ECE-305: Spring 2018
MOS Field Effect Transistors (MOSFETs)

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapters 15+16 (pp. 525-530, 563-599)

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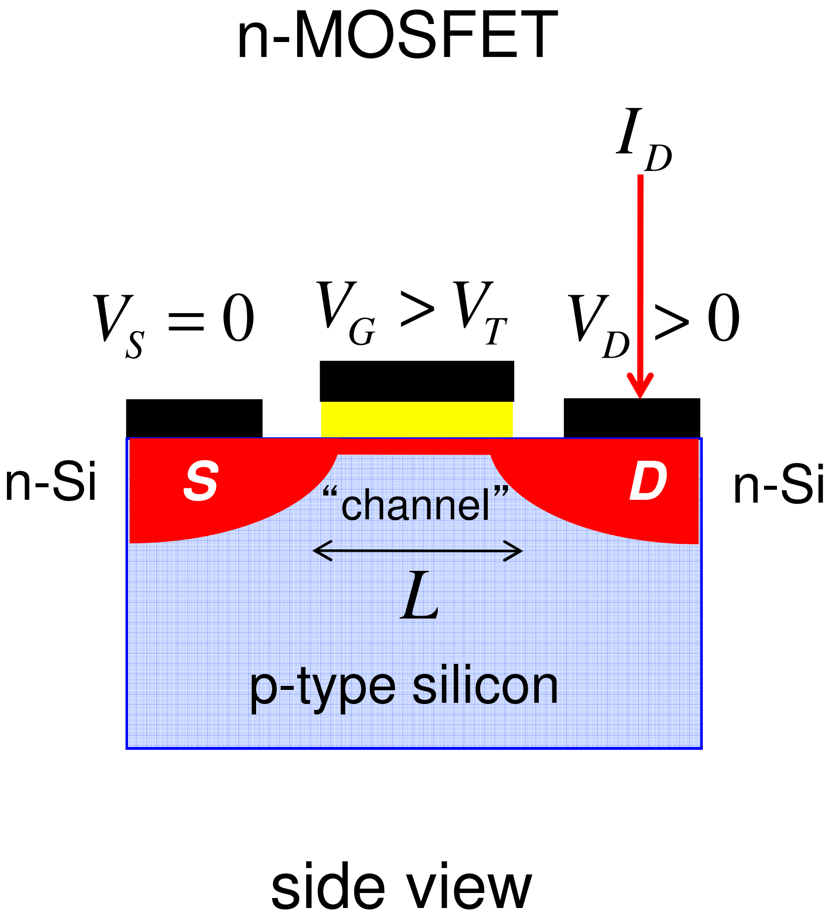
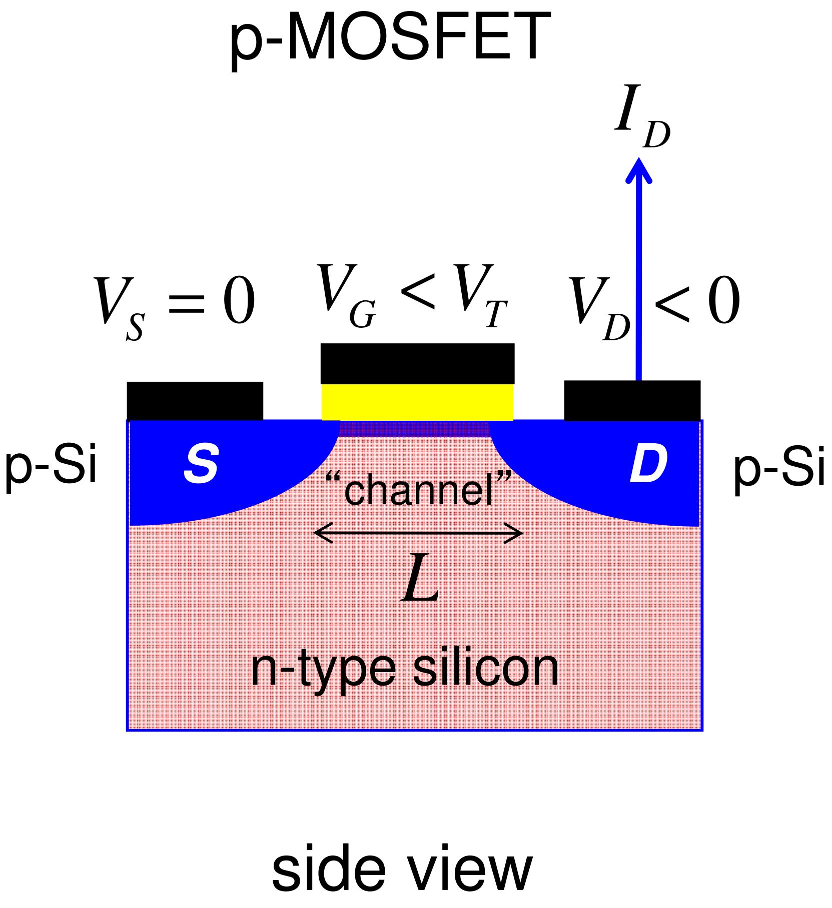
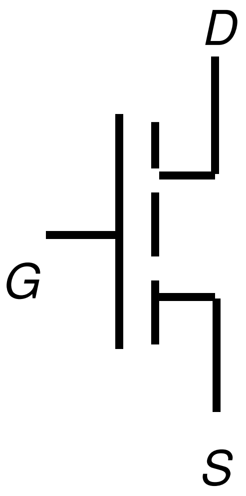
n-channel and p-channel MOSFETs

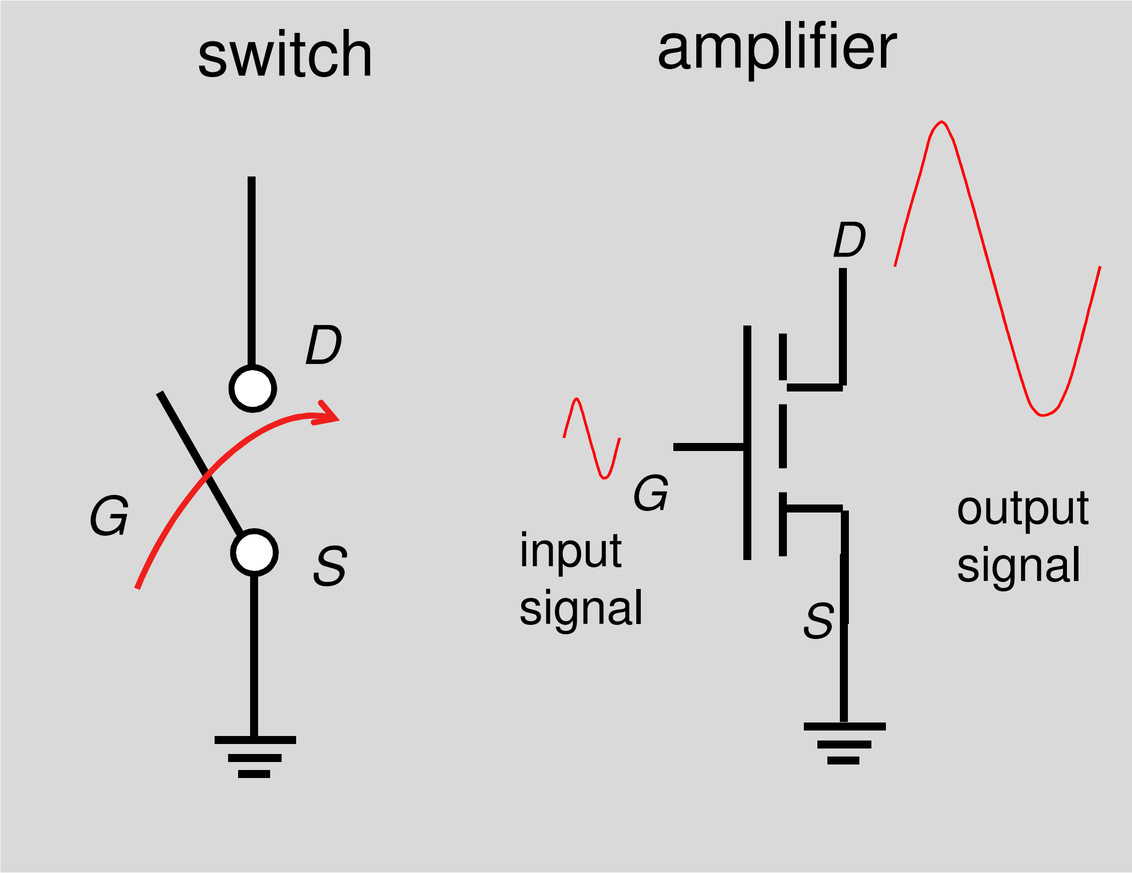




applications of MOSFETs

symbol

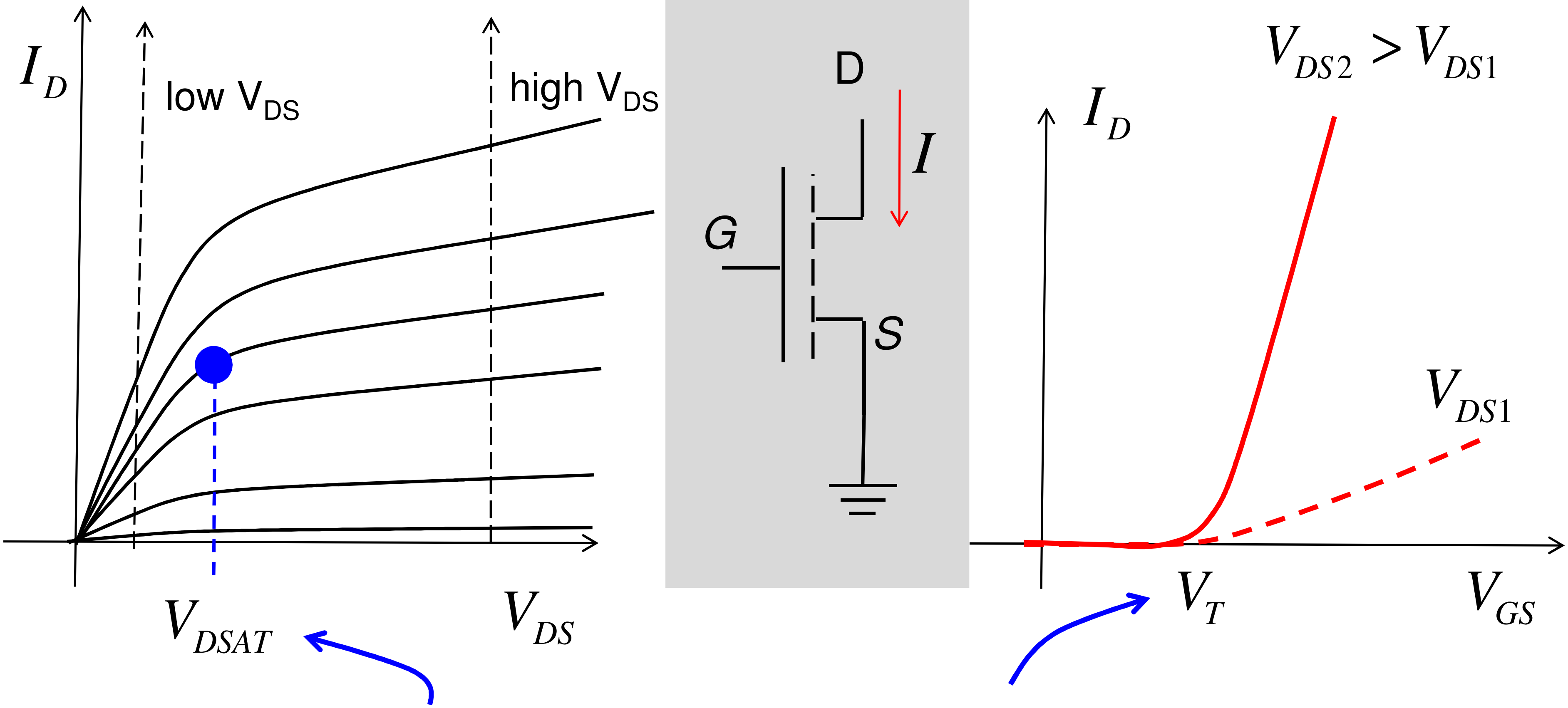




output vs. transfer characteristics

output characteristics

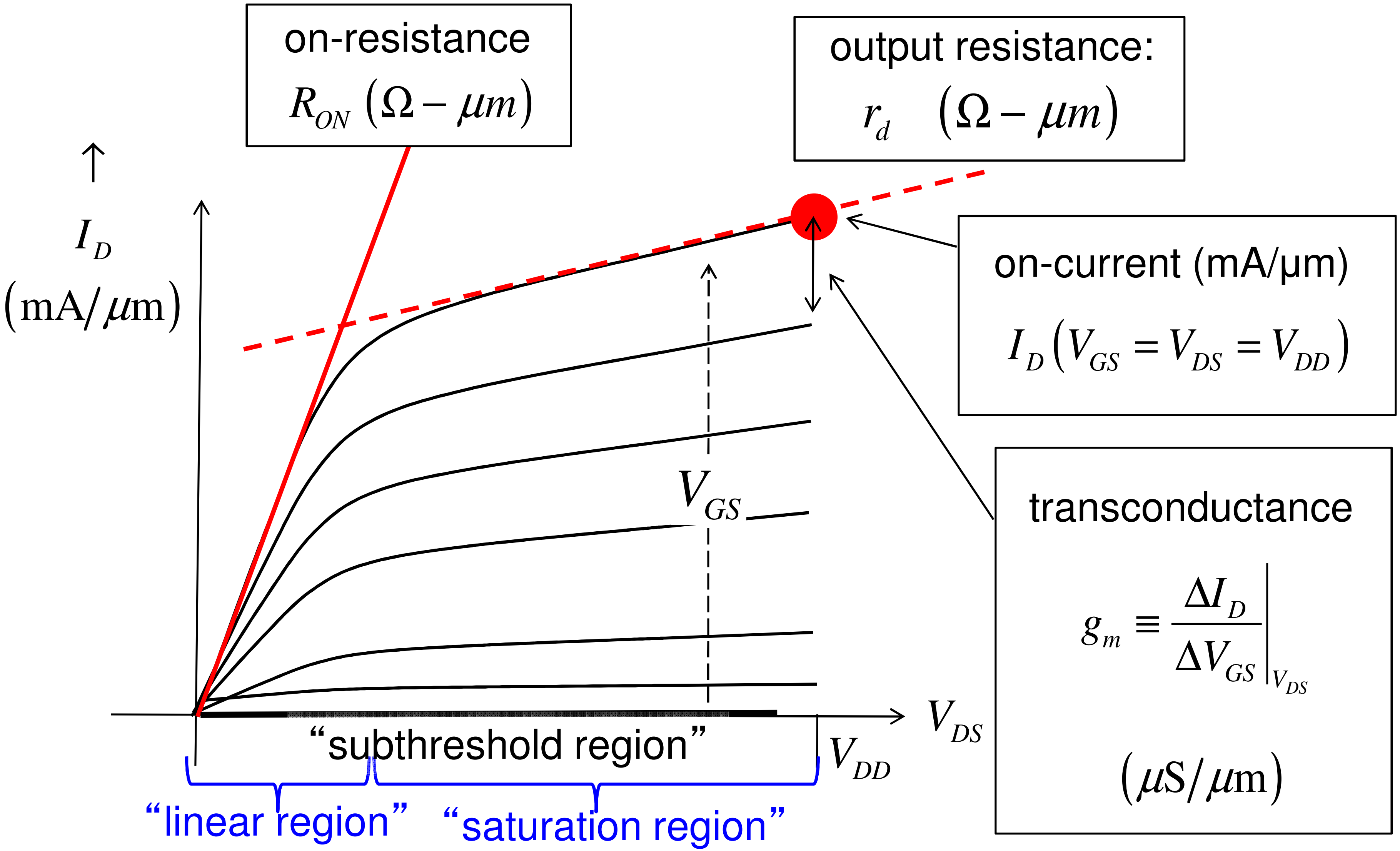
transfer characteristics



“saturation voltage”

