Physics and Engineering of CMOS Devices

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Outline of Today's Class

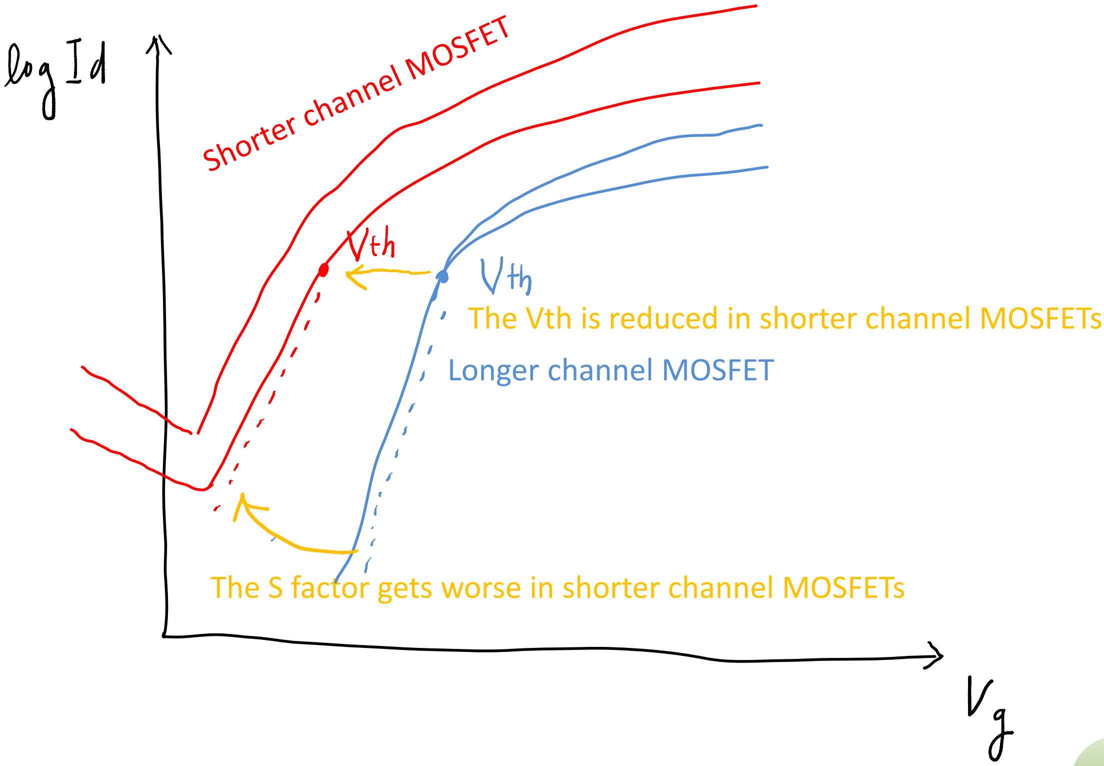
- Scaling
  - Constant-Field Scaling
  - Generalized Scaling
- Short Channel Effects
- Charge Sharing Model
- Quasi-2D Model
  - DIBL (Drain-induced Barrier Lowering)
  - Electric Field in Drain Depletion Region
- Saturation Velocity

Short Channel Effects

Short Channel Effects

- The threshold voltage (V_{th}) of MOS transistors is lowered as the dimensions of transistors are shrunken.
- The subthreshold slope (S Factor) gets worse in shorter channel MOS transistors.
- The threshold voltage moves to a lower value with an increase in the drain voltage (DIBL).

