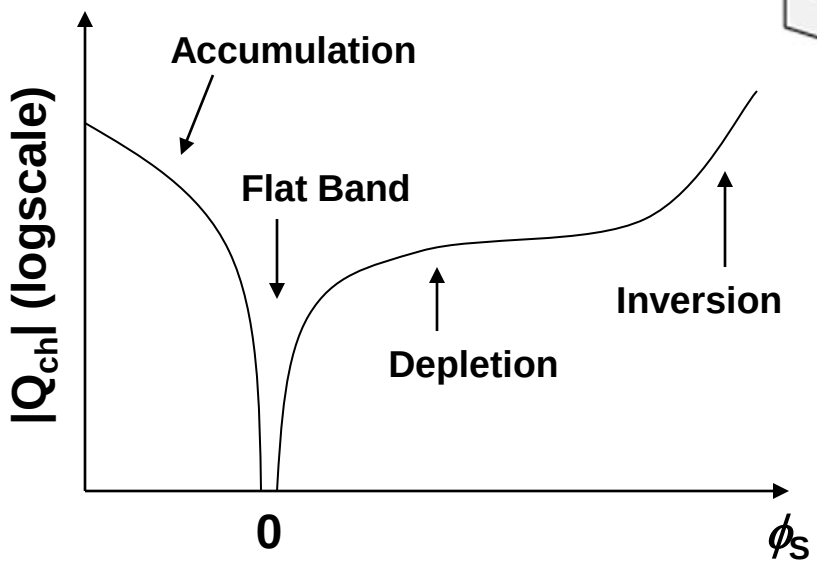
MOSFET I-V Characteristics

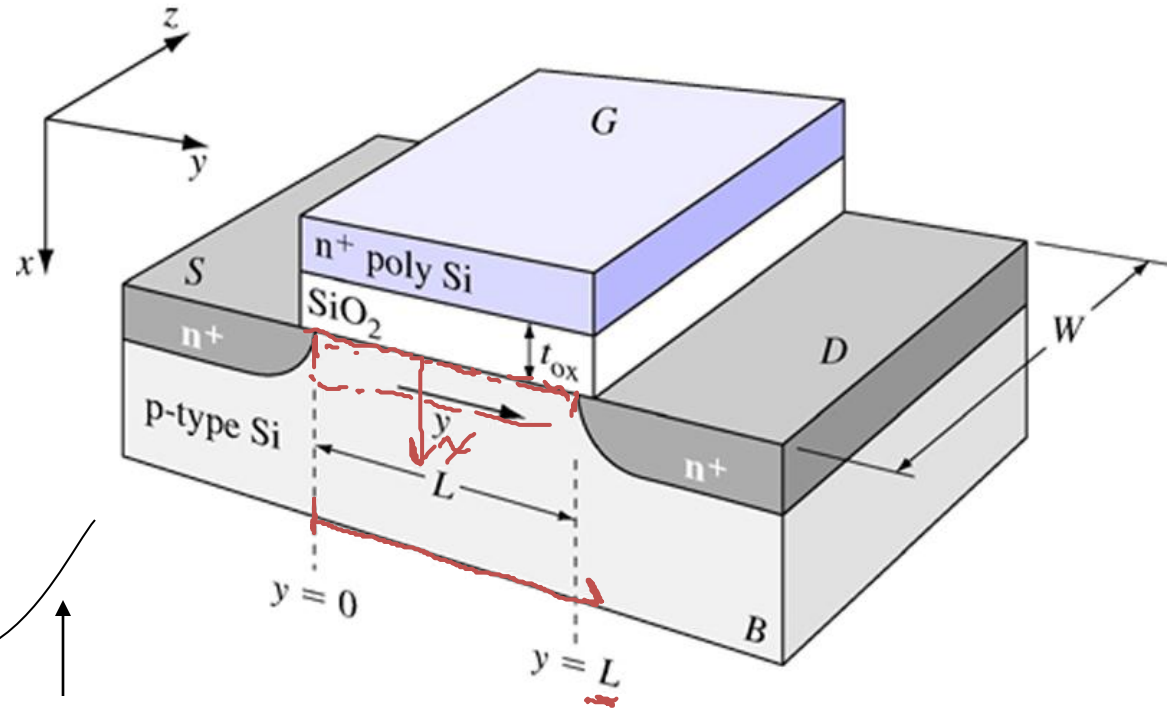
EECS 320

Introduction to Semiconductor Devices

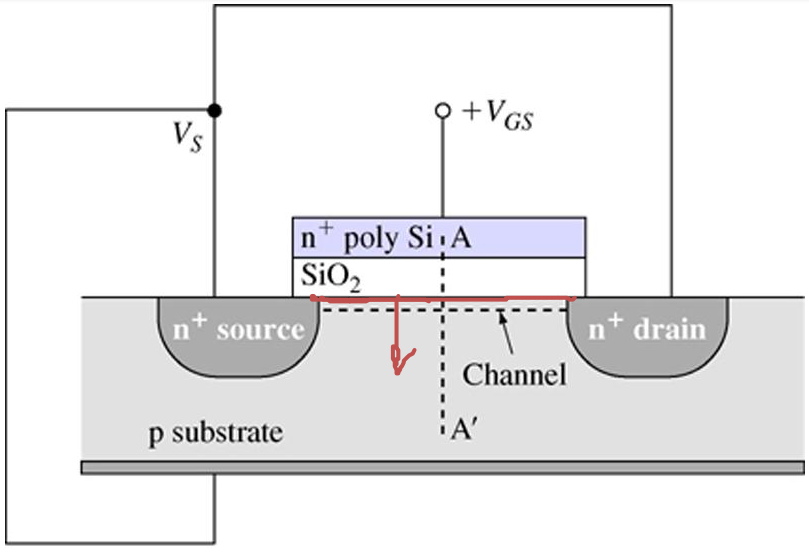
MOSFET Operation

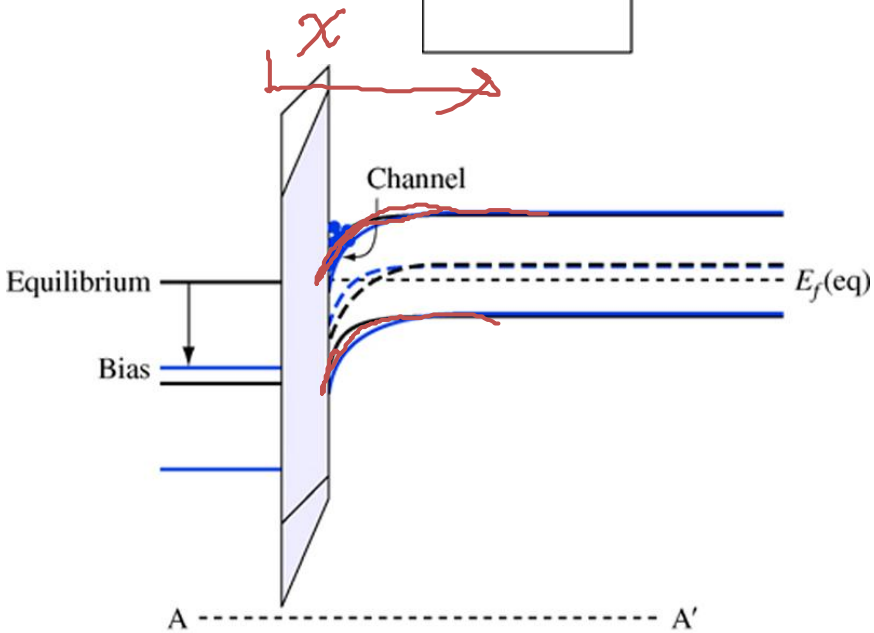
Control current flow between source/drain by gate potential