“threshold voltage”

MOSFET output characteristics
n-channel, enhancement mode (E-mode)



on-resistance

$R_{ON}\ (\Omega-\mu m)$

output resistance:

$r_d\quad(\Omega-\mu m)$

on-current (mA/μm)

$I_D\left(V_{GS}=V_{DS}=V_{DD}\right)$

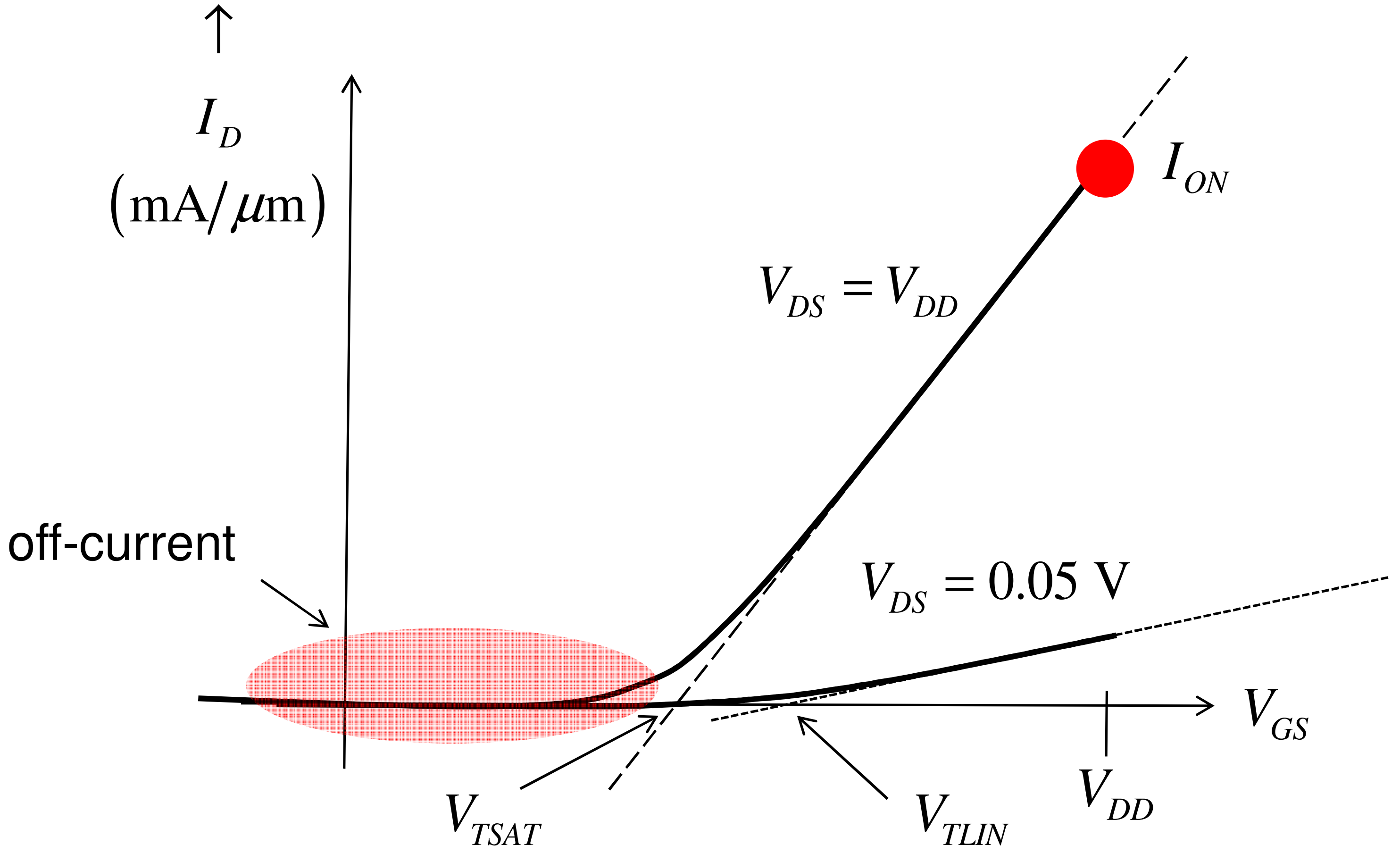
transconductance

$$g_m \equiv \left.\frac{\Delta I_D}{\Delta V_{GS}}\right|_{V_{DS}}$$

$(\mu\mathrm{S}/\mu\mathrm{m})$

MOSFET device metrics (ii)

transfer characteristics:

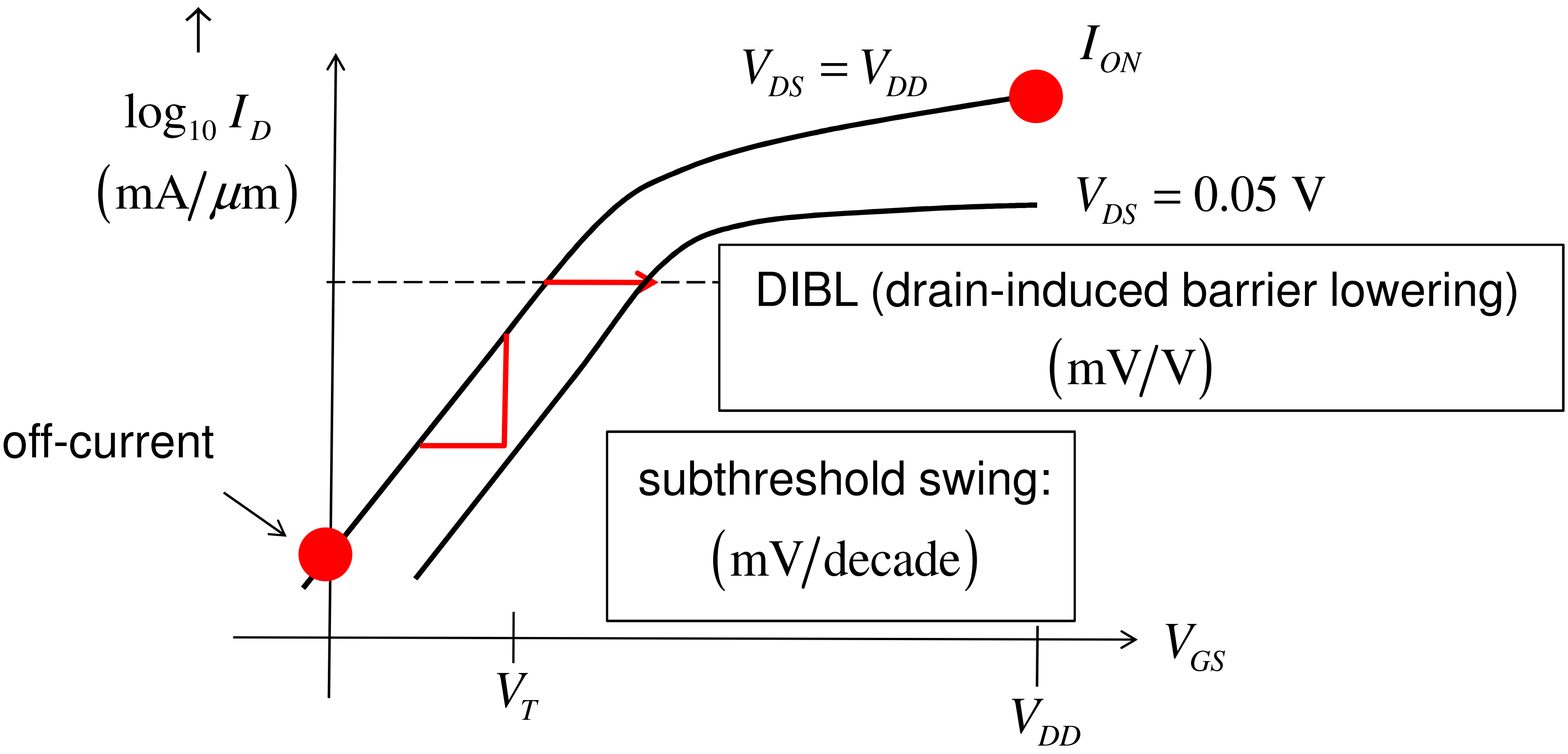


off-current

threshold voltage

MOSFET device metrics (iii)

transfer characteristics:

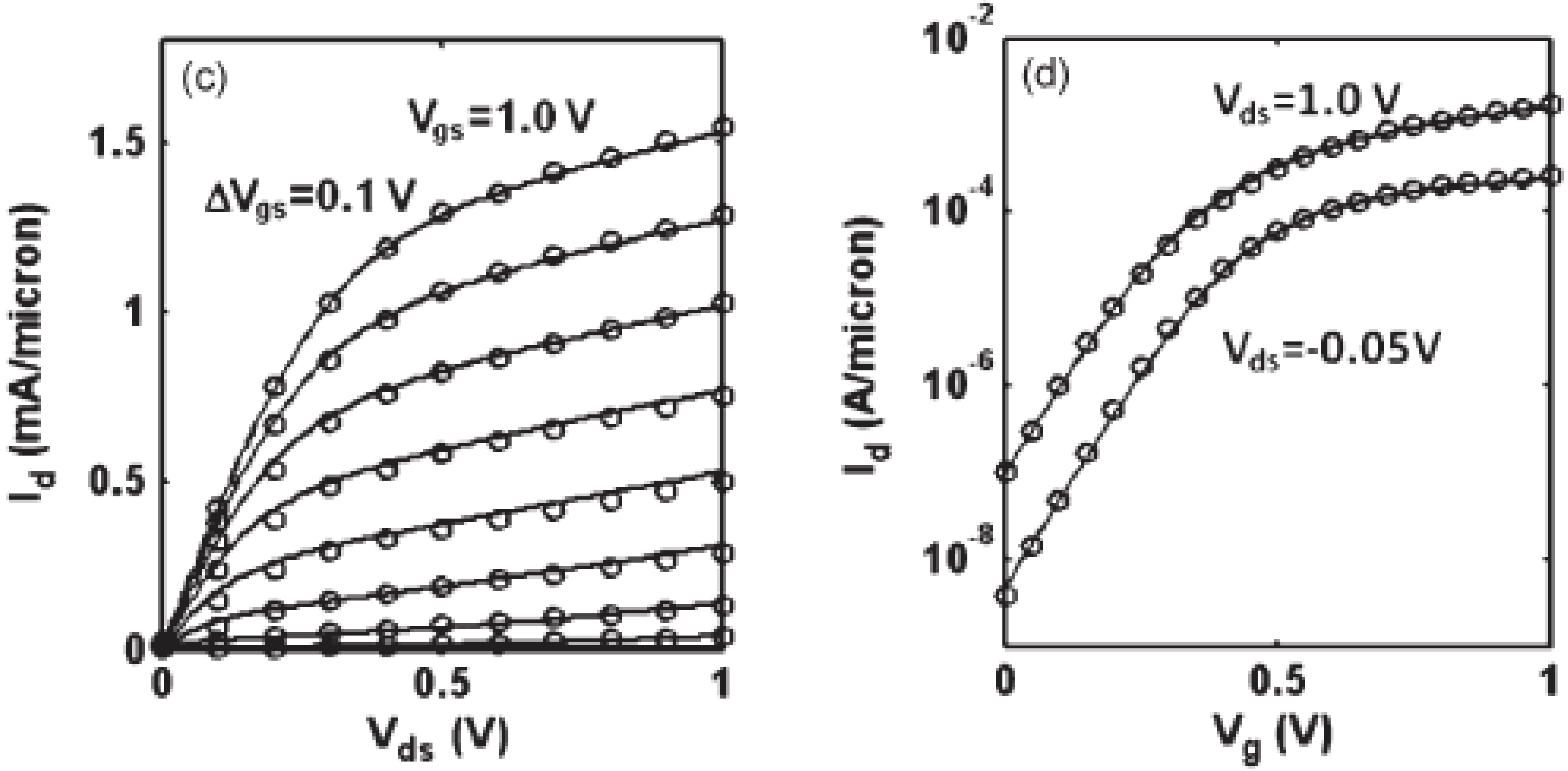


off-current

DIBL (drain-induced barrier lowering) $(\mathrm{mV/V})$

subthreshold swing: $(\mathrm{mV/decade})$

Example: 32 nm N-MOS technology



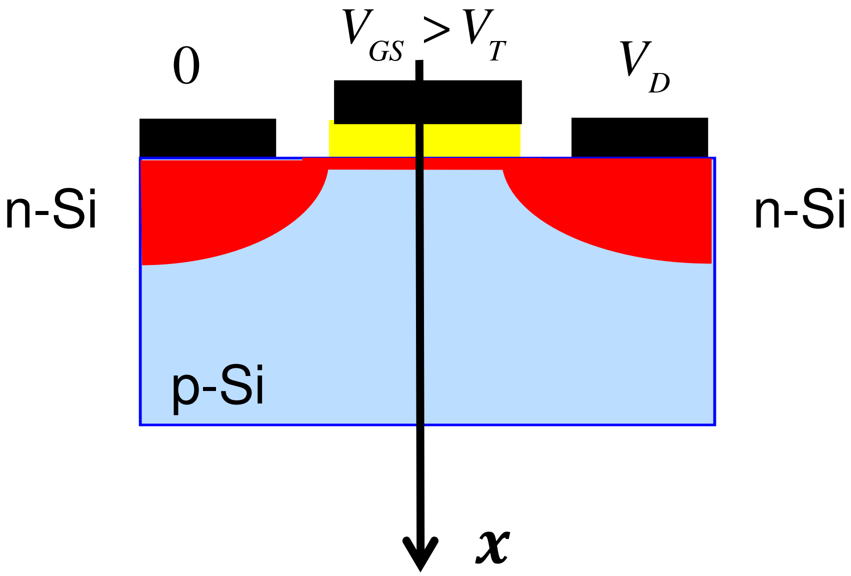
Key MOSFET characteristics

Given the measured characteristics of a MOSFET, you should be able to determine:

1. on-current: I_{ON}
2. off-current: I_{OFF}
3. subthreshold swing, S
4. drain induced barrier lowering: DIBL
5. threshold voltage: V_T(lin) and V_T(sat)
6. on resistance: R_{ON}
7. drain saturation voltage: V_{DSAT}
8. output resistance: r_o
9. *transconductance:* g_m

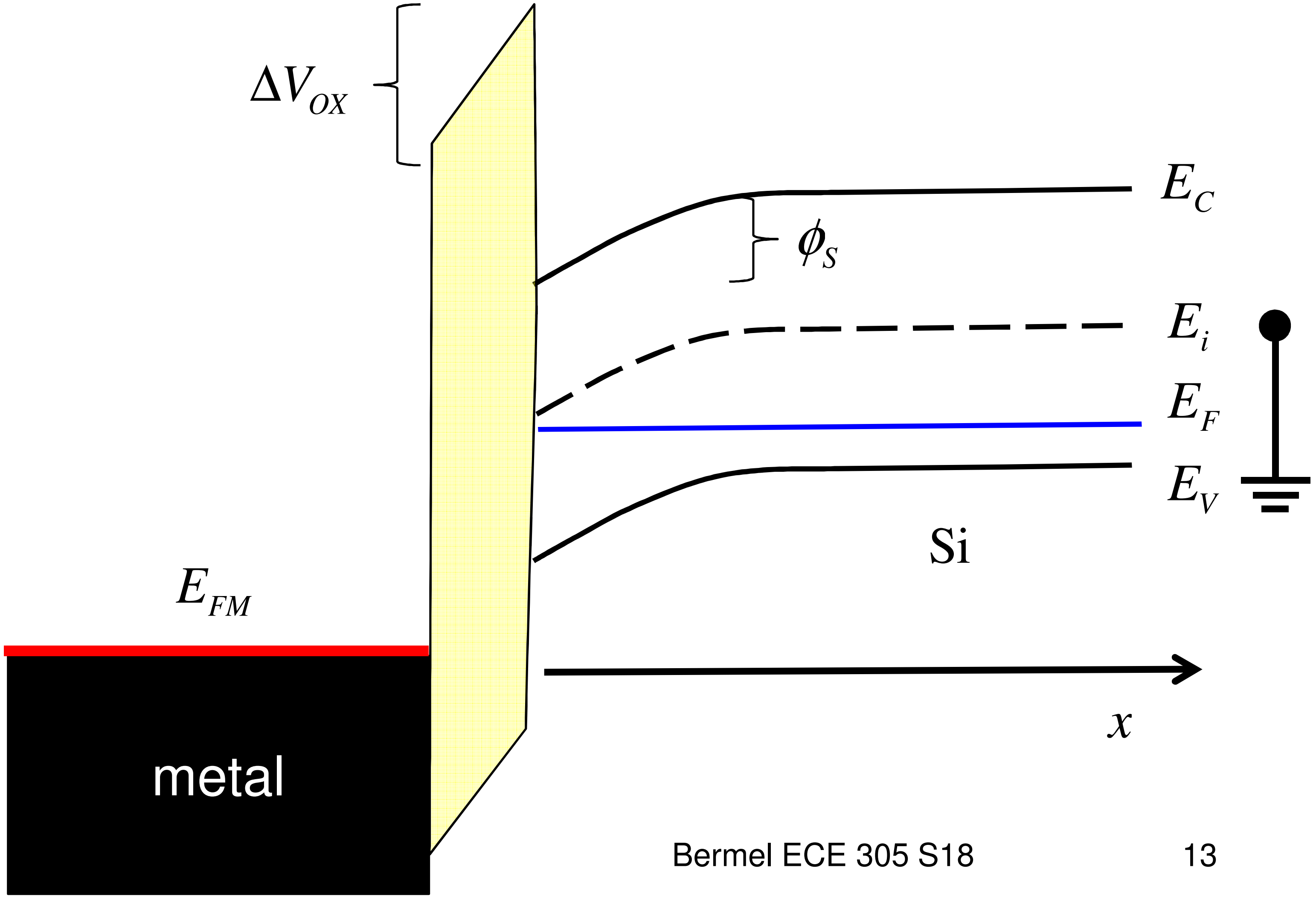
Our goal is to understand these device metrics.

understanding MOSFETs

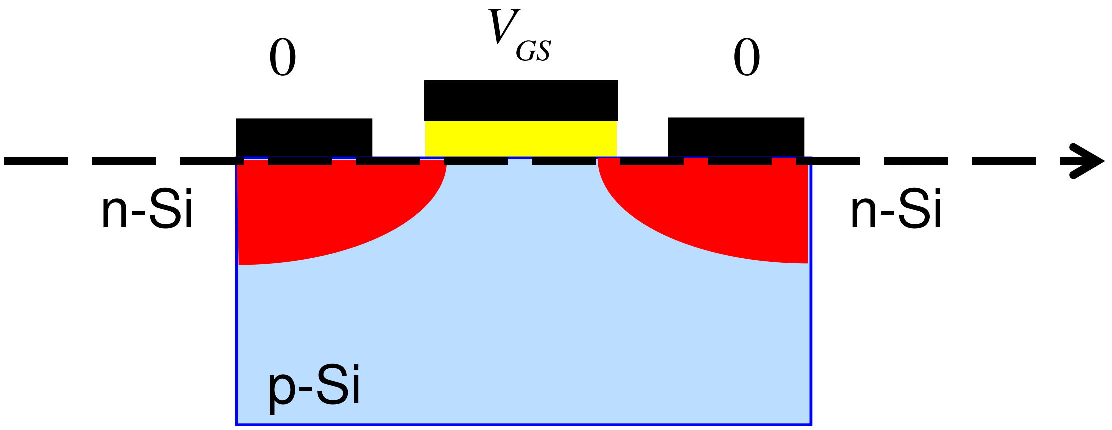


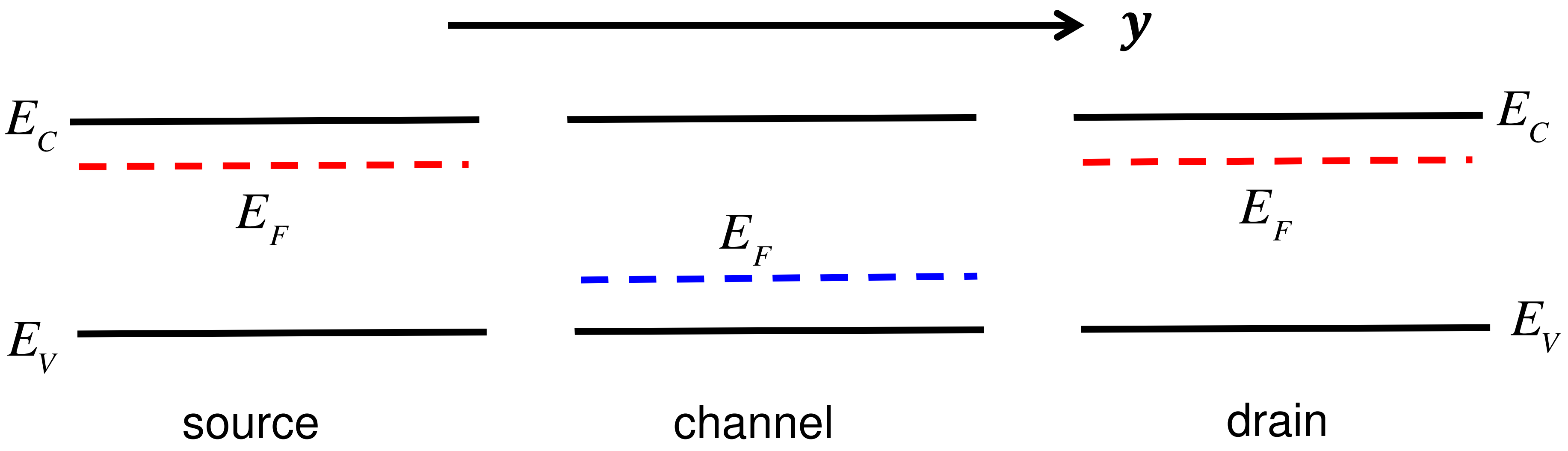
To understand any semiconductor device, we should first draw an ***Energy Band Diagram.***

normal to the channel

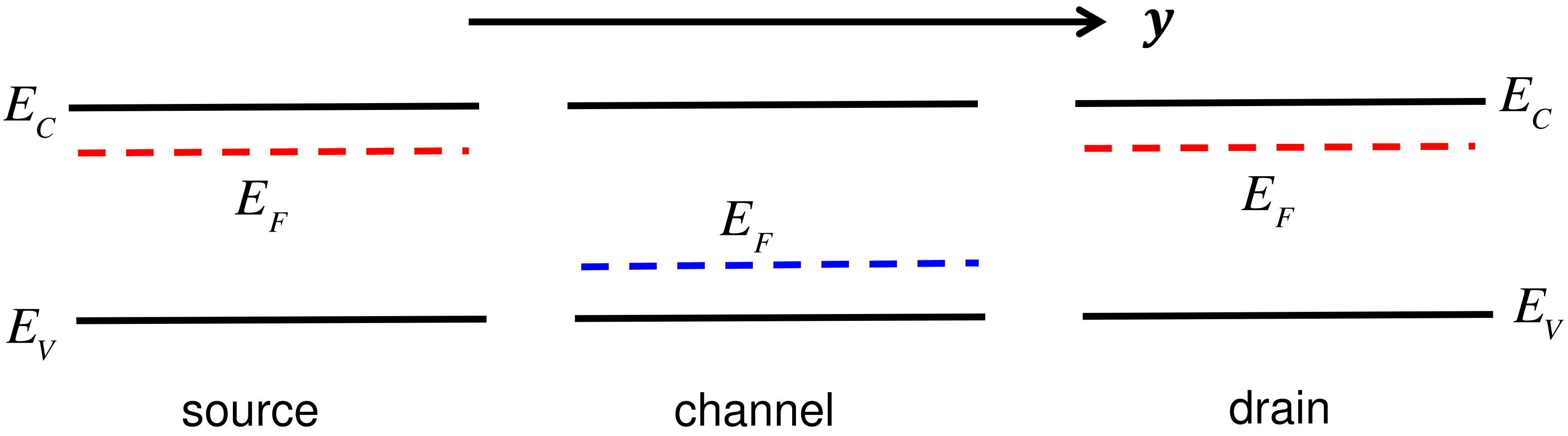


equilibrium E-band diagram: 3 separate pieces





equilibrium E-band diagram: 3 separate pieces



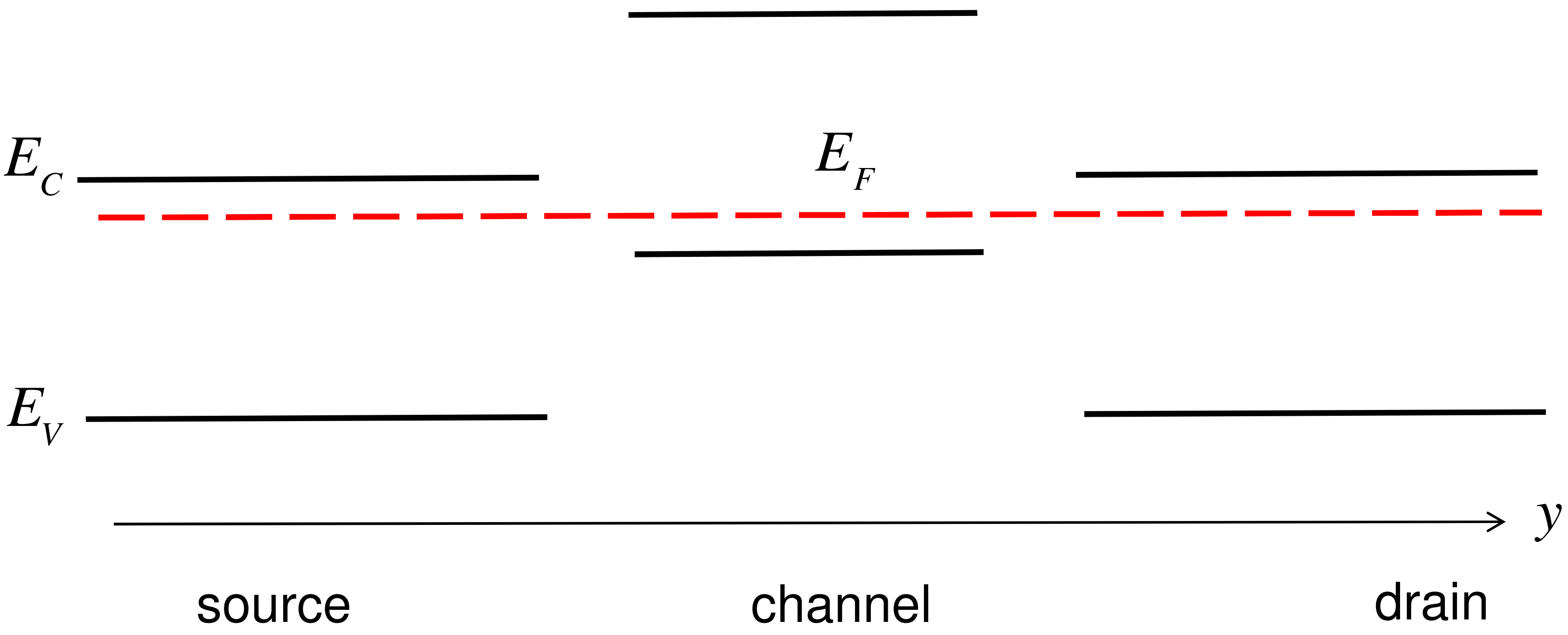
1) Equilibrium: Fermi level is constant

2) Changes in electrostatic potential, change the electron's energy.

