

EE-612:

Lecture 7

MOSFET IV: Part 1

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outline

- 1) Overview
- 2) Square law theory
- 3) PN junction effects

typical characteristics

130 nm technology ($L_G = 60 \text{ nm}$)

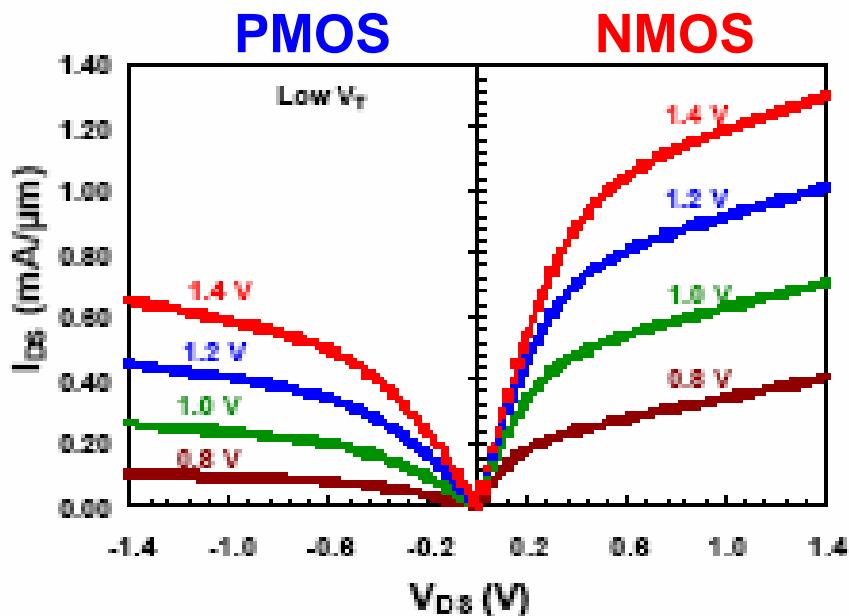
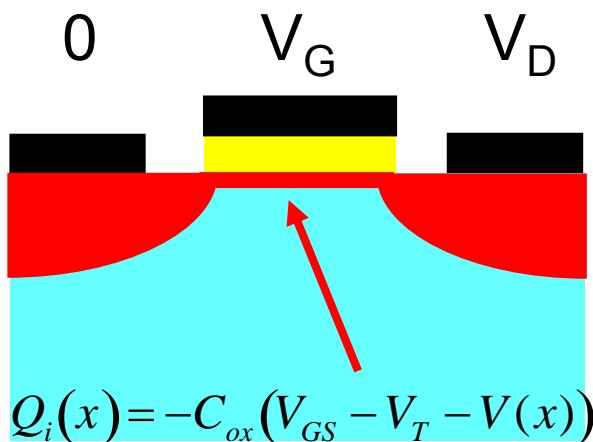


Figure 14: I-V curves for low V_T device ($L_{GATE}=60\text{nm}$)

Intel Technical J., Vol. 6, May 16, 2002.

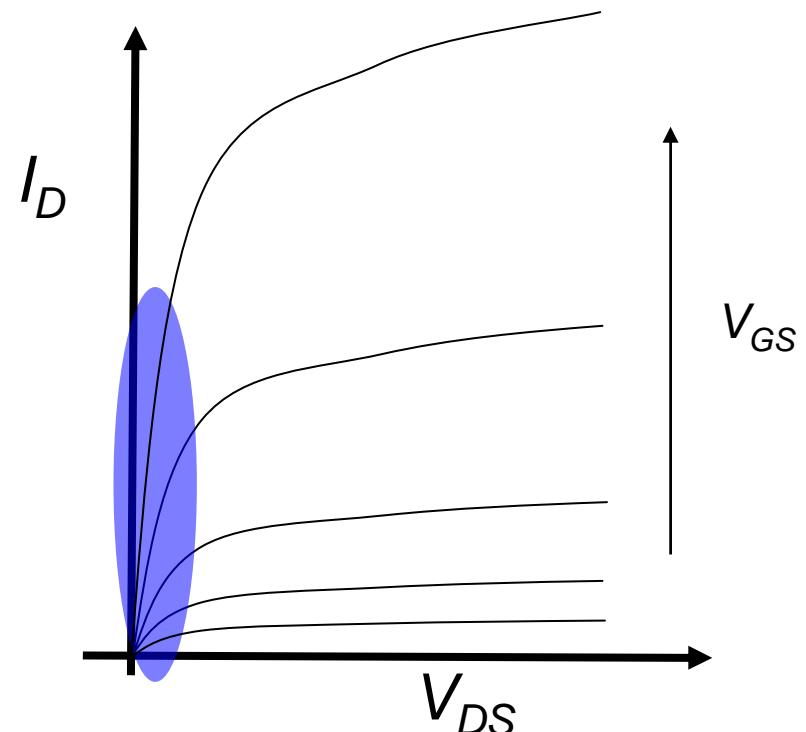
MOSFET IV: low V_{DS}



$$I_D = W Q_i(x) v_x(x) = W Q_i(0) v_x(0)$$

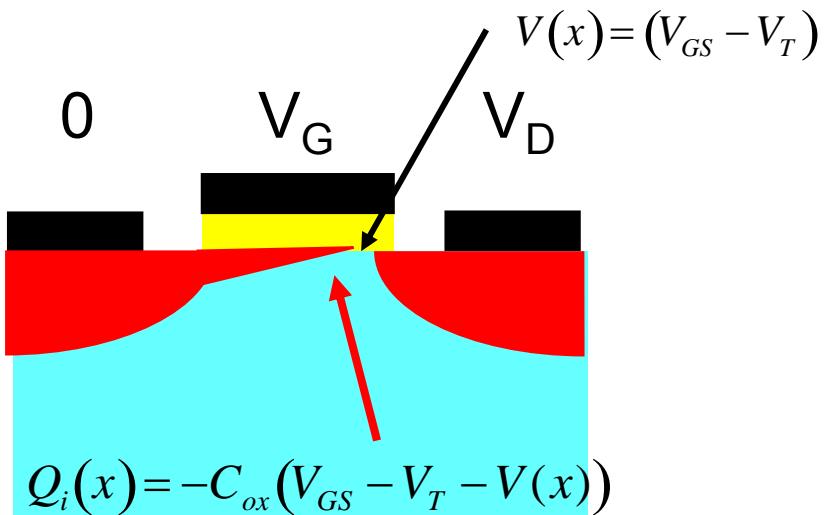
$$I_D = W C_{ox} (V_{GS} - V_T) \mu_{eff} E_x$$

