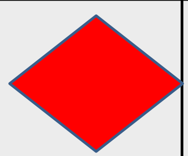
PURDUE
UNIVERSITY

NCN
www.nanohub.org

ECE606: Solid State Devices
Lecture 35: MOSFET I-V Characteristics (I)

Muhammad Ashraful Alam
alam@purdue.edu

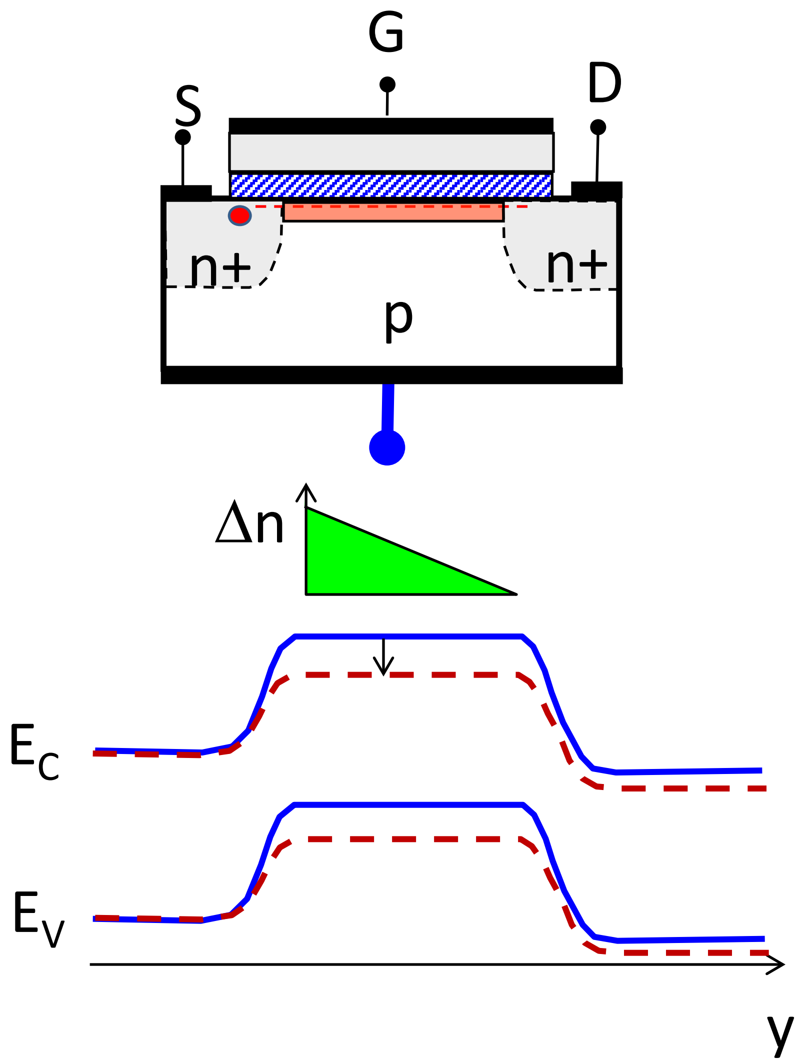
Topic Map

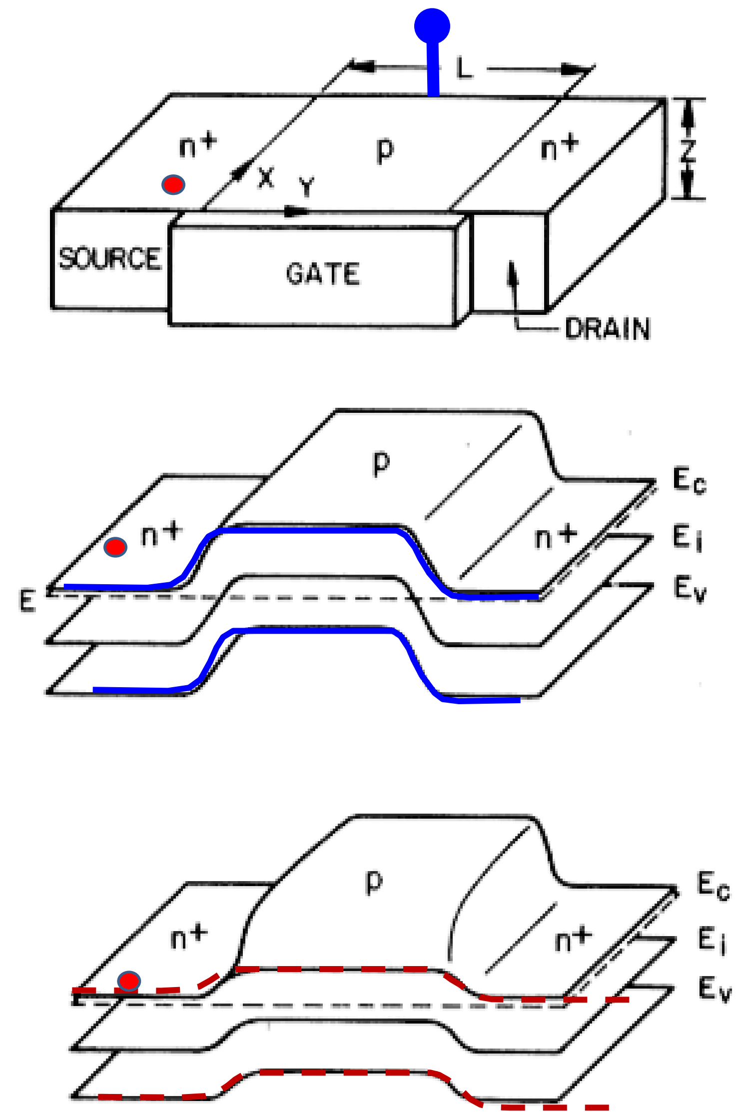
	Equilibrium	**DC**	Small signal	Large Signal	**Circuits**
Diode					
Schottky					
BJT/HBT					
MOSCAP **MOSFET**					

Outline

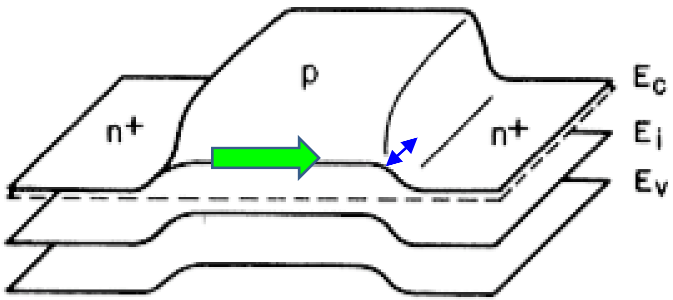
1. Introduction
2. **Sub-threshold (depletion) current**
3. Super-threshold, inversion current
4. Conclusion

