Section 30
MOSFET Introduction

30.2 Above-threshold, inversion current

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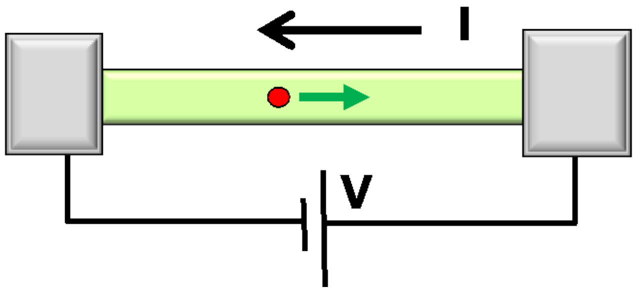


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area

- 30.1 Sub-threshold (depletion) current
- 30.2 Above-threshold, inversion current ← status
- 30.3 Velocity saturation in simplified theory
- 30.4 Comments on bulk charge theory & small transistors

Ref: Sec. 16.4 of SDF Chapter 18, SDF

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

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

Formula overview – derivation to follow

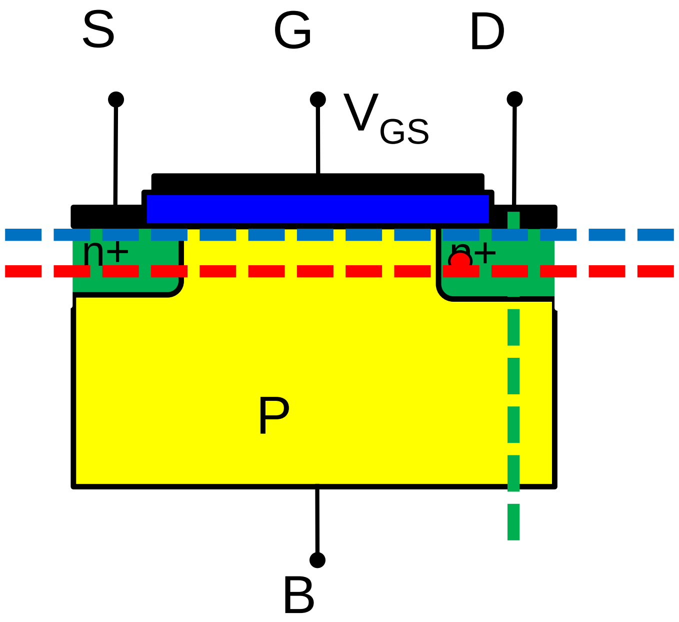
1) Square Law $Q_i(V) = -C_G\left[V_G - V_T - V\right]$

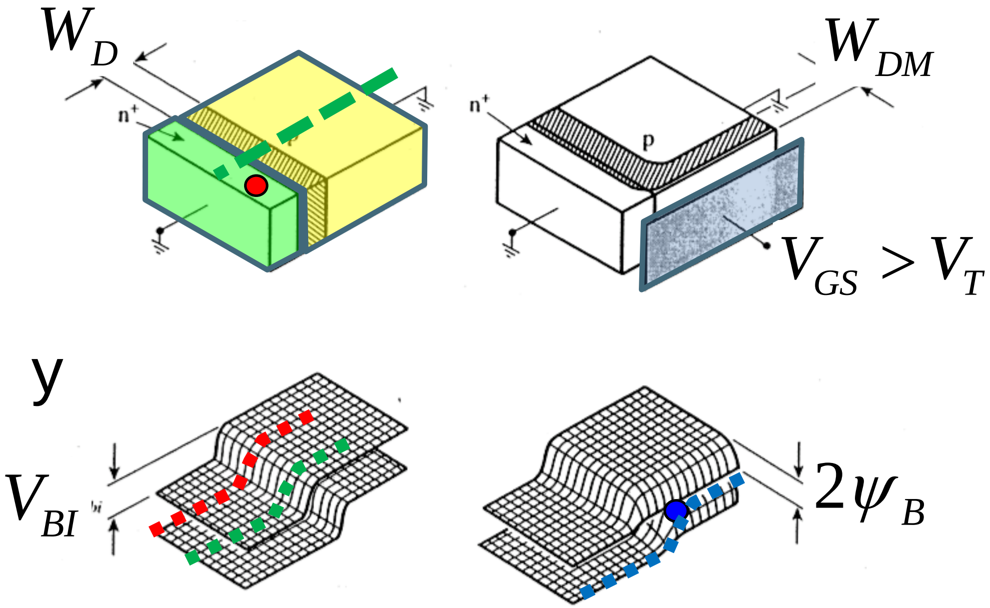
2) Bulk Charge $Q_i(V) = -C_G\left(V_G - V_{FB} - 2\psi_B - V - \frac{\sqrt{2q\varepsilon_{Si}N_A\left(2\phi_B + V\right)}}{C_O}\right)$

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

4) “Exact” (Pao-Sah or Pierret-Shields)

Effect of Gate Bias



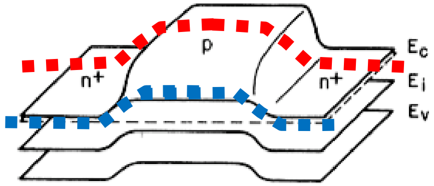


Gated doped or p-MOS with adjacent n⁺ region

a) gate biased at flat-band

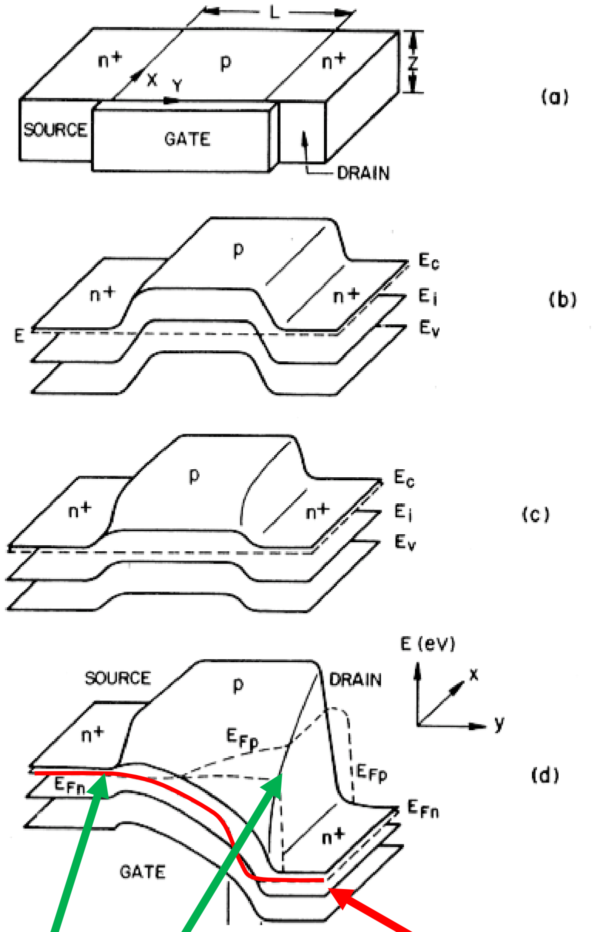
b) gate biased in inversion

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



No source-drain bias

The Effect of Drain Bias - 2D Band Diagram for n-MOSFET



a) device

b) equilibrium (flat band)

c) Equilibrium with V_G ($\psi_S > 0$)