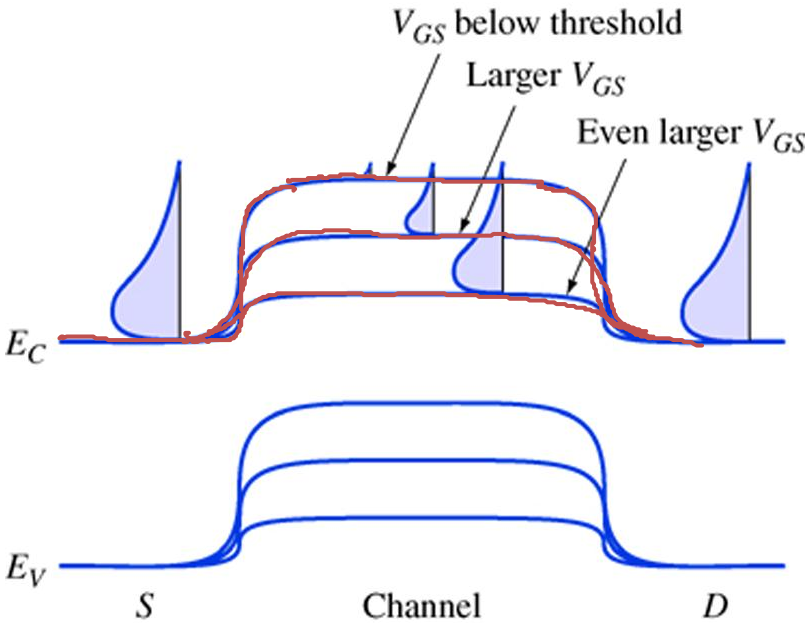




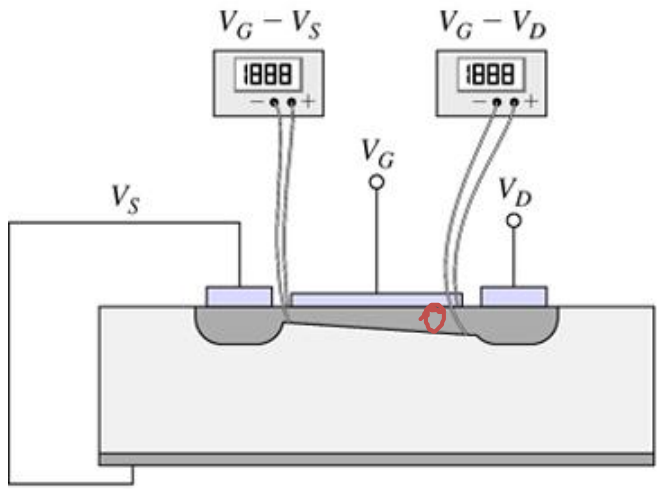
Band Diagrams

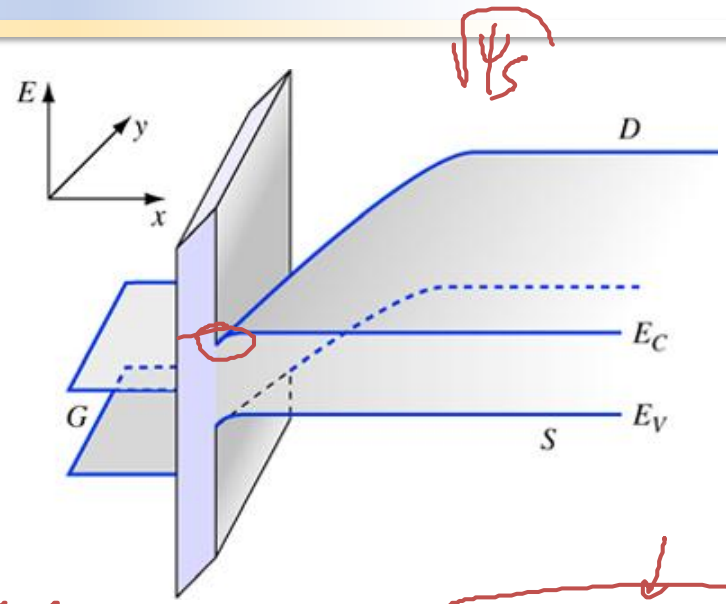


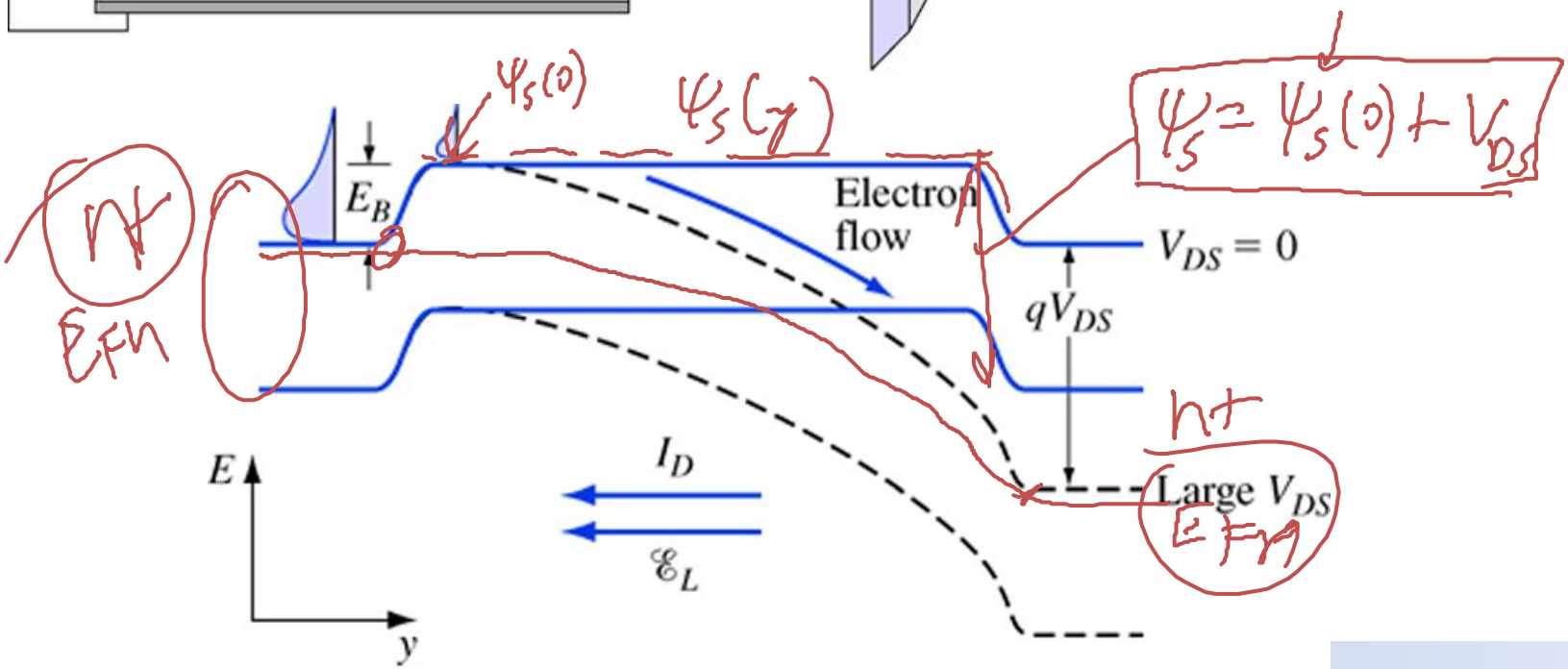




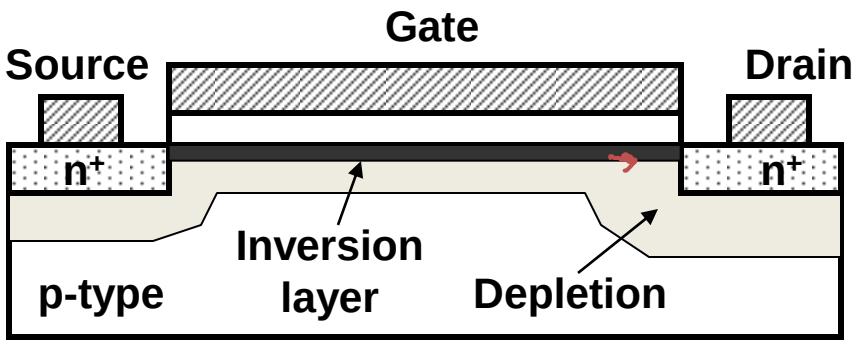
Band Diagrams Under Bias



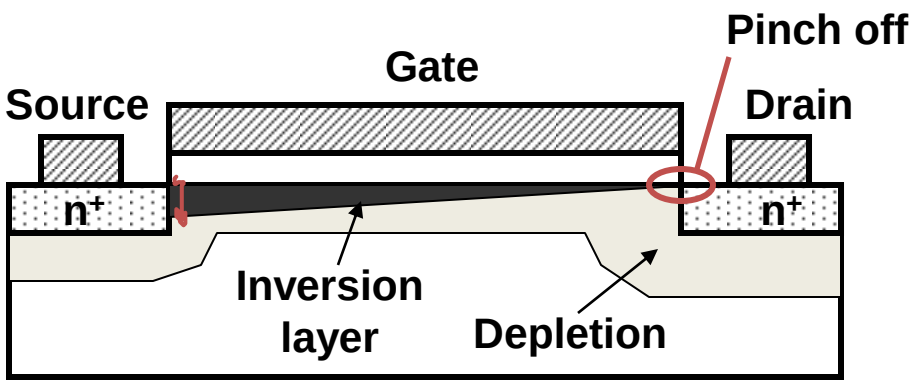




Drain Current Flow Through Inversion Layer

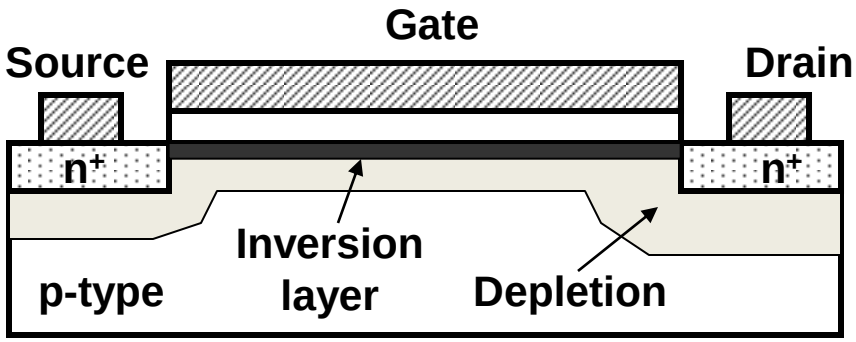


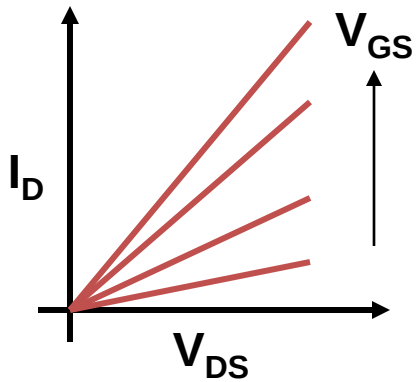
- Low V_{DS}
- Channel resistance determined by inversion charge, controlled by V_{GS}

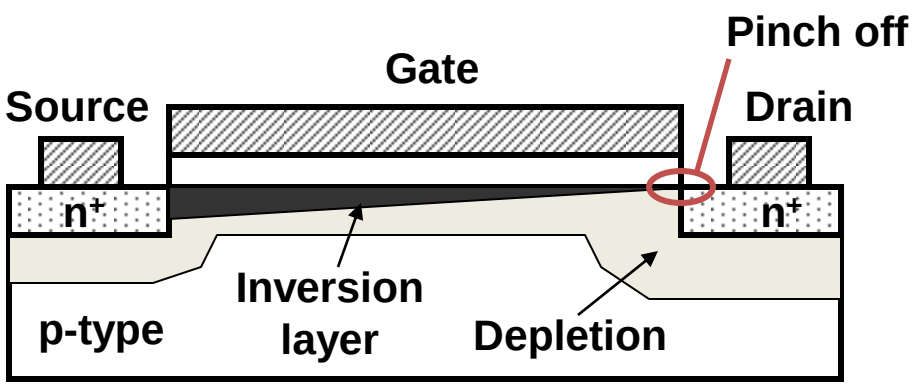


