

ELEN E3106/4106 Lecture 22

MOSFETs Part II

Outline

- Energy band diagrams
- MOSFET as a barrier-controlled device
- Key device metrics and how to find them
- Basic quantitative current-voltage model

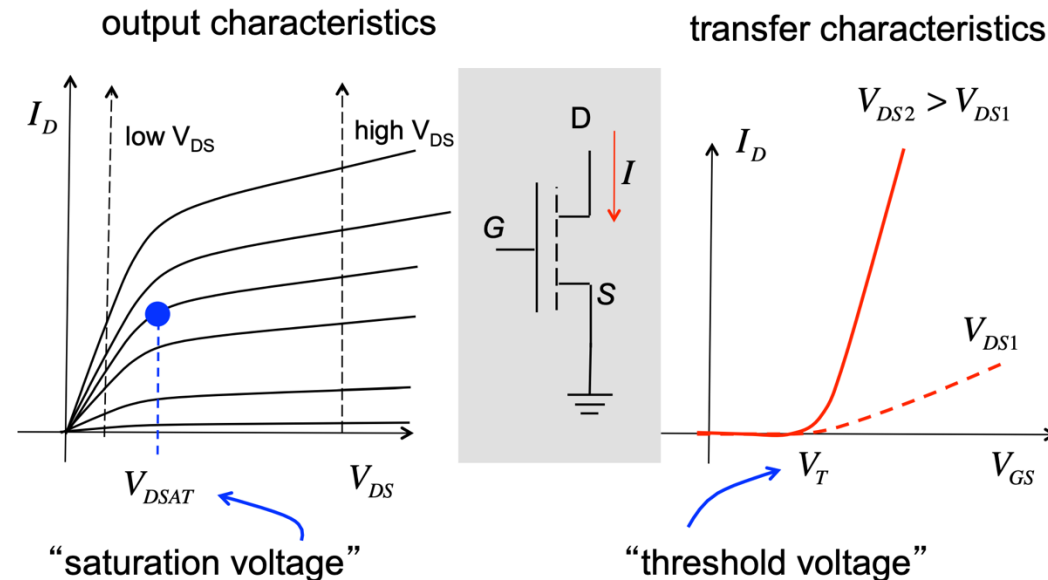
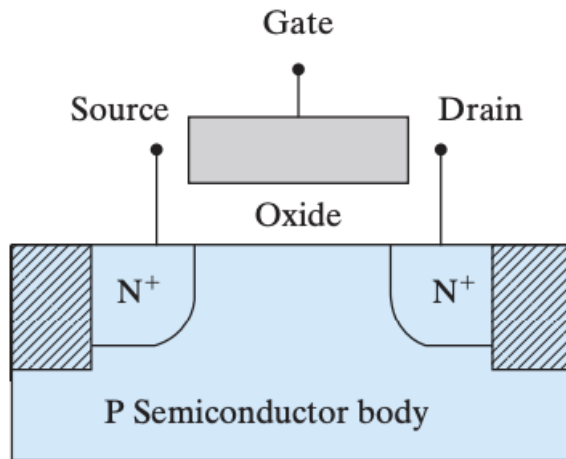
Assignments:

Homework 8 due Monday Dec. 1st by 11:59pm

Extra credit opportunity during in-class review session on Thursday December 4th

Recap so Far

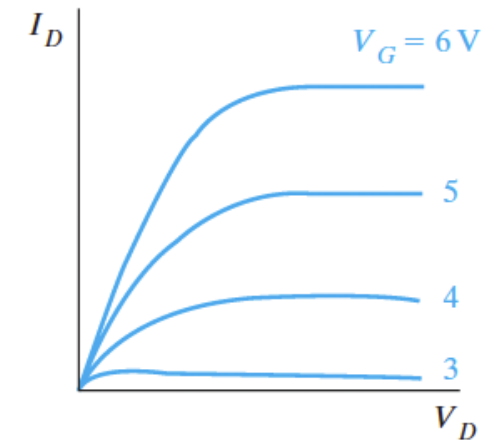
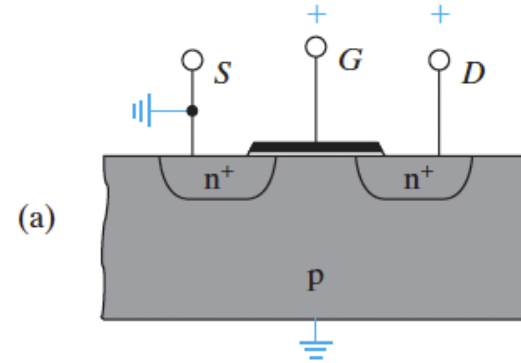
- MOSFETs are 3 terminal voltage-controlled (V_{gs}) current-sources (I_D)
- Field-effect: the gate voltage modulates the E-field and conductivity of the _____ under the gate, effectively controlling the flow of current between _____
- Gate structure incorporates MOS cap. MOS cap inversion layer is called the conducting _____
- We discussed NMOSFETs , PMOSFETs, depletion-mode, enhancement-mode (normally _____)
- Regions of operation: 1) _____ 2) _____ 3) _____