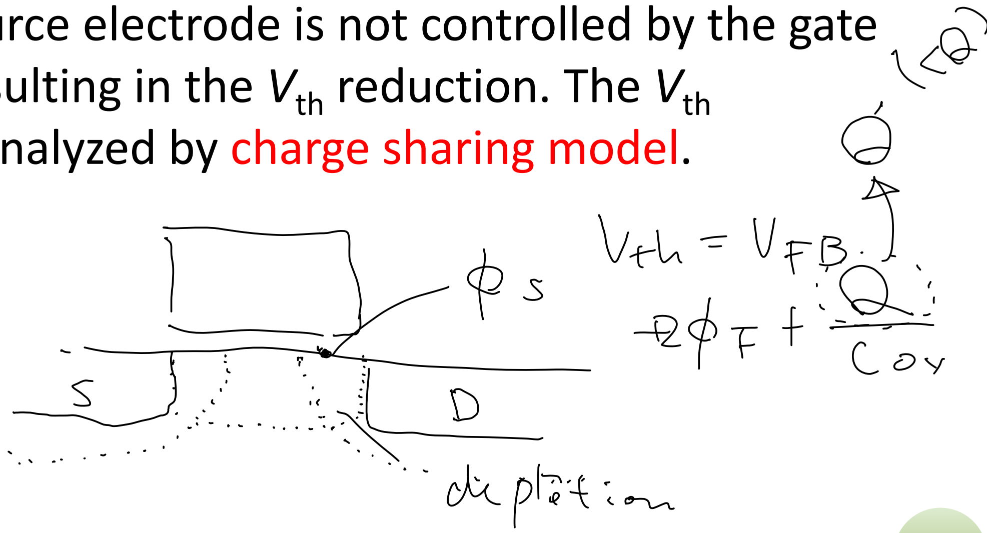
Short Channel MOSFETs



Charge Sharing Model

Charge Sharing Model

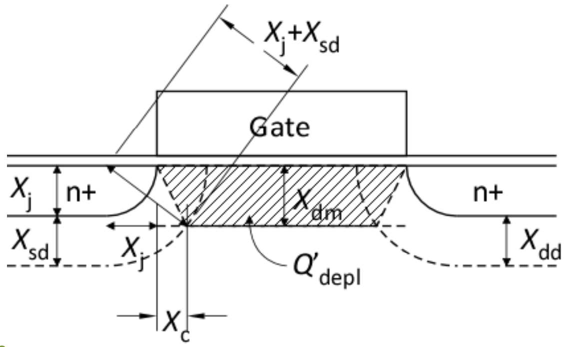
In MOS capacitors depletion charges are controlled by the gate electrode, whereas in MOS transistors the depletion charges are shared/controlled by three terminals: the gate, source, and drain electrodes. The depletion charges shared by source electrode is not controlled by the gate electrode, resulting in the V_{th} reduction. The V_{th} reduction is analyzed by charge sharing model.



Charge Sharing Model (2)

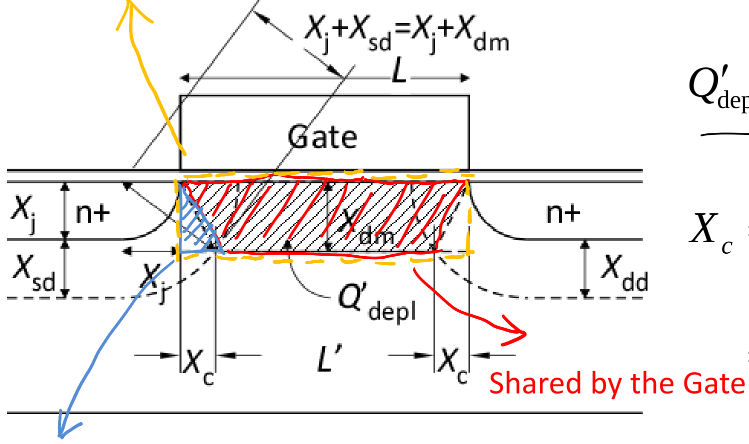
Assumptions for charge sharing model

- Drain voltage (V_d) is assumed to be zero.
- The edge structure of source/drain electrodes is a quarter circle.
- The depth of the source junction is the same as that of drain junction (X_j).
- The depletion layer width for the source/drain junction is equal to the maximum depletion layer width ($X_{sd} = X_{dd} = X_{dm}$).
- Charges at the source/drain ends are shared equally by the gate and source/drain electrodes.



Charge Sharing Model (3)

In MOS capacitor, depletion charges in this area is assumed to be shared only by the gate.



Shared by the Source

$$Q'_{\text{depl}} = qN_{\text{sub}} X_{dm} \frac{L+L'}{2L}$$

$$X_c = \sqrt{\left(X_j + X_{dm}\right)^2 - X_{dm}^{\;2}} - X_j$$

$$= X_j \left(\sqrt{1 + \frac{2X_{dm}}{X_j}} - 1 \right)$$

$$L' = L - 2X_c = L - 2X_j \left(\sqrt{1 + \frac{2X_{dm}}{X_j}} - 1 \right)$$

$$F \equiv \frac{L+L'}{2L} = 1 - \frac{X_j}{L} \left(\sqrt{1 + \frac{2X_{dm}}{X_j}} - 1 \right) \qquad Q'_{\text{depl}} = qN_{\text{sub}} X_{dm} F$$

Charge Sharing Model (4)

$$\Delta V_{th} = \frac{Q_{\text{depl}} - Q'_{\text{depl}}}{C_{ox}} = \frac{Q_{\text{depl}}}{C_{ox}} (1-F)$$

$$= \frac{Q_{\text{depl}}}{C_{ox}} \frac{X_j}{L} \left(\sqrt{1 + \frac{2X_{dm}}{X_j}} - 1 \right)$$

Therefore, the threshold voltage reduction is larger, if

- Oxide thickness is thicker,
- The junction depth is deeper,
- The substrate impurity concentration is smaller.