$$E_x = \frac{V_{DS}}{L}$$



$$I_D = \frac{W}{L} \mu_{eff} C_{ox} (V_{GS} - V_T) V_{DS}$$

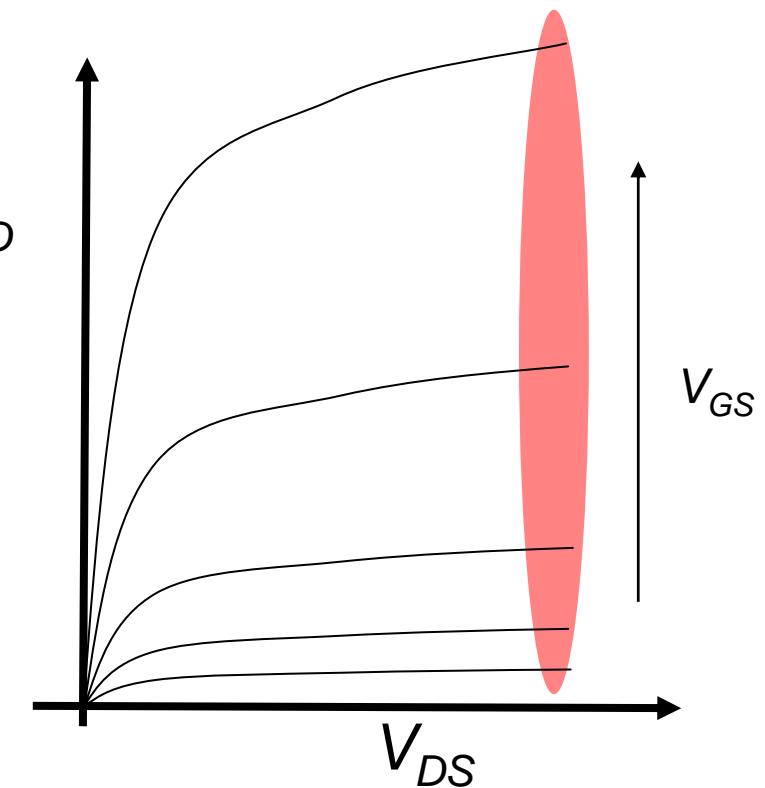
MOSFET IV: high V_{DS}



$$I_D = W Q_i(x) v_x(x) = W Q_i(0) v_x(0)$$

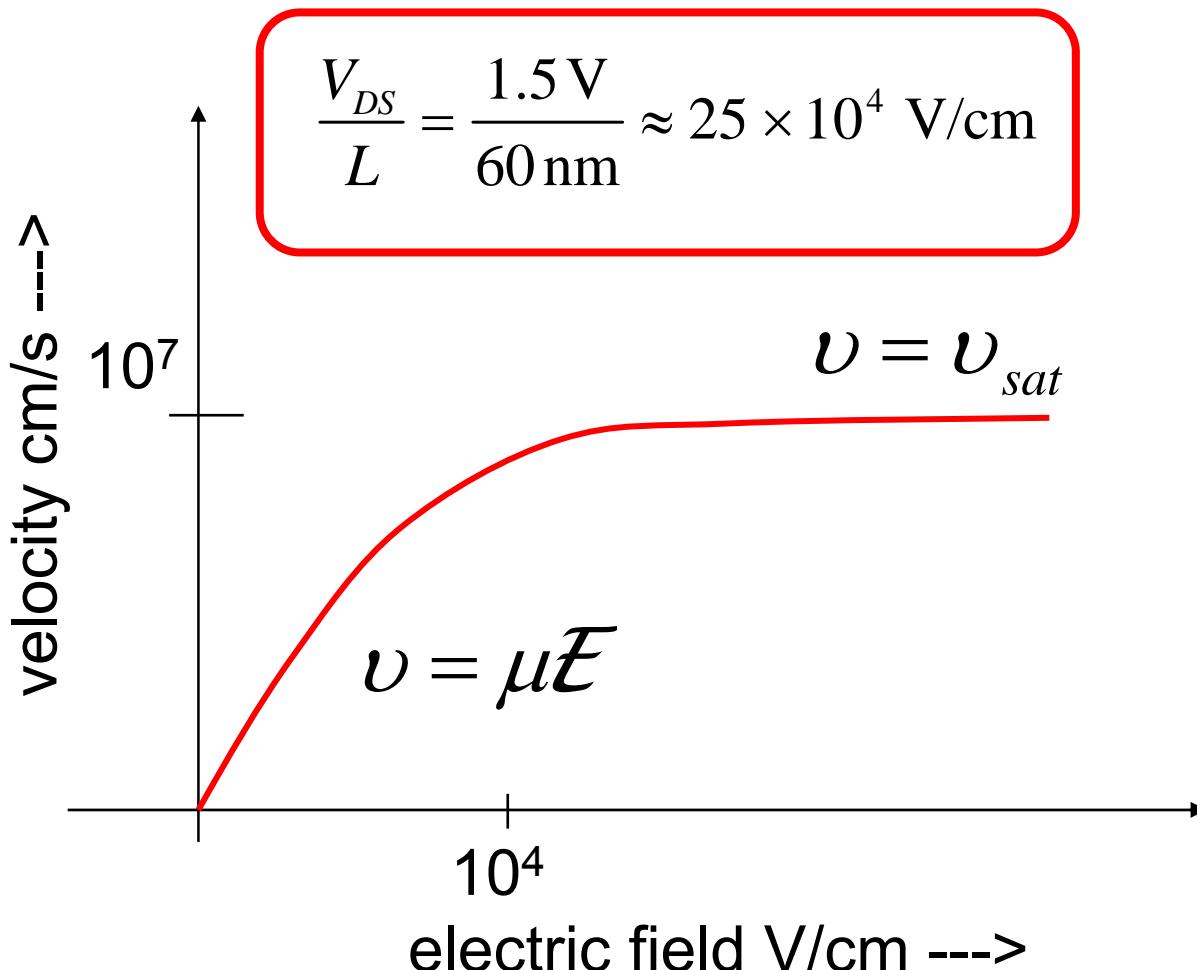
$$I_D = W C_{ox} (V_{GS} - V_T) \mu_{eff} E_x$$