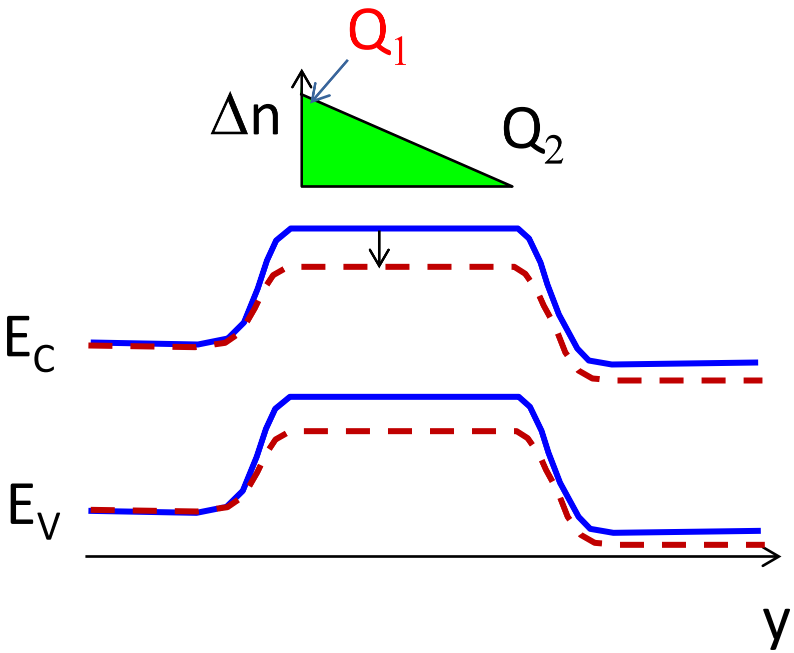
Subthreshold Region ($V_G < V_{th}$)

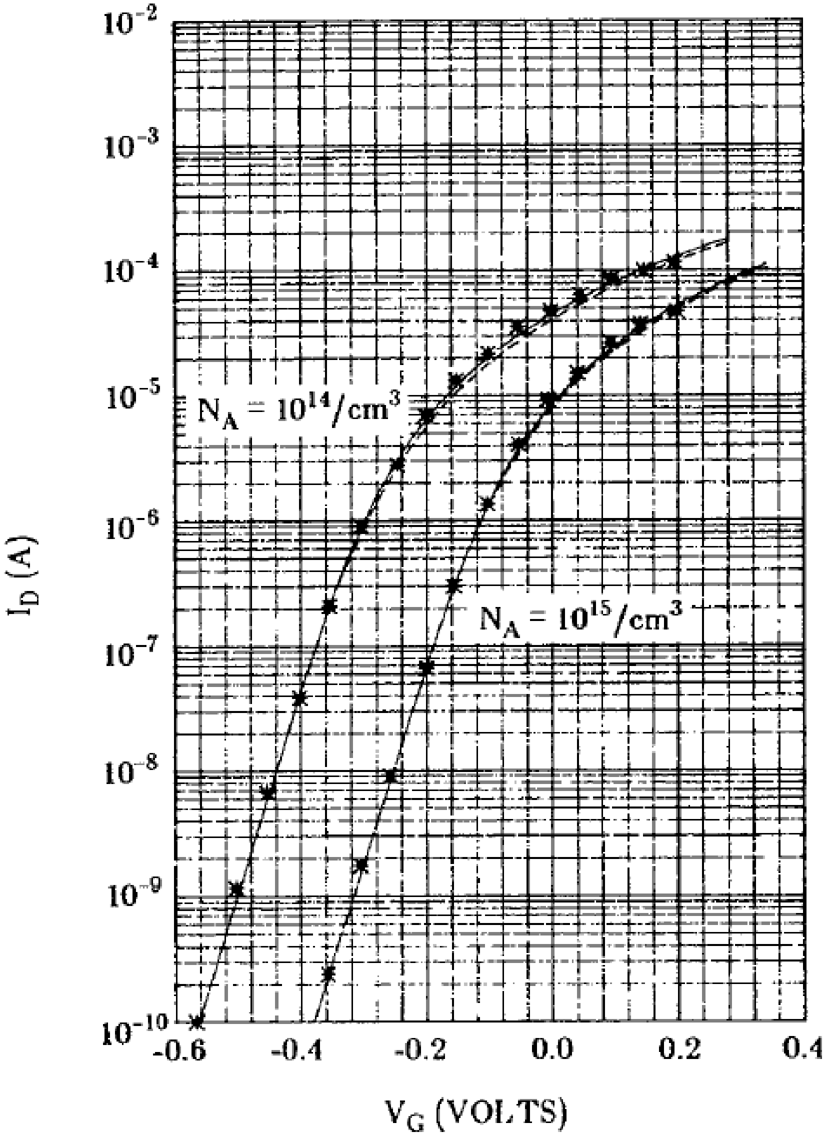




Subthreshold Region ($V_G < V_{th}$)







Recall the definition of body coefficient (*m*)

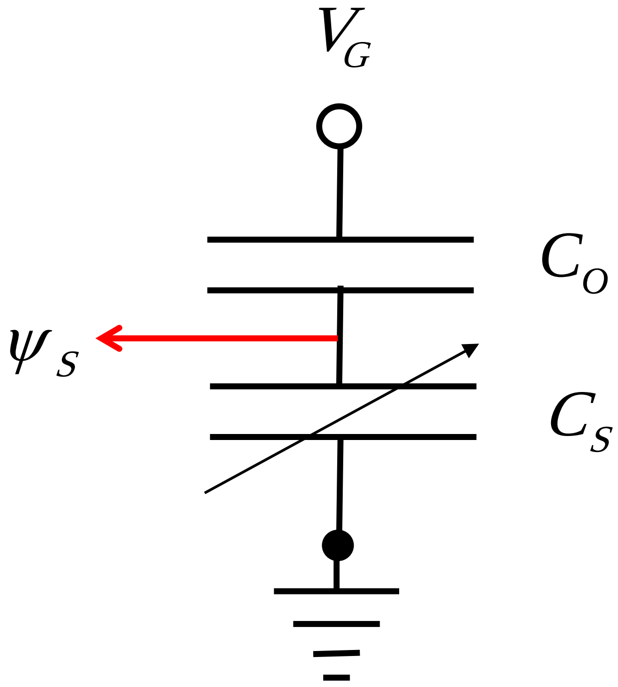
$$m = \left(1 + C_S / C_O\right)$$

'Body Effect Coefficient'

$$m = \left(1 + \kappa_S x_O / \kappa_0 W_T\right)$$

in practice:

$$1.1 \le m \le 1.4$$



$$\psi_S = \frac{C_O}{C_O + C_S} V_G \equiv \frac{V_G}{m}$$

Outline

1. Introduction
2. Sub-threshold (depletion) current
3. Super-threshold, inversion current
4. Conclusion

Post-Threshold MOS Current ($V_G > V_{th}$)

