_{eff}}{l_t})\right)(V_{bi} - \Phi_s) \\
& - \left(exp(-D_{sub}\frac{L_{eff}}{2l_{to}}) + 2exp(-D_{sub}\frac{L_{eff}}{l_{to}})\right)(E_{tao} + E_{tab}V_{bseff})\,V_{ds}
\end{aligned}
$$

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

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

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

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

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

(δ1=0.001)

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

$$V_{bc} = 0.9(\phi s - \frac{K1^2}{4K2^2})$$

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

B.1.2 Effective Vgs-Vth

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

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

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

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 Rds>0 or $\lambda \neq 1$:

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

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

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

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

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

For Rds=0, λ=1:

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

$$A_{bulk} = (1 + \frac{K_1}{2\sqrt{\Phi_s - V_{bseff}}} \{ \frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} [1 - A_{gs} V_{gsteff} (\frac{L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}})^2] + \frac{B_o}{Weff' + B_1} \}) \frac{1}{1 + K_{ETA} V_{bseff}}$$

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

B.1.5 Effective Vds

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

B.1.6 Drain Current Expression

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

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

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

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

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

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

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

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

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

B.1.7 Substrate Current

$$I_{sub} = \frac{\alpha_o}{L_{eff}}(V_{ds} - V_{dseff})\exp(-\frac{\beta_o}{V_{ds} - V_{dseff}})\frac{I_{dso}}{1 + \frac{R_{ds}I_{dso}}{V_{dseff}}}\left(1 + \frac{V_{ds} - V_{dseff}}{V_A}\right)$$

B.1.8 Polysilicon Depletion Effect

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

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

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

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

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

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

B.1.9 Effective Channel Length and Width

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

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

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

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

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

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

B.1.10 Drain/Source Resistance

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

B.1.11 Temperature Effects

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

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

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

$$R_{dsw(T)} = R_{dsw(Tnorm)} + P_{rt}\left(\frac{T}{T_{norm}} - 1\right)$$

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

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

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

B.2 Capacitance Model Equations

B.2.1 Dimension Dependence

$$\delta \mathrm{W_{eff}} = DWC + \frac{Wl}{\mathrm{L}^{Wln}} + \frac{Ww}{\mathrm{W}^{Wwn}} + \frac{Wwl}{\mathrm{L}^{Wln}\mathrm{W}^{Wwn}}$$

$$\delta \mathrm{L_{eff}} = DLC + \frac{Ll}{\mathrm{L}^{Lln}} + \frac{Lw}{\mathrm{W}^{Lwn}} + \frac{Lwl}{\mathrm{L}^{Lln}\mathrm{W}^{Lwn}}$$

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

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

B.2.2 Overlap Capacitance (for NMOS)

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 (Vgs <0)

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

else

$$\frac{Q_{overlap,s}}{W_{active}} = (\text{CGS0} + \text{CKAPPA}\,\text{CGS1})\,\text{V}_{\text{gs}}$$

(3) for capmod=2

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

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

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 (Vgd <0)

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

else

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

(3) for capmod=2

$$V_{gd,overlap} = \frac{1}{2}\left\{\left(V_{gd} - \delta_2\right) + \sqrt{\left(V_{gd} - \delta_2\right)^2 - 4\delta_2}\right\} \quad where \quad \delta_2 = 0.02$$

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

B.2.2.3 Gate Overlap Charge

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

B.2.3 Instrinsic Charges

(1) for capmod=0

a) Accumulation region (Vgs <Vfb+Vbs)

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

$$Q_{sub} = -Q_g$$

$$Q_{inv} = 0$$

b) Subthreshold region (Vgs <Vth)

$$Q_b = -W_{active} L_{active} C_{ox} \frac{K_1^{\,2}}{2} \left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{fb} - V_{bs}\right)}{K_1^{\,2}}} \right)$$

$$Q_g = -Q_b$$

$$Q_{inv} = 0$$

c) Strong inversion (Vgs>Vth)