$$E_x \approx \frac{V_{GS} - V_T}{L}$$

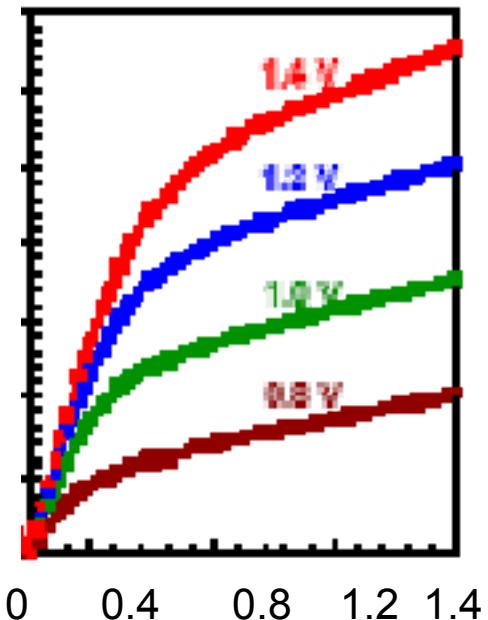
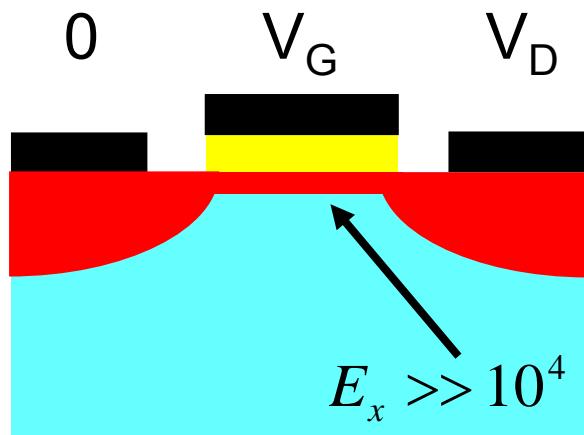


$$I_D = \frac{W}{2L} \mu_{eff} C_{ox} (V_{GS} - V_T)^2$$

velocity saturation



MOSFET IV: velocity saturation

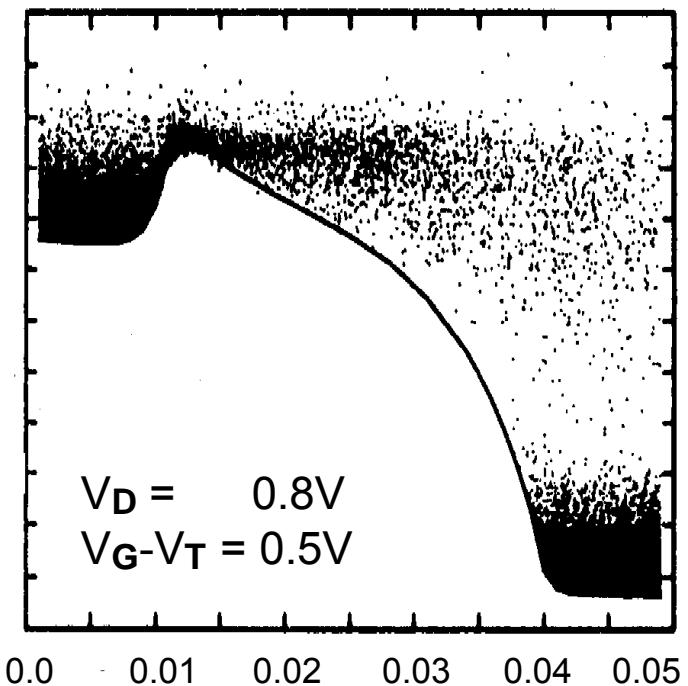


$$I_D = W Q_i(x) v_x(x) = W Q_i(0) v_x(0)$$

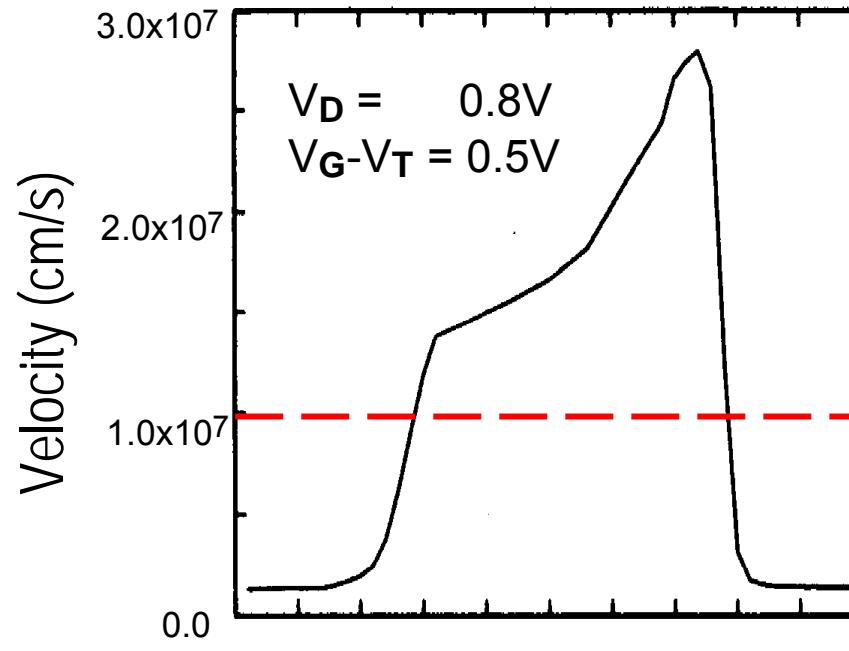
$$I_D = W C_{ox} (V_{GS} - V_T) v_{sat}$$

