Chapter 3: Channel Charge and Subthreshold Swing Models

3.1 Channel Charge Model

The channel charge density in subthreshold for zero V_{ds} is written as

(3.1.1)

$$Q_{chsubs0} = \sqrt{\frac{qNDEP\varepsilon_{si}}{2\Phi_s}} v_t \cdot \exp\left(\frac{V_{gse} - V_{th} - Voff'}{nv_t}\right)$$

where

(3.1.1a)

$$Voff' = VOFF + \frac{VOFFL}{L_{eff}}$$

VOFFL is used to model the length dependence of *Voff*' on non-uniform channel doping profiles.

In strong inversion region, the density is expressed by

(3.1.2)

$$Q_{chs0} = C_{oxe} \cdot \left(V_{gse} - V_{th}\right)$$

A unified charge density model considering the charge layer thickness effect is derived for both subthreshold and inversion regions as

(3.1.3)

$$Q_{ch0} = C_{oxeff} \cdot V_{gsteff}$$

where C_{oxeff} is modeled by

(3.1.4)

$$C_{oxeff} = \frac{C_{oxe} \cdot C_{cen}}{C_{oxe} + C_{cen}} \quad with\, C_{cen} = \frac{e_{si}}{X_{DC}}$$

and X_{DC} is given as

(3.1.5)

$$X_{DC} = \frac{1.9 \times 10^{-9}\ \mathrm{cm}}{1 + \left(\frac{V_{gsteff} + 4(VTH0 - VFB - \Phi_s)}{2TOXP} \right)^{0.7}}$$

In the above equations, V_{gsteff}, the effective (V_{gse}-V_{th}) used to describe the channel charge densities from subthreshold to strong inversion, is modeled by

(3.1.6a)

$$V_{gsteff} = \frac{nv_t \ln\left\{1 + \exp\left[\frac{m^*(V_{gse} - V_{th})}{nv_t}\right]\right\}}{m^* + nC_{oxe} \cdot \sqrt{\frac{2\Phi_s}{qNDEPe_{si}}} \exp\left[-\frac{(1 - m^*)(V_{gse} - V_{th}) - Voff'}{nv_t}\right]}$$

where

(3.1.6b)

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

MINV is introduced to improve the accuracy of G_m, G_m/I_d and G_m^2/I_d in the moderate inversion region.

To account for the drain bias effect, The y dependence has to be included in (3.1.3). Consider first the case of strong inversion

$$Q_{chs}(y) = C_{oxeff} \cdot (V_{gse} - V_{th} - A_{bulk} V_F(y)) \tag{3.1.7}$$

$V_F(y)$ stands for the quasi-Fermi potential at any given point y along the channel with respect to the source. (3.1.7) can also be written as

$$Q_{chs}(y) = Q_{chs0} + \Delta Q_{chs}(y) \tag{3.1.8}$$

The term $\Delta Q_{chs}(y) = -C_{oxeff} A_{bulk} V_F(y)$ is the incremental charge density introduced by the drain voltage at y.

In subthreshold region, the channel charge density along the channel from source to drain can be written as

$$Q_{chsubs}(y) = Q_{chsubs0} \cdot \exp\left(-\frac{A_{bulk} V_F(y)}{n v_t} \right) \tag{3.1.9}$$

Taylor expansion of (3.1.9) yields the following (keeping the first two terms)

$$Q_{chsubs}(y) = Q_{chsubs0}\left(1 - \frac{A_{bulk}V_F(y)}{nv_t}\right) \tag{3.1.10}$$

Similarly, (3.1.10) is transformed into

$$Q_{chsubs}(y) = Q_{chsubs0} + \Delta Q_{chsubs}(y) \tag{3.1.11}$$

where $\Delta Q_{chsubs}(y)$ is the incremental channel charge density induced by the drain voltage in the subthreshold region. It is written as

$$\Delta Q_{chsubs}(y) = -Q_{chsubs0} \cdot \frac{A_{bulk}V_F(y)}{nv_t} \tag{3.1.12}$$

To obtain a unified expression for the incremental channel charge density $\Delta Q_{ch}(y)$ induced by V_{ds}, we assume $\Delta Q_{ch}(y)$ to be

$$\Delta Q_{ch}(y) = \frac{\Delta Q_{chs}(y) \cdot \Delta Q_{chsubs}(y)}{\Delta Q_{chs}(y) + \Delta Q_{chsubs}(y)} \tag{3.1.13}$$

Substituting $\Delta Q_{ch}(y)$ of (3.1.8) and (3.1.12) into (3.1.13), we obtain

$$\Delta Q_{ch}(y) = -\frac{V_F(y)}{V_b} Q_{ch0} \tag{3.1.14}$$

where $V_b = (V_{gsteff} + nv_t) / A_{bulk}$. In the model implementation, n of V_b is replaced by a typical constant value of 2. The expression for V_b now becomes

(3.1.15)

$$V_b = \frac{V_{gsteff} + 2v_t}{A_{bulk}}$$

A unified expression for $Q_{ch}(y)$ from subthreshold to strong inversion regions is

(3.1.16)

$$Q_{ch}(y) = C_{oxeff} \cdot V_{gsteff} \cdot \left(1 - \frac{V_F(y)}{V_b}\right)$$

3.2 Subthreshold Swing *n*

The drain current equation in the subthreshold region can be expressed as

(3.2.1)

$$I_{ds} = I_0 \left[1 - \exp\left(-\frac{V_{ds}}{v_t}\right)\right] \cdot \exp\left(\frac{V_{gs} - V_{th} - V_{off}'}{nv_t}\right)$$

where

(3.2.2)

$$I_0 = m\frac{W}{L}\sqrt{\frac{qe_{si}NDEP}{2\Phi_s}}v_t^{\,2}$$

v_t is the thermal voltage and equal to k_BT/q. $V_{off}' = VOFF + VOFFL / L_{eff}$ is the offset voltage, which determines the channel current at $V_{gs} = 0$. In (3.2.1), n is the subthreshold swing parameter. Experimental data shows that the subthreshold swing is a function of channel length and the interface state density. These two mechanisms are modeled by the following

$$n = 1 + NFACTOR \cdot \frac{C_{dep}}{C_{oxe}} + \frac{Cdsc\_Term + CIT}{C_{oxe}} \tag{3.2.3}$$

where *Cdsc-Term*, written as

$$Cdsc\_Term = \left(CDSC + CDSCD \cdot V_{ds} + CDSCB \cdot V_{bseff}\right) \cdot \frac{0.5}{\cosh\left(DVT1 \frac{L_{eff}}{l_t}\right) - 1}$$

represents the coupling capacitance between drain/source to channel. Parameters *CDSC*, *CDSCD* and *CDSCB* are extracted. Parameter *CIT* is the capacitance due to interface states. From (3.2.3), it can be seen that subthreshold swing shares the same exponential dependence on channel length as the *DIBL* effect. Parameter *NFACTOR* is close to 1 and introduced to compensate for errors in the depletion width capacitance calculation.