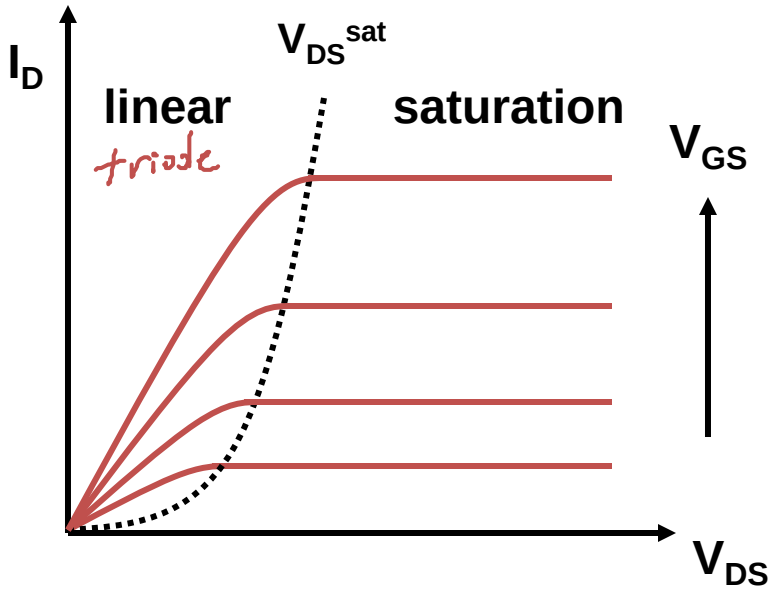
- Depletion width and inversion charge varies along channel at larger V_{DS}
- Channel pinches off at larger V_{GS} (V_{DS}^{sat})

Qualitative I-V Characteristics

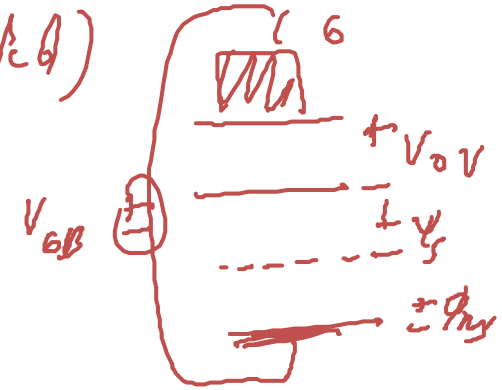








$V_{GS} = V_{GB}$ (Gate + Body are grounded)



$$V_{GS} = \phi_{ms} + \psi_s + V_{ox}$$

$$= \phi_{ms} + \psi_s + \frac{-Q_s}{C_{ox}}$$

$$= \phi_{ms} + \psi_s + \frac{1}{C_{ox}}\left(|Q_B| + |Q_n|\right)$$

$$|Q_n| = C_{ox}\left[V_{GS} - \left(\phi_{ms} + \psi_s + |Q_B|/C_{ox}\right)\right]$$