$$I_D = -\frac{W}{L_{ch}} \mu_{eff} \int_0^{V_{DS}} Q_i(V)\, dV$$

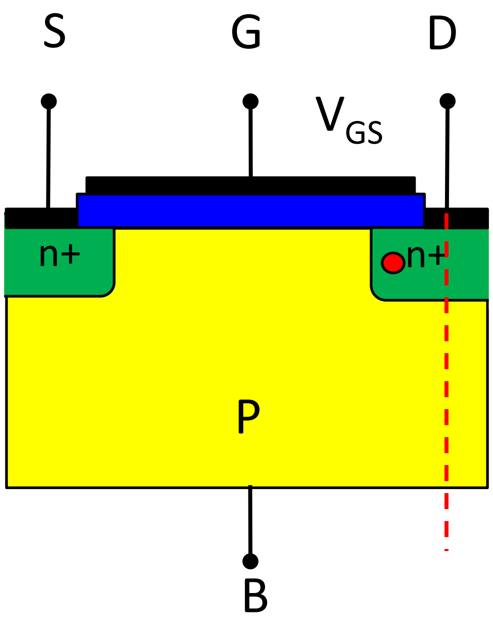
1) Square Law $\quad Q_i(V) = -C_G\left[V_G - V_T - V\right)]$

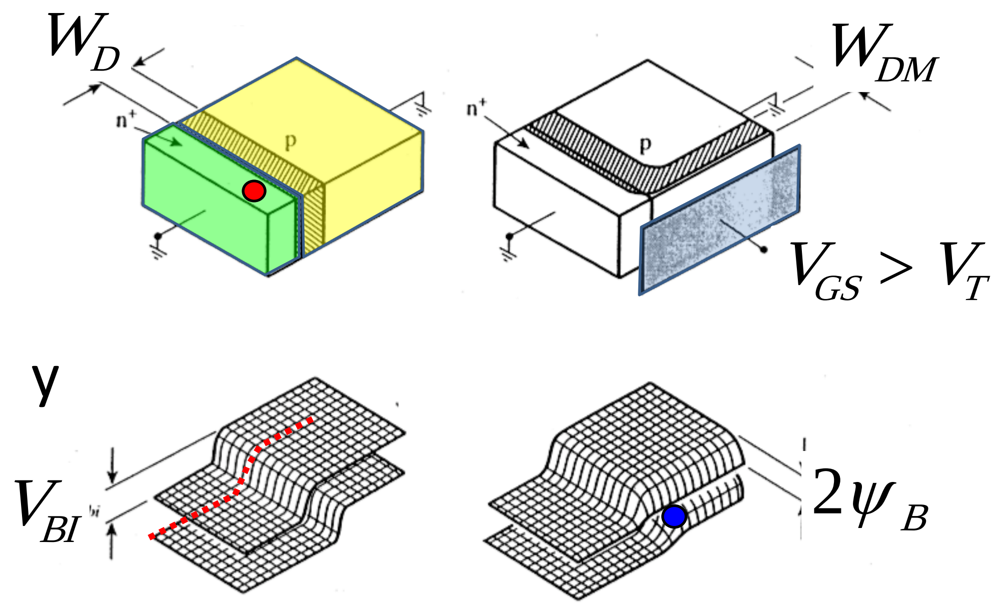
2) Bulk Charge $\quad Q_i(V) = -C_G\left(V_G - V_{FB} - 2\psi_B - V - \frac{\sqrt{2q\varepsilon_{Si} N_A (2\phi_B + V)}}{C_O}\right)$

3) Simplified Bulk Charge $\quad Q_i(V) = -C_G\left[V_G - V_T - mV\right)]$

4) "Exact" (Pao-Sah or Pierret-Shields)

Effect of Gate Bias





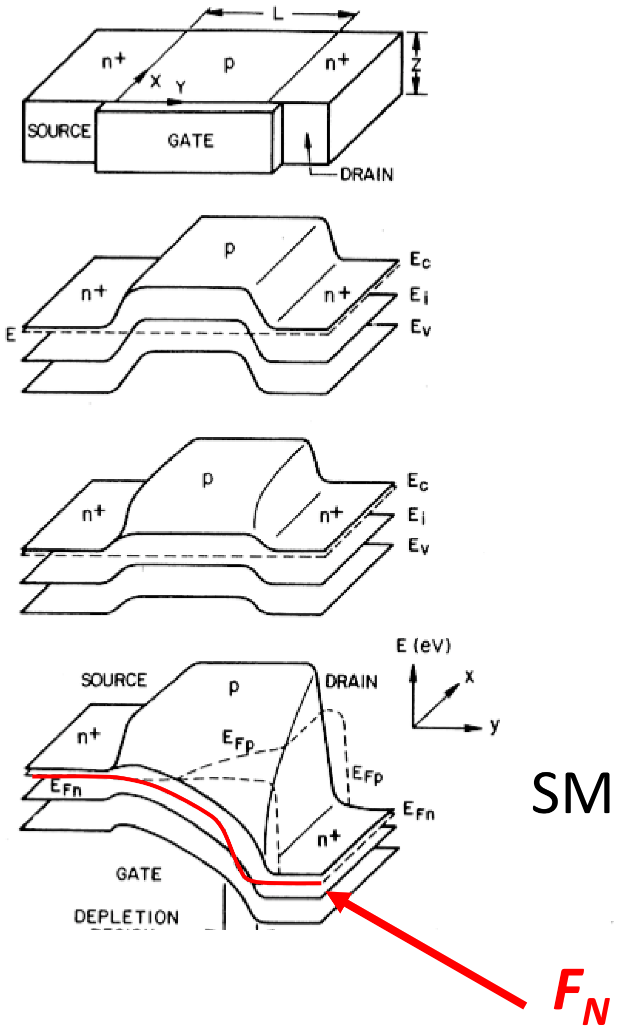
Gated doped or p-MOS with adjacent n^+ region