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

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

$$A_{bulk0} = \left(1 + \frac{K_1}{2\sqrt{\Phi_s - V_{bs}}}\{\frac{A_0 L_{eff}}{L_{eff} + 2\sqrt{X_J X_{dep}}} + \frac{B_o}{W_{eff}' + B_1}\}\right)\frac{1}{1 + K_{ETA} V_{bs}}$$

$$V_{th} = V_{fb} + \Phi_s + K_1\sqrt{\Phi_s - V_{bsf}}$$

(i) 50/50 Charge partition

if Vds<Vdsat

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

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

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

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

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 (Vds <Vdsat)

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

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

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

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

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

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 Vds <Vdsat

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

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

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

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

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

otherwise

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

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

$$Q_d = 0$$

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

(2) for capmod=1

if (Vgs <Vfb+Vbs+Vgsteffcv)

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

else

$$Q_{g1} = W_{active} L_{active} C_{ox} \frac{K_1^2}{2} \left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{FB} - V_{gsteff} cv - V_{bs}\right)}{K_1^2}} \right)$$

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

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

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

$$A_{bulk0} = \left(1+\frac{K_1}{2\sqrt{\Phi_s - V_{bseff}}}\left\{\frac{A_0 L_{eff}}{L_{eff}+2\sqrt{X_J X_{dep}}}+\frac{B_o}{W_{eff}'+B_1}\right\}\right)\frac{1}{1+K_{ETA}V_{bseff}}$$

$$V_{gsteffcv} = n\, v_t \ln\left[1+\exp\left(\frac{V_{gs}-V_{th}}{n\, v_t}\right)\right]$$

if (Vds <=Vdsat)

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

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

(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 (Vds >Vdsat)

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

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

(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) for capmod=2

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

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

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

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

$$vfb = V_{th} - \phi_s - K_1\sqrt{\phi_s}$$

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

$$Q_{sub0} = -W_{active} L_{active} C_{ox} \frac{K_1^{2}}{2}\left(-1 + \sqrt{1 + \frac{4\left(V_{gs} - V_{FBeff} - V_{gsteff\,cv} - V_{bseff}\right)}{K_1^{2}}}\right)$$

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

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

$$A_{bulk0} = \left(1+\frac{K_1}{2\sqrt{\Phi_s - V_{bseff}}}\left\{\frac{A_0 L_{eff}}{L_{eff}+2\sqrt{X_J X_{dep}}}+\frac{B_o}{W_{eff}'+B_1}\right\}\right)\frac{1}{1+K_{ETA}V_{bseff}}$$

$$V_{gsteffcv} = n\,v_t \ln\left[1+\exp\left(\frac{V_{gs}-V_{th}}{n\,v_t}\right)\right]$$

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

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

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

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

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

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

B.2.3.3 0/100 Charge Partition

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

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

B.2.4 Intrinsic Capacitances (with Body bias and DIBL)

$$C_{(s,d,g,b),g} = \frac{\partial Q_{s,d,g,b}}{\partial V_{gsteffcv}} \frac{\partial V_{gsteffcv}}{\partial V_{gt}}$$

$$C_{(s,d,g,b),s} = -\frac{\partial Q_{s,d,g,b}}{\partial V_{ds}} + \frac{\partial Q_{s,d,g,b}}{\partial V_{gsteffcv}} \frac{\partial V_{gsteffcv}}{\partial V_{gt}} \left(\frac{\partial V_{th}}{\partial V_{ds}} + \frac{\partial V_{th}}{\partial V_{bs}} \right)$$

$$C_{(s,d,g,b),d} = \frac{\partial Q_{s,d,g,b}}{\partial V_{ds}} - \frac{\partial Q_{s,d,g,b}}{\partial V_{gsteff}cv} \frac{\partial V_{gsteffcv}}{\partial V_{gt}} \frac{\partial V_{th}}{\partial V_{ds}}$$

$$C_{(s,d,g,b),b} = \frac{\partial Q_{s,d,g,b}}{\partial V_{bs}} - \frac{\partial Q_{s,d,g,b}}{\partial V_{gsteff}{}^{cv}} \frac{\partial V_{gsteffcv}}{\partial V_{gt}} \frac{\partial V_{th}}{\partial V_{bs}}$$

B.3 NQS Model Equations:

