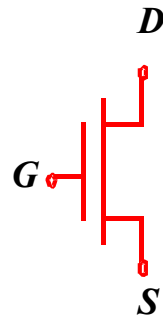
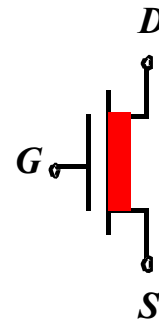


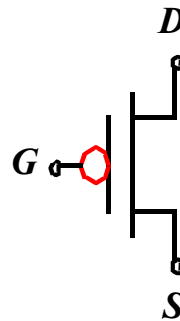
MOS Transistors - Types and Symbols



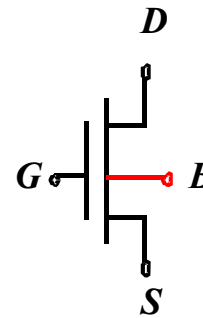
NMOS Enhancement



NMOS Depletion

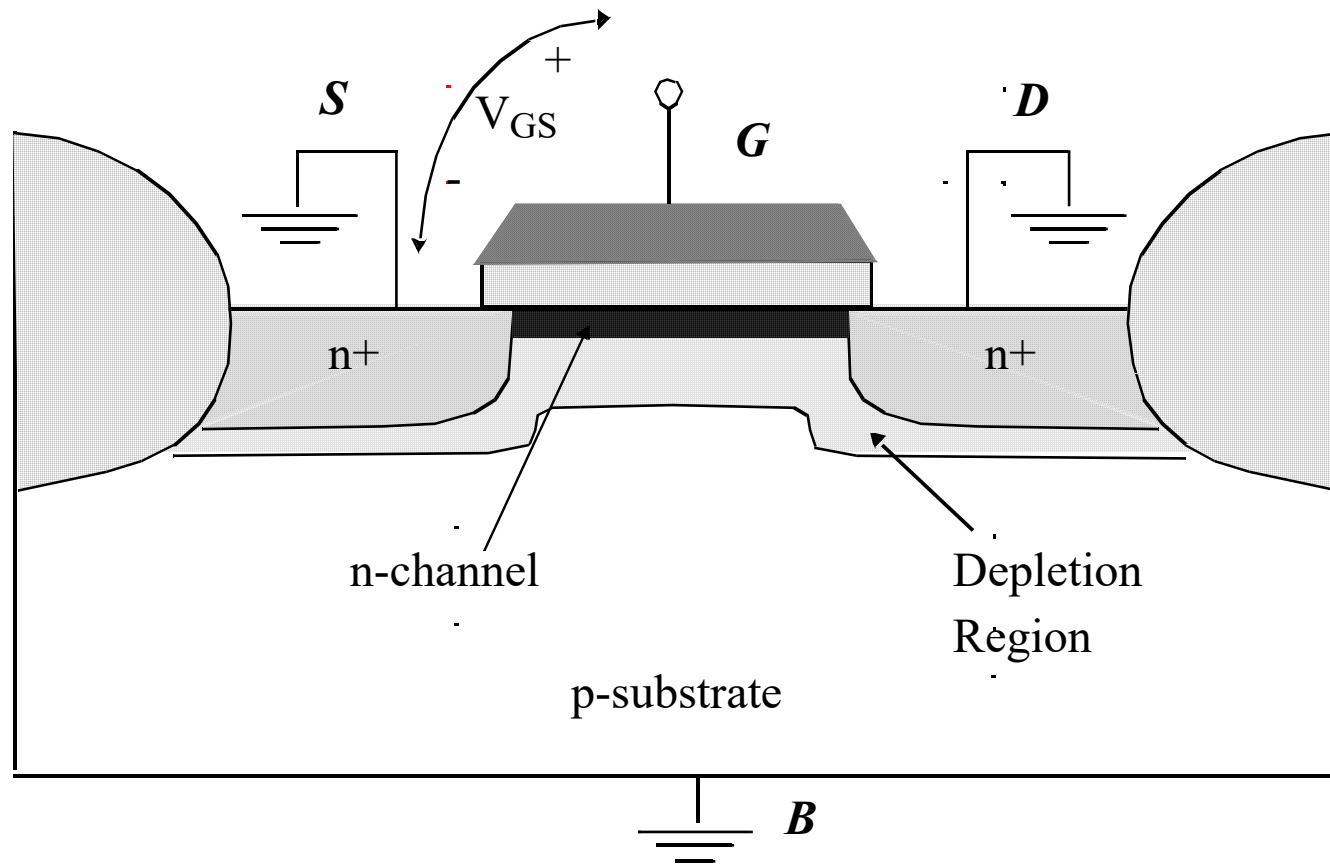


PMOS Enhancement



**NMOS with
Bulk Contact**

Threshold Voltage: Concept



The Threshold Voltage

$$V_T = \phi_{ms} - 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{SS}}{C_{ox}} - \frac{Q_I}{C_{ox}}$$

Workfunction Difference ↑ ↑ ↑ Implants
 Depletion Layer Charge Surface Charge

Body Effect Coefficient

$$V_T = V_{T0} + \gamma(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|})$$