$$I_D = W C_{ox} v_{sat} (V_{GS} - V_T)$$

MOSFET IV: velocity overshoot



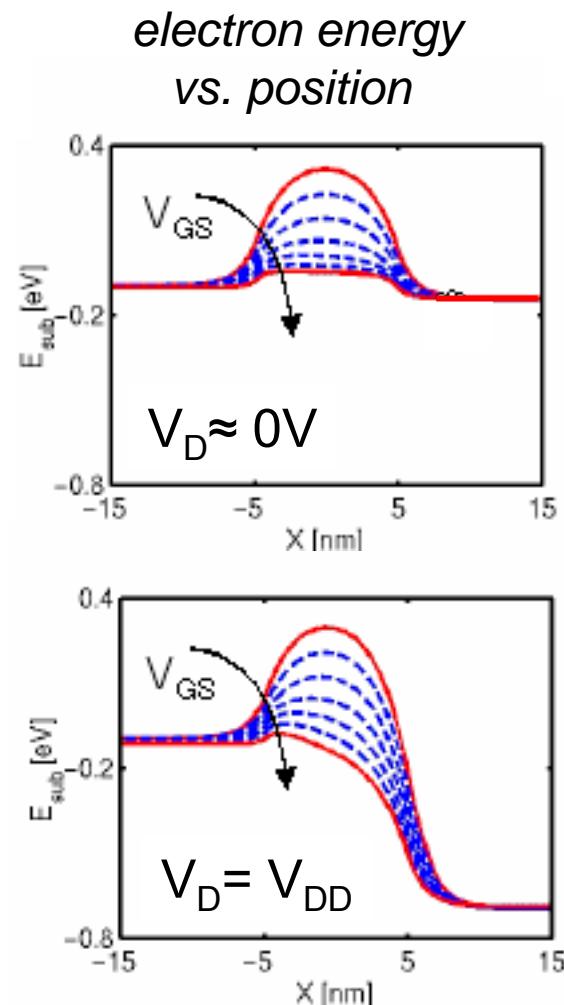
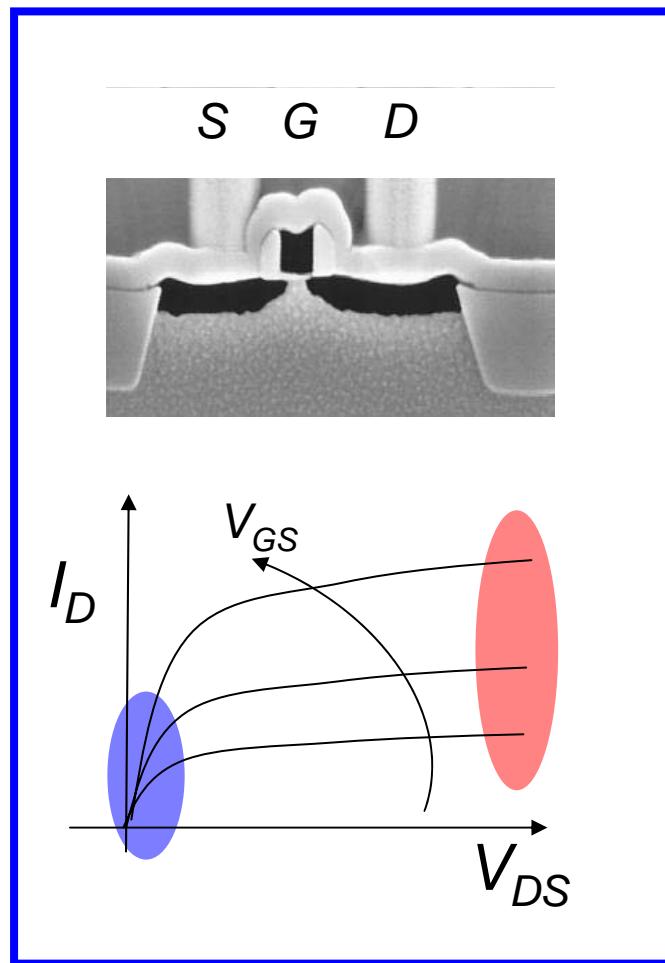
Position along Channel (μm)



Position along Channel (mm)

Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

The MOSFET as a BJT

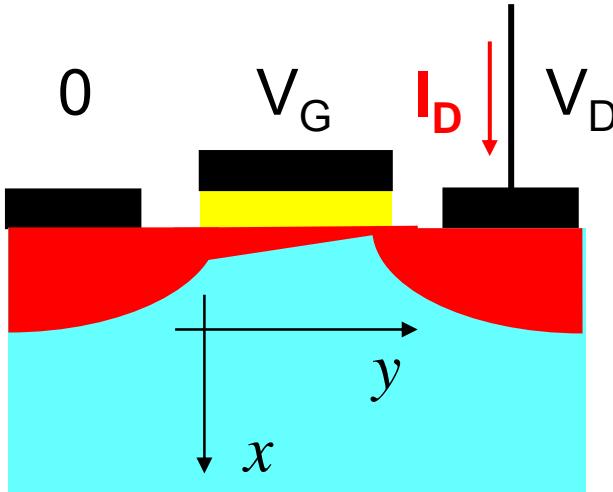


E.O. Johnson, *RCA Review*, 34, 80, 1973

outline

- 1) Overview
- 2) Square law theory**
- 3) PN junction effects

I-V formulation



$$I_D = W Q_i(y) v_y(y)$$

$$I_D = -W Q_i(y) \mu_{eff} \frac{dV}{dy}$$

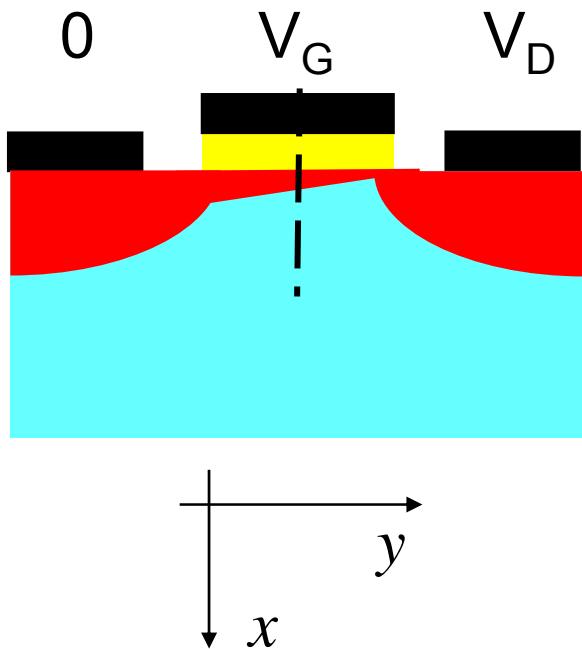
$$I_D dy = -W Q_i(V) \mu_{eff} dV$$

to include diffusion:

$$\frac{dV}{dy} \rightarrow \frac{dF_n}{dy}$$

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

gradual channel approximation



for $0 \leq y \leq L$

$$V = V(y)$$

$$V(0) = 0$$

$$V(L) = V_D$$

$$Q_i = Q_i(y)$$

$$MOS-C : Q_i = -C_G (V_G - V_T)$$

$$GCA : E_y \ll E_x$$

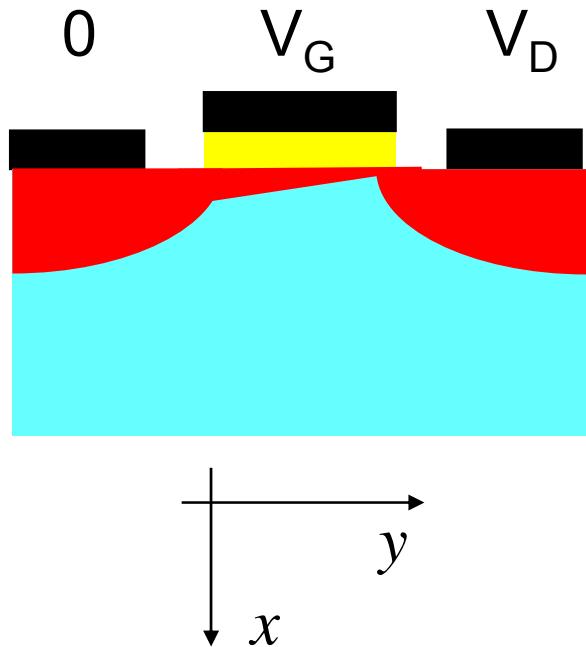
$$V_G - V_T > 0$$



(subthreshold current will require a separate treatment)