a) gate biased at flat-band

b) gate biased in inversion

A. Grove, *Physics of Semiconductor Devices*, 1967.

The Effect of Drain Bias



2D band diagram for an n-MOSFET

a) device

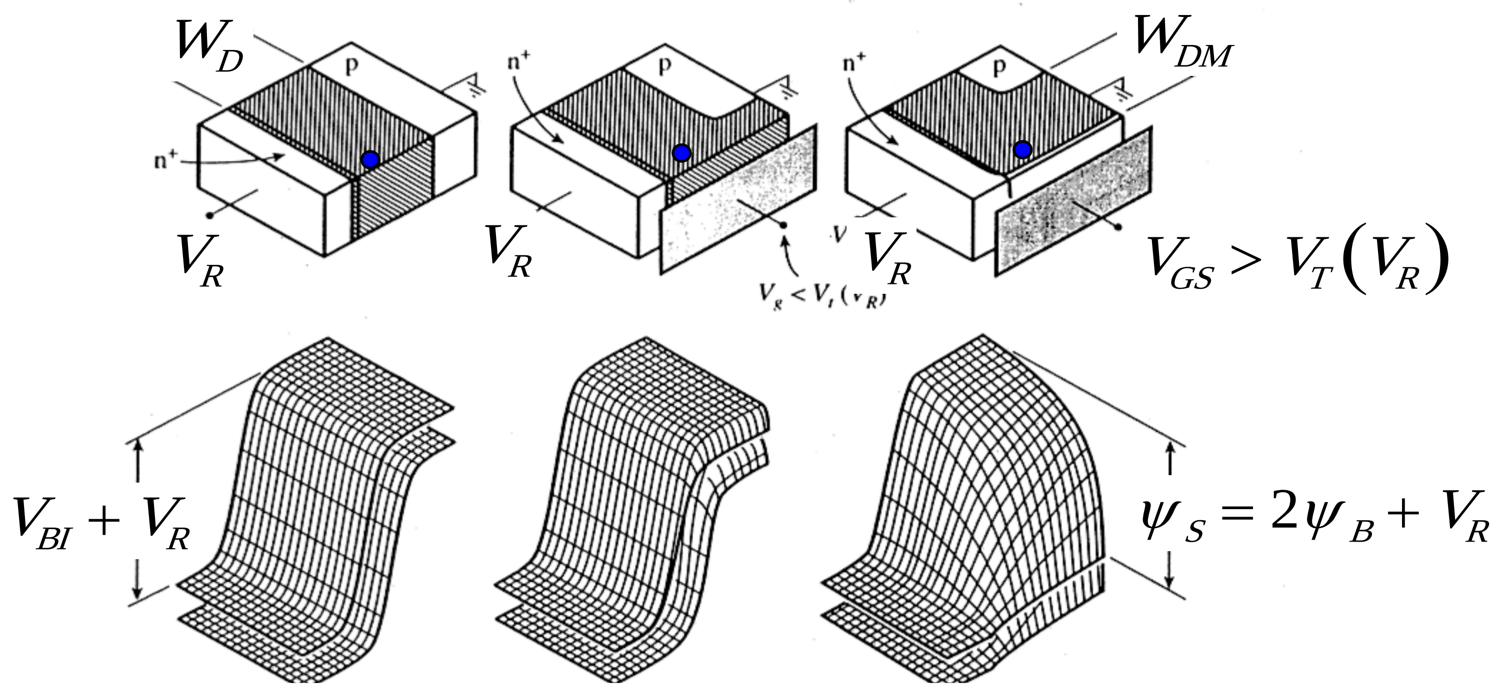
b) equilibrium (flat band)

c) equilibrium ($\psi_S > 0$)

d) non-equilibrium with V_G and V_D >0 applied

SM. Sze, *Physics of Semiconductor Devices*, 1981 and Pao and Sah.