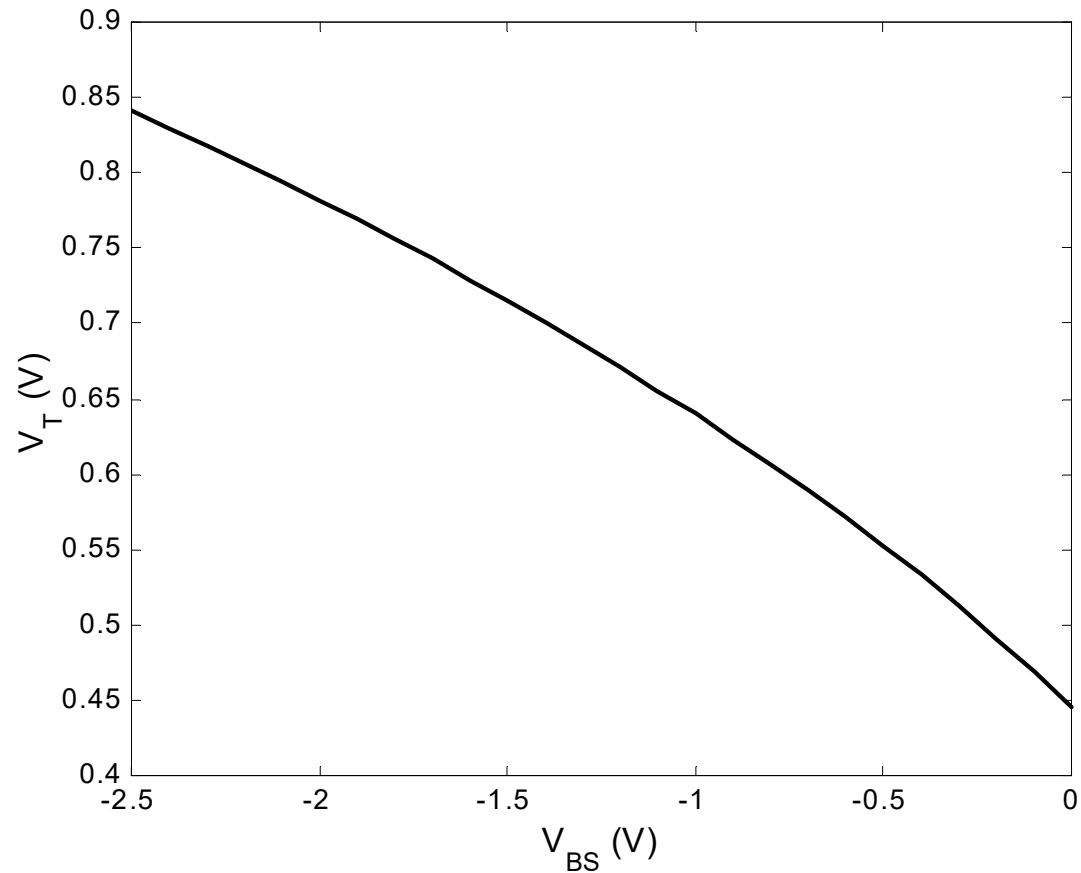
with

$$V_{T0} = \phi_{ms} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{SS}}{C_{ox}} - \frac{Q_I}{C_{ox}}$$