$$Q_i(y) = -C_G [V_G - V_T - V(y)]$$

IV relation

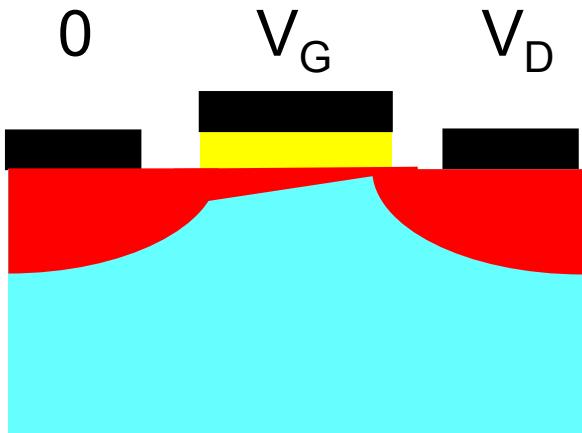


$$I_D = -\frac{W}{L} \mu_{eff} \int_0^{V_{DS}} Q_i(V) dV$$

$$I_D = +\mu_{eff} C_G \frac{W}{L} \int_0^{V_D} [V_G - V_T - V] dV$$

$$I_D = +\mu_{eff} C_G \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

pinch-off



$$Q_i(L) = -C_G [V_G - V_T - V_D]$$

when $V_D = V_G - V_T$,
then $Q_i(L) = 0$

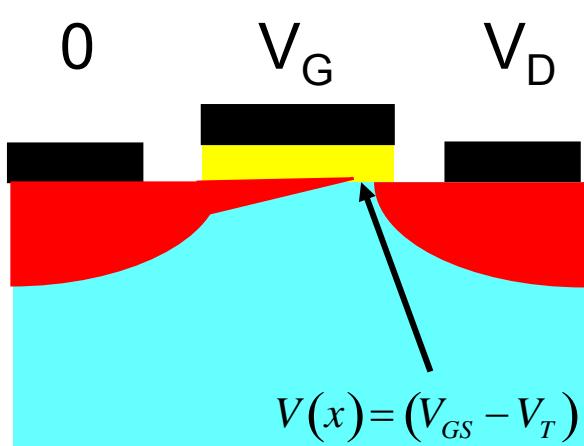
$E_y \gg E_x$ GCA fails!

$$I_D = +\mu_{eff} C_G \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

$$V_{GS} > V_T$$

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

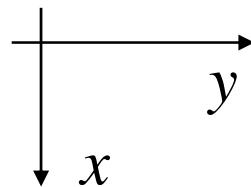
beyond pinch-off



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

channel is pinched-off near the drain
but current still flows.

$$I_D \approx I_D (V_{DS} = V_{GS} - V_T)$$



$$L' \approx L$$

$$I_D = +\mu_{eff} C_G \frac{W}{2L'} (V_{GS} - V_T)^2$$

$$V_{GS} > V_T$$

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

the electric field

small V_{DS}

$$I_D = \mu_{eff} C_G \frac{W}{L} (V_{GS} - V_T) V_{DS}$$

$$I_D = W C_G (V_{GS} - V_T) \mu_{eff} E_y(0)$$

$$E_y(0) = \frac{V_{DS}}{L}$$

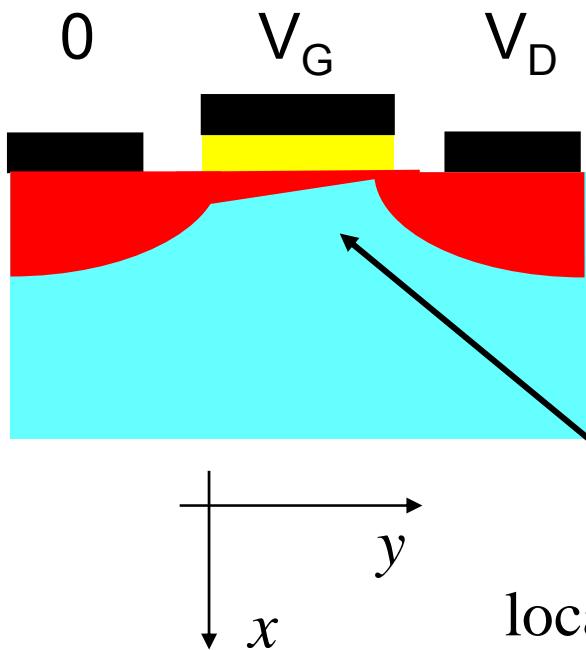
large V_{DS}

$$I_D = \mu_{eff} C_G \frac{W}{2L} (V_{GS} - V_T)^2$$

$$I_D = W C_G (V_{GS} - V_T) \mu_{eff} E_y(0)$$

$$E_y(0) = \frac{(V_{GS} - V_T)}{2L}$$

but...