$\approx 2\psi_F$ capacitor in strong inv.

$$|Q_n| = C_{ox}\left[V_{GS} - \left(\phi_{ms} + \psi_s(y) + \frac{|Q_B|}{C_{ox}}\right)\right]$$

$\psi_s(0) + V(y)$

$$\psi_s(L) - \psi_s(0) = V_{DS}$$

$$\psi_s(y) = \psi_s(0) + V(y)$$

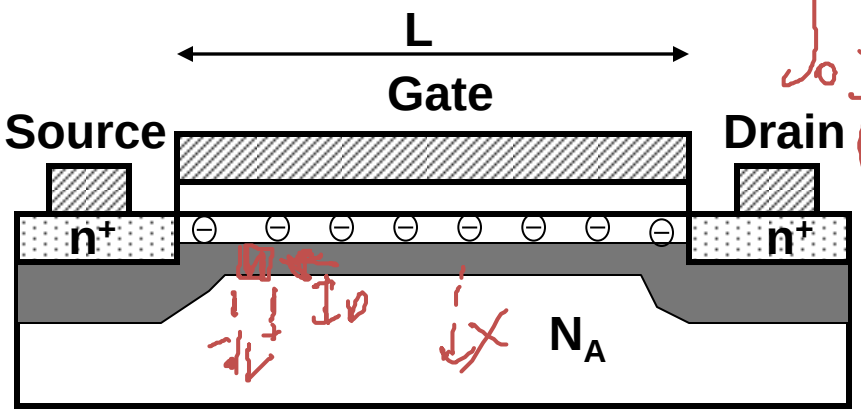
$V(y) \Rightarrow$ $V(0) = 0$, $V(L) = V_{DS}$

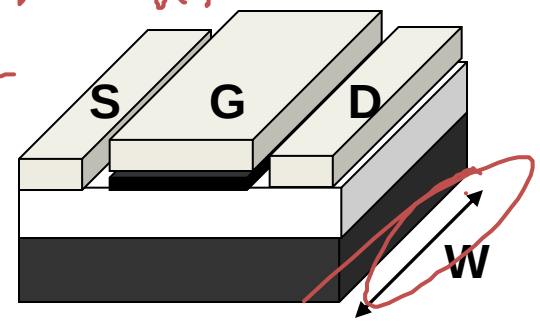
$$|Q_n| = C_{ox}\left[V_{GS} - V_T - V(y)\right]$$

I-V Characteristics: Square Law Theory

$$\int_0^L I_d\,dy = \int_{V(0)}^{V(L)=V_{DS}} W\mu_n|Q_n|\,dV$$

$$(I_d)L$$





Calculate I_D Determining Channel Charge (Drift current only)

$$(V_{GS}-V_T)V_{DS} - \frac{1}{2}V_{DS}^2\Big|_0^{V_{DS}}$$

$$dV(y) = I_D dR(y)$$

$$dV(y) = I_D dR(y) = I_D \frac{dy}{W\mu_n|Q_n|}$$

$$|Q_n| = C_{ox}\left(V_{GS} - V_T - V(y)\right)$$

$$I_D = \frac{W}{L}\mu_n C_{ox}\int_0^{V_{DS}}\left(V_{GS} - V_T - V\right)dV(y)$$

$$\boxed{I_D = \frac{W}{L}\mu_n C_{ox}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}}$$

Includes variation of inversion layer charge with V_{DS}

I-V Characteristics – Saturation

Linear

$(V_{GS}-V_T)$

$$I_D = \frac{W}{L}\mu_n C_{ox}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}$$