and

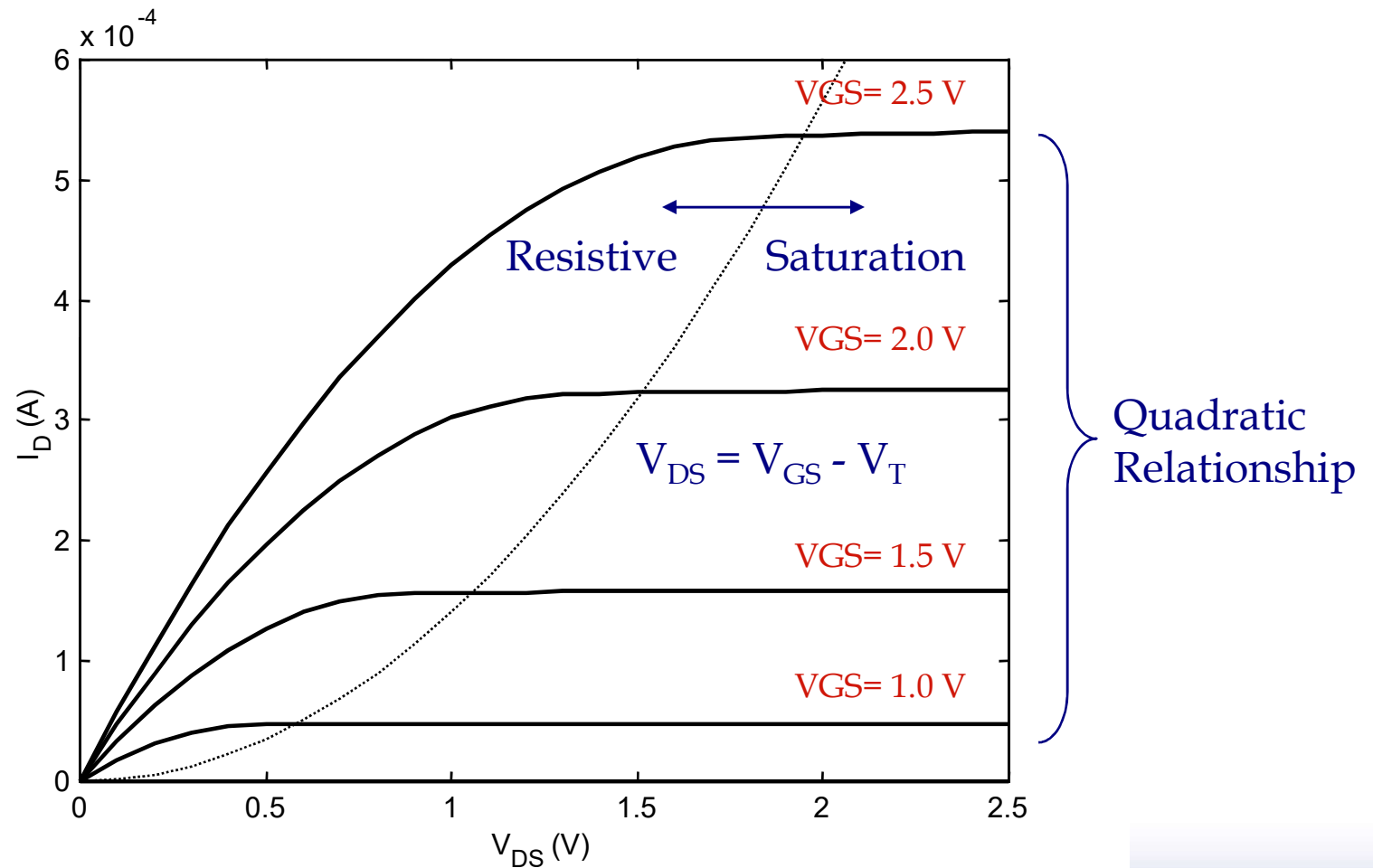
$$\gamma = \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}}$$