Quasi-static equilibrium channel charge:

$$Q_{eq} = -(Q_g + Q_b)$$

Actual channel charge and *Qdef* obtained from subcircuit (Figure 5-2):

$$Q_{ch} = Q_{eq} - Q_{def}$$

$$g_\tau = \frac{1}{\tau} = \frac{1}{\tau_{drift}} + \frac{1}{\tau_{diff}}$$

$$\tau_{drift} = \frac{C_{ox} W_{eff} L_{eff}^{3}}{\mu_{eff}\, \varepsilon \left| Q_{eq} - \alpha Q_{def} \right|} \approx \frac{\zeta}{\left| Q_{eq} \right|}$$

where,

$\varepsilon \equiv$ Elmore Constant $(default = 5)$ $0.0 \le \alpha \le 1.0\ (default = 0.5)$

and

$$\zeta = \frac{C_{ox} W_{eff} L_{eff}^{3}}{\mu_{eff}\, \varepsilon}$$

$$\tau_{diff} = \frac{q L_{eff}^{2}}{16 \mu_{eff} KT}$$

B.4 Flicker Noise

There exists two models for flicker noise. Each of these can be toggled by the **noimod** flag.

1. For noimod=1 and 4

$$Flicker\ Noise = \frac{K_f I_{ds}^{af}}{C_{ox} L_{eff}^{2} f^{ef}}$$

2. For noimod=2 and 3

1. Vgs>Vth+0.1:

$$Flicker\ Noise = \frac{vtq^2 I_{ds} \mu_{eff}}{f^{Ef} L_{eff}^{2} C_{ox} 10^8} [N_{oia} \log(\frac{No + 2x10^{14}}{Nl + 2x10^{14}}) + N_{oib}(No - Nl)$$
$$+ 0.5 N_{oic}(No^2 - Nl^2)] + \frac{vt I_{ds}^{2} \Delta L_{clm}}{f^{Ef} L_{eff}^{2} W_{eff} 10^8} \frac{N_{oia} + N_{oib} Nl + N_{oic} Nl^2}{(Nl + 2x10^{14})^2}$$

where V_{tm} is the thermal voltage, μ_{eff} is the effective mobiity at the given bias condition, L_{eff} and W_{eff} are the effective channel length and width, respectively. The parameter N_0 is the charge density at the source given by:

$$N_0 = \frac{C_{ox}(V_{GS} - V_{TH})}{q}$$

The parameter N_l is the charge density at the drain given by:

$$N_l = \frac{C_{ox}(V_{GS} - V_{TH} - V_{DS}')}{q}$$

$$V_{DS}' = MIN(V_{DS}, V_{DSAT})$$

ΔLclm refers to channel length reduction due to CLM and is given by:

$$\Delta L_{clm} = \begin{cases} Litl \times \log\left(\dfrac{\dfrac{V_{DS} - V_{DSAT}}{Litl} + Em}{E_{SAT}}\right) & \text{if VDS > VDSAT} \\ 0 & \text{otherwise} \end{cases}$$

$$E_{SAT} = \frac{2 \times Vsat}{u_{eff}}$$

2. Otherwise,

$$FlickerNoise = \frac{S_{limit} \times S_{wi}}{S_{limit} + S_{wi}}$$

Where, S_{limit} is the flicker noise calculated at Vgs=Vth+0.1 and S_{wi} is given by:

$$Swi = \frac{N_{oia} Vt I_{ds}^{2}}{W_{eff} L_{eff} \quad f^{Ef} \, 4x10^{36}}$$

B.5 Channel Thermal Noise

There exists two models for channel thermal noise. Each of these can be toggled by the **noimod** flag.

1. For noimod=1 and 3

$$\frac{8kT}{3}(gm + gds + gmb)$$

2. For noimod=2 and 4

$$\frac{4KT\mu_{eff}}{L_{eff}^{2}} |Q_{inv}|$$

$$Q_{inv} = -W_{eff} L_{eff} C_{ox} V_{gsteff} (1 - \frac{A_{bulk}}{2(V_{gsteff} + 2vt)} V_{dseff})$$

The derivation for this last thermal noise expression is based on the noise model found in [35].