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

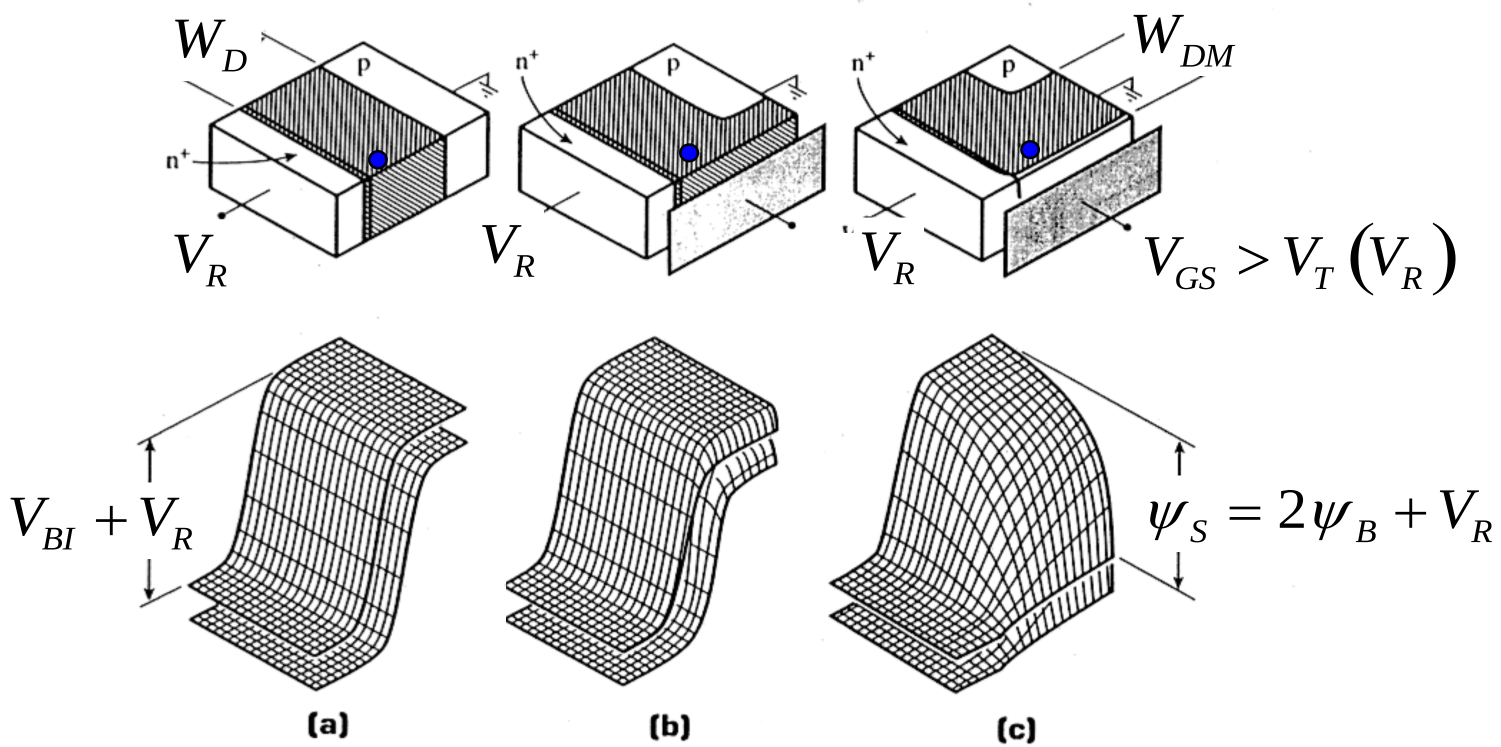
Depletion very different in source and drain side

F_N

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

Gate voltage must ensure channel formation=> LARGE

Effect of a Reverse Bias at Drain



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

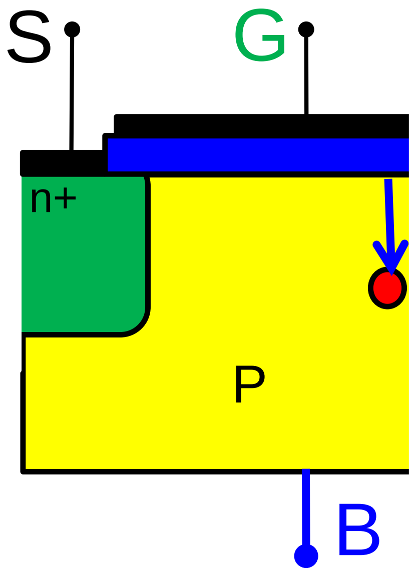
a) gate biased at flat-band

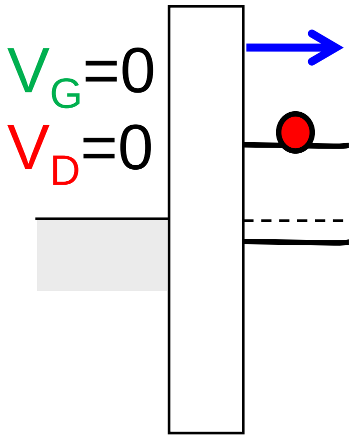
b) gate biased in depletion

c) gate biased in inversion

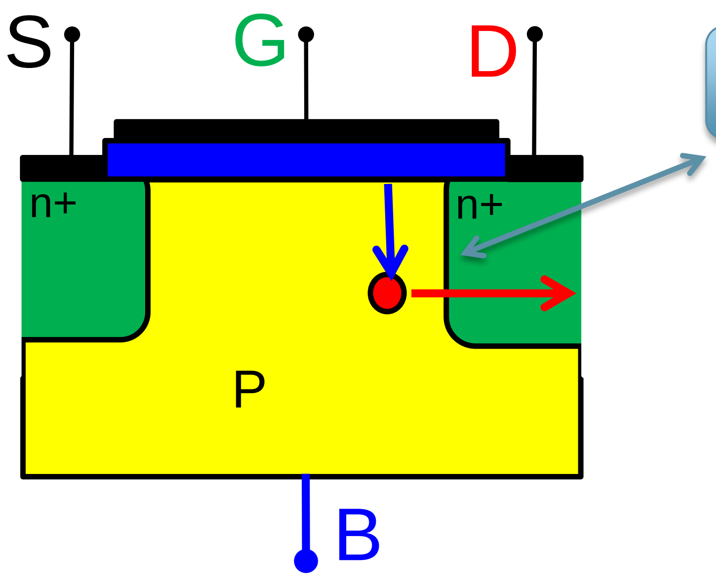
A. Grove, *Physics of Semiconductor Devices*, 1967.

Inversion Charge in the Channel

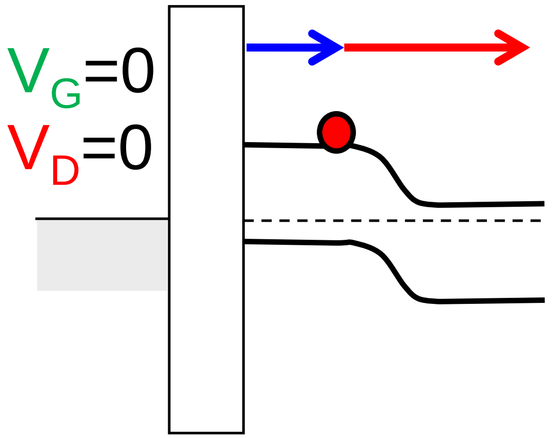


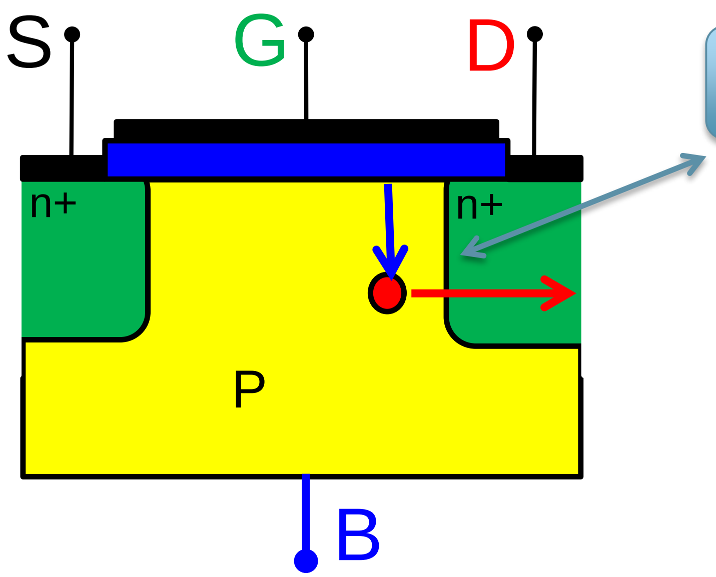


Inversion Charge in the Channel



Band diagrams (Gate – Channel - Drain)