The Body Effect

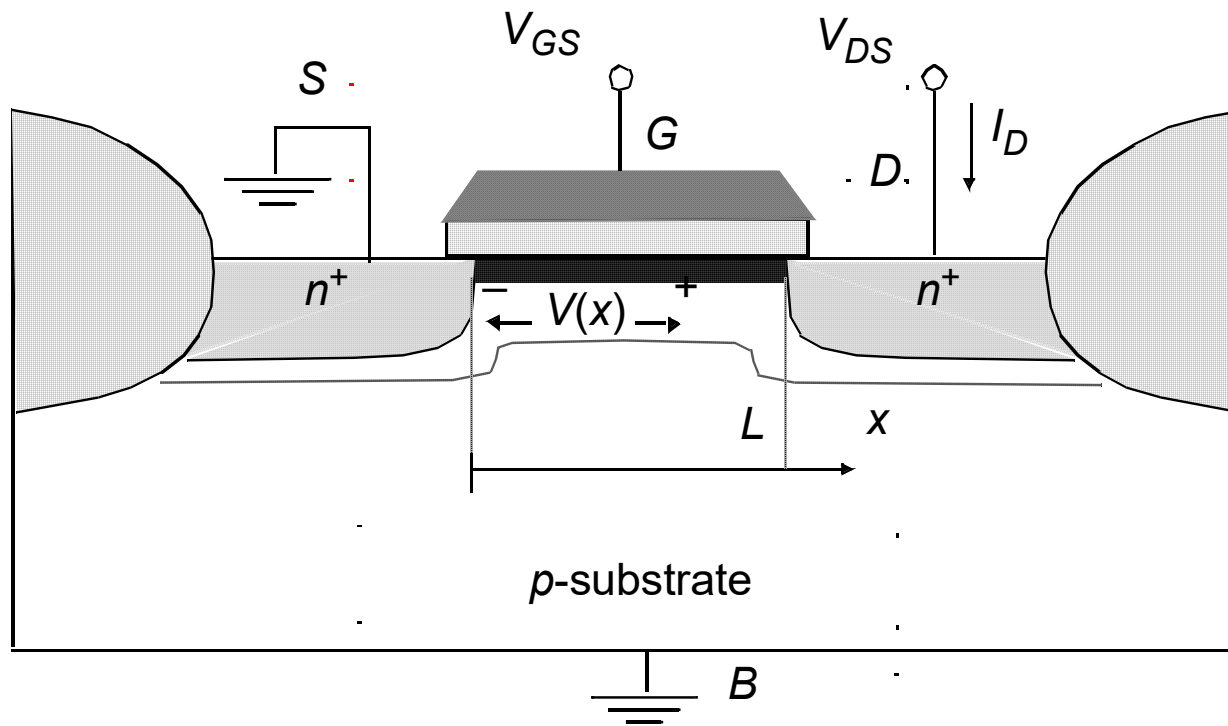


Current-Voltage Relations

A good ol' transistor

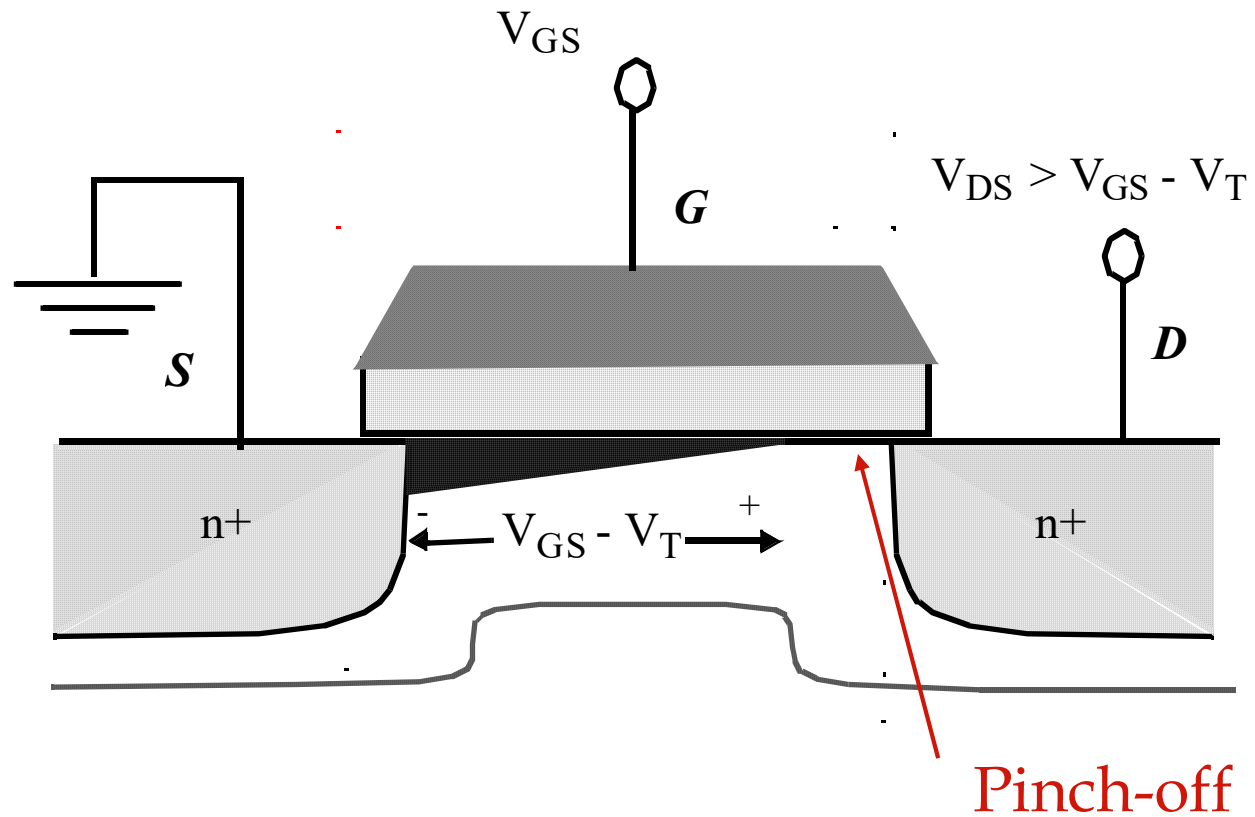


Transistor in Linear



MOS transistor and its bias conditions

Transistor in Saturation



Current-Voltage Relations Long-Channel Device

Linear Region: $V_{DS} \leq V_{GS} - V_T$

$$I_D = k'_n \frac{W}{L} \left((V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

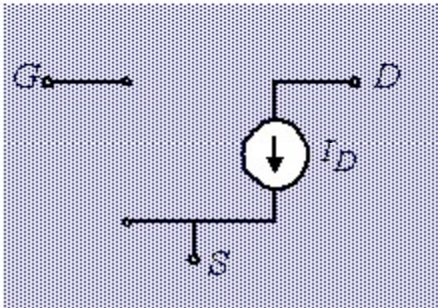
with

$$k'_n = \mu_n C_{ox} = \frac{\mu_n \epsilon_{ox}}{t_{ox}} \quad \text{Process Transconductance Parameter}$$