$$E_C(y) = E_{C0} - q\phi(y)$$

$$E_V(y) = E_{V0} - q\phi(y)$$

putting the 3 pieces together (equilibrium)

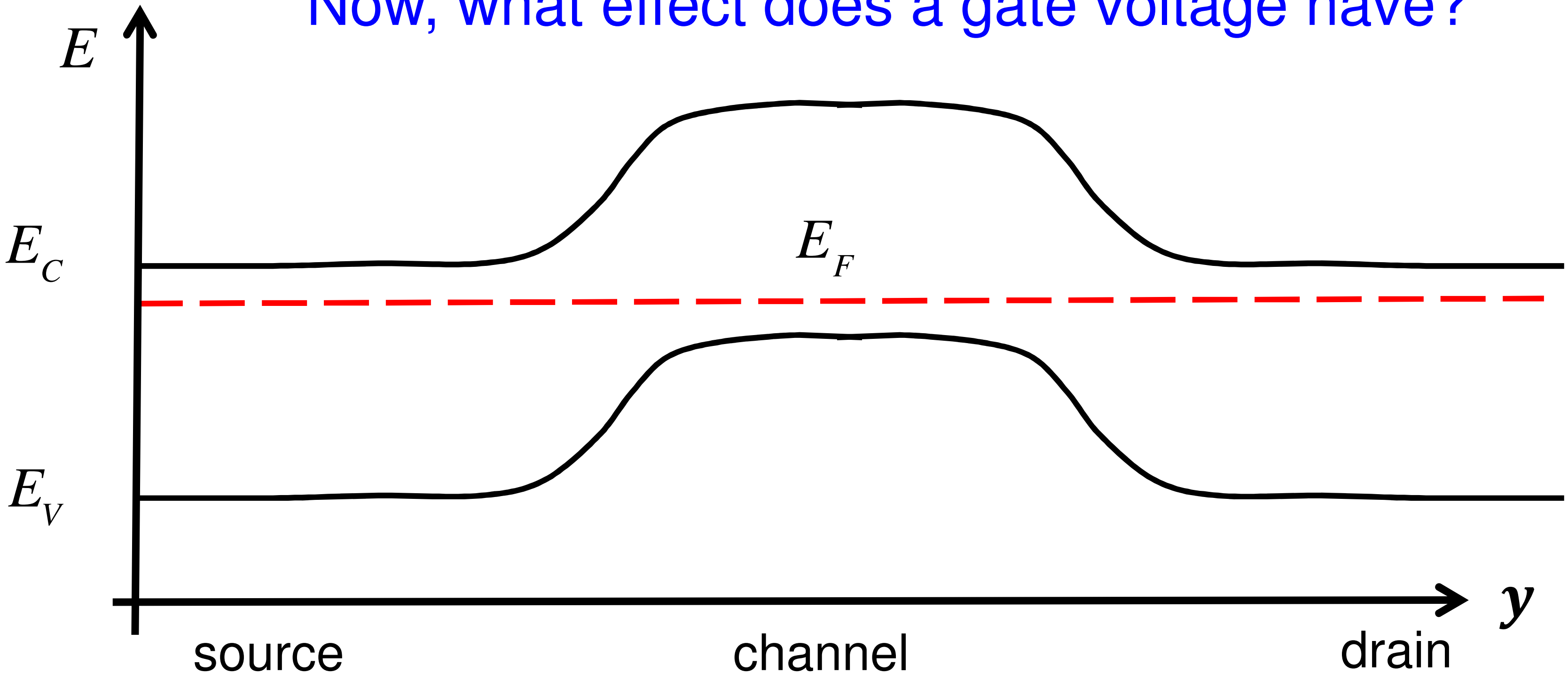


$$E_C(y) = E_{C0} - q\phi(y)$$

$$E_V(x) = E_{V0} - q\phi(y)$$

final result: one semiconductor with 3 regions

Now, what effect does a gate voltage have?

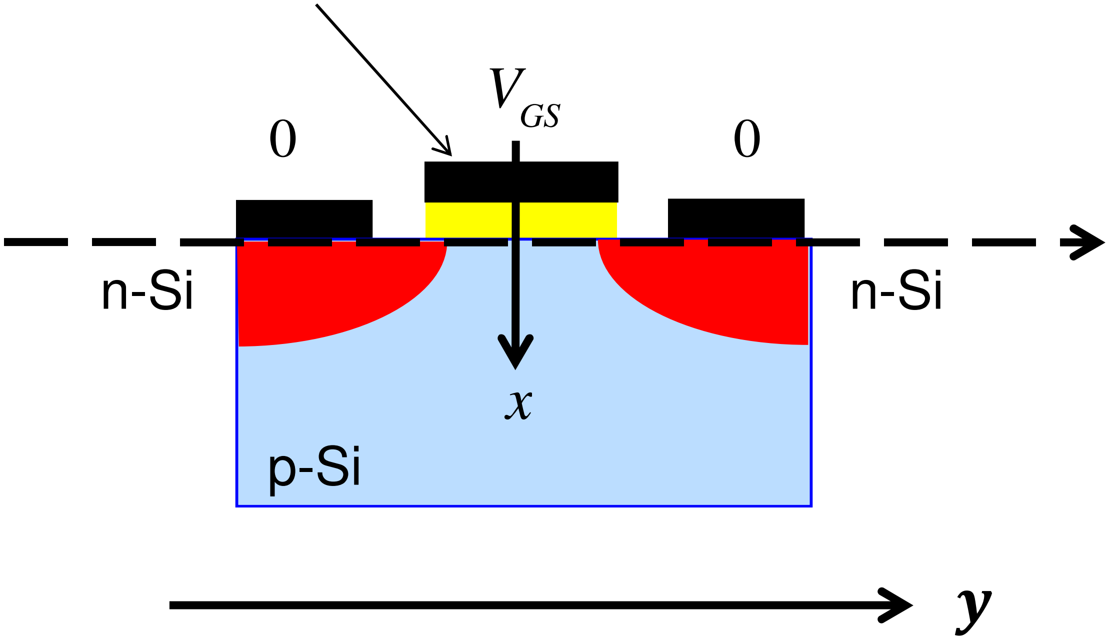


$$E_C(y) = E_{C0} - q\phi(y)$$

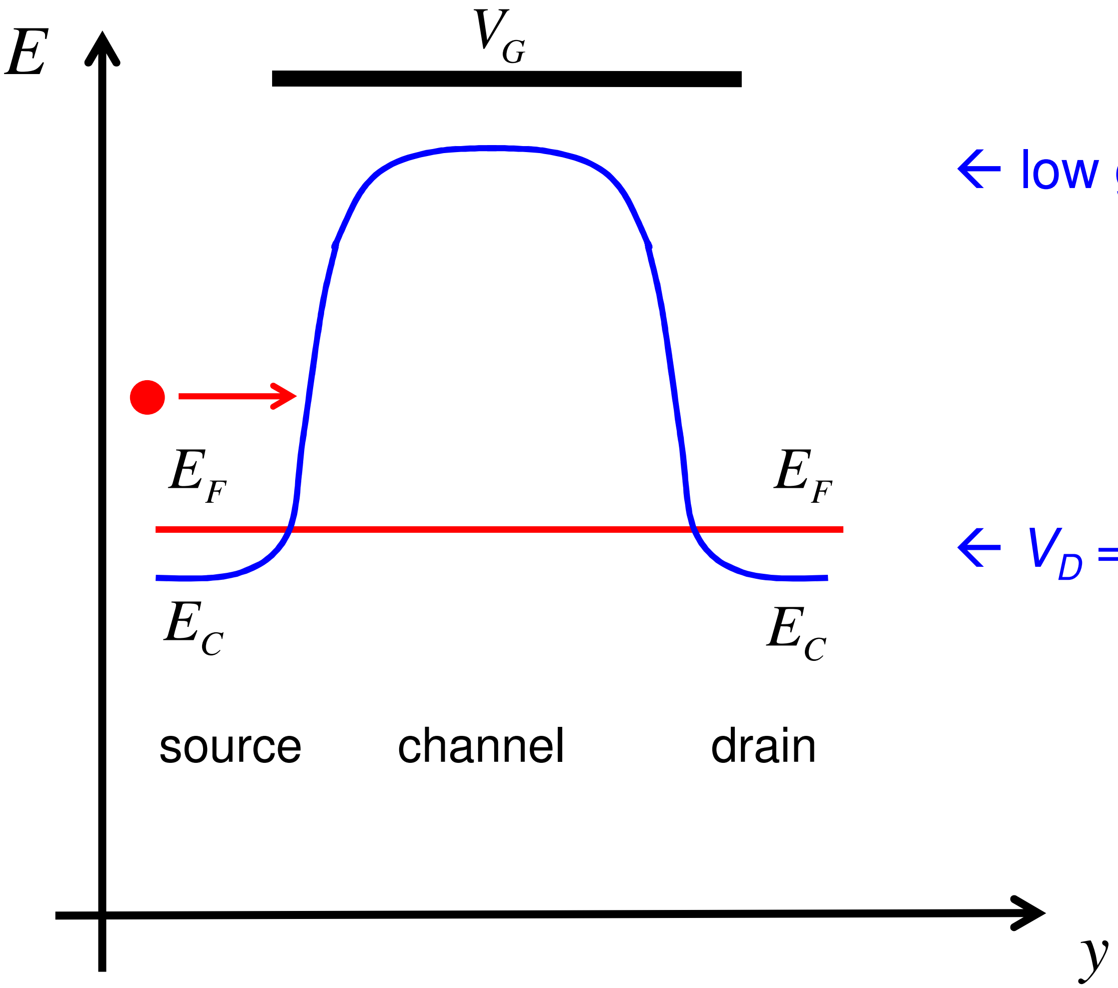
$$E_V(y) = E_{V0} - q\phi(y)$$

equilibrium energy band diagram

A positive gate voltage will **increase** the electrostatic potential in the channel and therefore **lower** the electron energy in the channel.