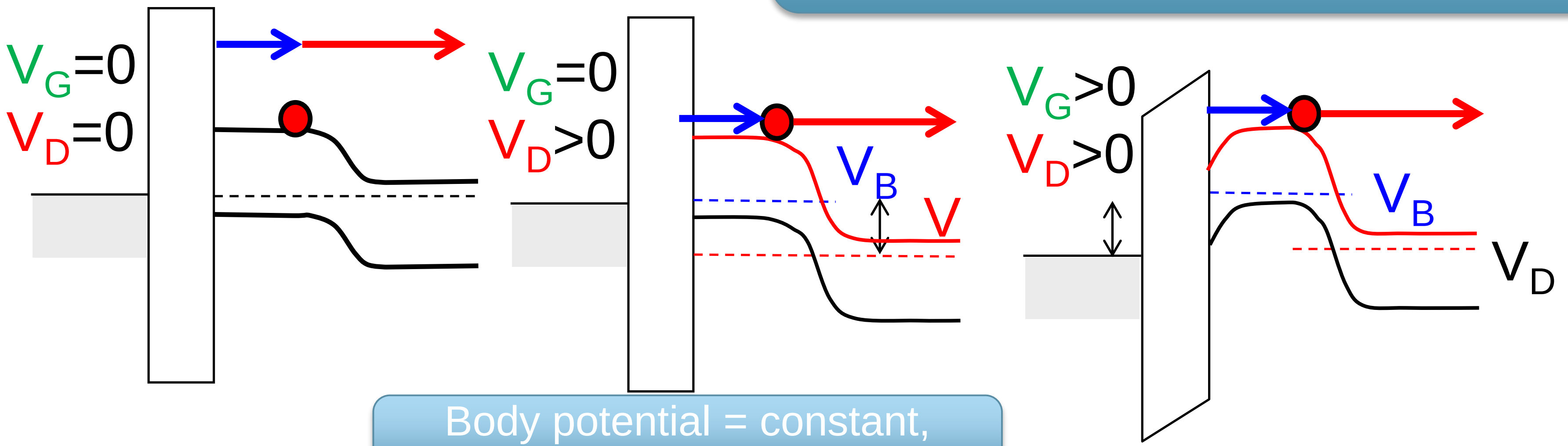




Band diagrams (Gate – Channel - Drain)

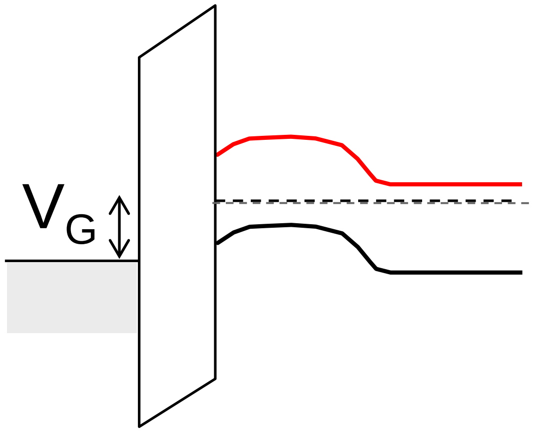
$$Q_i = -C_{ox}(V_G - V_{th} - V) + qN_A(W_T(V) - W_T(V=0))$$

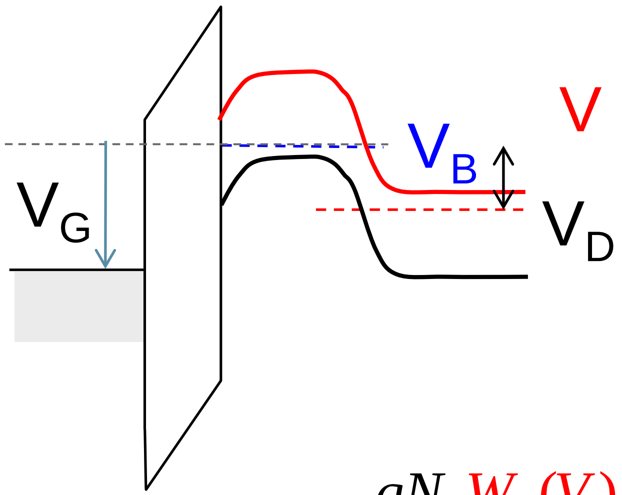
Due to drain bias, additional gate voltage (as compared to threshold in MOSCAP) is now needed to invert the channel throughout its length



Body potential = constant,
n+ region potential lowered

Inversion Charge at one point in Channel





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

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

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

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

Threshold voltage in the presence of drain bias

Approximations for Inversion Charge

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

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

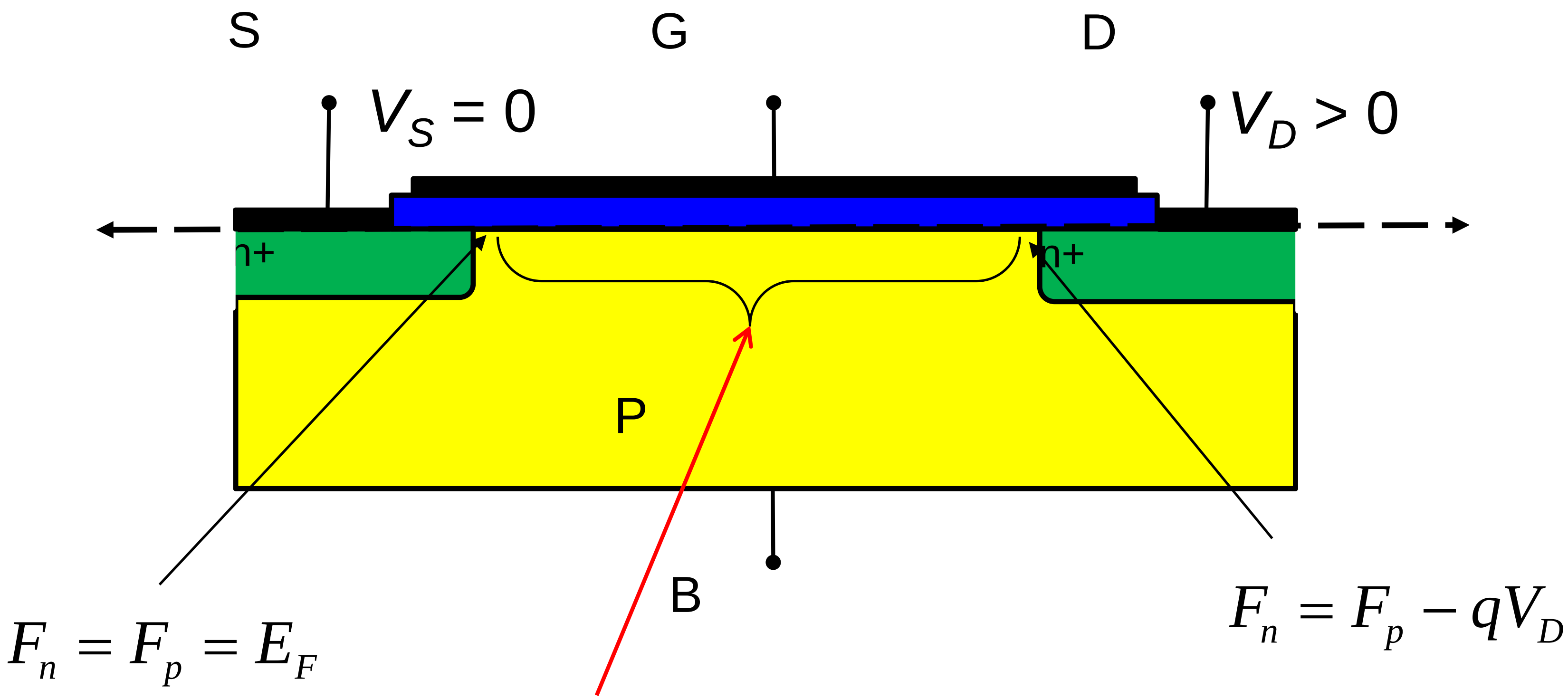
$$Q_i = -C_O(V_G - V_{th} - V) + qN_A\left(W_T(V) - W_T(V=0)\right)$$