Saturation Mode: $V_{DS} \geq V_{GS} - V_T$ Channel Length Modulation

$$I_D = \frac{k'_n W}{2 L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

A model for manual analysis



$$V_{DS} > V_{GS} - V_T$$

$$I_D = \frac{k'_n W}{2 L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

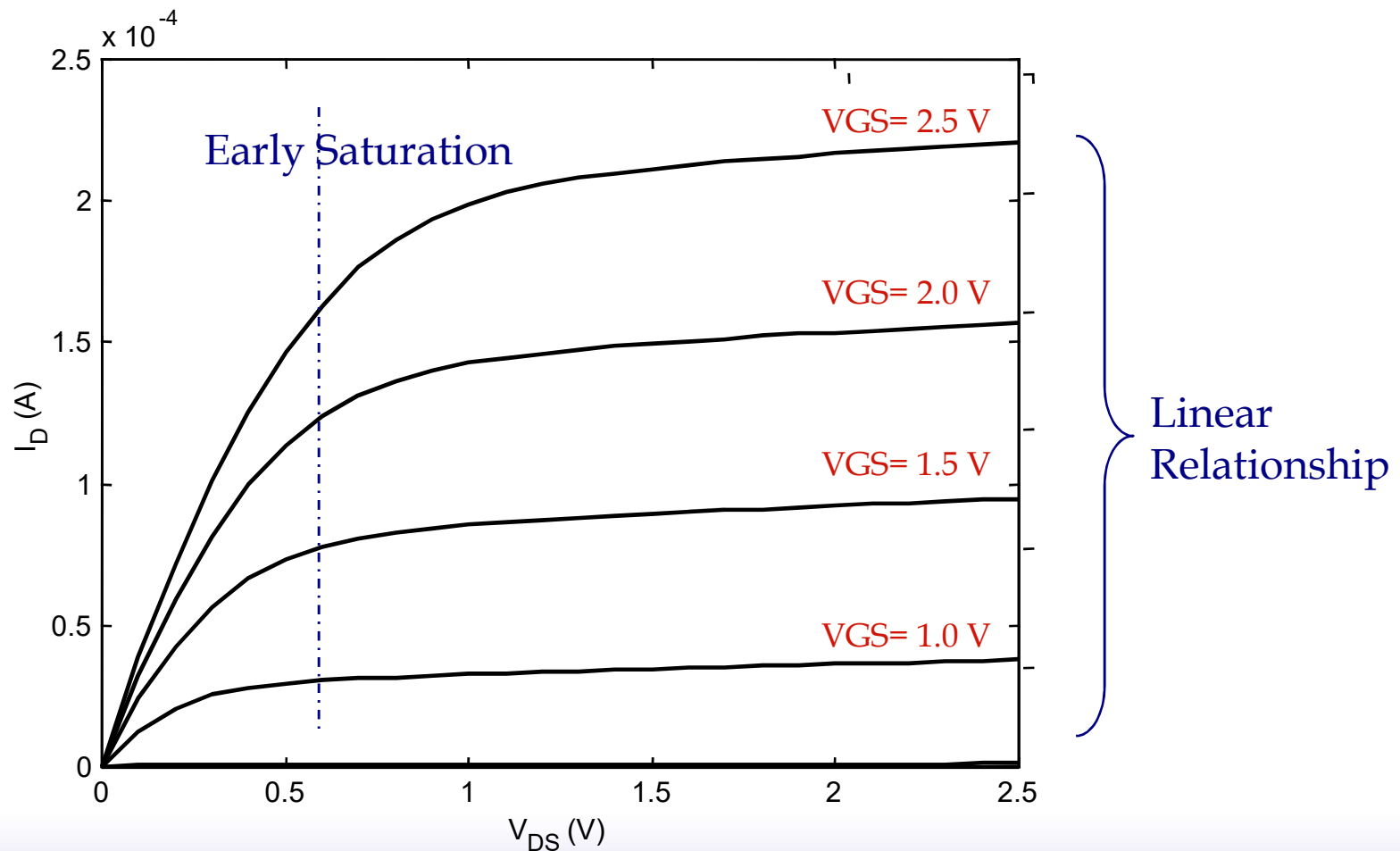
$$V_{DS} < V_{GS} - V_T$$

$$I_D = k'_n \frac{W}{L} \left((V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right)$$

