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# APPENDIX B: Equation List

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## B.1 I-V Model

### B.1.1 Threshold Voltage

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

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

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

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

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

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

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

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

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

$$(\delta 1=0.001)$$

$$V_{bseff} = V_{bc} + 0.5[V_{bs} - V_{bc} - d_1 + \sqrt{(V_{bs} - V_{bc} - d_1)^2 - 4d_1 V_{bc}}]$$

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

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

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

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

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

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

### B.1.3 Mobility

For mobMod=1

$$\mathbf{m}_{ff} = \frac{\mathbf{m}_b}{1 + (U_a + U_c V_{bseff}) \left( \frac{V_{gsteff} + 2V_{th}}{T_{ox}} \right) + U_b \left( \frac{V_{gsteff} + 2V_{th}}{T_{ox}} \right)^2}$$

For mobMod=2

$$\mathbf{m}_{ff} = \frac{\mathbf{m}_b}{1 + (U_a + U_c V_{bseff}) \left( \frac{V_{gsteff}}{T_{ox}} \right) + U_b \left( \frac{V_{gsteff}}{T_{ox}} \right)^2}$$

For mobMod=3

$$\mathbf{m}_{ff} = \frac{\mathbf{m}_b}{1 + [U_a \left( \frac{V_{gsteff} + 2V_{th}}{T_{ox}} \right) + U_b \left( \frac{V_{gsteff} + 2V_{th}}{T_{ox}} \right)^2] (1 + U_c V_{bseff})}$$

### B.1.4 Drain Saturation Voltage

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

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

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

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

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

$$I = A_1 V_{gsteff} + A_2$$

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

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

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

$$E_{sat} = \frac{2n_{at}}{m_{ff}}$$

### B.1.5 Effective $V_{ds}$

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

### B.1.6 Drain Current Expression

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

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

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

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

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

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

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

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

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

### B.1.7 Substrate Current

$$I_{sub} = \frac{a_0 + a_1 \cdot L_{eff}}{L_{eff}} (V_{ds} - V_{dseff}) \exp\left(-\frac{b_0}{V_{ds} - V_{dseff}}\right) \frac{I_{ds0}}{1 + \frac{R_{ds}I_{ds0}}{V_{dseff}}} \left(1 + \frac{V_{ds} - V_{dseff}}{V_A}\right)$$

**B.1.8 Polysilicon Depletion Effect**

$$V_{poly} = \frac{1}{2} X_{poly} E_{poly} = \frac{q N_{gate} X_{poly}^2}{2 \epsilon_{si}}$$

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

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

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

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

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

**B.1.9 Effective Channel Length and Width**

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

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

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

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

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

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

### B.1.10 Source/Drain Resistance

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

### B.1.11 Temperature Effects

$$V_{th}(T) = V_{th}(T_{norm}) + (K_{T1} + K_{T1l} / L_{eff} + K_{T2} V_{bseff})(T / T_{norm} - 1)$$

$$\mathbf{m}(T) = \mathbf{m}(T_{norm}) \left( \frac{T}{T_{norm}} \right)^{\mathbf{m}}$$

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



## Capacitance Model Equations

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

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

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

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

## B.2 Capacitance Model Equations

### B.2.1 Dimension Dependence

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

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

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

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

### B.2.2 Overlap Capacitance

#### B.2.2.1 Source Overlap Capacitance

(1) for capMod = 0

$$\frac{Q_{overlap,s}}{W_{active}} = CGS0V_{gs}$$

(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

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

$$V_{gs,overlap} = \frac{1}{2} \left( V_{gs} + d_1 - \sqrt{(V_{gs} + d_1)^2 + 4d_1} \right) \quad d_1 = 0.02$$

## Capacitance Model Equations

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### B.2.2.2 Drain Overlap Capacitance

(1) for capMod = 0

$$\frac{Q_{overlap,d}}{W_{active}} = CGD0V_{gd}$$

(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

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

(3) for capMod = 2

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

$$V_{gd,overlap} = \frac{1}{2} \left( V_{gd} + d_1 - \sqrt{(V_{gd} + d_1)^2 + 4d_1} \right) \quad d_1 = 0.02$$

### B.2.2.3 Gate Overlap Charge

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

### B.2.3 Intrinsic Charges

#### (1) capMod = 0

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

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

$$Q_{\text{sub}} = -Q_g$$

$$Q_{\text{inv}} = 0$$

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

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

$$Q_g = -Q_b$$

## Capacitance Model Equations

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$$Q_{inv} = 0$$

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

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

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

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

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

(i) 50/50 Charge partition

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

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

## Capacitance Model Equations

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

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

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

otherwise

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

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

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

(ii) 40/60 channel-charge Partition

## Capacitance Model Equations

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

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

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

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

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

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

otherwise

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

## Capacitance Model Equations

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

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

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

(iii) 0/100 Channel-charge Partition

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

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

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

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



## Capacitance Model Equations

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

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

otherwise

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

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

$$Q_d = 0$$

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

(2) **capMod = 1**

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

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

## Capacitance Model Equations

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

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

$$Q_{gl} = W_{active} L_{active} C_{ox} (V_{gs} - V_{fb} - V_{bs} - V_{gsteffcv})$$

else

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

$$Q_{bl} = -Q_{gl}$$

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

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

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

## Capacitance Model Equations

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

$$\text{if } (V_{ds} \leq V_{dsat})$$

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

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

(i) 50/50 Channel-charge Partition

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

(ii) 40/60 Channel-charge partition

## Capacitance Model Equations

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

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

(iii) 0/100 Channel-charge Partition

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

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

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

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

$$Q_b = Q_{b1} - W_{active} L_{active} C_{ox} \frac{(V_{gsteff}^{cv} - V_{dsat})}{3}$$