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

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 …



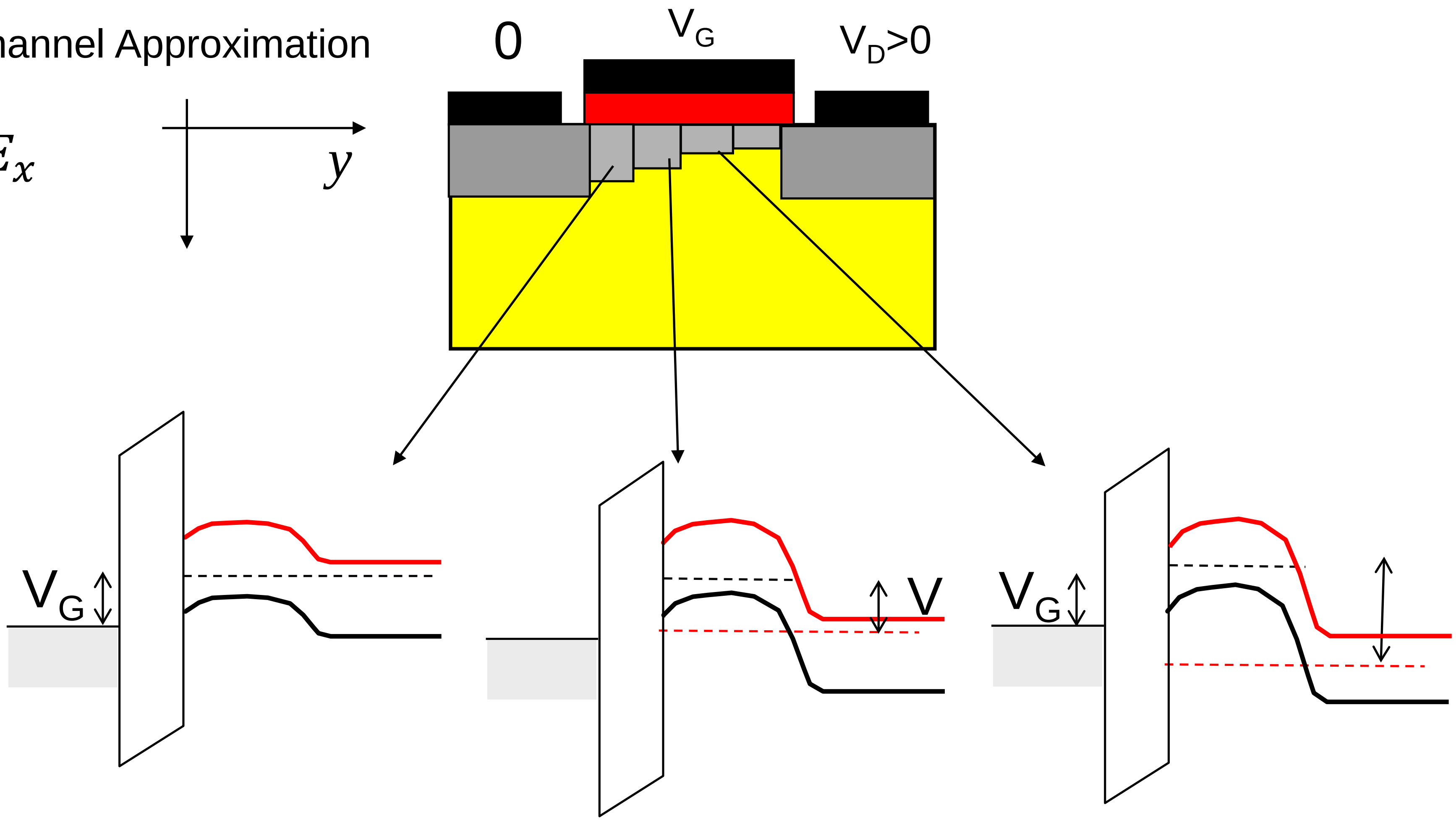
F_n increasingly negative from source to drain
(reverse bias increases from source to drain)