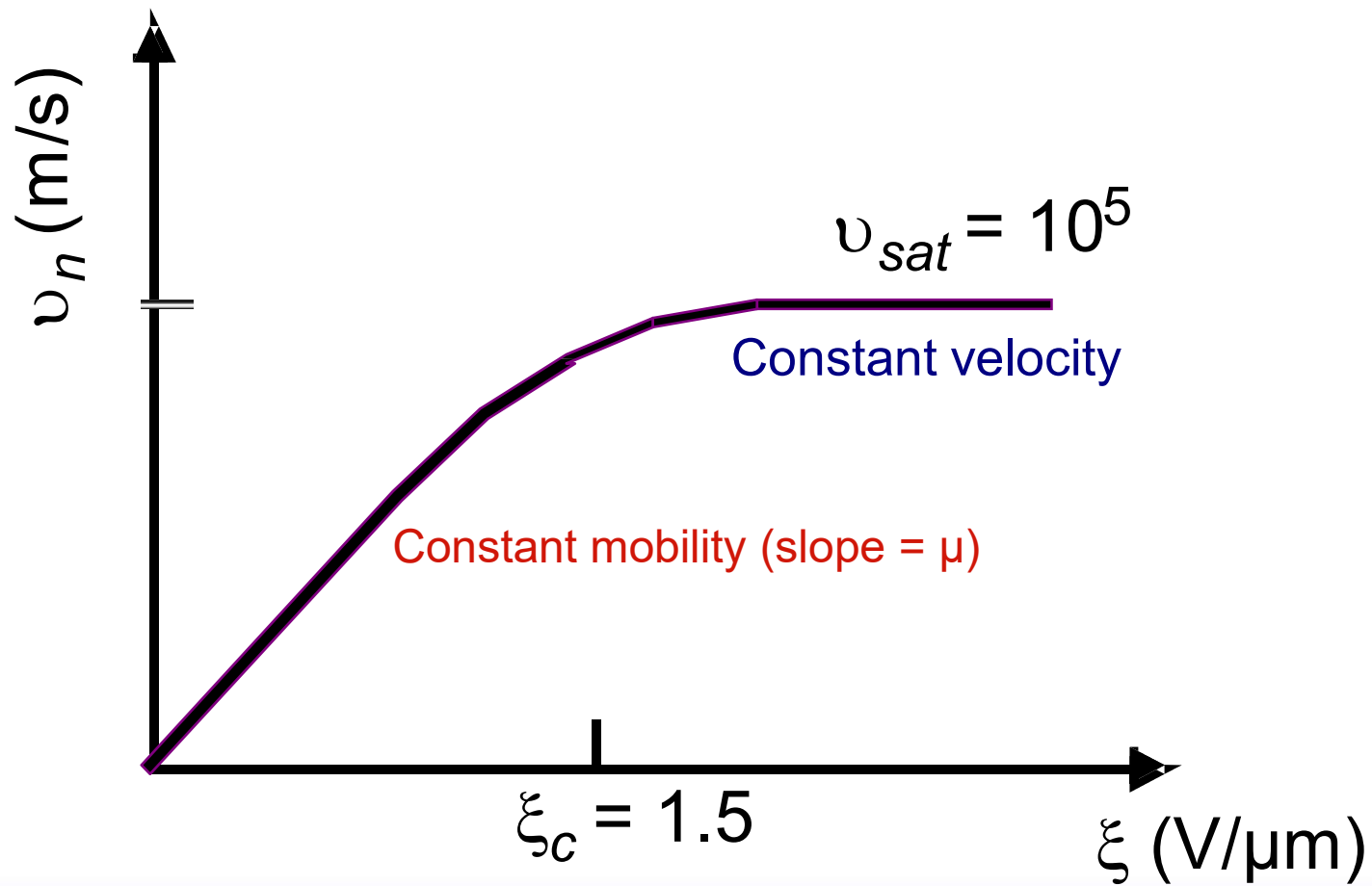
with

$$V_T = V_{T0} + \gamma \left(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|} \right)$$

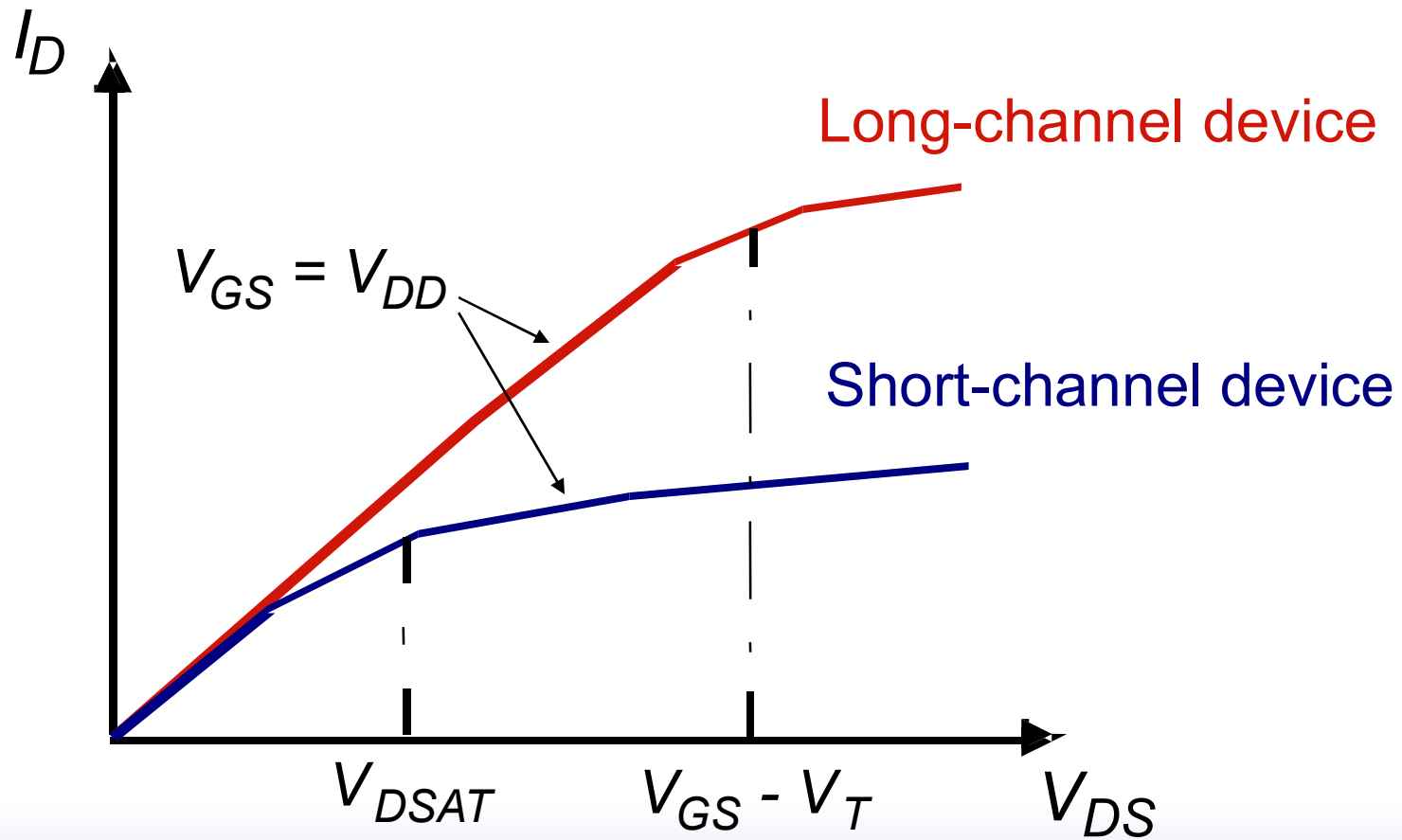
Current-Voltage Relations The Deep-Submicron Era