Effect of a Reverse Bias at Drain



Gated doped or p-MOS with adjacent, reverse-biased n^+ region

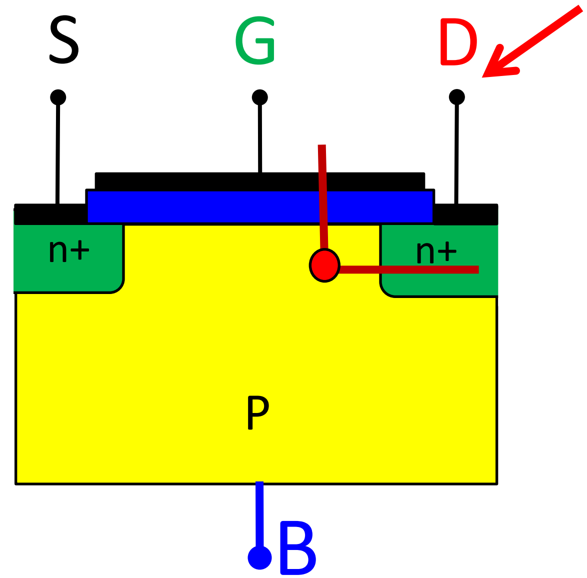
a) gate biased at flat-band

b) gate biased in depletion

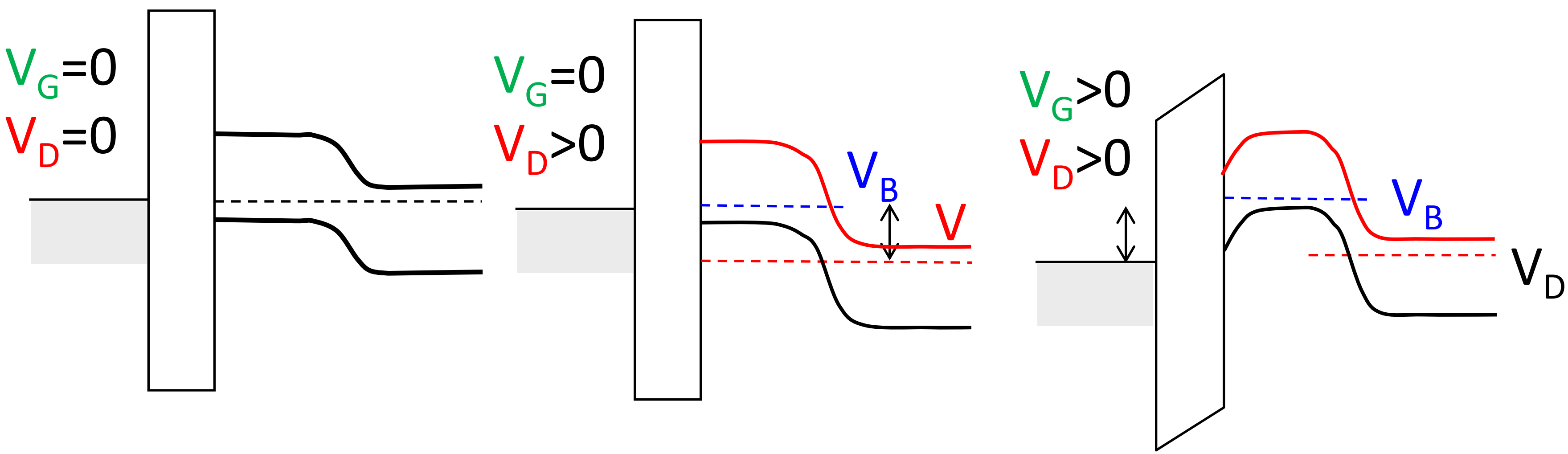
b) gate biased in inversion

A. Grove, *Physics of Semiconductor Devices*, 1967.

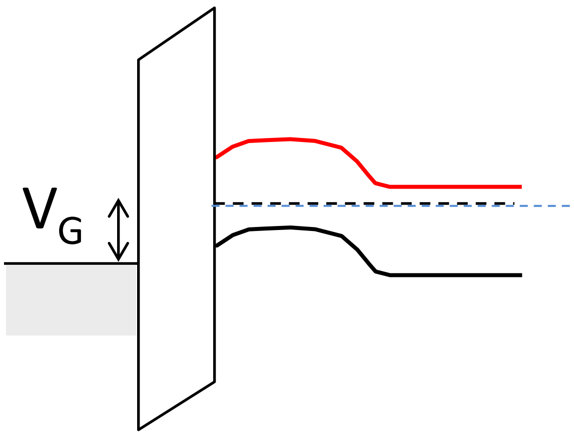
Inversion Charge in the Channel

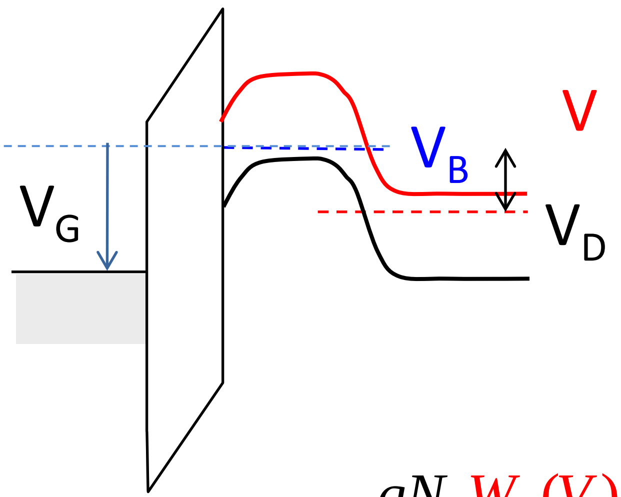


$$Q_i = -C_{ox}(V_G - V_{th} - V) + qN_A(W_T(V) - W_T(V=0))$$



Inversion Charge at one point in Channel





$$V_{th} = 2\phi_F - \frac{qN_A W_T(V=0)}{C_{ox}}$$

$$V_{th}^* = \left(2\phi_F + V\right) - \frac{qN_A W_T(V)}{C_{ox}}$$

$$V_{th}^* = V_{th} + V - \frac{qN_A\left(W_T(V) - W_T(V=0)\right)}{C_{ox}}$$

$$Q_i = -C_{ox}(V_G - V_{th}^{\ *})$$

Approximations for Inversion Charge

$$Q_i = -C_O(V_G - V_{th} - V) + qN_A\left(W_T(V) - W_T(V=0)\right)$$

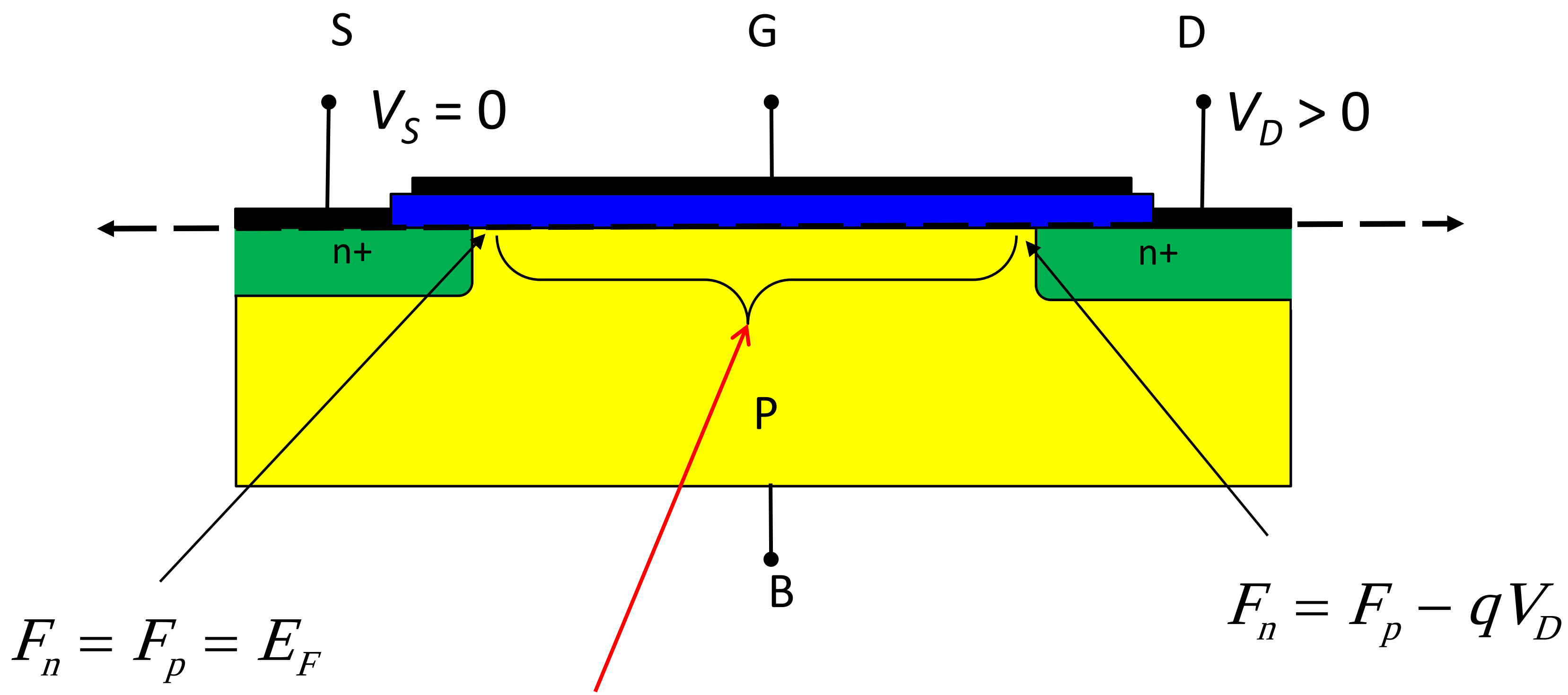
$$= -C_O(V_G - V_{th} - V) + \left[\sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B + V\right)} - \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B\right)}\right]$$

Approximations:

$Q_i \approx -C_{ox}(V_G - V_{th} - V)$ Square law approximation …

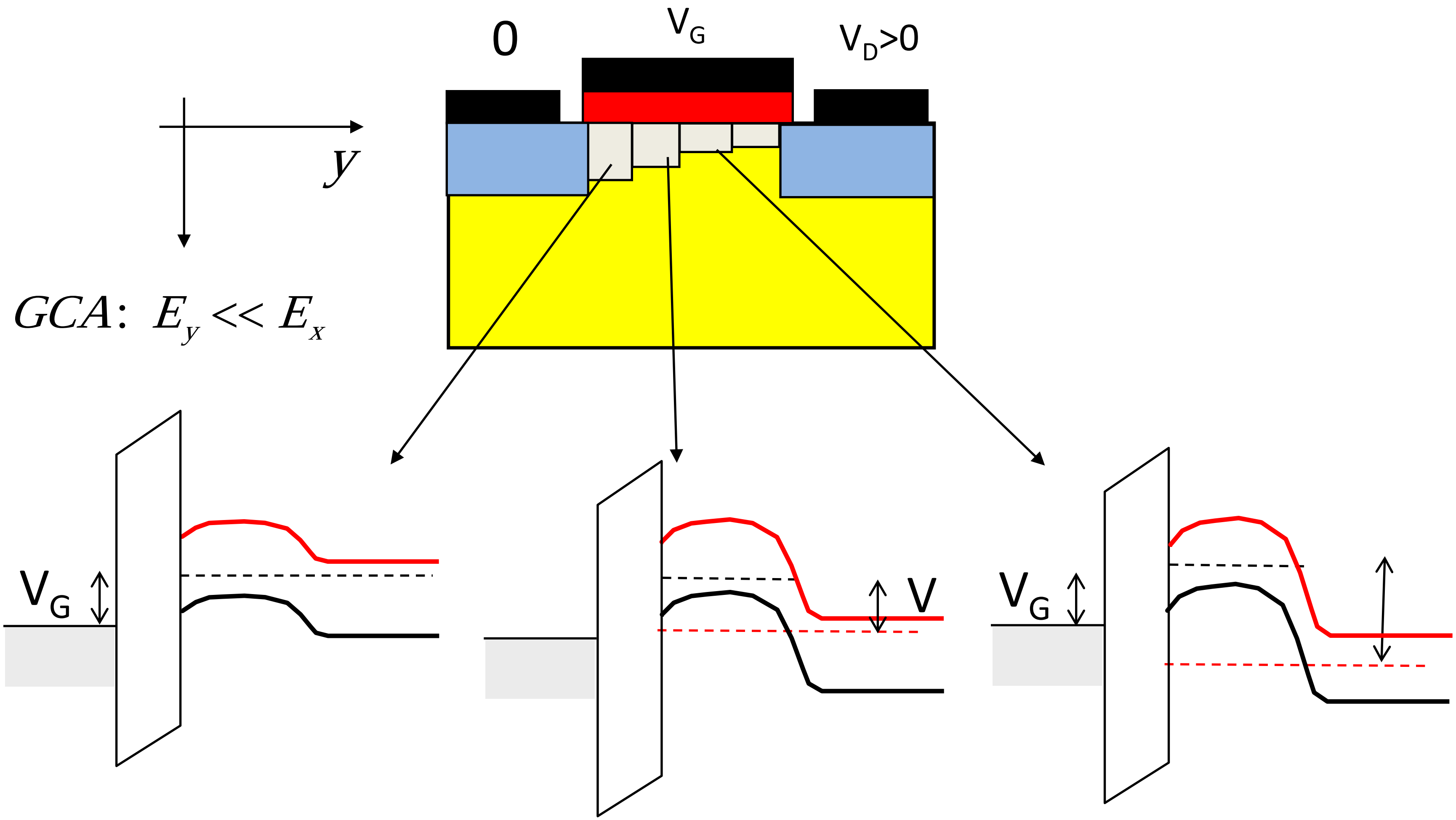
$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$ Simplified bulk charge approximation …

The MOSFET



F_n increasingly negative from source to drain (reverse bias increases from source to drain)