Elements of Square-law Theory

Voltage and hence inversion charge vary spatially

Gradual Channel Approximation
GCA

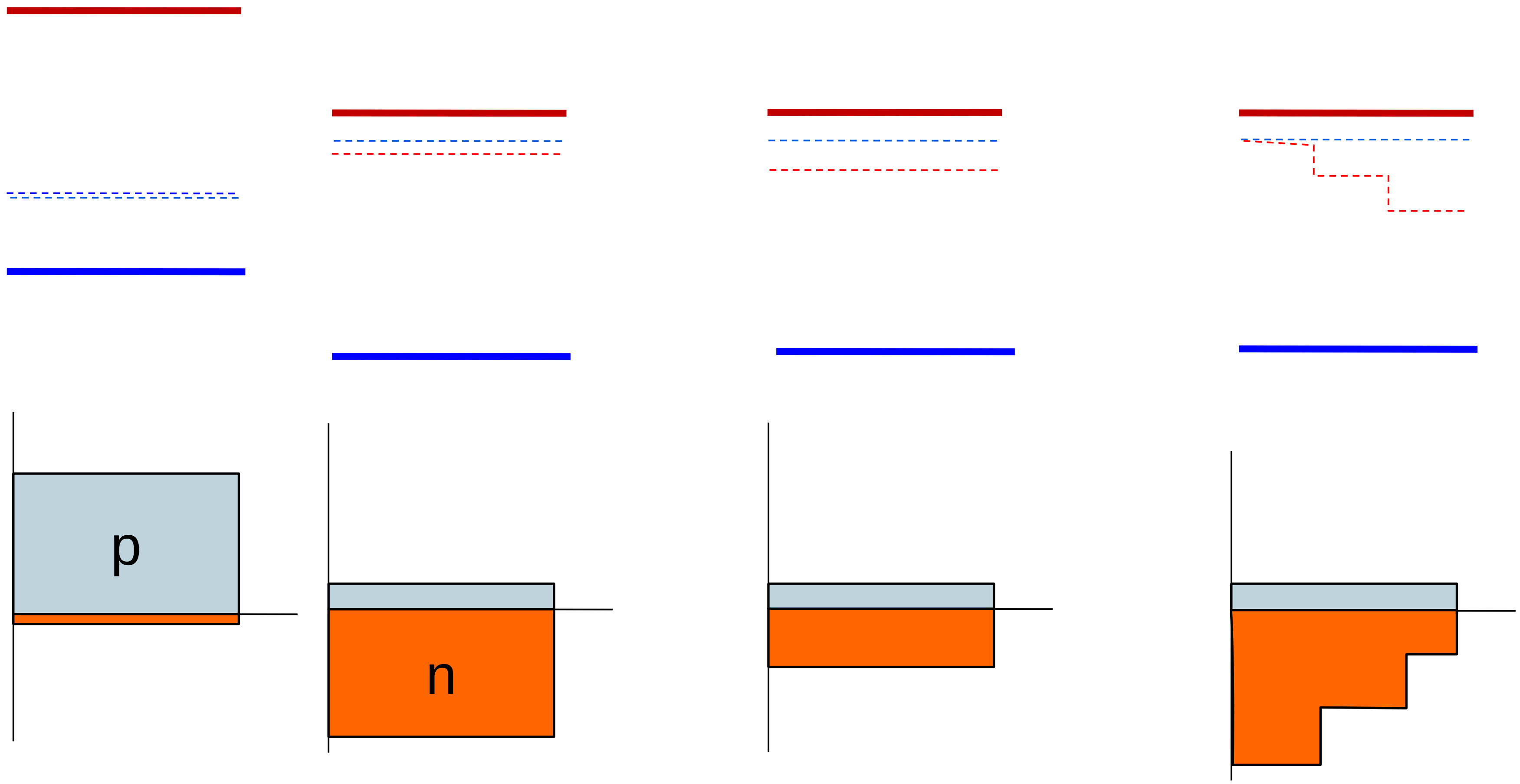
$E_y << E_x$



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

Charge along the channel ....

$$n = N_C e^{-(E_C - F_n)\beta} \qquad p = N_C e^{(E_V - F_p)\beta}$$



Charge along the channel ...

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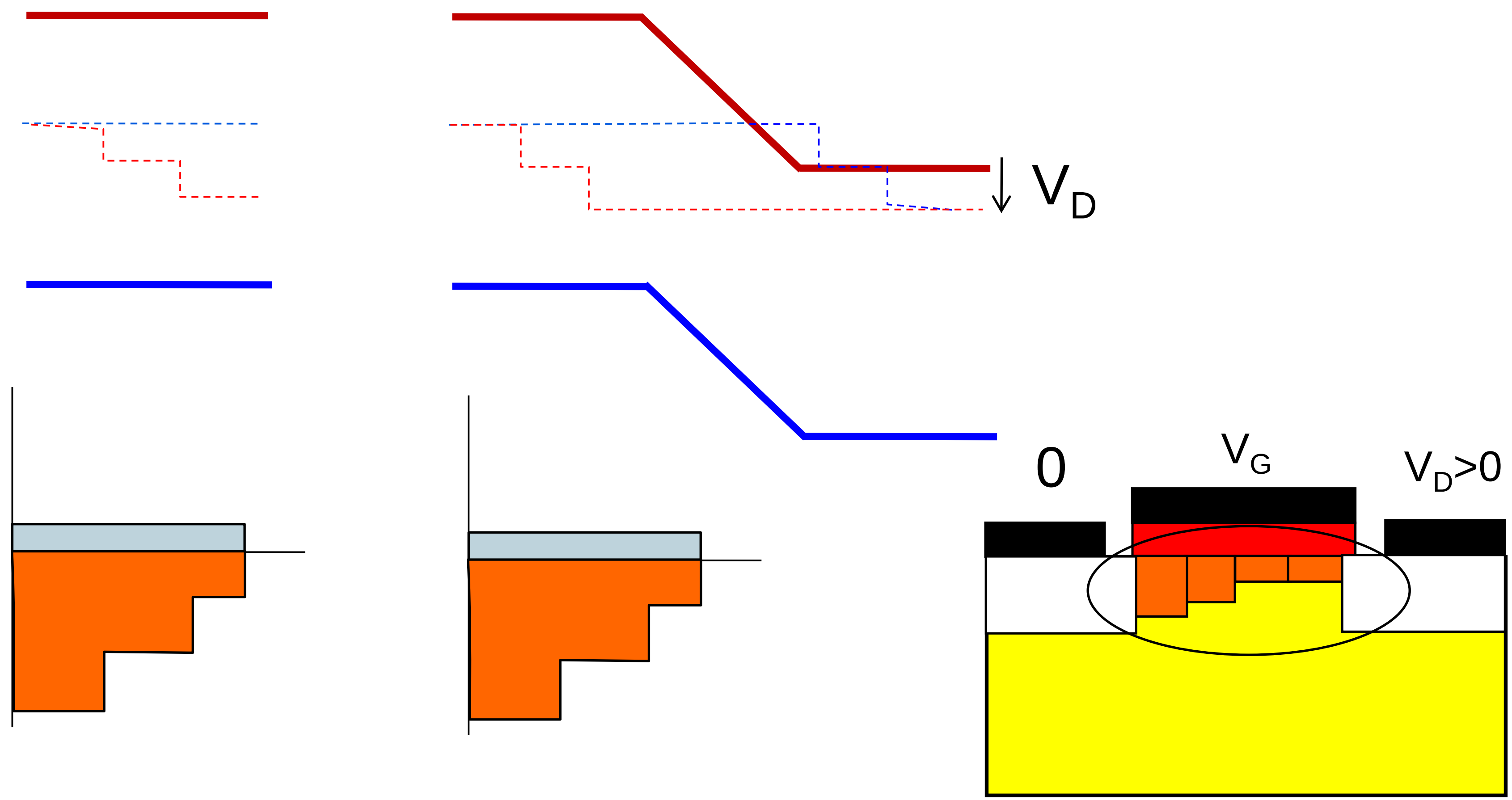
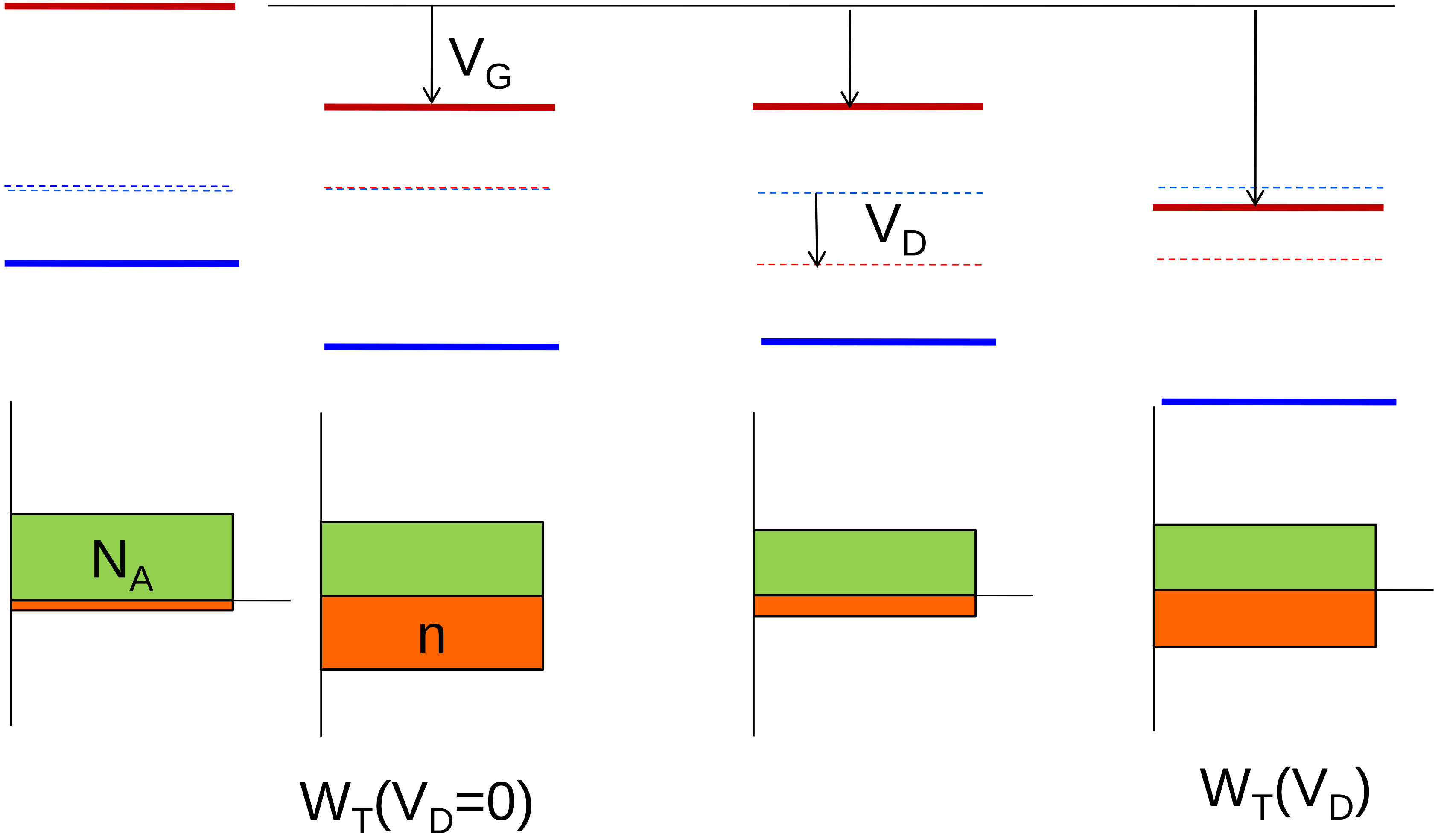
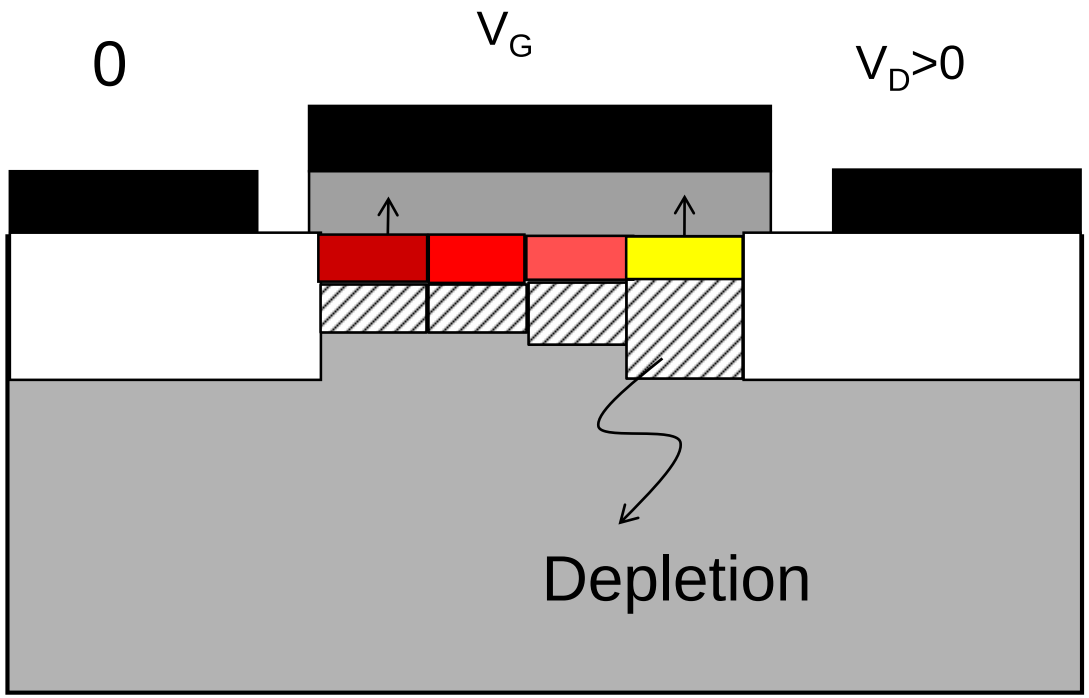