the transistor as a barrier controlled device

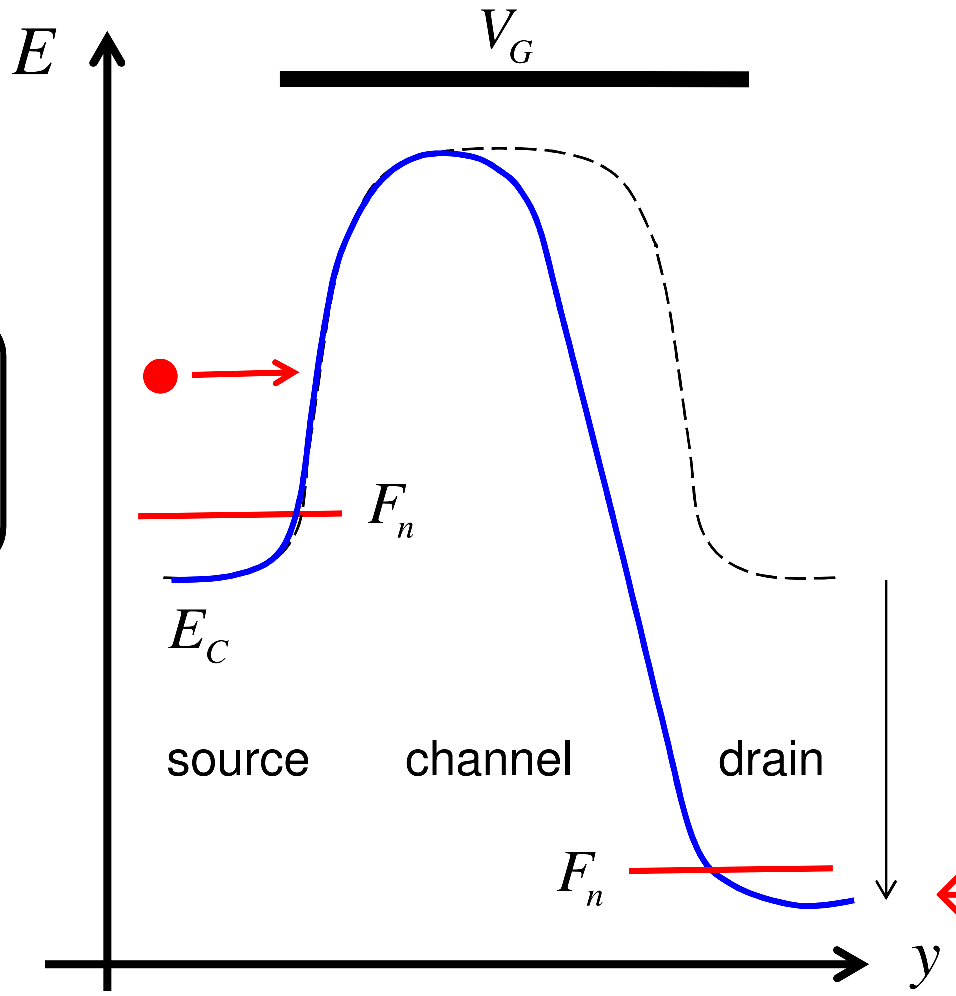


← low gate voltage

← $V_D = V_S = 0$

the transistor as a barrier controlled device

$$\boxed{E = -qV}$$

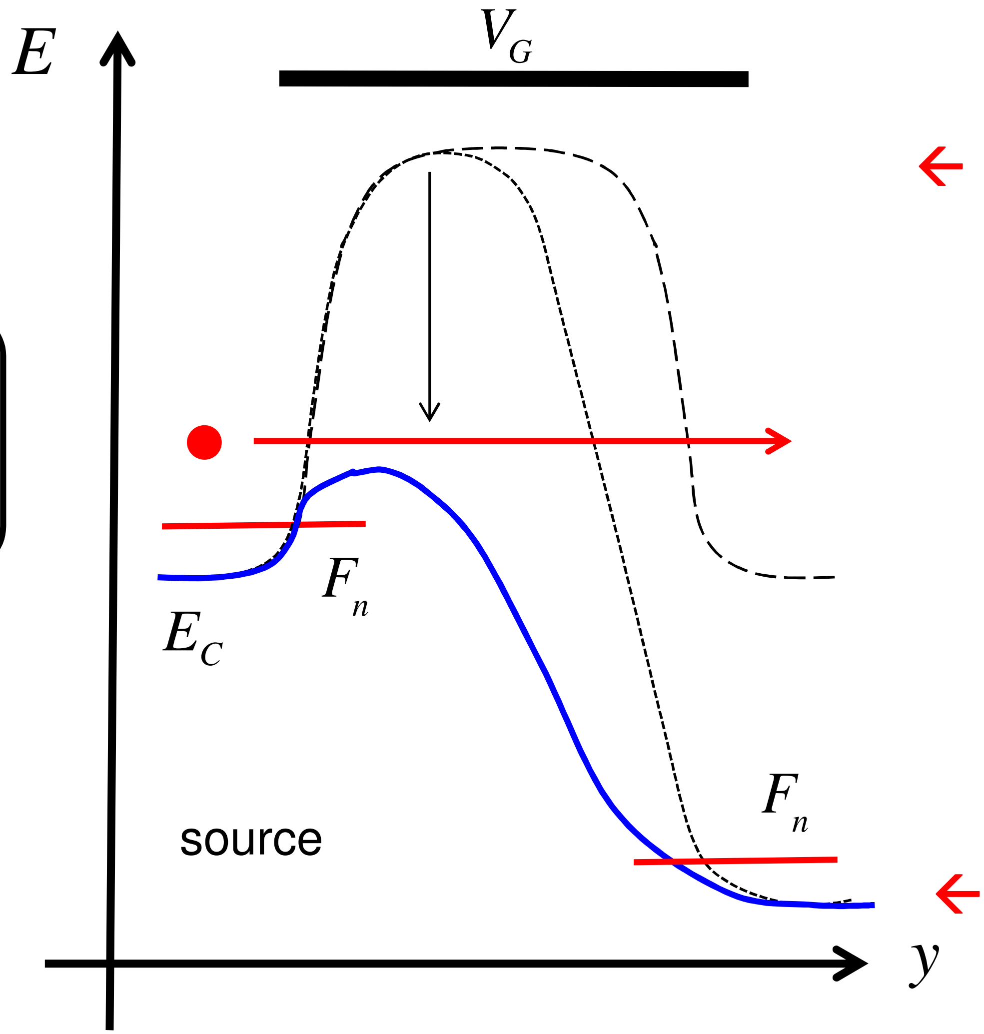


← low gate voltage

← **high** drain voltage

the transistor as a barrier controlled device

$$E = -qV$$

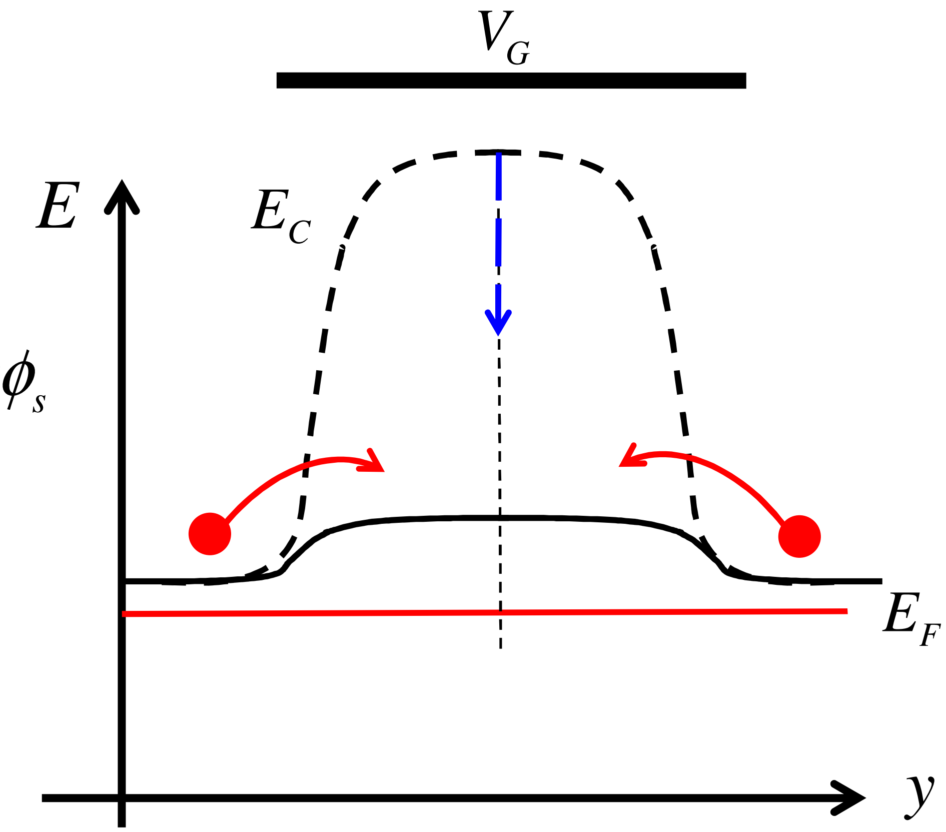


← **high** gate voltage

← **high** drain voltage

effect of gate voltage first

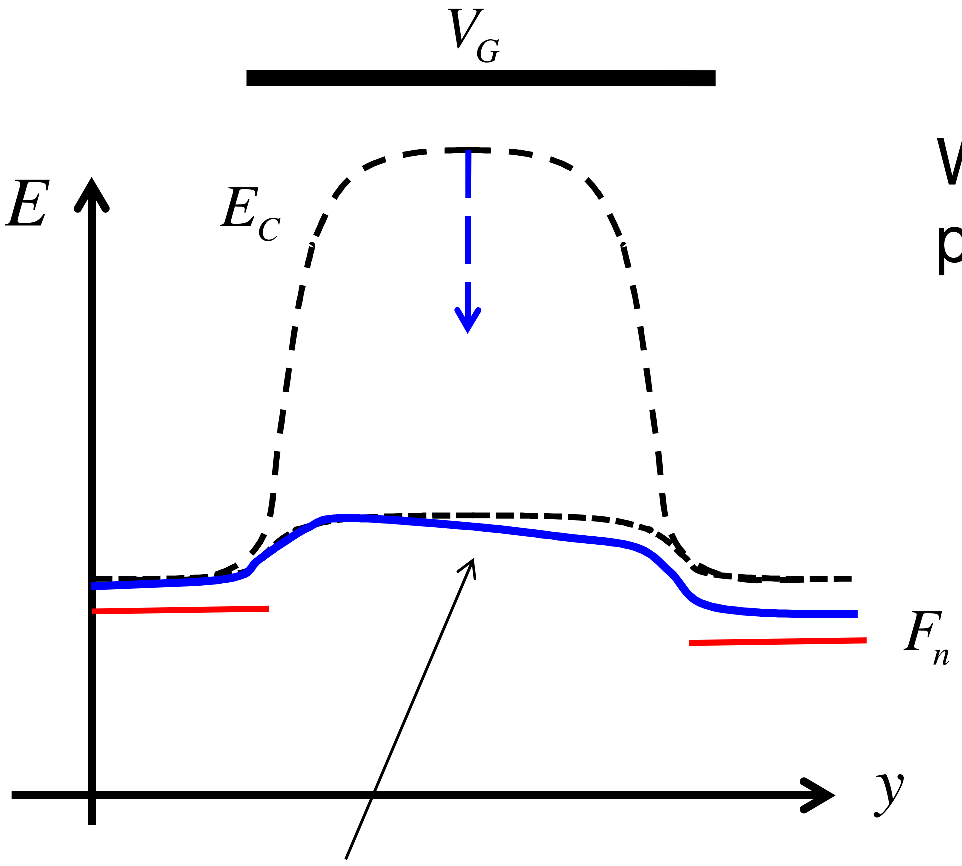
$$E_C = E_{C0} - q\phi_s$$



← low gate voltage

← high gate voltage

Now add a small drain voltage



constant electric field
substantial electron density

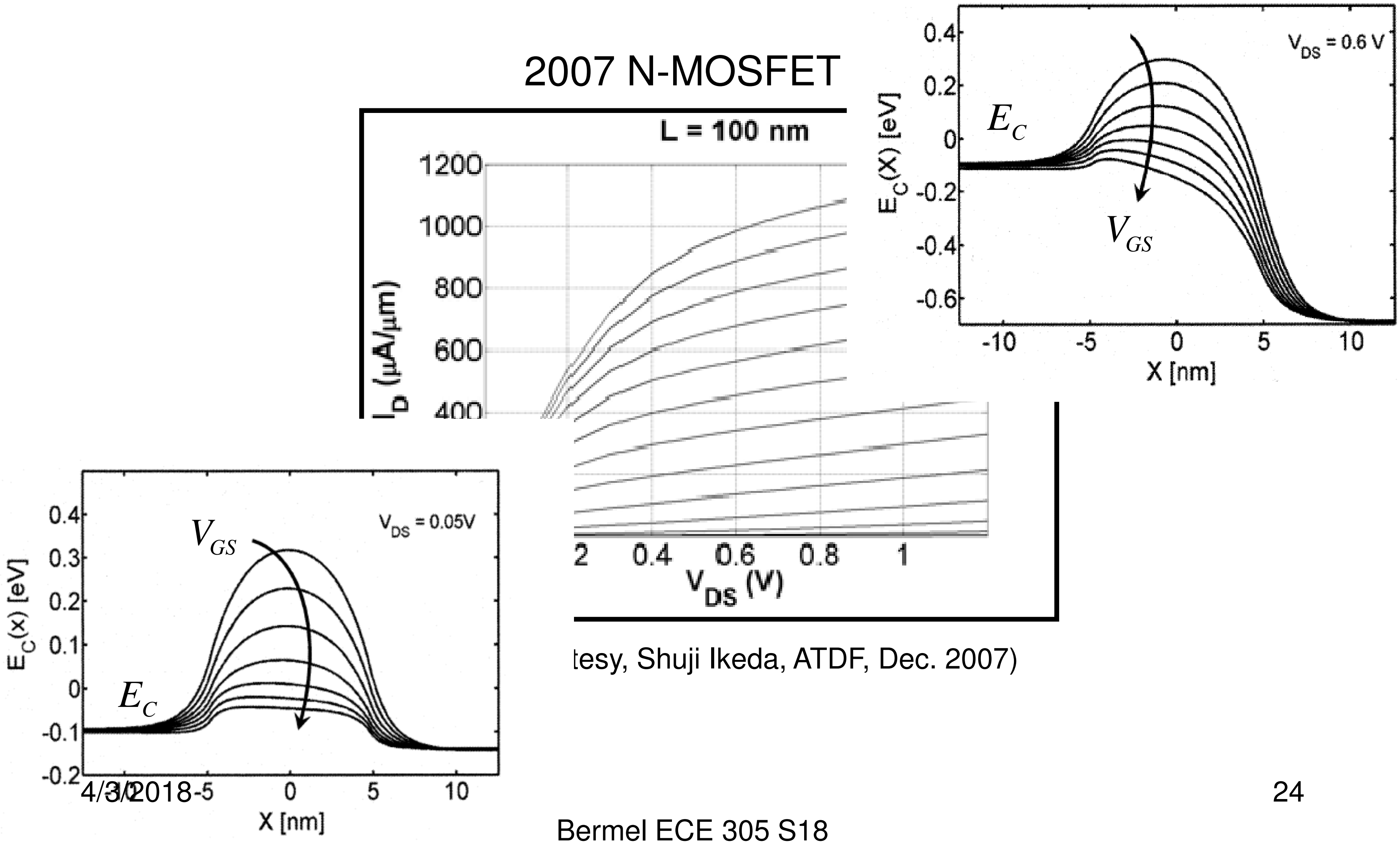
What if we apply a small positive voltage to the drain?

1) The Fermi level in the drain is lowered.

2) The conduction band is lowered too, but the electron density stays the same.

how transistors work

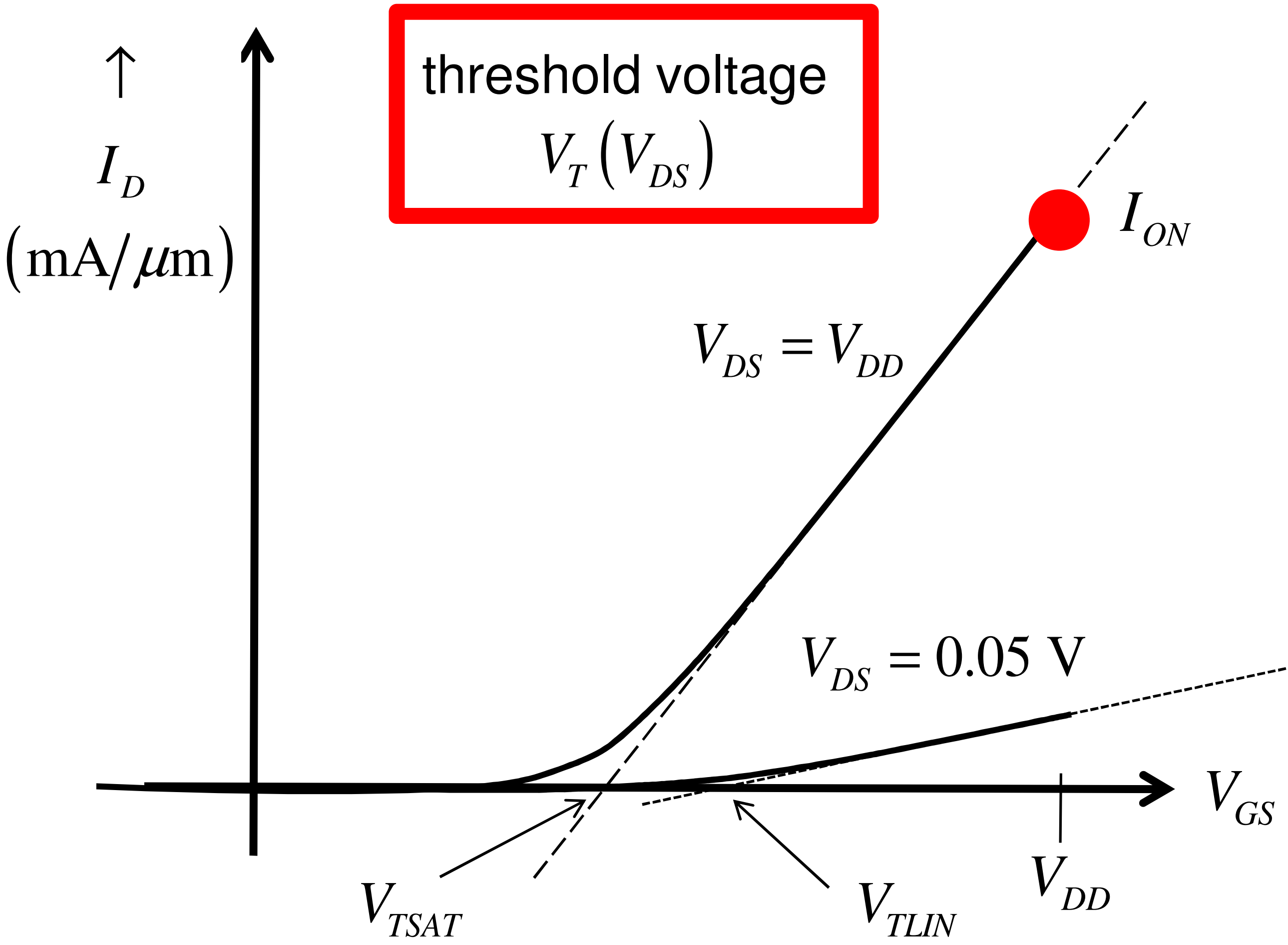
2007 N-MOSFET



tesy, Shuji Ikeda, ATDF, Dec. 2007)