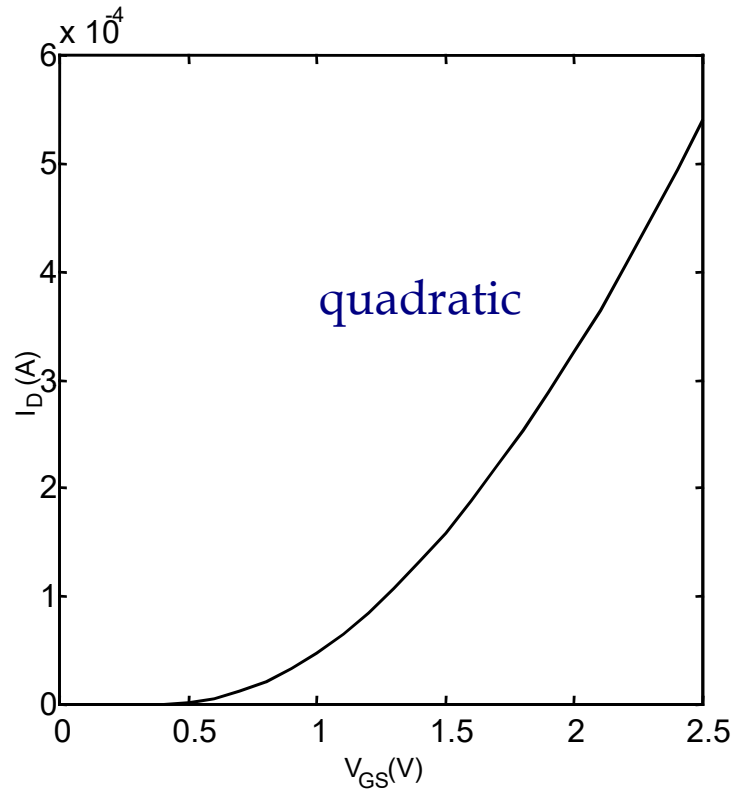
Velocity Saturation



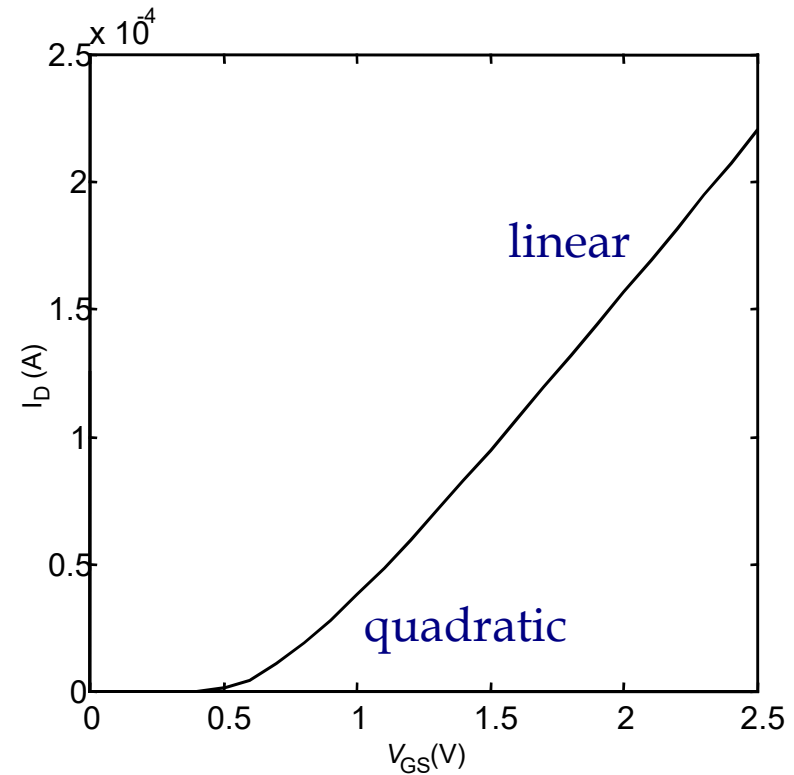
Perspective



I_D versus V_{GS}