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

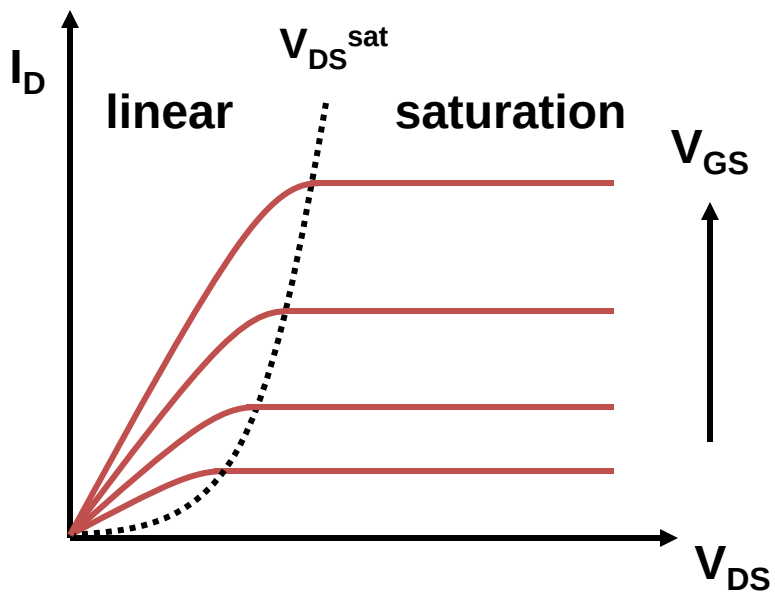
Saturation

$$I_D = \frac{W}{2L}\mu_n C_{ox}(V_{GS} - V_T)^2$$

$(V_{DS,sat}) = (V_{GS}-V_T)$

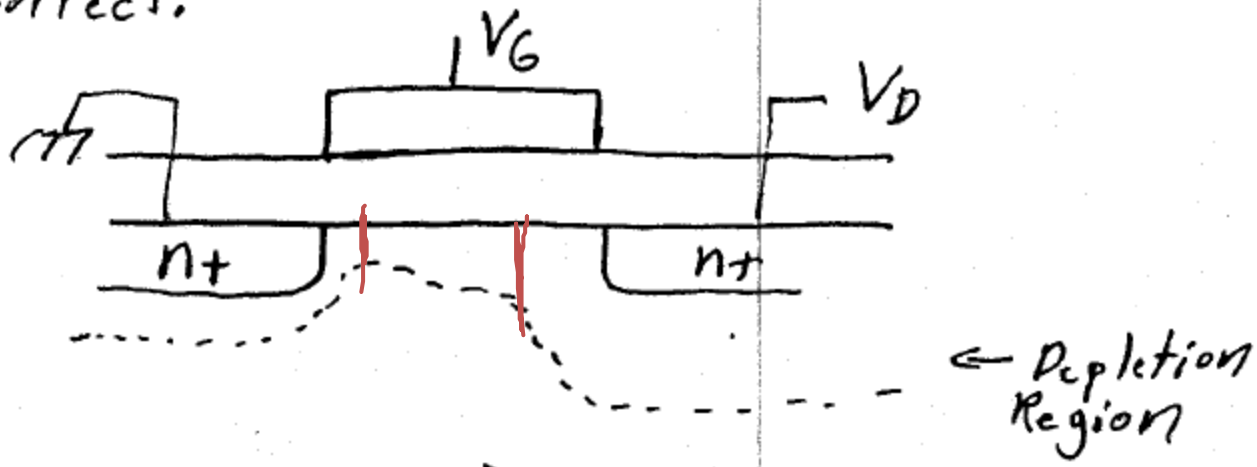
$$|V_{DS}| > |V_{GS} - V_T|$$

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

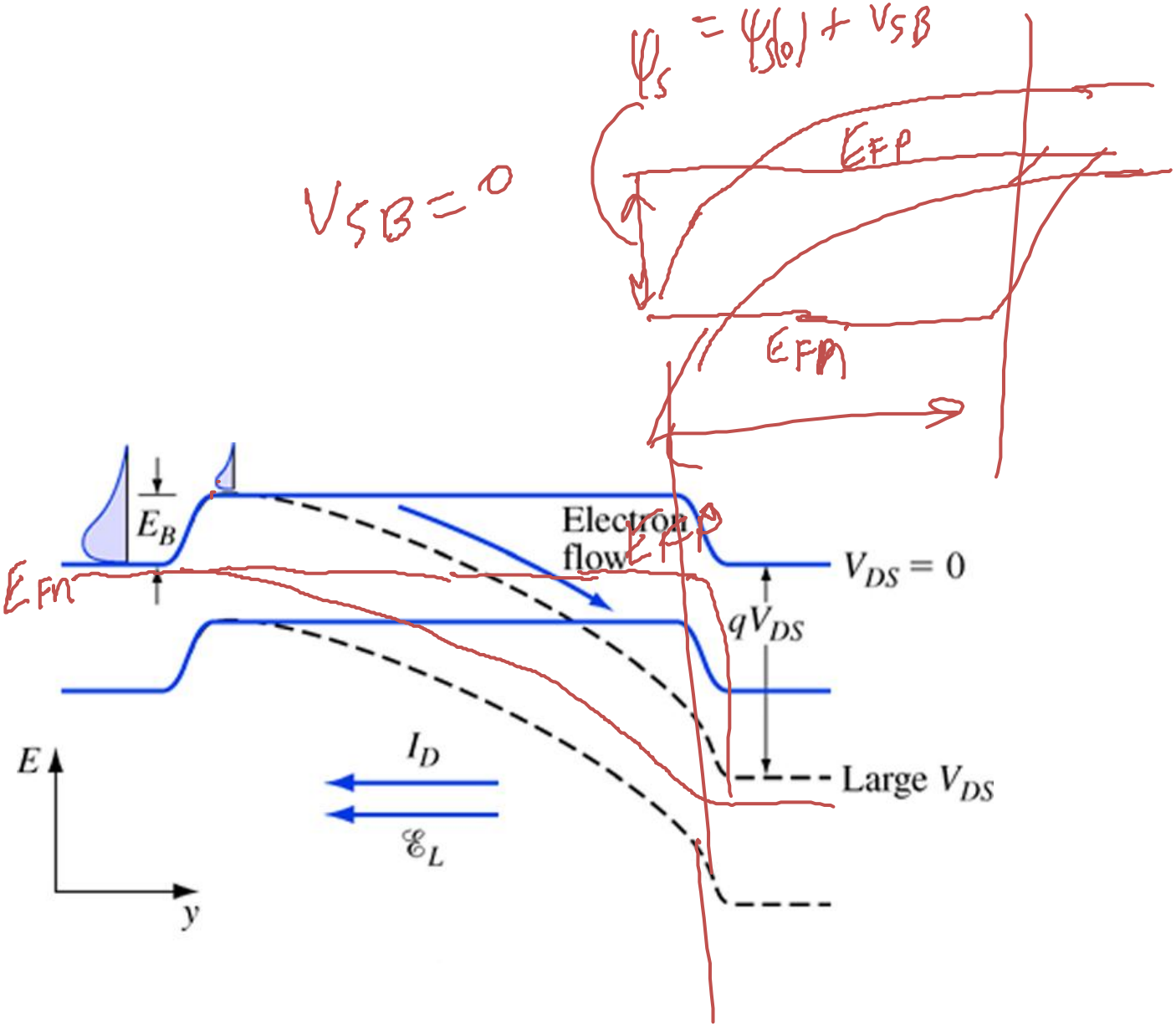


Bulk Charge Effect

The square-law relationship for saturation current contains a significant error. It assumes the the depletion charge is constant vs position along the channel (y-direction). In saturation this is not correct.



$|Q_B|$ increases toward drain


$\psi_s = \psi_{s(0)} + V_{SB}$
$V_{SB} = 0$
E_{FP}
E_{FN}
E_B
Electron flow
E_{FP}
$V_{DS} = 0$
E_{FN}
qV_{DS}
Large V_{DS}
E
I_D
$\mathscr{E}_L$
y

We can correct for this by returning to our expression for Q_{INV}

Previously

$$Q_{INV} \approx -C_{ox}\left[V_{GS} - \phi_{ms} - \underbrace{\psi_H}_{\approx 2\psi_F} + \frac{Q_D(\psi_H)}{C_{ox}}\right]$$

Now including V_{DS}

$$Q_{INV} \approx -C_{ox}\left[V_{GS} - \phi_{ms} - \psi_H - V(y) + \frac{Q_D(\psi_H + V(y))}{C_{ox}}\right]$$

$$= -C_{ox}\left[V_{GS} - V_T - V(y) + \frac{1}{C_{ox}}\left\{Q_D(\psi_H + V(y)) - Q_D(\psi_H)\right\}\right]$$

$$|Q_n| = C_{ox}\left[V_{GS} - V_T - V(y) + \frac{1}{C_{ox}}\left[Q_D(\psi_H + V(y)) - Q_n(\psi_H)\right]\right]$$

Repeating the integral $I_D = \frac{W}{L}\int_0^{V_{DS}} \mu_n |Q_{INV}(y)|\, dV$ yields

$$I_D = \frac{W}{L}\mu_n C_{ox}\left\{\left[(V_{GS}-V_T)V_{DS} - \frac{1}{2}V_{DS}^2\right] - \left[\frac{(2q\epsilon_s N_A \psi_H)^{1/2}}{C_{ox}}\right]\psi_H\left[\frac{2}{3}\left(\left(1+\frac{V_{DS}}{\psi_H}\right)^{3/2}-1\right]-\frac{V_{DS}}{\psi_H}\right]\right\}$$

or

$$I_D = \frac{W}{L}\mu_n C_{ox}\left\{\left[(V_{GS}-V_T)V_{DS} - \frac{1}{2}V_{DS}^2\right] - \frac{|Q_D(\psi_H)|}{C_{ox}}\psi_H\left[\frac{2}{3}\left(\left(1+\frac{V_{DS}}{\psi_H}\right)^{3/2}-1\right)-\frac{V_{DS}}{\psi_H}\right]\right\}$$