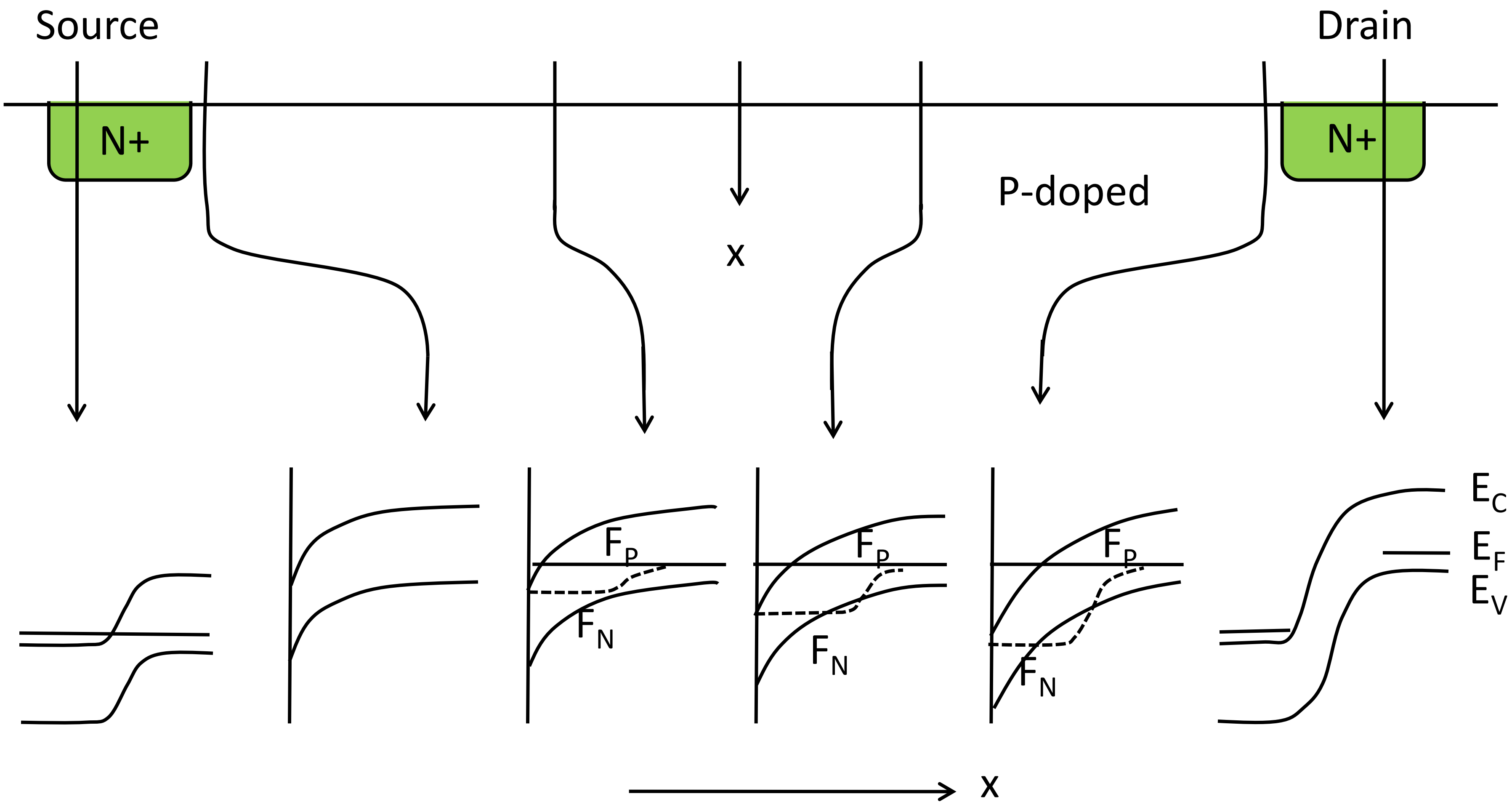
Elements of Square-law Theory



$$GCA:\ E_y << E_x$$

$$Q_i(y) = -C_{ox}\left[V_G - V_{th} - mV(y)\right]$$

Another view of Channel Potential



Square Law Theory

$$J_1 = Q_1 \mu \mathcal{E}_1 = Q_1 \mu \left.\frac{dV}{dy}\right|_1$$

$$J_2 = Q_2 \mu \mathcal{E}_2 = Q_2 \mu \left.\frac{dV}{dy}\right|_2$$

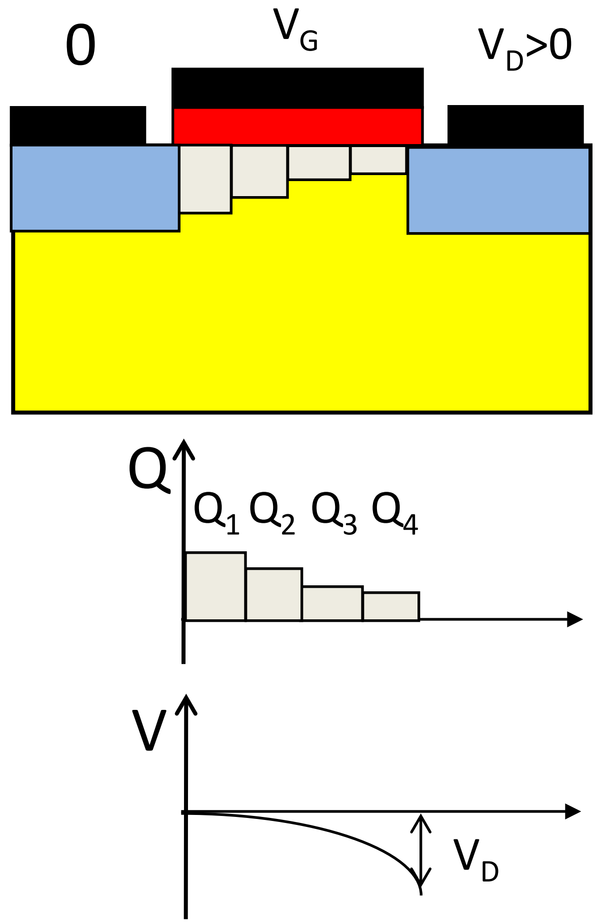
$$J_3 = Q_3 \mu \mathcal{E}_3 = Q_3 \mu \left.\frac{dV}{dy}\right|_3$$

$$J_4 = Q_4 \mu \mathcal{E}_4 = Q_4 \mu \left.\frac{dV}{dy}\right|_4$$

$$\sum_{i=1,N} \frac{J_i dy}{\mu} = \sum_{i=1,N} Q_i \, dV$$

$$\frac{J_D}{\mu} \sum_{i=1,N} dy = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

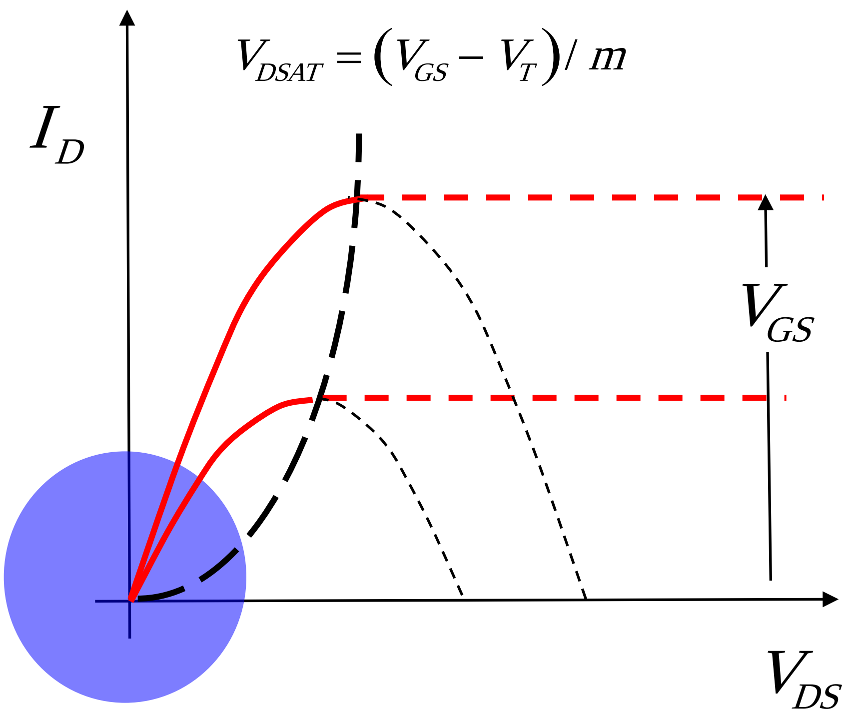
$$J_D = \frac{\mu C_{ox}}{L_{ch}} \left[\left(V_G - V_{th}\right)V_D - m\frac{V_D^{\;2}}{2} \right]$$



Square Law or Simplified Bulk Charge Theory

$$I_D = W\frac{\mu C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\ 2}}{2}\right]$$

$$\frac{dI_D}{dV} = 0 = (V_G - V_{th}) - mV_D \Rightarrow V_{D,sat} = \left(V_G^{\ *} - V_{th}\right)/m$$



$$I_D = \frac{W\mu C_o}{2mL_{ch}}(V_G - V_T)^2$$

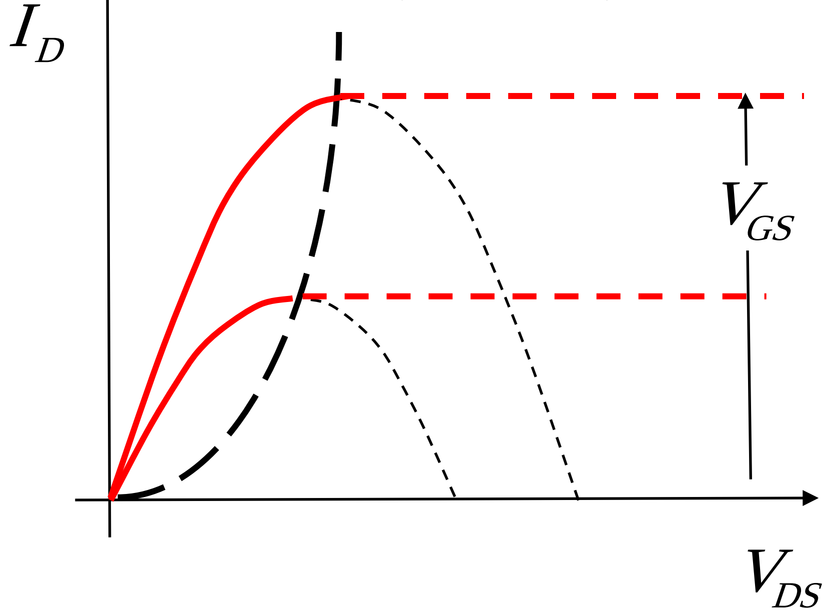
$$J_D = \frac{\mu C_{ox}}{L_{ch}}\left[(V_G - V_{th})V_D - m\frac{V_D^{\ 2}}{2}\right]$$