Depletion into the channel ….

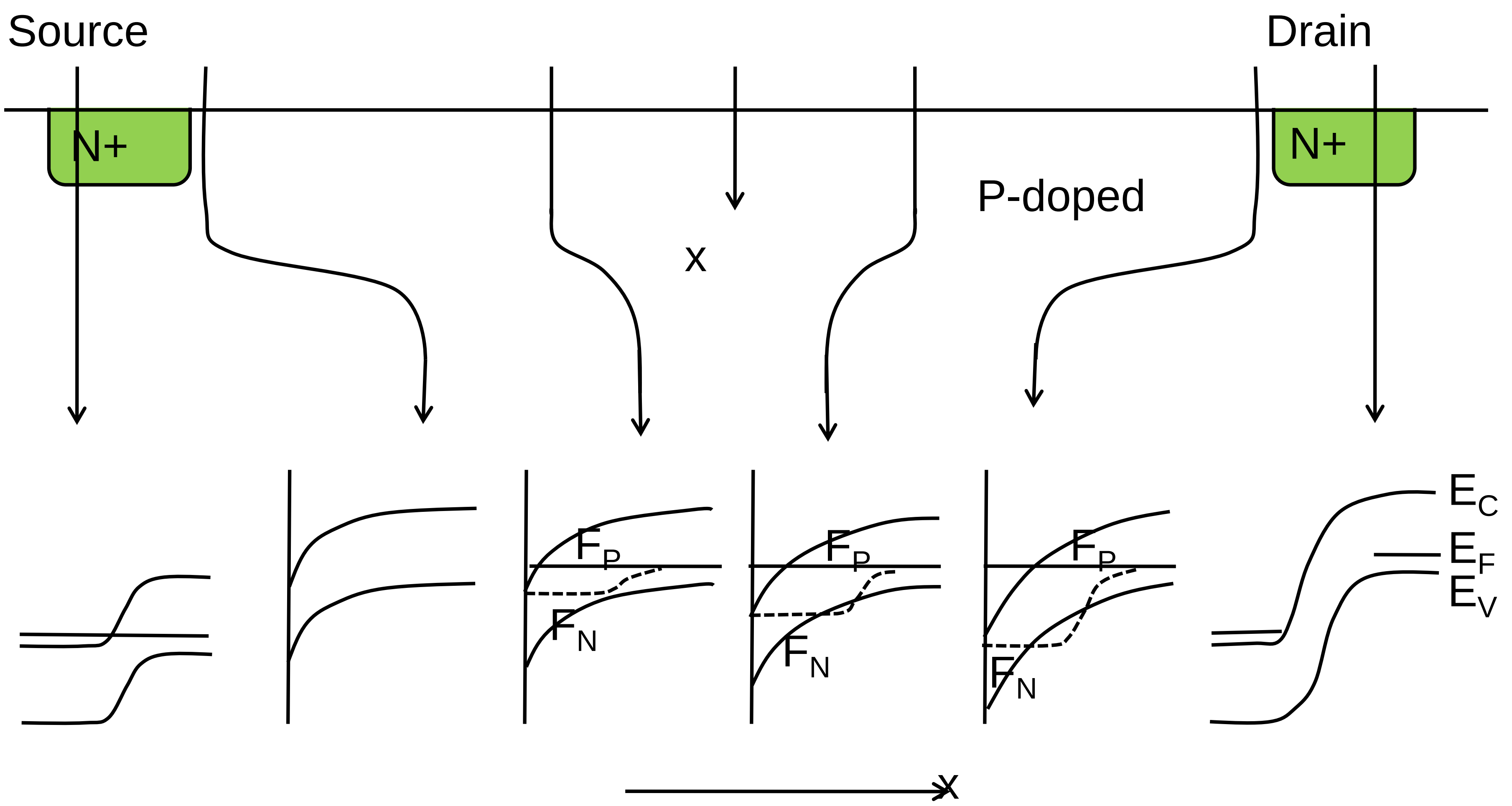
$$n = N_C e^{-(E_C - F_n)\beta} \qquad p = N_C e^{(E_V - F_p)\beta}$$