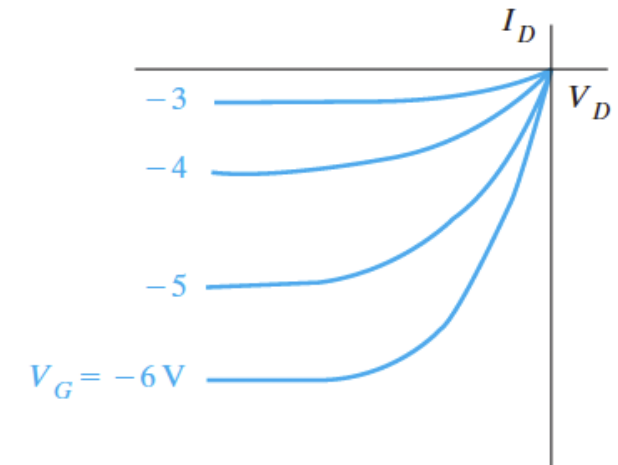
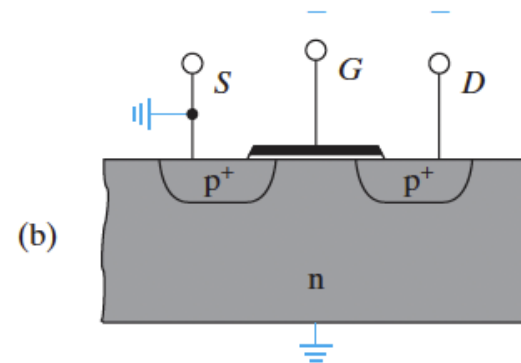
Sources: C. Hu *Modern Semiconductor Devices for Integrated Circuits*, M. Lundstrom ECE 305 Slides