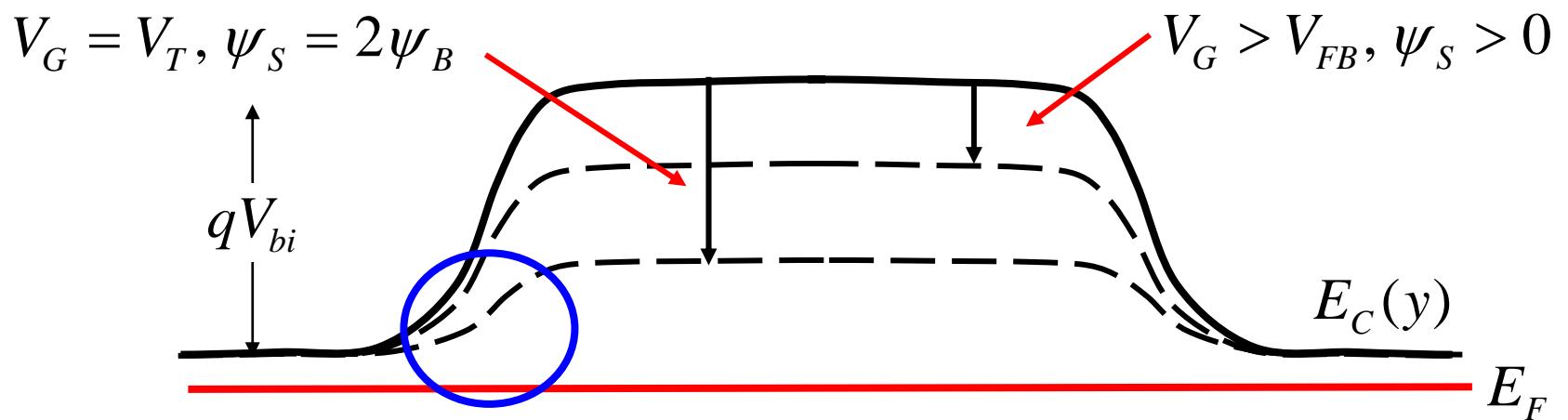
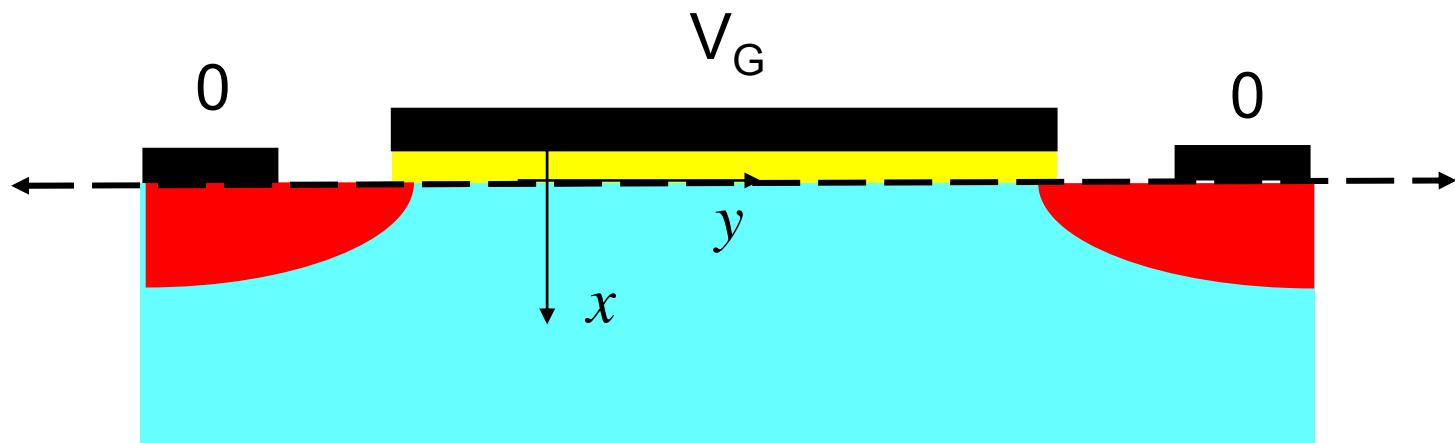
$$Q_i(y) = -C_G [V_G - V'_T(y) - V(y)]$$

local threshold voltage, V'_T , depends on y .

outline

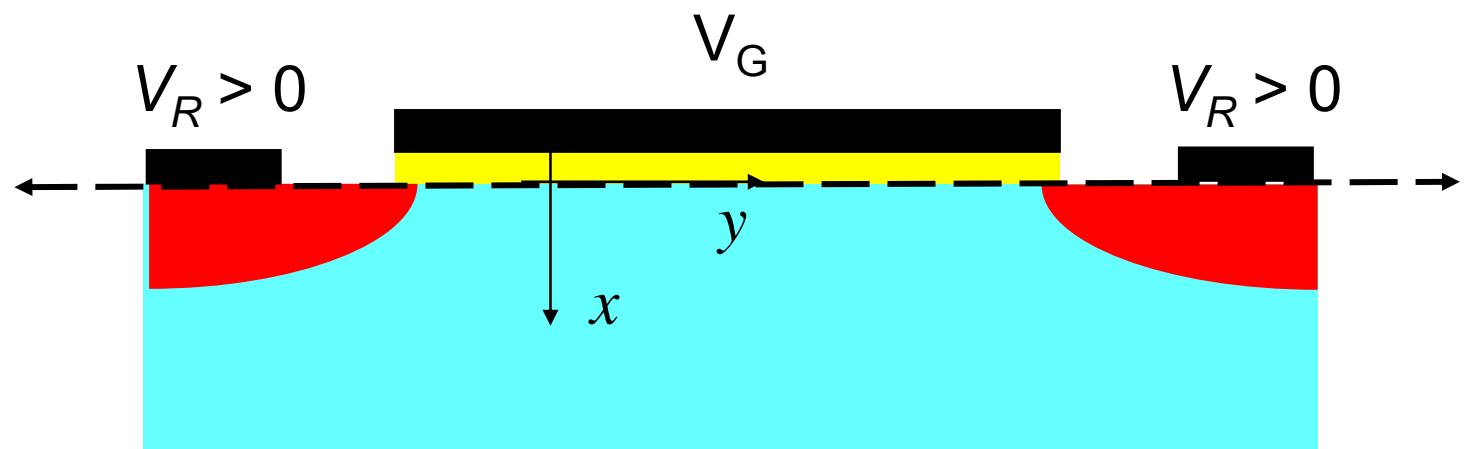
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energy band diagram along the channel