However, the charge sharing model is not suitable for analyzing MOSFET operation under strong-inversion condition.

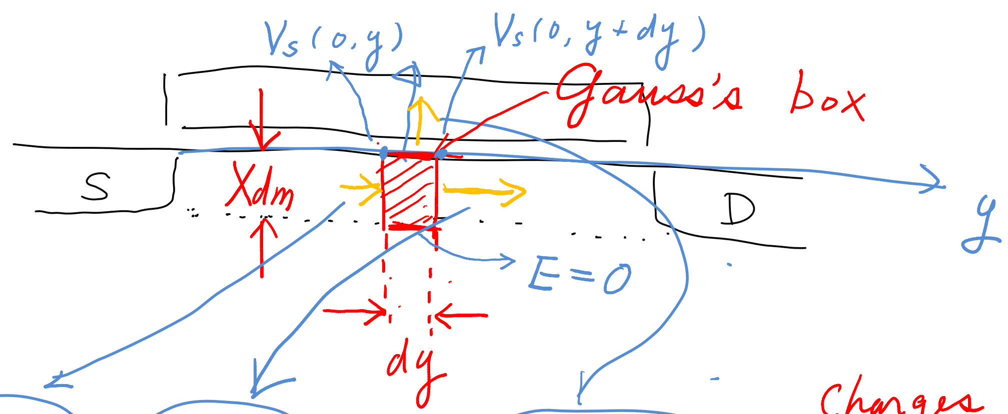
Quasi-2D Model

Quasi-2D Model (1)

The charge sharing model is suitable for analyzing MOSFET operation with small drain voltage. Since in the charge sharing model the surface potential is assumed to be constant along the channel direction, the model is inaccurate at a high drain voltage. In the quasi-2D model, the Poisson's equation is solved analytically, and thus the quasi-2D model is better to analyze V_{th} shift in shorter channel MOSFETs.

Z.-H. Liu et al., "Threshold Voltage Model for Deep-Submicrometer MOSFET's," *IEEE Trans. Electron Dev.*, **40** (1), p86, 1993.

Quasi-2D Model (2)



$$\kappa_s \varepsilon_0 \frac{X_{\text{depl}}}{\eta}\left[-\frac{V_s(0,y)}{dy}+\frac{V_s(0,y+dy)}{dy}\right]+\kappa_{ox}\varepsilon_0\frac{V_{gs}-V_{FB}-V_s(y)}{t_{ox}}dy = qN_{\text{sub}}X_{\text{depl}}dy$$

$$\kappa_s \varepsilon_0 \frac{X_{\text{depl}}}{\eta}\frac{d^2V_s(0,y)}{dy^2}+\kappa_{ox}\varepsilon_0\frac{V_{gs}-V_{FB}-V_s(y)}{t_{ox}} = qN_{\text{sub}}X_{\text{depl}}$$

Quasi-2D Model (3)

$$\frac{d^2V_s(0,y)}{dy^2}+\frac{\kappa_{ox}}{\kappa_s}\frac{\eta}{X_{\text{depl}}t_{ox}}\left[V_{gs}-V_{FB}-V_s(y)-\frac{qN_{\text{sub}}X_{\text{depl}}t_{ox}}{\kappa_{ox}\varepsilon_0}\right]=0$$

$$\frac{d^2V_s(0,y)}{dy^2}+\frac{1}{l^2}\left[V_{gs}-V_{th0}-V_s(y)\right]=0$$

$$l \equiv \sqrt{\frac{\kappa_s}{\kappa_{ox}}\frac{X_{\text{depl}}t_{ox}}{\eta}} \qquad V_{th0}\equiv V_{FB}+\frac{qN_{\text{sub}}X_{\text{depl}}t_{ox}}{\kappa_{ox}\varepsilon_0}$$

$$\frac{d^2V_s(y)}{dy^2}-\frac{1}{l^2}V(y)=-\frac{1}{l^2}\left[V_{gs}-V_{th0}\right]$$

$$V_s(y)=C_1(y)e^{y/l}+C_2(y)e^{-y/l}$$