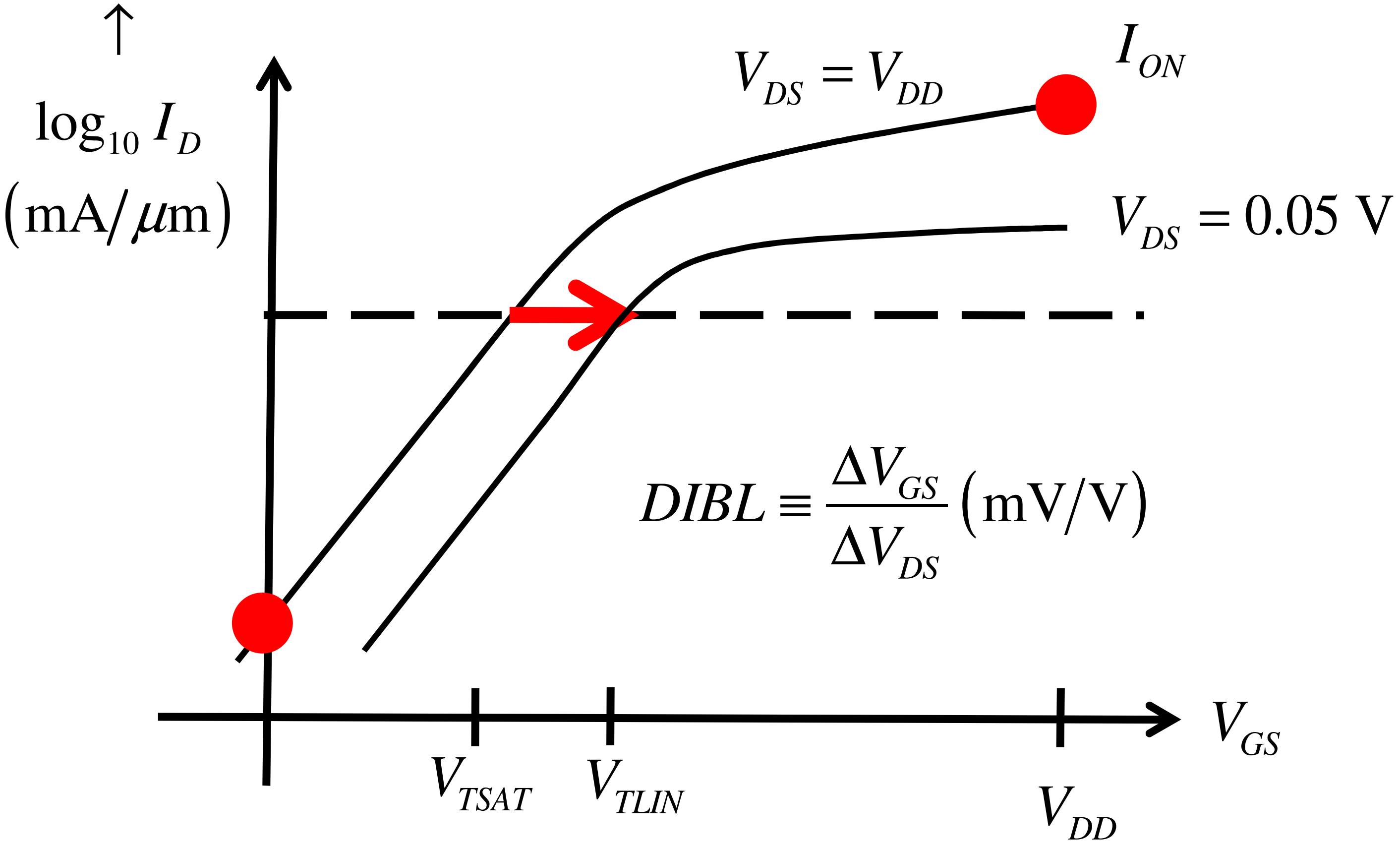
understanding DIBL

threshold voltage $V_T(V_{DS})$



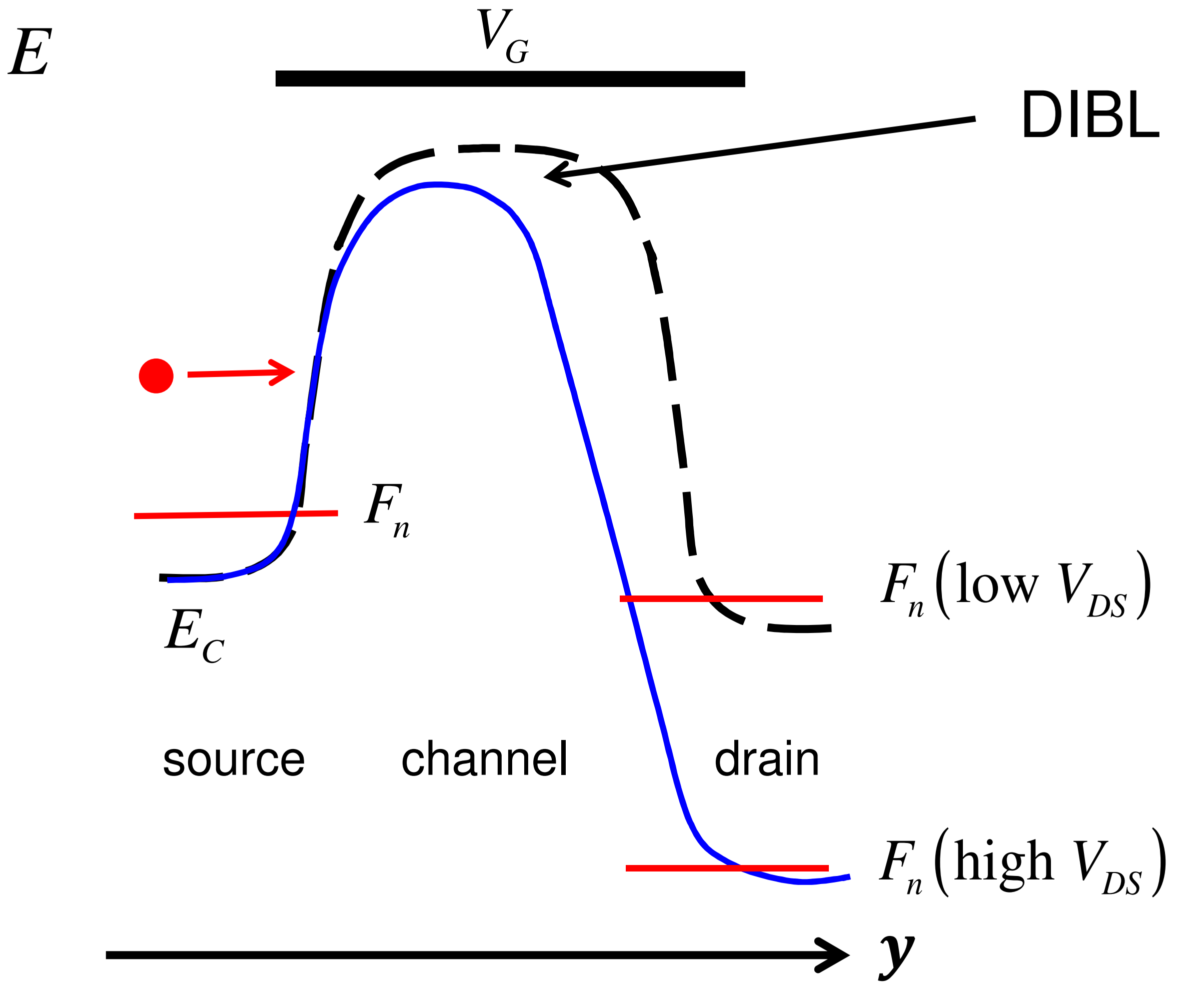
understanding DIBL

transfer characteristics:

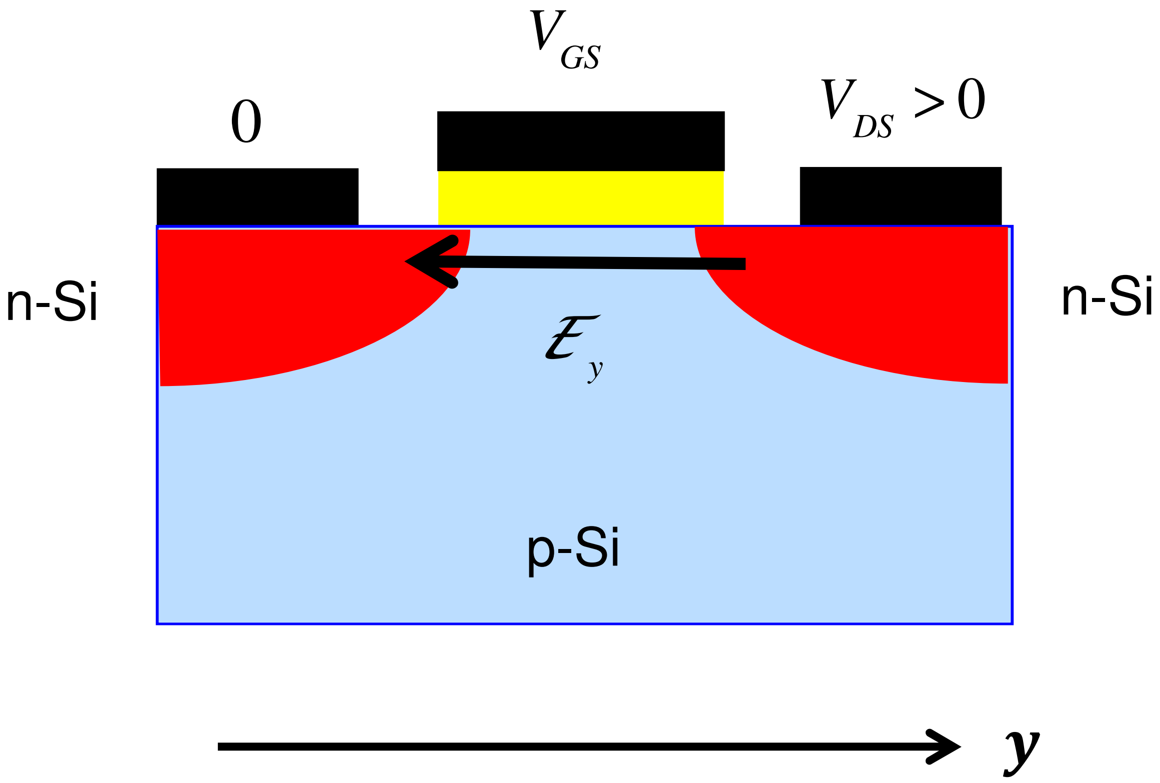


$$DIBL \equiv \frac{\Delta V_{GS}}{\Delta V_{DS}} (\text{mV/V})$$

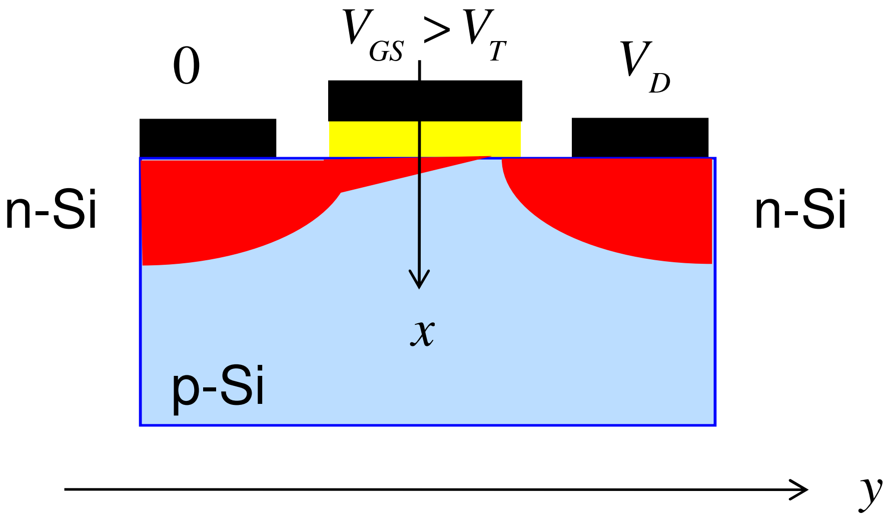
understanding DIBL



understanding DIBL

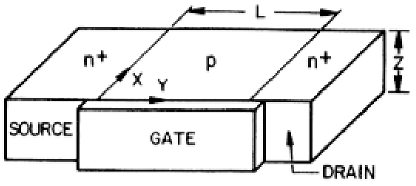


2D energy band diagrams

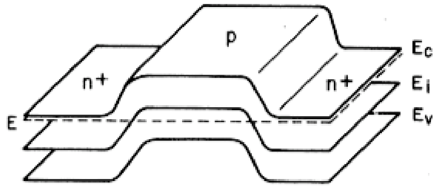


We have been discussing energy band diagrams from the source to the drain along the top of the Si, but more generally, we should look at the 2D energy band diagram.