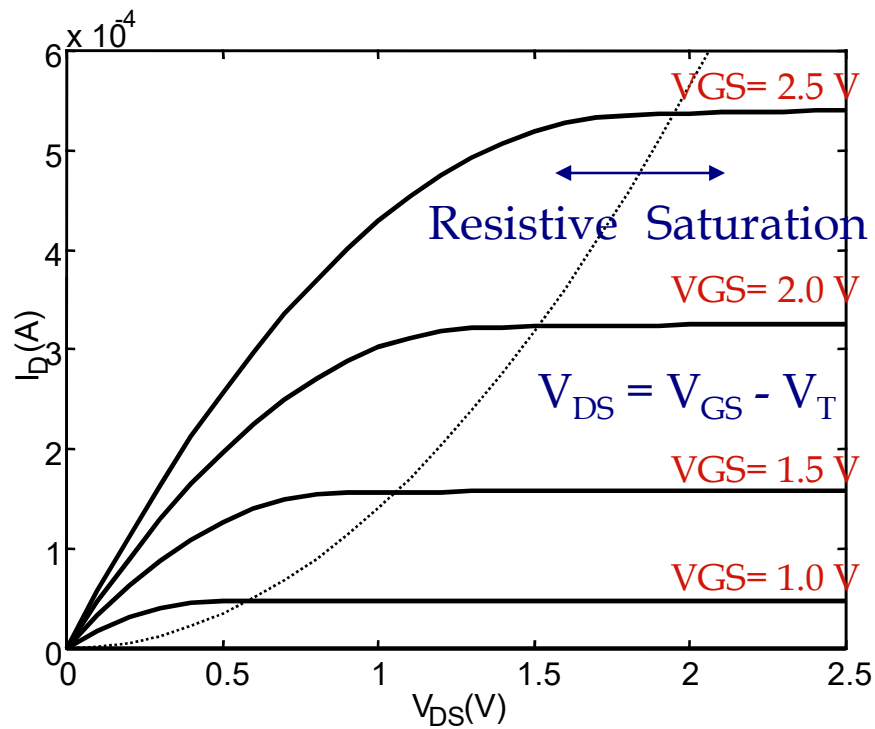


Long Channel

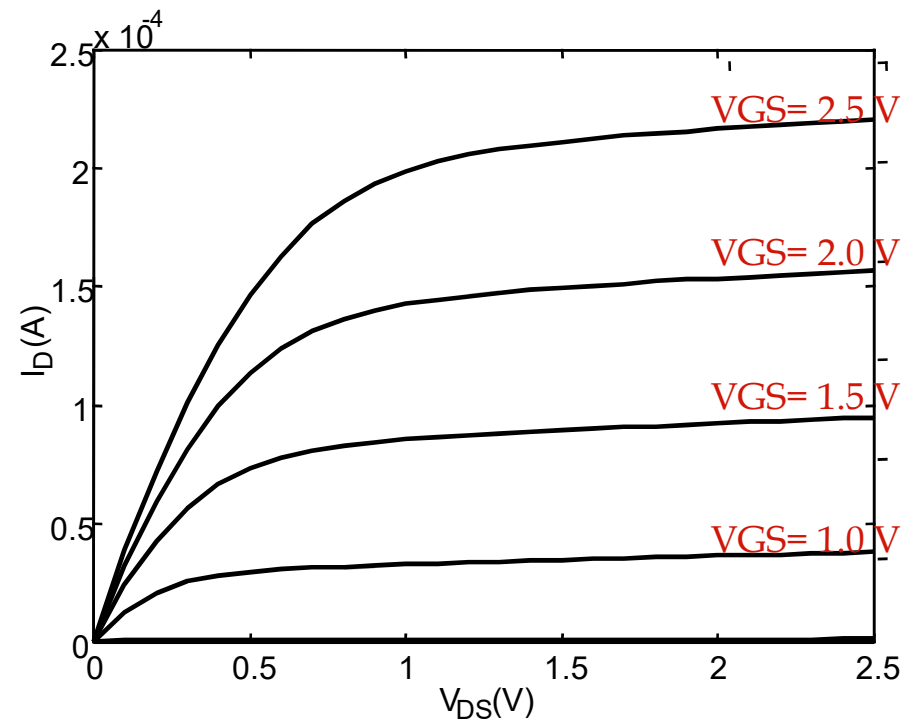


Short Channel

I_D versus V_{DS}



Long Channel



Short Channel