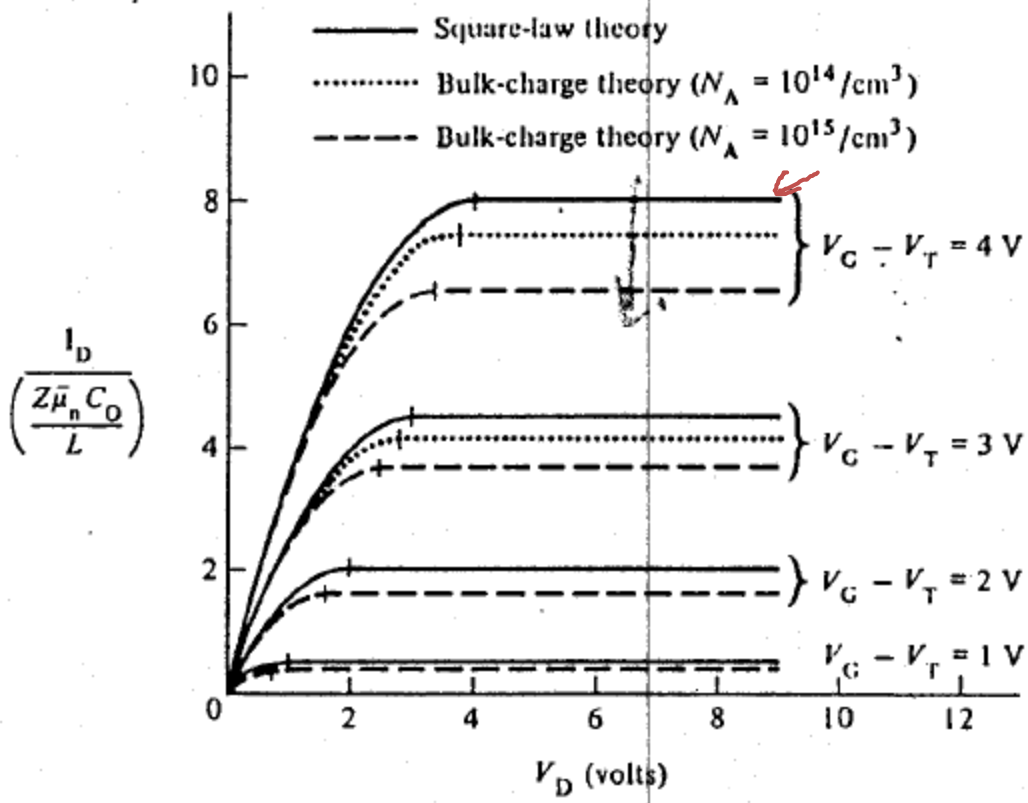


Fig. 5.8 Comparison of the I_D–V_D characteristics derived from the square-law and bulk-charge theories. The bulk-charge curves were computed assuming $x_o = 0.1\mu$ and $T = 23°C$.

From Field Effect Devices, Pierret, p 92

Note that this correction becomes important before the onset of saturation. Also note that it shifts the onset of saturation to lower voltages.

$Q_{inv} = 0$ when at the drain

$$V_{DS} = V_{DS}^{sat} = (V_{GS} - V_T) - \frac{|\varphi_D(\psi_H)|}{C_{ox}} \left\{ \left[\frac{(V_{GS} - V_T)}{\psi_H} + \left(1 + \frac{|\varphi_D(\psi_H)|}{2\psi_H C_{ox}}\right)^2 \right]^{1/2} - \left(1 + \frac{|\varphi_D(\psi_H)|}{2\psi_H C_{ox}}\right) \right\}$$

Channel Length Modulation

For $V_{DS}>V_{DS}^{sat}$, channel length reduced, I_D enhanced

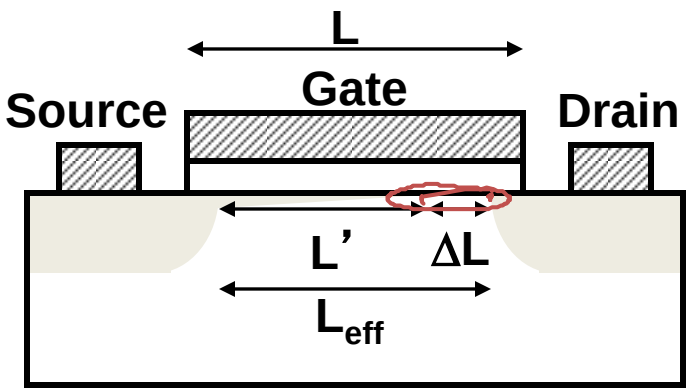
Use λ, channel length modulation parameter