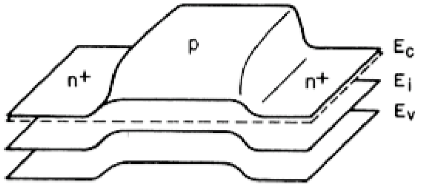
2D energy band diagram on n-MOSFET



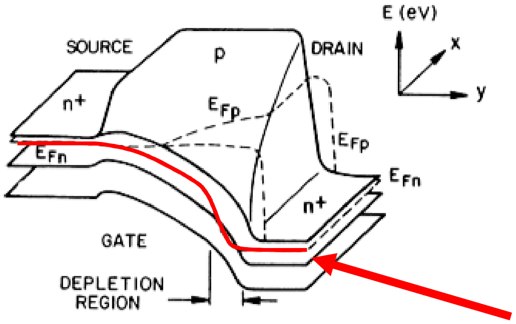
a) device



b) equilibrium (flat band)



c) equilibrium ($\phi_S > 0$)

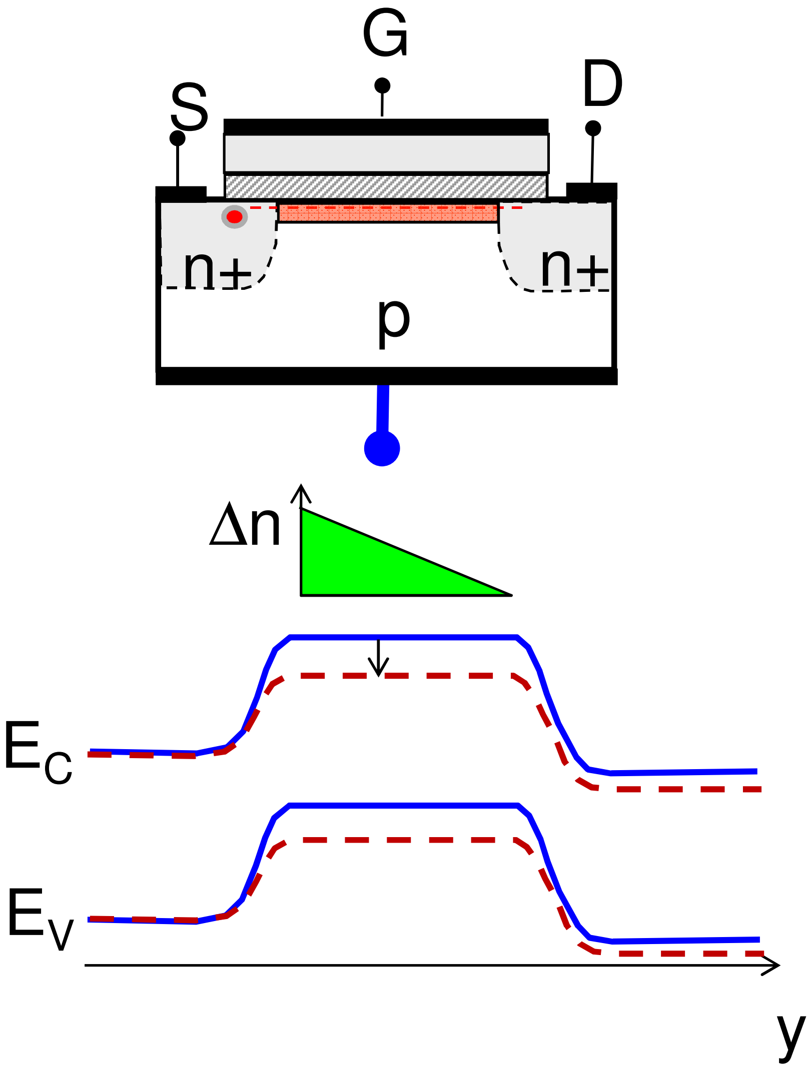


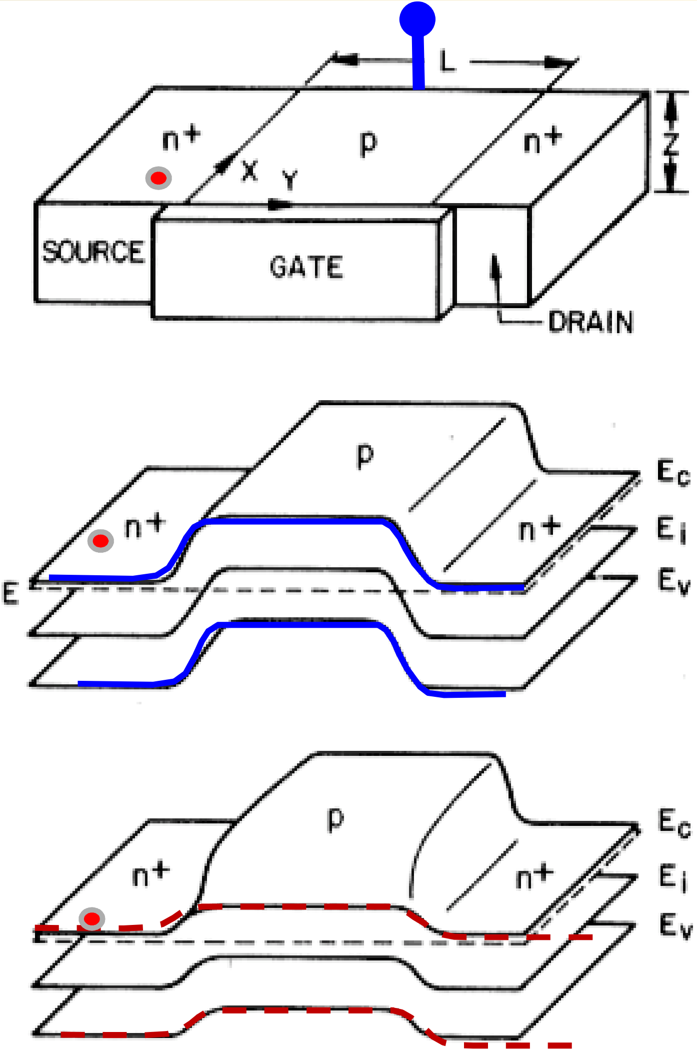
F_N

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

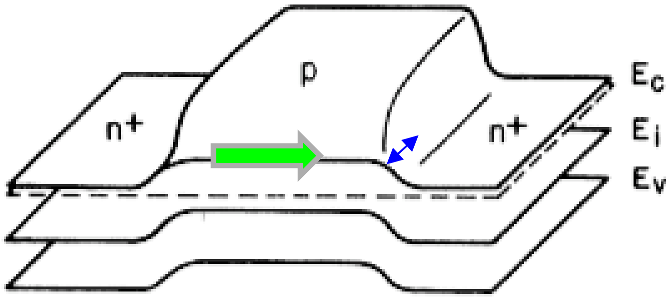
S.M. Sze, Physics of Semiconductor Devices, 1981 and Pao and Sah.

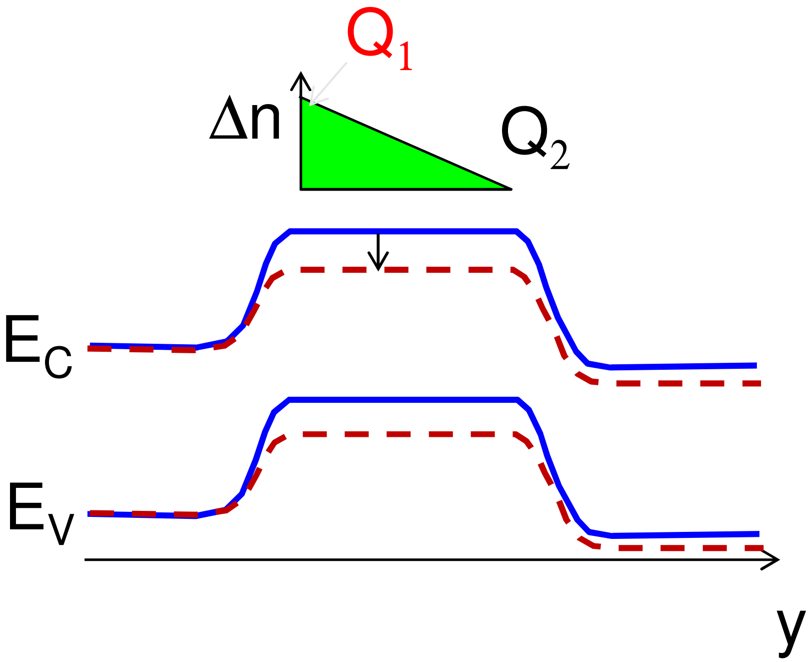
Subthreshold Region ($V_G < V_{th}$)

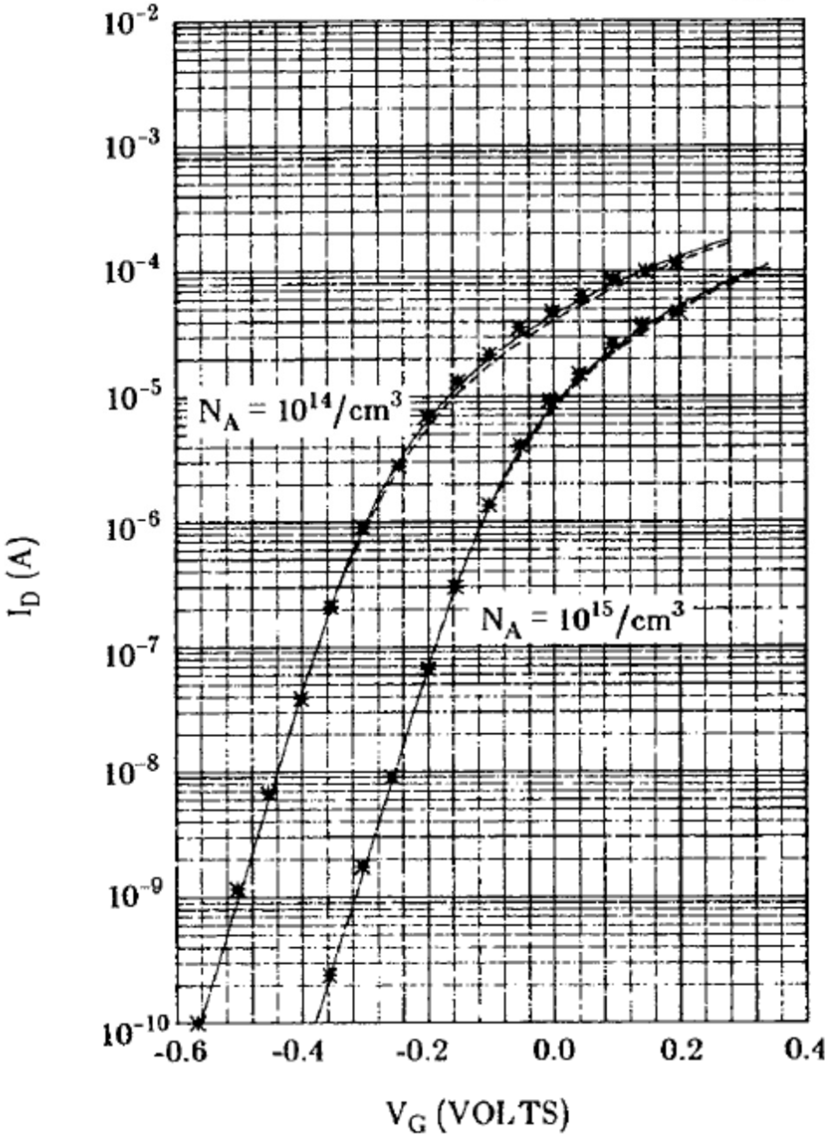




Subthreshold Region ($V_G < V_{th}$)



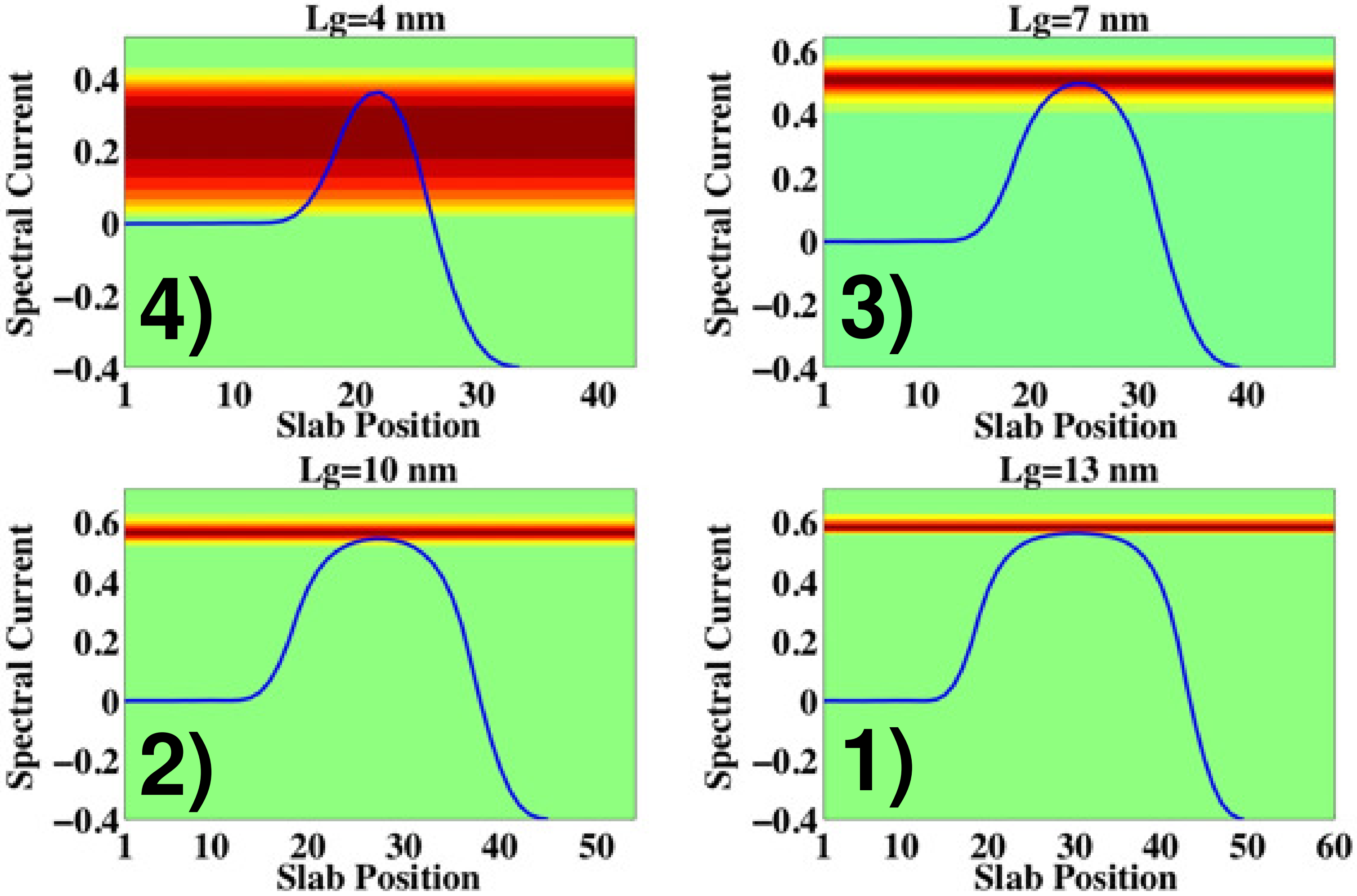




essential physics of a transistor

A MOSFET (and most transistors) are barrier-controlled devices.

limits to barrier control: quantum tunneling



from M. Luisier, ETH Zurich / Purdue

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

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

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

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

Recall the definition of body coefficient (*m*)