Depletion into the channel ...



Another view of Channel Potential



Square Law Theory

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

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

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

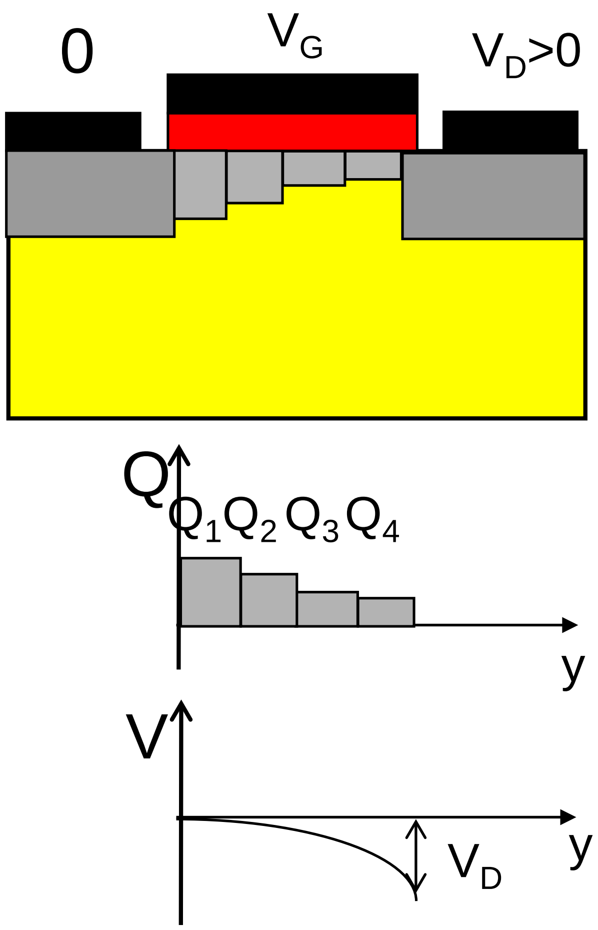
$$J_4 = Q_4 \mu \mathcal{E}_4 = Q_4 \mu \left.\frac{dV}{dy}\right|_4$$

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

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

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

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

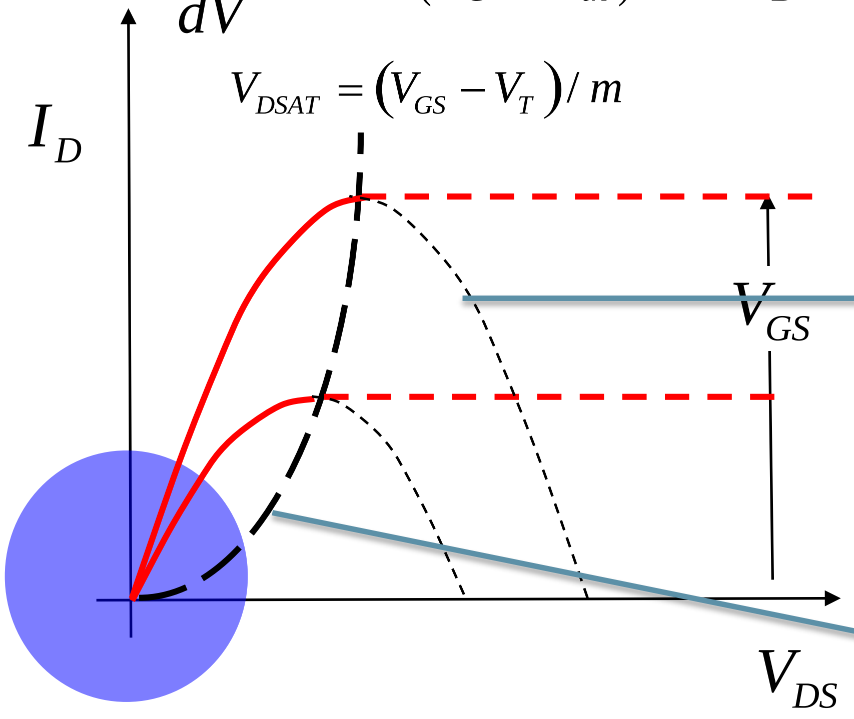


Square Law or Simplified Bulk Charge Theory

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

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

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



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

Unphysical, since current does not decrease with increase in Vd

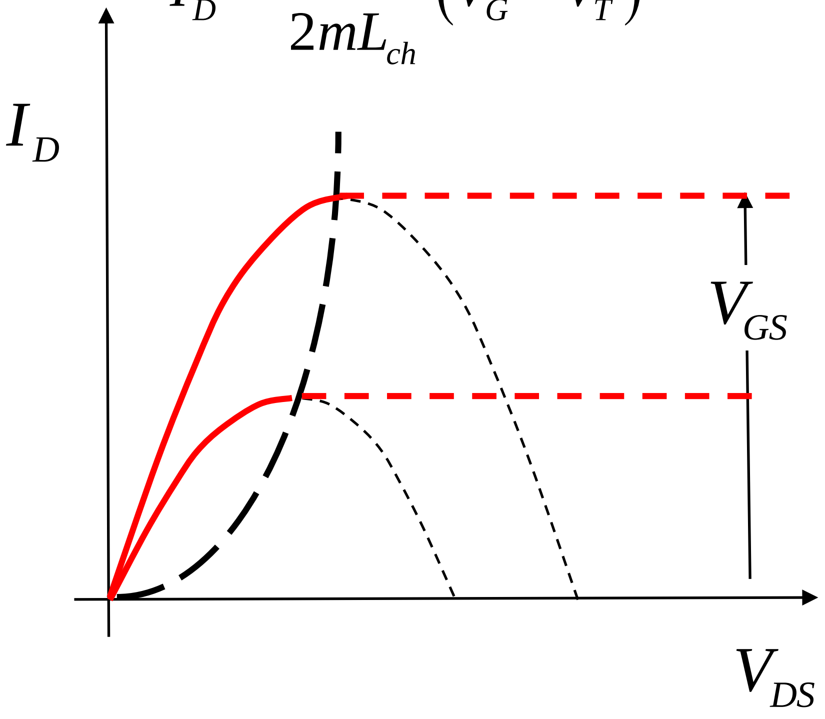
Region of validity for the expression for currents

