APPENDIX B: Equation List

B.1 I-V Model

B.1.1 Threshold Voltage

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

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

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

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

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

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

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

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

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

($\delta1$=0.001)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$R_{dsw(T)} = R_{dsw(T_{norm})} + \mathrm{Pr}_t(\frac{T}{T_{norm}} - 1)$$

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

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

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

B.2 Capacitance Model Equations

B.2.1 Dimension Dependence

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

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

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

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