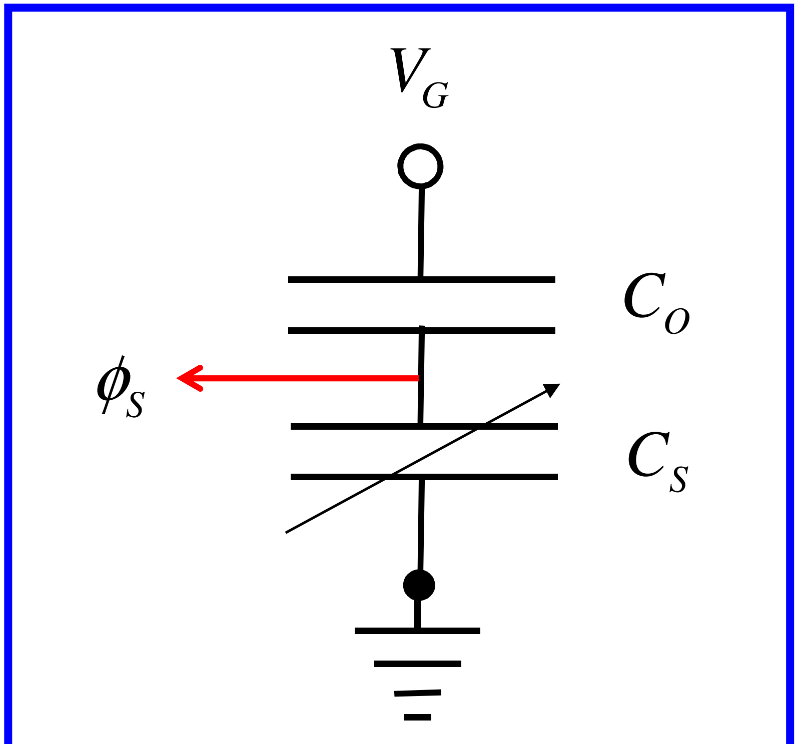
$$m \equiv \left(1 + C_S / C_O\right)$$

'Body Effect Coefficient'

$$m = \left(1 + K_S x_O / K_0 W_T\right)$$

in practice:

$$1.1 \le m \le 1.4$$



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

Square Law Theory

Not true at high fields

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

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

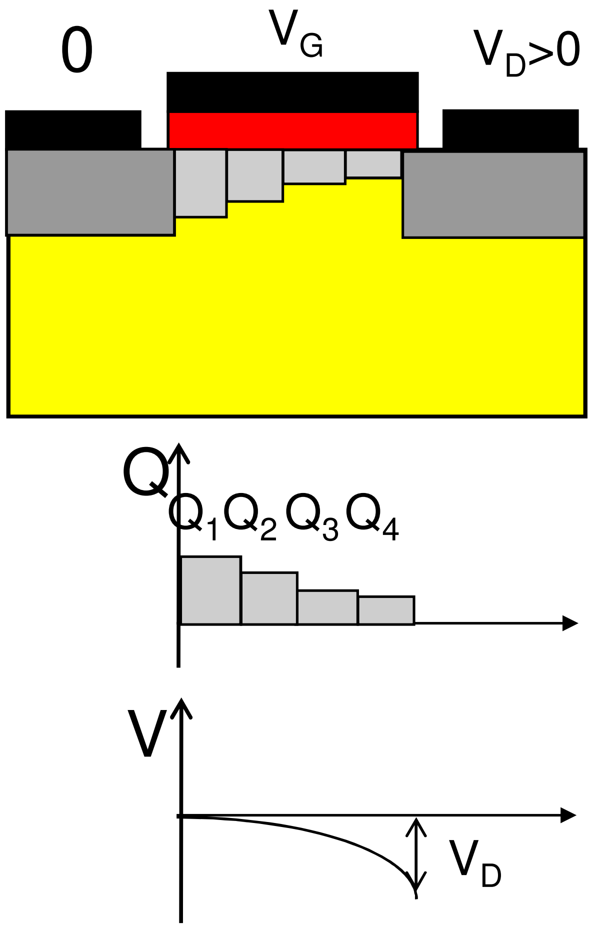
$$J_3 = Q_3 \mu \mathcal{E}_3 = Q_3 \mu \left.\frac{dV}{dy}\right|_3$$

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

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

$$\frac{J_D}{\mu} \sum_{i=1,N} dy = \int_0^{V_D} C_0 (V_G - V_T - mV) dV$$

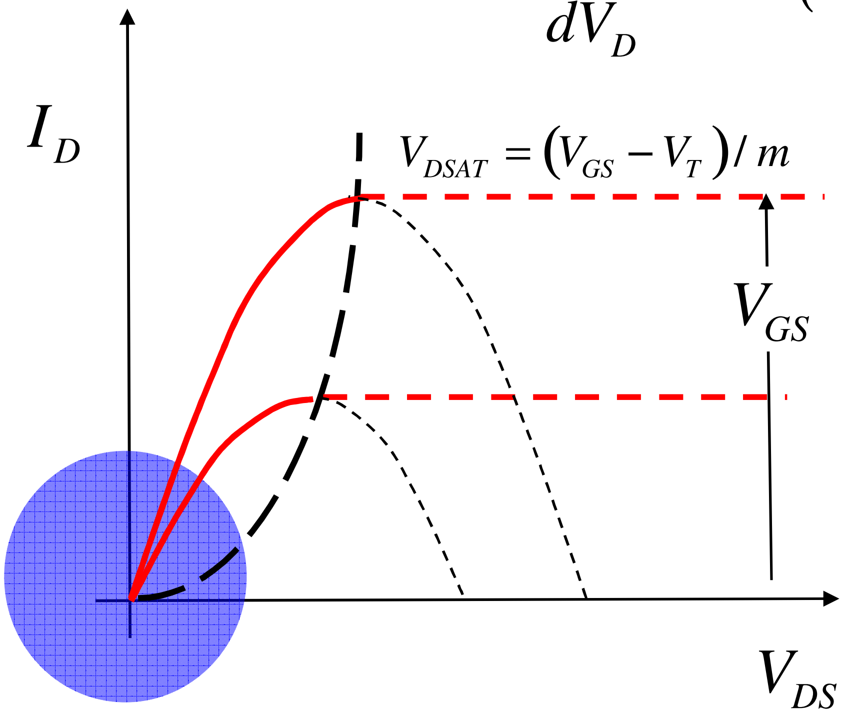
$$J_D = \frac{\mu C_o}{L} \left[(V_G - V_T) V_D - m \frac{V_D^{\,2}}{2} \right]$$



Square Law or Simplified Bulk Charge Theory

$$I_D = Z\frac{\mu C_o}{L}\left[(V_G - V_T)V_D - m\frac{V_D{}^2}{2}\right]$$

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



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

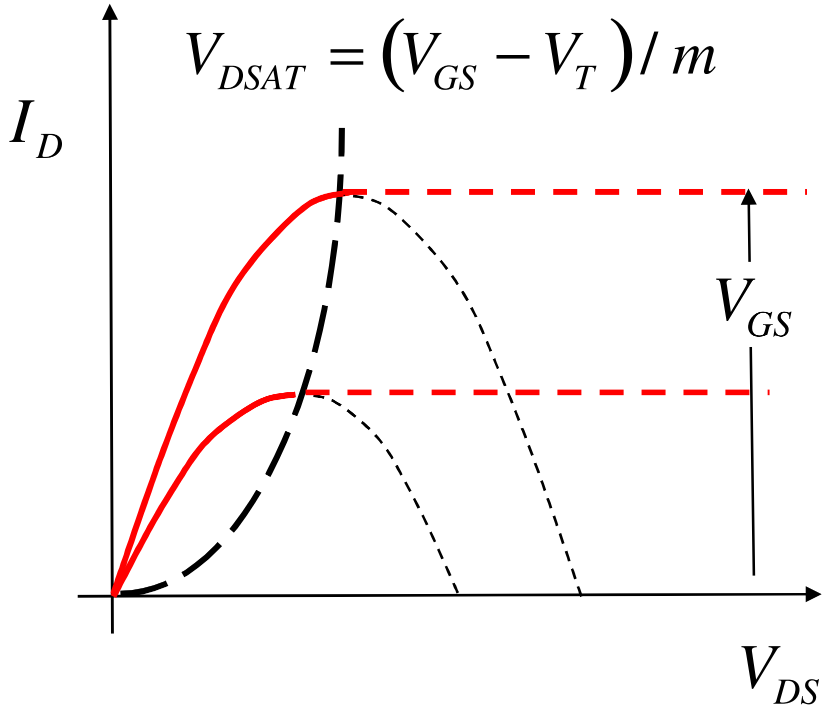
$$J_D = \frac{\mu C_o}{L}\left[(V_G - V_T)V_D - m\frac{V_D{}^2}{2}\right]$$

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

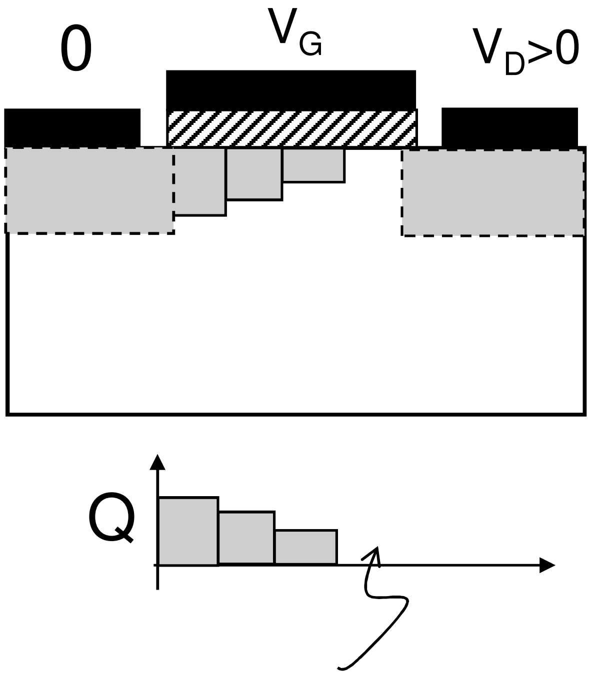
Why does the curve roll over?

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

$$Q_i \approx -C_o(V_G - V_T \;\; - mV)$$

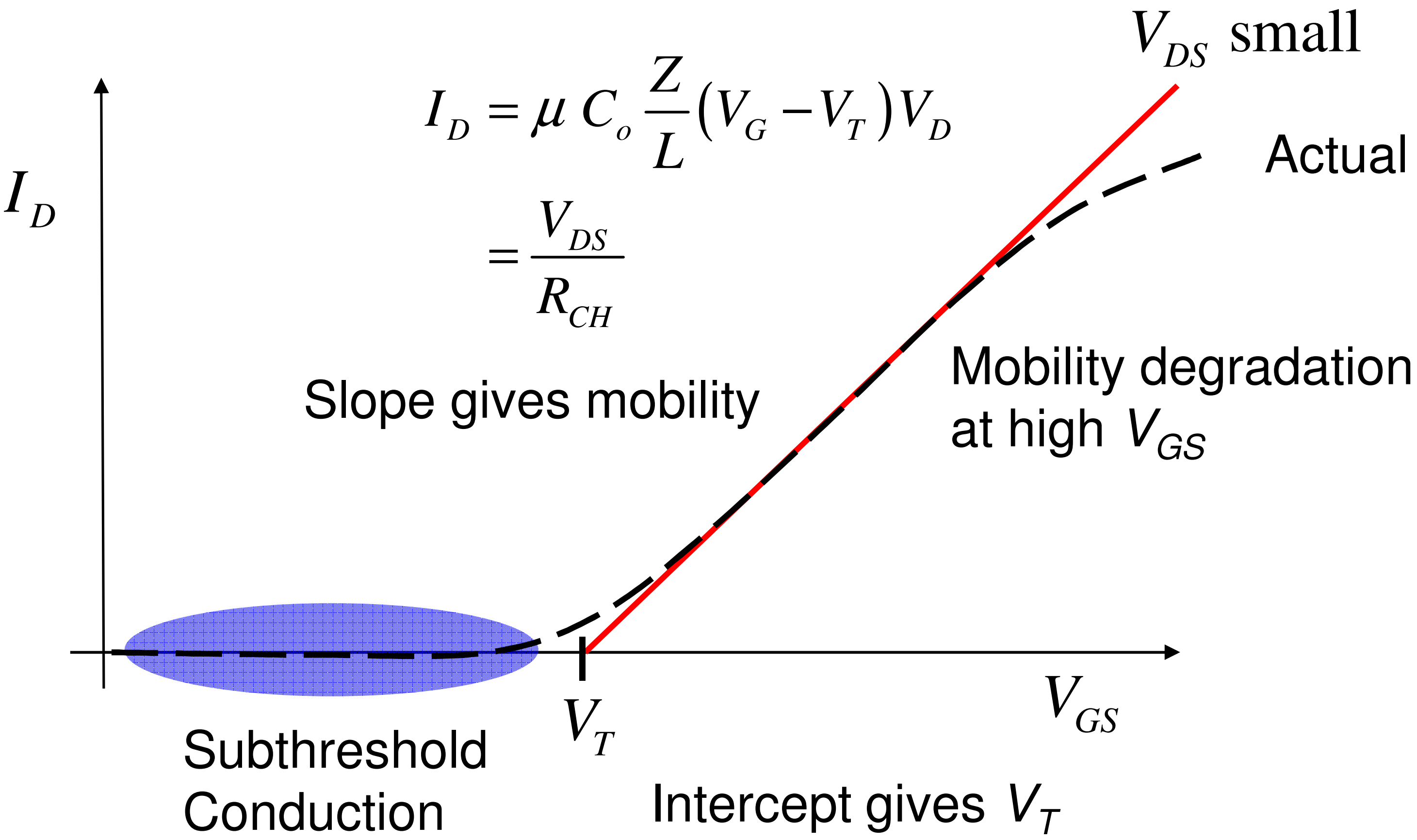


$$V_{DSAT} = (V_{GS} - V_T)/m$$



loss of inversion

Linear Region (Low V_{DS})



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

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

Slope gives mobility

Mobility degradation at high V_{GS}

Subthreshold Conduction

Intercept gives V_T

conclusions

- The MOS capacitor is the foundation for MOS field effect transistors (MOSFETs), characterized by many device metrics
- MOSFETs differs from MOSCAPs in that the field from the S/D contacts now causes current flow
- Two regimes: diffusion-dominated subthreshold and drift-dominated super-threshold, define the key I_D-V_D-V_G characteristics of a MOSFET
- The simple bulk charge theory allows calculation of drain currents, but there are important limitations to this theory