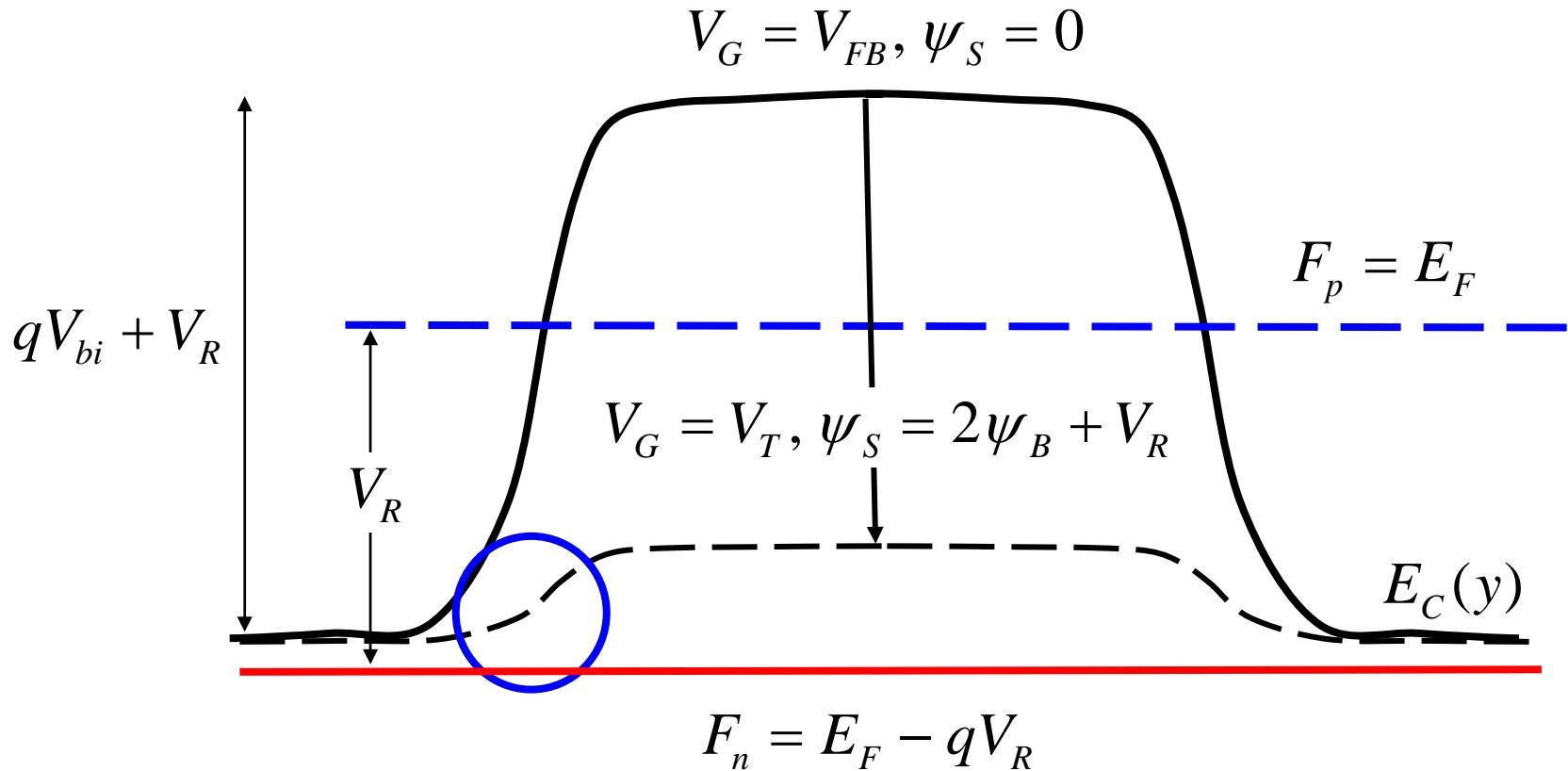


$$\Delta E = q(V_{bi} - 2\psi_B) = k_B T \ln(N_D/N_A) \approx 0.1 \text{ eV}$$

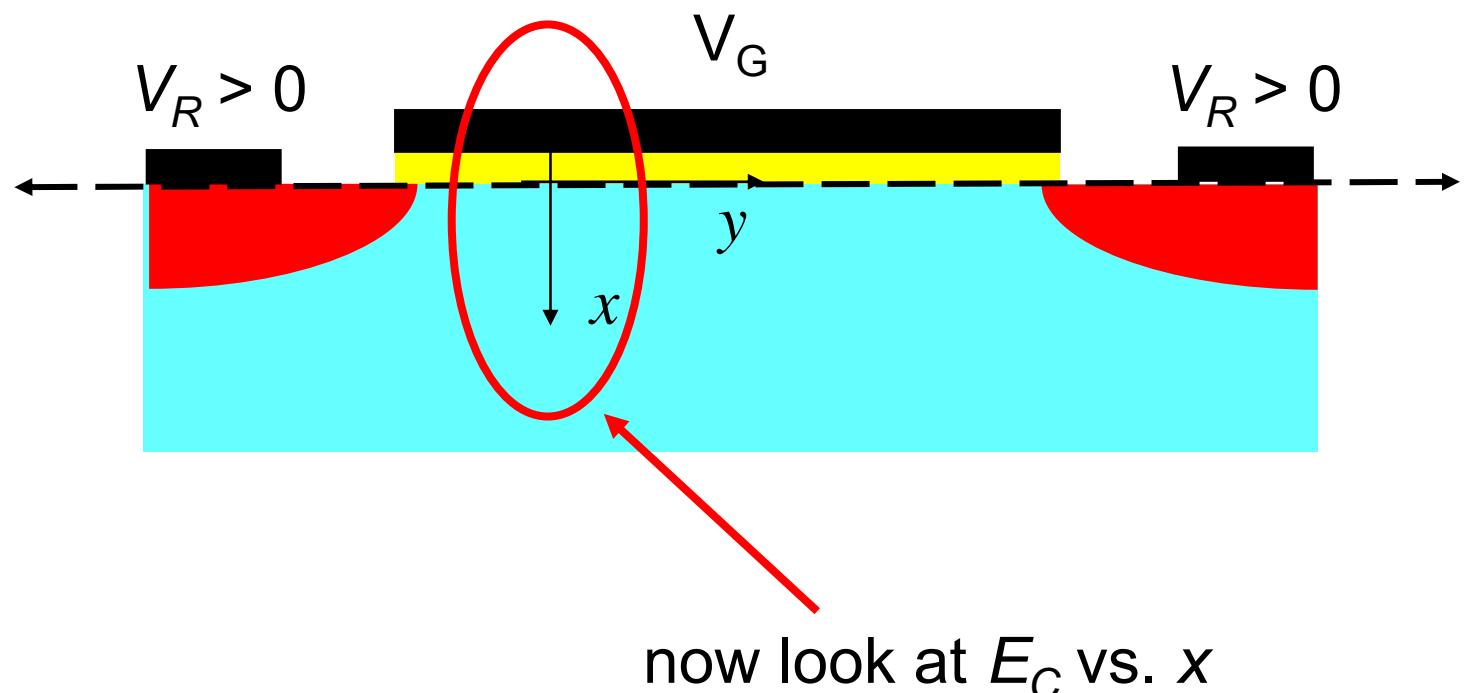
effect of a reverse bias



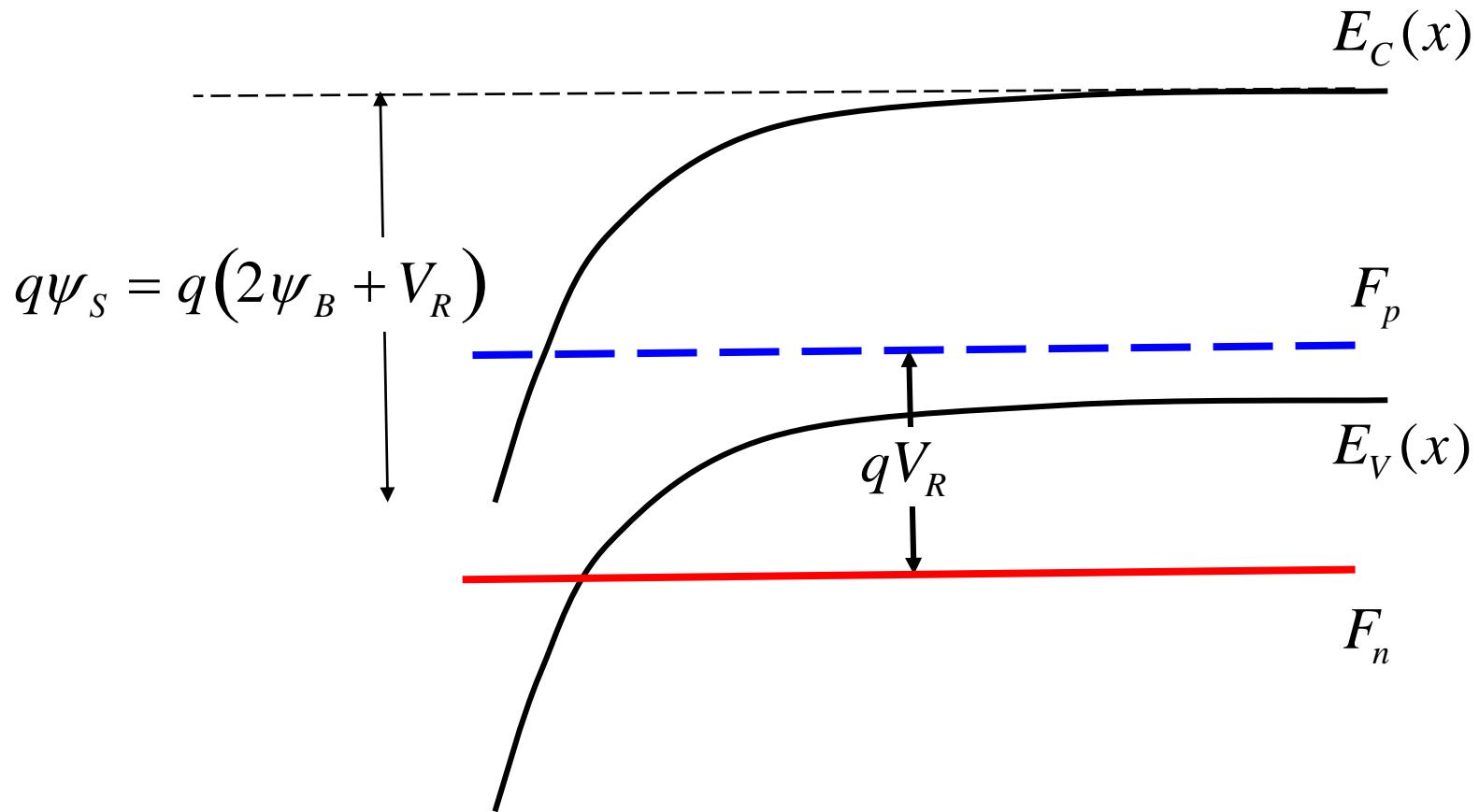
effect of a reverse bias



effect of a reverse bias



effect of a reverse bias



effect of a reverse bias

no reverse bias:

$$V_T = V_{FB} + 2\psi_B + \sqrt{2q\varepsilon_{Si}N_A(2\psi_B)} / C_{ox}$$