Recap so Far

- NMOSFET: inversion channel is n-type,
 V_{ds}, V_{gs}, V_t, I_D are _____

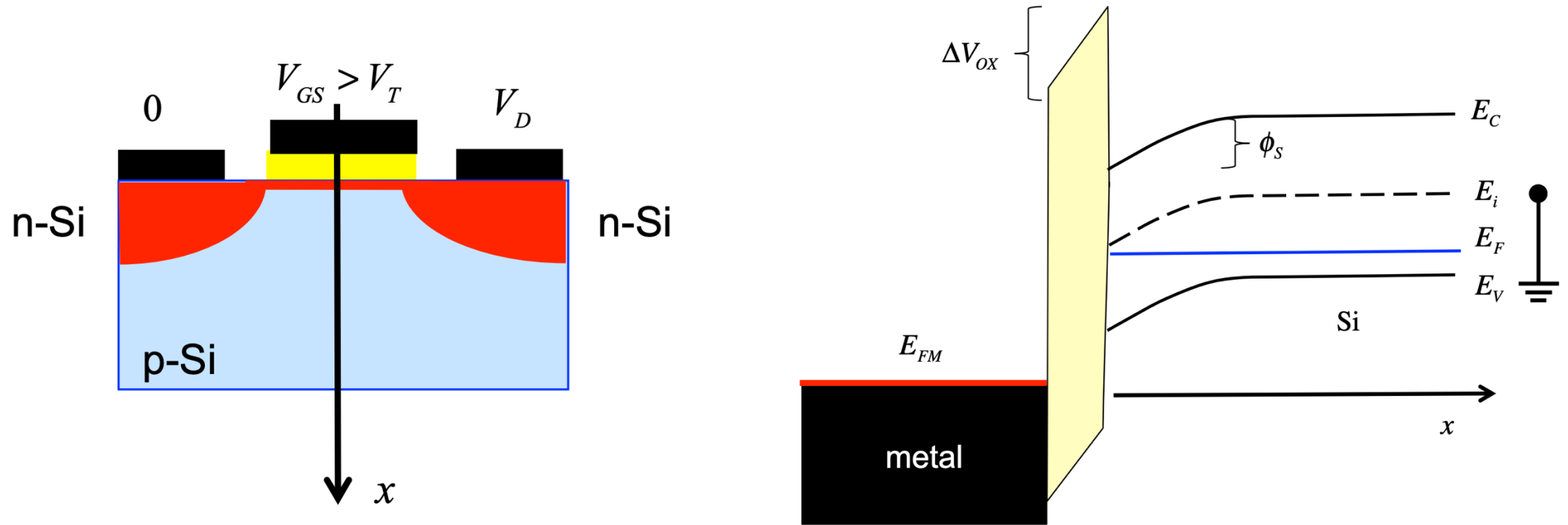


- PMOSFET: inversion channel is p-type,
 V_{ds}, V_{gs}, V_t, I_D are _____



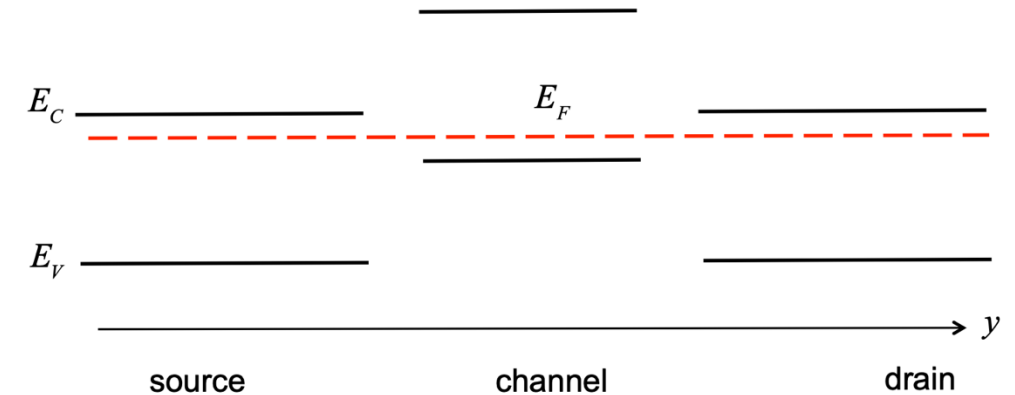
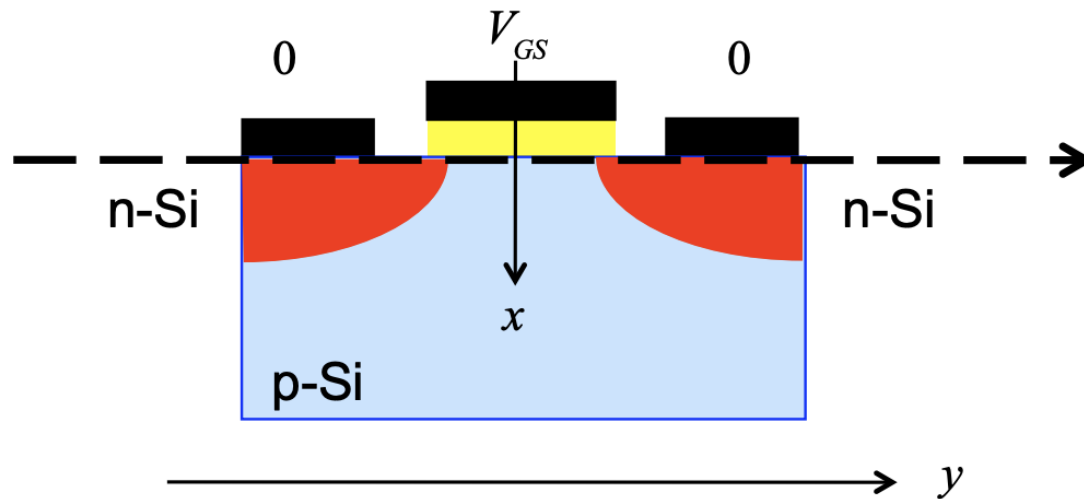
MOSFET Energy Band Diagram in Equilibrium

- Let's look at the MOSFET energy band diagram
- Normal to the channel, we have our _____
- What type of MOSFET is this?