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

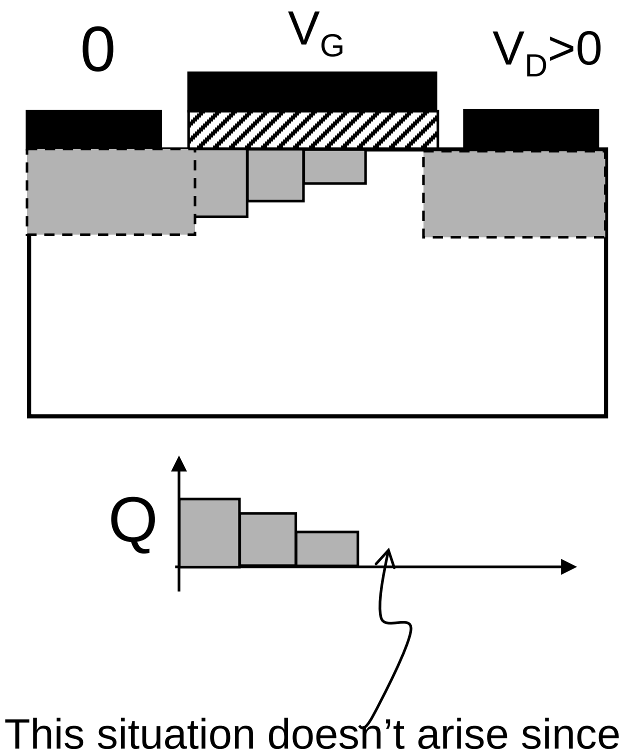
Why square law? And why does it become invalid

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

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



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



This situation doesn't arise since electrons travelling from left to right are swept into the drain under the effect of the reverse bias applied

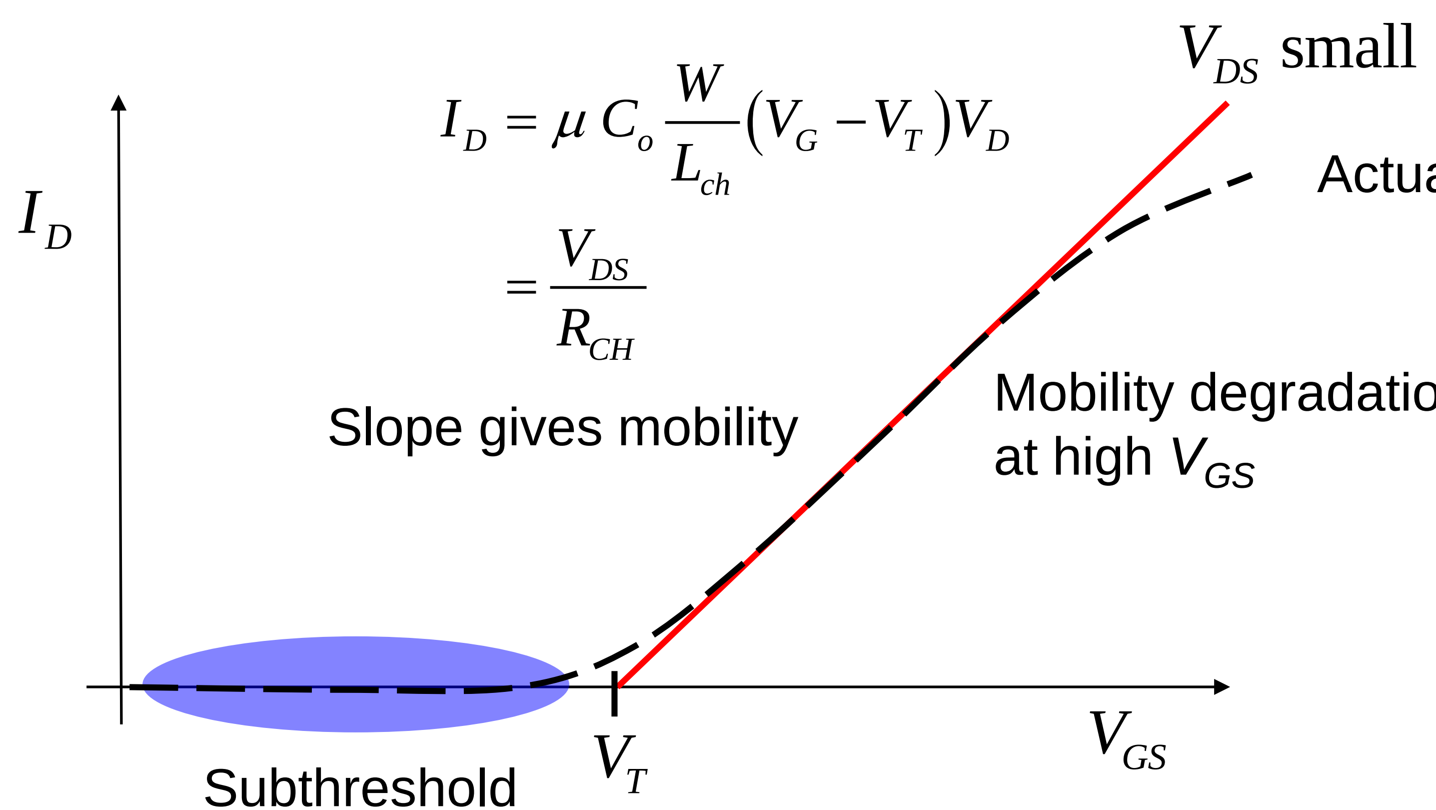
Linear Region (Low V_{DS})

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

$$I_D = \mu\, C_o \frac{W}{L_{ch}}\left(V_G - V_T\right)V_D$$

$$= \frac{V_{DS}}{R_{CH}}$$

Slope gives mobility

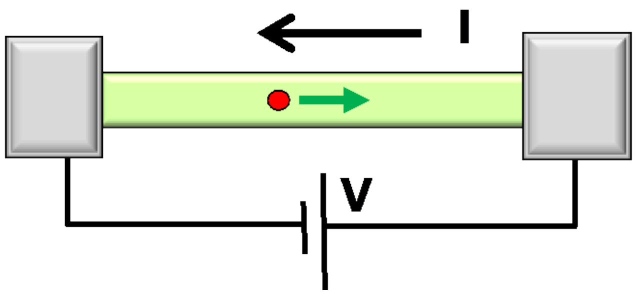


Mobility degradation at high V_{GS}

Subthreshold Conduction

Intercept gives V_T

Can get V_T also from C-V



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area

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2 • 30.2 Above-threshold, inversion current ← status

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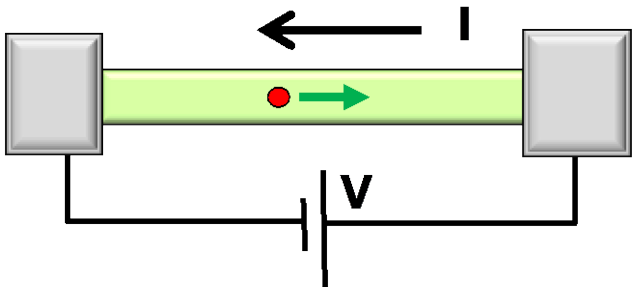

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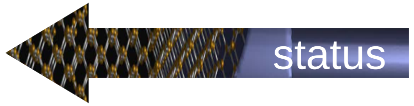
- 30.3 Velocity saturation in simplified theory 

- 30.4 Comments on bulk charge theory & small transistors

Ref: Sec. 16.4 of SDF Chapter 18, SDF