## Capacitance Model Equations

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(i) 50/50 Channel-charge Partition

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

(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

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

## Capacitance Model Equations

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

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

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

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

$$V_{FBeff} = vfb - 0.5 \left\{ V_3 + \sqrt{V_3^2 + 4d_3 vfb} \right\} \quad \text{where} \quad V_3 = vfb - V_{gb} - d_3; \quad d_3 = 0.02$$

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

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

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

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

## Capacitance Model Equations

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

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

$$V_{cveff} = V_{dsat,cv} - 0.5 \left\{ V_4 + \sqrt{V_4^2 + 4d_4 V_{dsat,cv}} \right\} \quad \text{where} \quad V_4 = V_{dsat,cv} - V_{ds} - d_4; \quad d_4 = 0.02$$

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

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

## Capacitance Model Equations

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### B.2.3.1 50/50 Charge partition

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

### B.2.3.2 40/60 Channel-charge Partition

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

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

### B.2.3.3 0/100 Charge Partition

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

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



## Capacitance Model Equations

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### (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.

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

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

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

$$V_{gbacc} = \frac{1}{2} \cdot \left[ V_0 + \sqrt{V_0^2 + 4d_3 V_{fb}} \right]$$

$$V_0 = V_{fb} + V_{bseff} - V_{gs} - d_3$$

$$V_{FBeff} = vfb - 0.5 \left\{ V_3 + \sqrt{V_3^2 + 4d_3 vfb} \right\} \quad \text{where} \quad V_3 = vfb - V_{gb} - d_3; \quad d_3 = 0.02$$

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

$$C_{cen} = \frac{e_{si}}{X_{DC}}$$

## Capacitance Model Equations

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$$\Phi_d = \Phi_s - 2\Phi_B = n_t \ln \left( \frac{V_{gsteffcv} \cdot (V_{gsteffcv} + 2K_{lox} \sqrt{2\Phi_B})}{moin \cdot K_{lox}^2 n_t} \right)$$

$$Q_{sub} = -WLC_{oxeff} \cdot \frac{K_{lox}^2}{2} \cdot \left[ -1 + \sqrt{1 + \frac{4(V_{gs} - V_{FBeff} - V_{bseffs} - V_{gsteffcv})}{K_{lox}^2}} \right]$$

$$V_{cveff} = V_{dsat} - \frac{1}{2} \cdot \left( V_1 + \sqrt{V_1^2 + 4d_3 V_{dsat}} \right)$$

$$V_1 = V_{dsat} - V_{ds} - d_3$$

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

$$Q_{inv} = -WLC_{oxeff} \cdot \left[ V_{gsteffcv} - j_d - \frac{1}{2} A_{bulk} V_{cveff} + \frac{A_{bulk}^2 V_{cveff}^2}{12 \cdot \left( V_{gsteffcv} - j_d - \frac{A_{bulk} V_{cveff}}{2} \right)} \right]$$

## Capacitance Model Equations

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

(i) 50/50 Charge Partition

$$Q_S = Q_D = \frac{1}{2} Q_{inv} = -\frac{WLC_{oxeff}}{2} \left[ V_{gsteffv} - J_d - \frac{1}{2} A_{bulk} V_{cveff} + \frac{A_{bulk}^2 V_{cveff}^2}{12 \cdot \left( V_{gsteffv} - J_d - A_{bulk} V_{cveff} / 2 \right)} \right]$$

(ii) 40/60 Charge Partition

$$Q_S = -\frac{WLC_{oxeff}}{2 \left( V_{gsteffv} - J_d - A_{bulk} V_{cveff} / 2 \right)^2} \left[ \left( V_{gsteffv} - J_d \right)^3 - \frac{4}{3} \left( V_{gsteffv} - J_d \right)^2 A_{bulk} V_{cveff} + \frac{2}{3} \left( V_{gsteffv} - J_d \right) \left( A_{bulk} V_{cveff} \right)^2 - \frac{2}{15} \left( A_{bulk} V_{cveff} \right)^3 \right]$$

$$Q_D = -\frac{WLC_{oxeff}}{2 \left( V_{gsteffv} - J_d - A_{bulk} V_{cveff} / 2 \right)^2} \left[ \left( V_{gsteffv} - J_d \right)^3 - \frac{5}{3} \left( V_{gsteffv} - J_d \right)^2 A_{bulk} V_{cveff} + \left( V_{gsteffv} - J_d \right) \left( A_{bulk} V_{cveff} \right)^2 - \frac{1}{5} \left( A_{bulk} V_{cveff} \right)^3 \right]$$

(iii) 0/100 Charge Partition

$$Q_S = -\frac{WLC_{oxeff}}{2} \cdot \left[ V_{gsteffcv} - J_d + \frac{1}{2} A_{bulk} V_{cveff} - \frac{A_{bulk}^2 V_{cveff}^2}{12 \cdot \left( V_{gsteffcv} - J_d - A_{bulk} V_{cveff} / 2 \right)} \right]$$

## Capacitance Model Equations

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