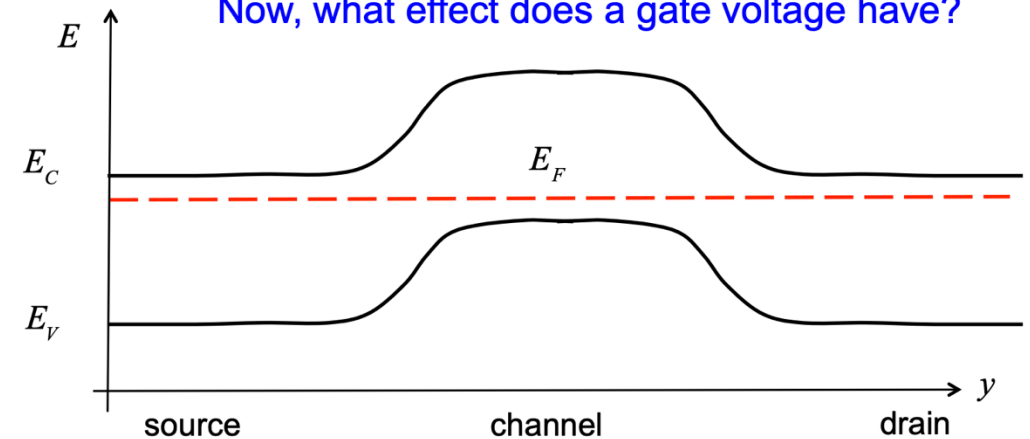


MOSFET Energy Band Diagram in Equilibrium

- Parallel to the channel, we have a similar structure to the _____
- Recall: to draw our band diagrams in equilibrium, we first align the Fermi levels in the different regions, and then connect E_C and E_V

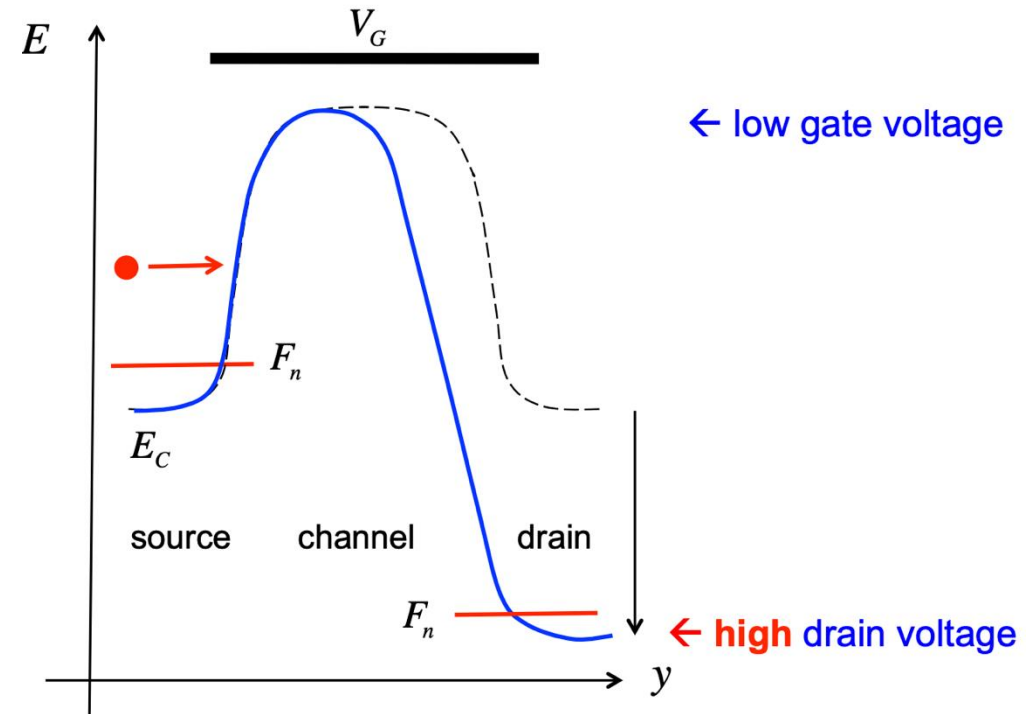
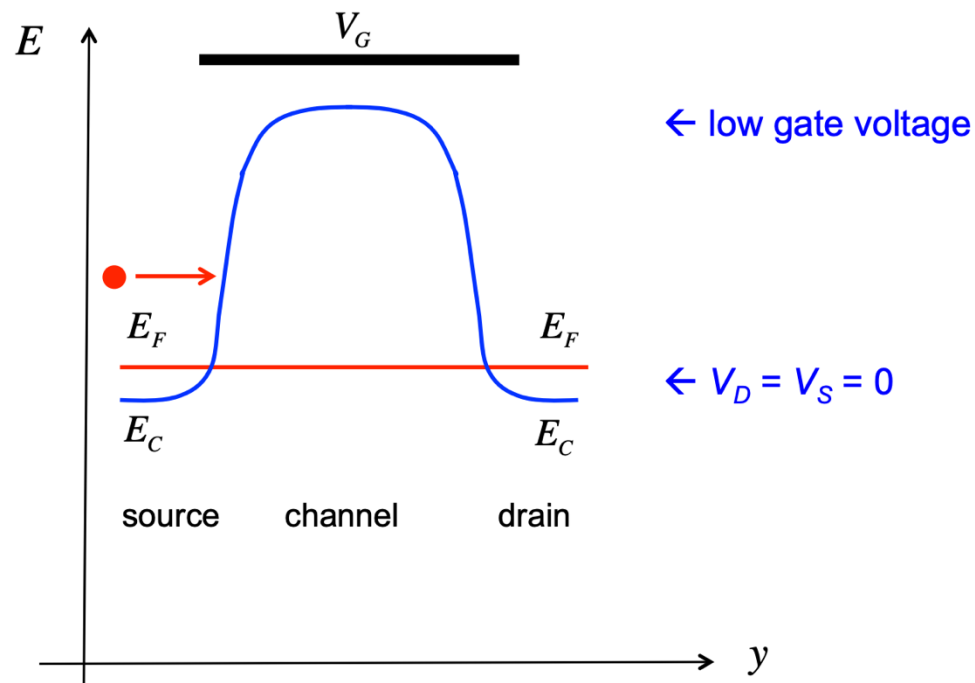