$$I_D = \mu\, C_o \frac{W}{L}(V_G - V_T)V_D$$

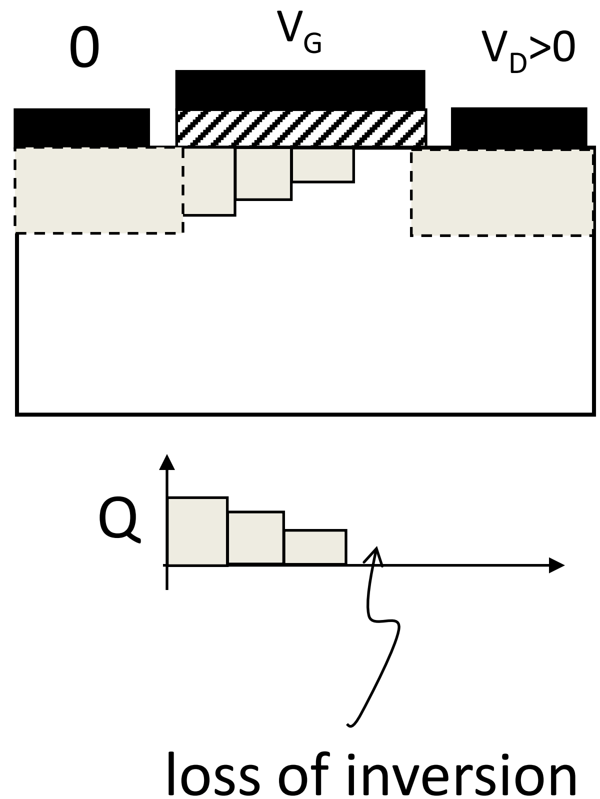
Why does the curve roll over?

$$I_D = \frac{W \mu C_o}{2mL_{ch}} (V_G - V_T)^2$$

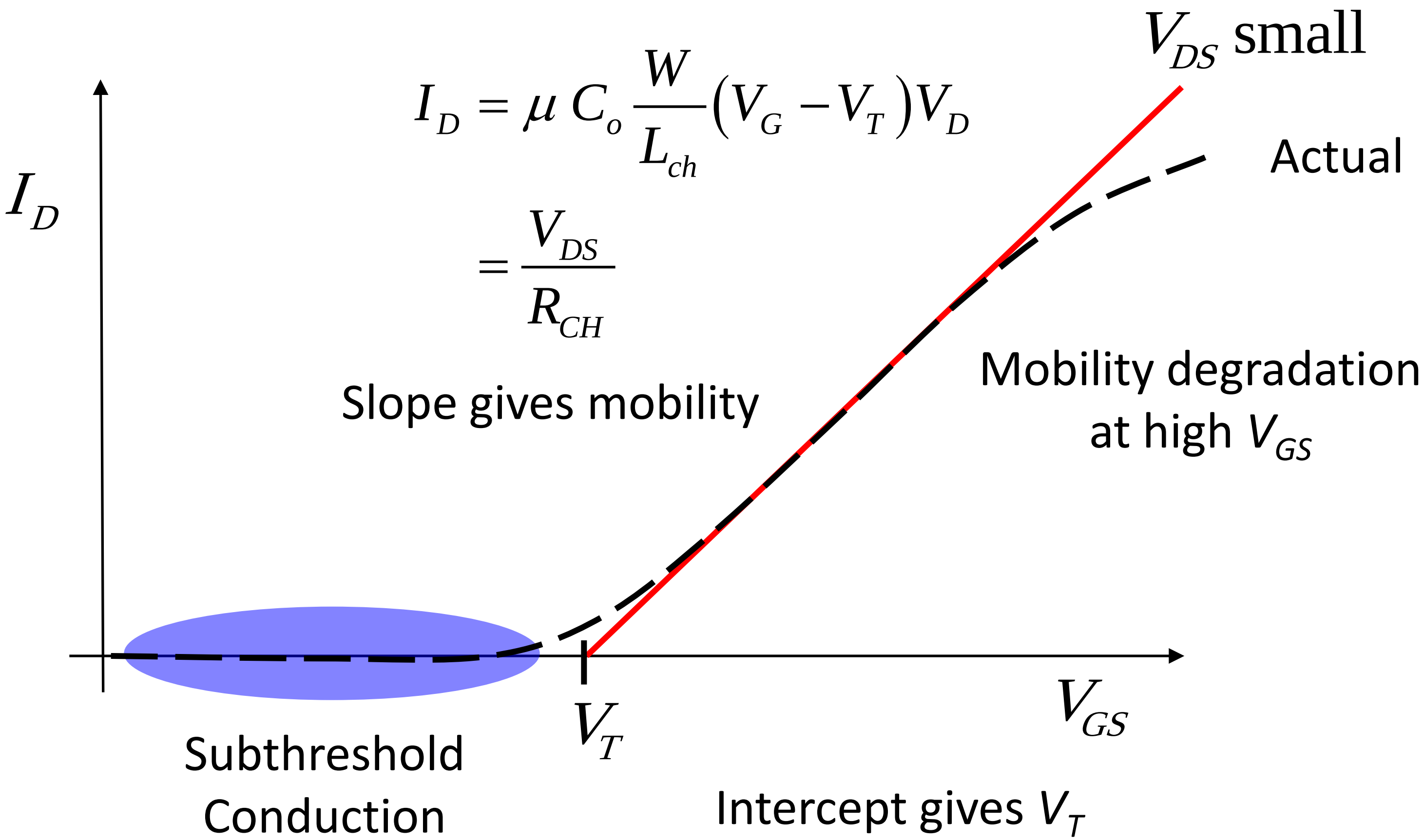
$$V_{DSAT} = \left(V_{GS} - V_T\right) / \ m$$



$$Q_i \approx -C_{ox}(V_G - V_{th} \ - mV)$$



Linear Region (Low V_{DS})



Summary

1) MOSFET differs from MOSCAP in that the field from the S/D contacts now causes a current to flow.
2) Two regimes, diffusion-dominated Subthreshold and drift-dominated super-threshold characteristics, define the I_D-V_D-V_G characteristics of a MOSFET.
3) The simple bulk charge theory allows calculation of drain currents and provide many insights, but there are important limitations of the theory as well.