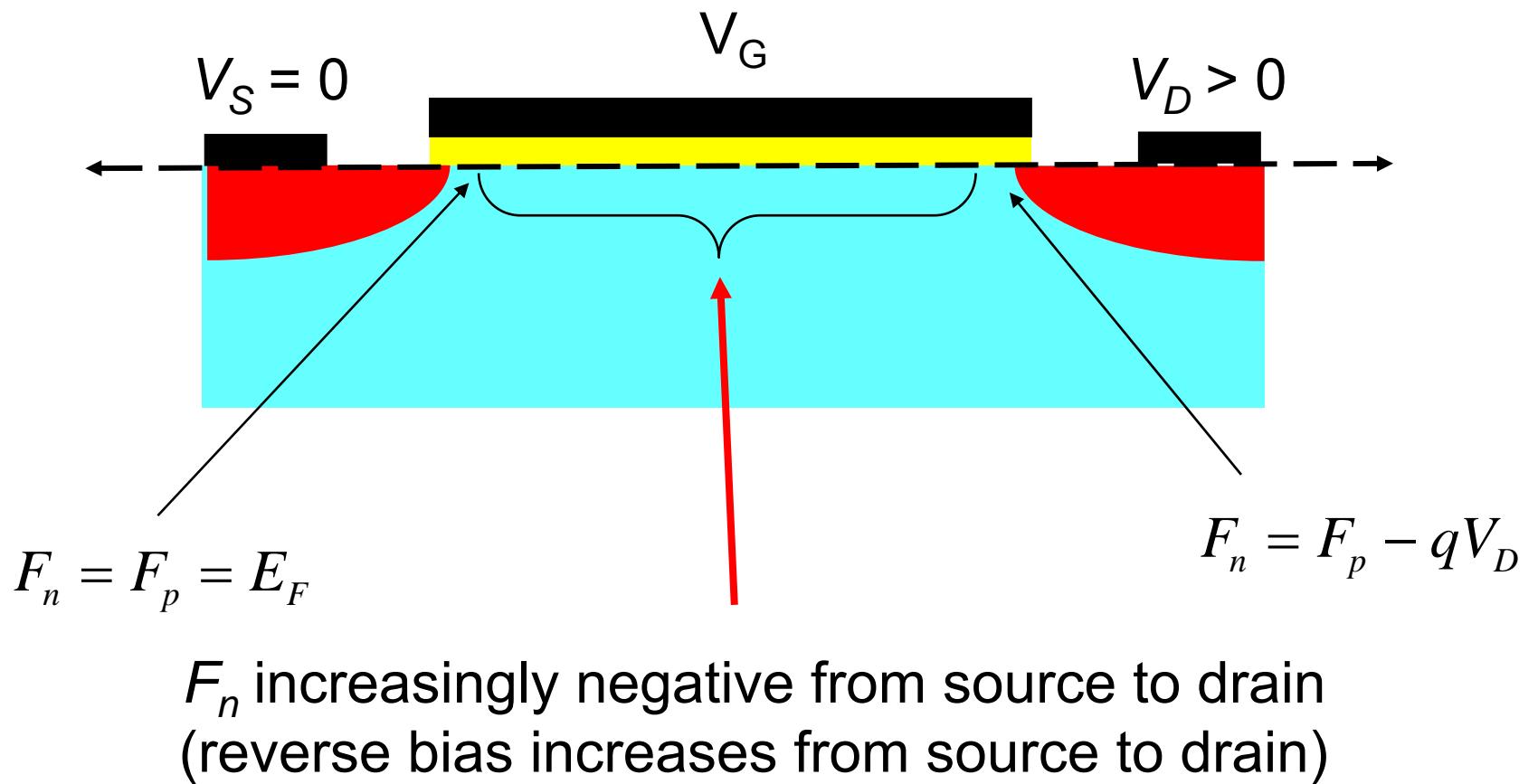
with reverse bias (V_G at onset of inversion):

$$V_G = V_{FB} + 2\psi_B + \underline{V_R} + \underline{\sqrt{2q\varepsilon_{Si}N_A(2\psi_B + V_R)}} / C_{ox}$$

V_T of the MOSFET is defined as V_{GS} at the onset of inversion

$$V_T = V_G - V_R = V_{FB} + 2\psi_B + \sqrt{2q\varepsilon_{Si}N_A(2\psi_B + V_R)} / C_{ox}$$

back to the MOSFET



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