Now, what effect does a gate voltage have?



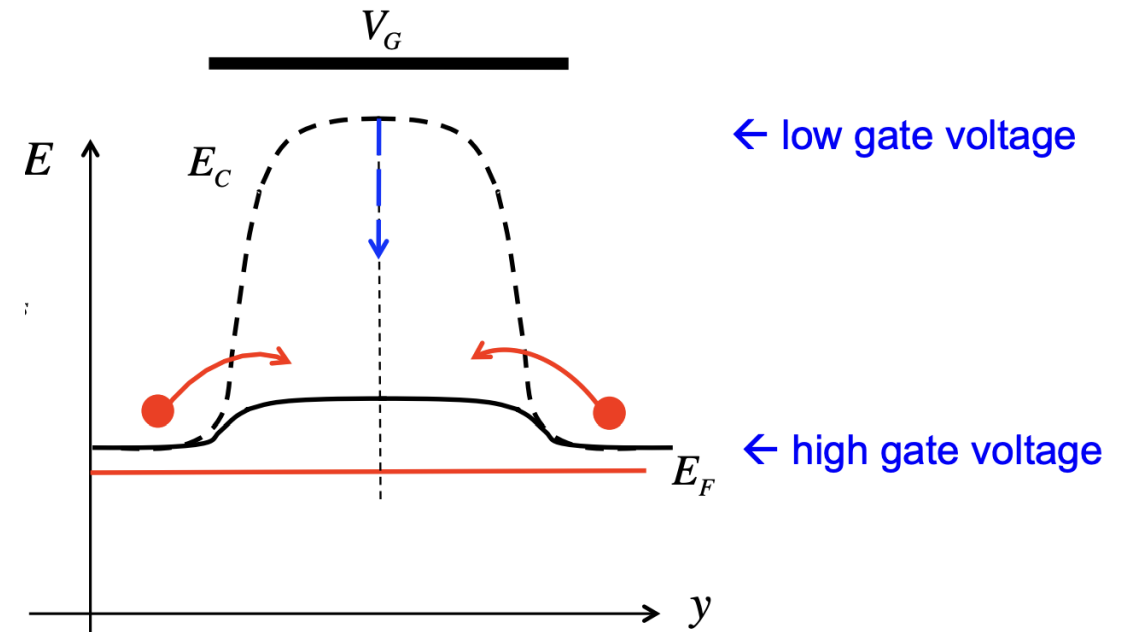
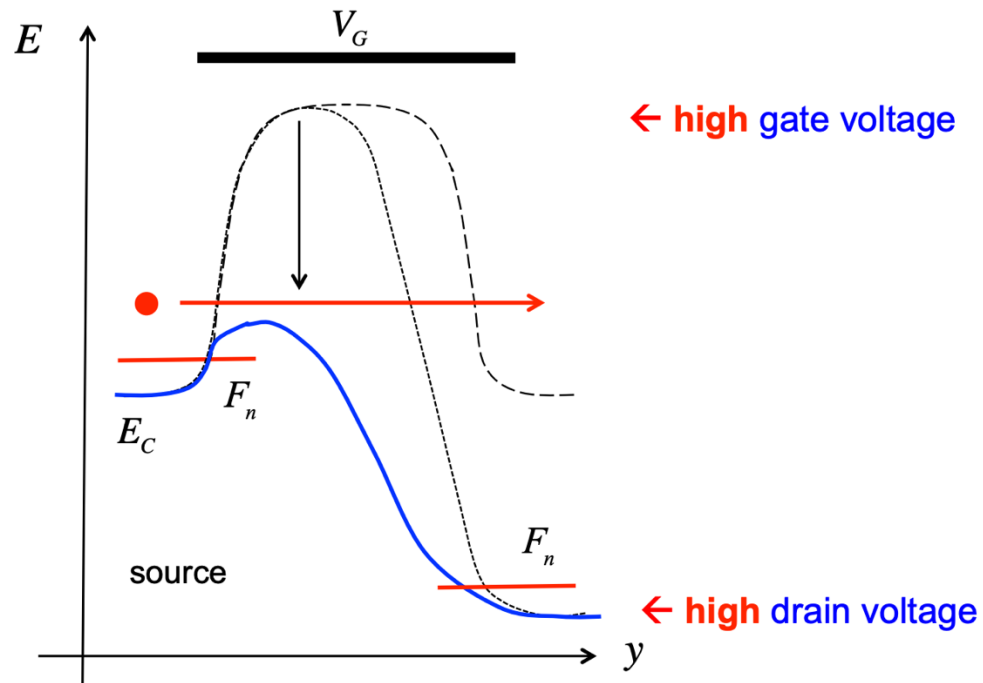
MOSFET As a Barrier-Controlled Device