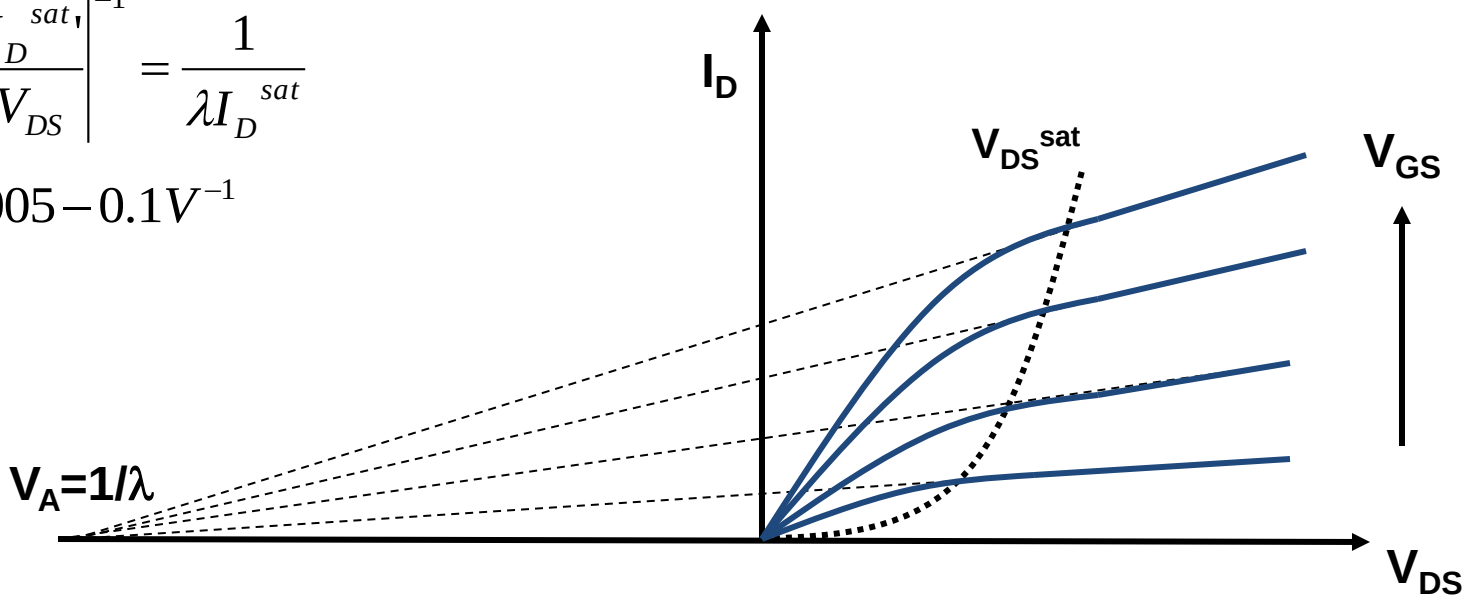
$$L' = L_{eff} - \Delta L$$

$$I_D^{sat\prime} = I_D^{sat}\left(1+\lambda V_{DS}\right)$$

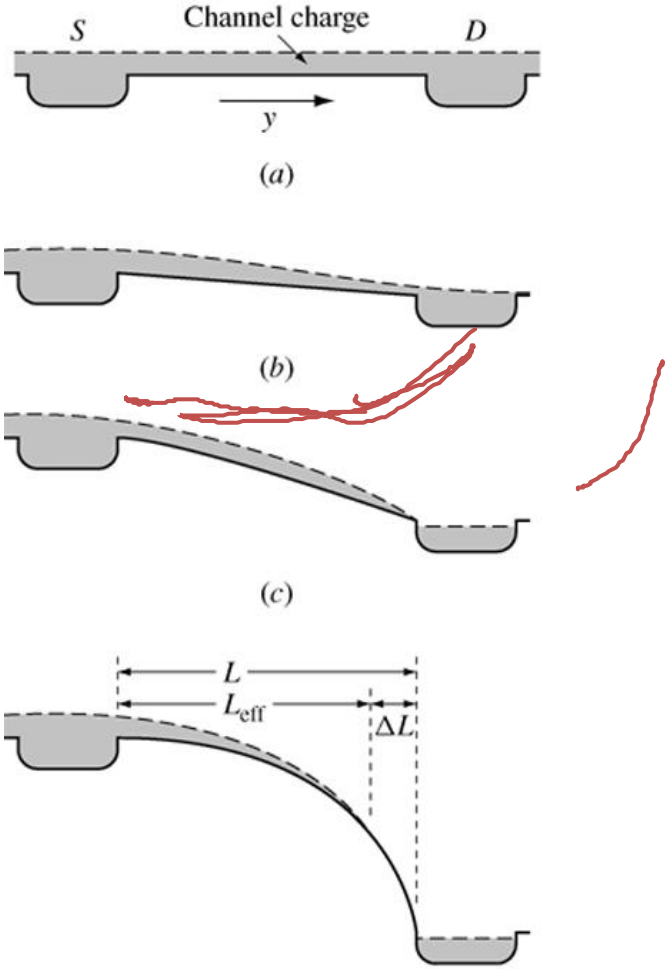
$$r_0 = \left|\frac{\partial I_D^{sat\prime}}{\partial V_{DS}}\right|^{-1} = \frac{1}{\lambda I_D^{sat}}$$

$$\lambda \approx 0.005 - 0.1V^{-1}$$





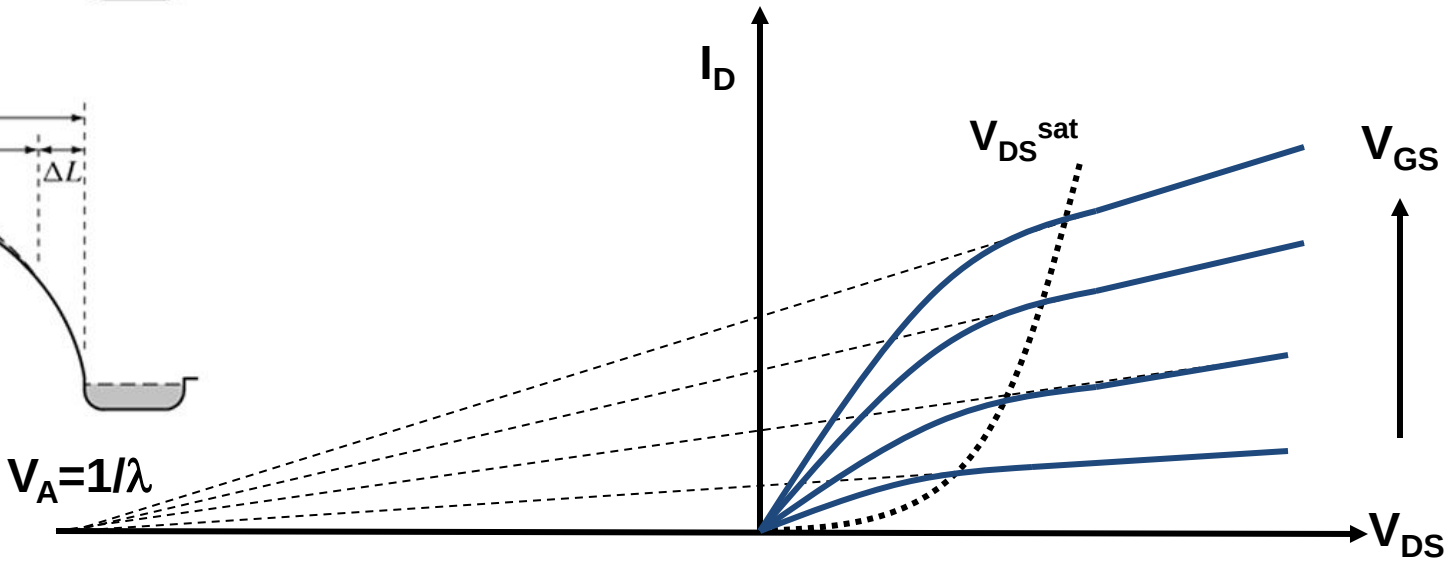
Channel Length Modulation



Also called Early effect

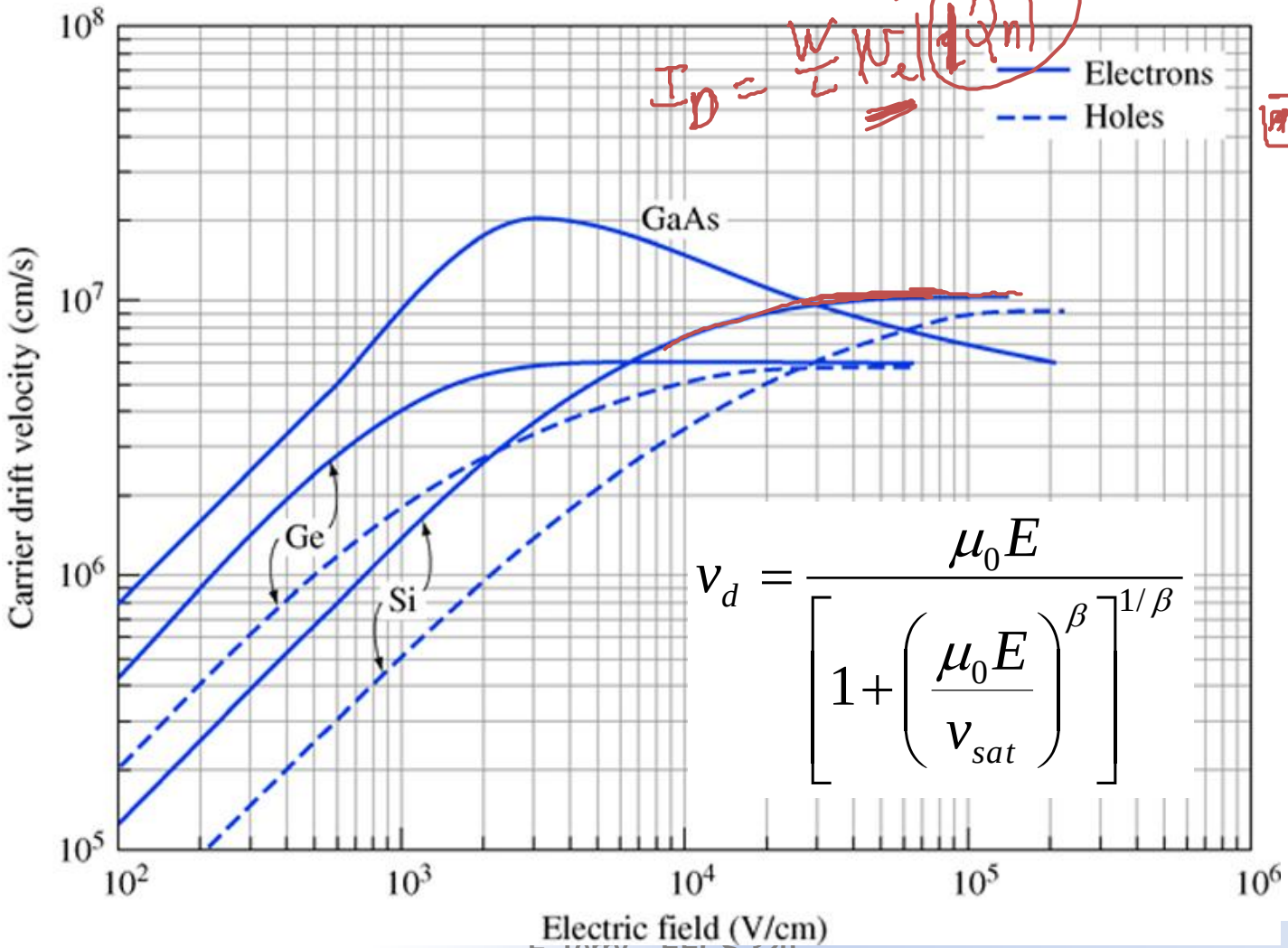
$$r_0 = \left| \frac{\partial I_D^{sat}}{\partial V_{DS}} \right|^{-1} = \frac{1}{\lambda I_D^{sat}}$$

$$\lambda \approx 0.005 - 0.1 V^{-1}$$



Recall Velocity Saturation at High Field

At high fields, mobility not constant, velocity "saturates"



$$v_d = \frac{\mu_0 E}{\left[1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^{\beta}\right]^{1/\beta}}$$

$I_D = \frac{W}{L} W_e |(Q_n)|$

v_{sat}

ΔL

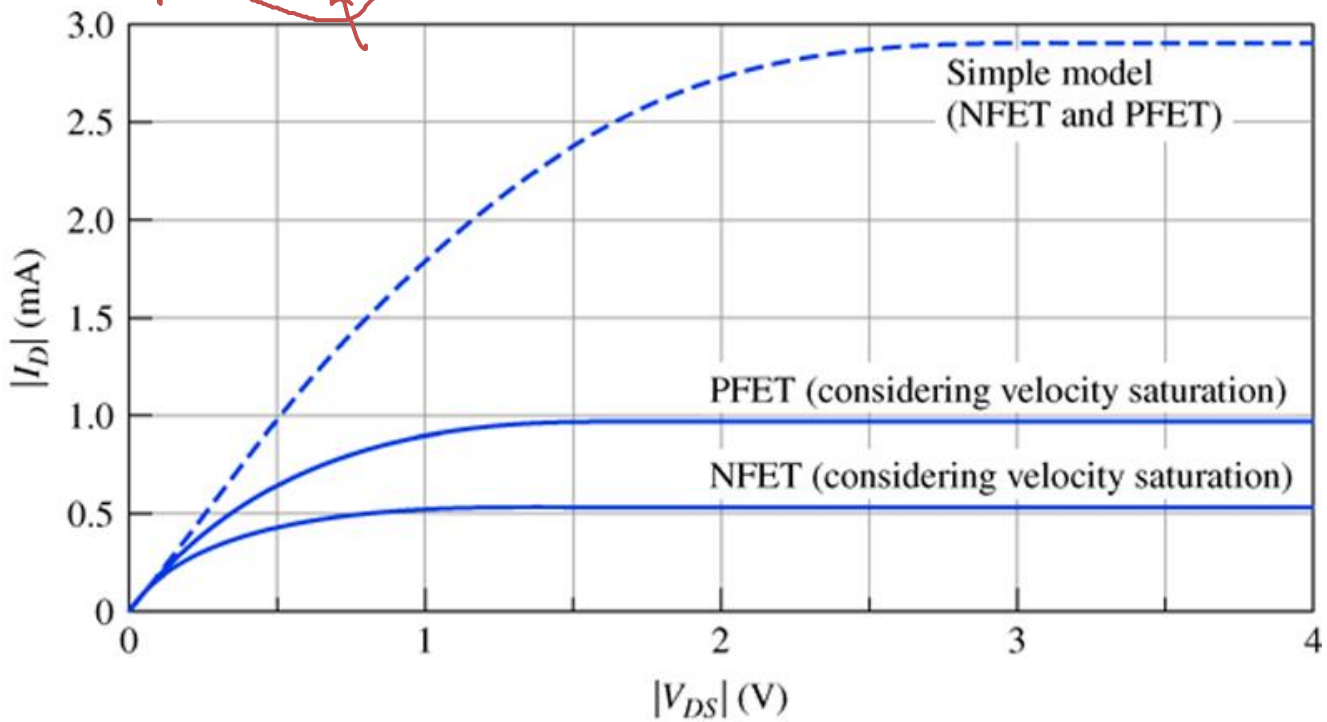
Effect on MOSFET Drain Current

$I_d dy + I_D \frac{\mu_{LF}}{v_{SA}} dy \frac{dV}{dy} = W|Q_n| \mu dV$

Channel mobility decreases, saturation current decreases

$$I_D dy = \frac{-WQ_{ch}\mu_{lf} dV_{ch}}{1+\frac{\mu_{lf}|E_L|}{v_{sat}}} \longrightarrow I_D = \frac{I_D(\text{no velocity saturation})}{1+\frac{\mu_{lf}V_{DS}}{Lv_{sat}}}$$

$|E_L| = \left(\frac{dV}{dy}\right)$



Note that V_{DSsat} also decreases

MOSFET I-V Including Velocity Saturation

Account for degradation in channel mobility and v_{sat}

$$I_D = \frac{I_D(\text{no velocity saturation})}{1+\dfrac{\mu_{lf} V_{DS}}{L v_{sat}}}$$

After substitution and simplification:

$$I_D = \frac{W}{L}\left(\frac{\mu_{lf}}{1+\dfrac{\mu_{lf} V_{DS}}{L v_{sat}}}\right) C_{ox}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right) V_{DS}$$

Linear (V_{GS}-V_T>V_{DSsat})

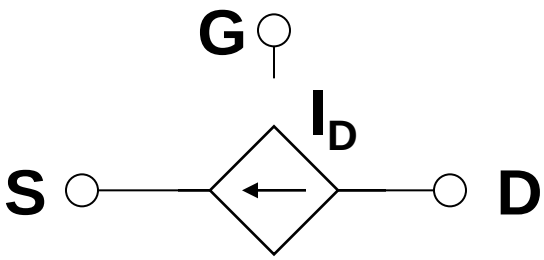
$$I_{Dsat} = C_{ox} W v_{sat}\left(V_{GS} - V_T - V_{DSsat}\right)$$

Saturation (V_{GS}-V_T<V_{DSsat})

$$V_{DSsat} = \frac{v_{sat}}{\mu_{lf}} L\left[\left(1+\frac{2\mu_{lf}\left|V_{GS}-V_T\right|}{v_{sat} L}\right)^{1/2} - 1\right] \approx \frac{v_{sat}}{\mu_{lf}} L$$

Unified Model for MOSFET

Develop one I-V model dividing into linear, saturation, and velocity saturation operation



$$I_D = \frac{\mu_{lf} C_{ox} W}{L}\left(V_{GS} - V_T - \frac{V_{\min}}{2}\right) V_{\min}\left(1 + \lambda V_{DS}\right)$$

$$V_{\min} = \min\left(V_{GS} - V_T, V_{DS}, V_{DSsat}\right) \qquad V_{DSsat} \approx \frac{v_{sat}}{\mu_{lf}} L$$

- $V_{min} = V_{DS}$: linear
- $V_{min} = V_{GS}-V_T$: saturation
- $V_{min} = V_{DSsat}$: velocity sat

Excellent analytical expression for MOSFET I-V for first-order calculations, commonly used in digital design (EECS 312)

The above is for NMOS, what changes for PMOS?