- We can think of the channel under the gate as a barrier to e- flow
- The height of the barrier (and _____) is modulated by the gate voltage
- Imagine we have a low $V_{gs} < \text{_____}$ and $V_{ds} = 0$ (left)
- Even as we increase $V_{ds} > 0$, the barrier to e- from source to channel is still high (right)
- Device is still _____ \rightarrow very little I_D



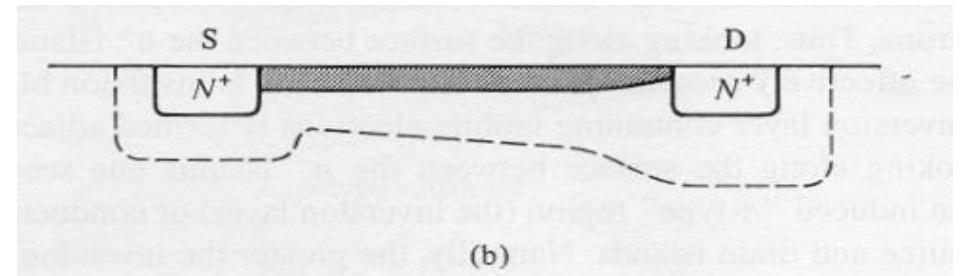
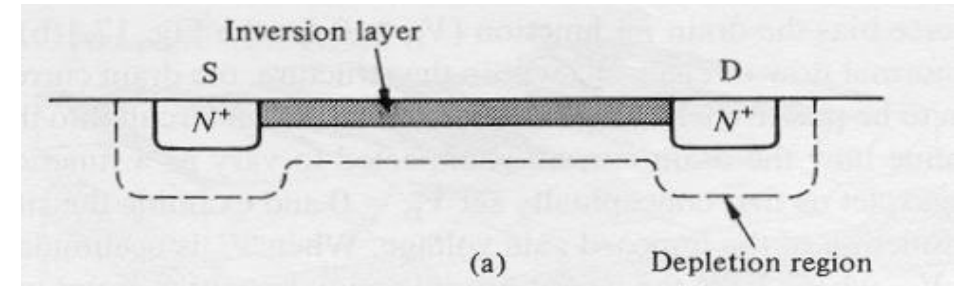
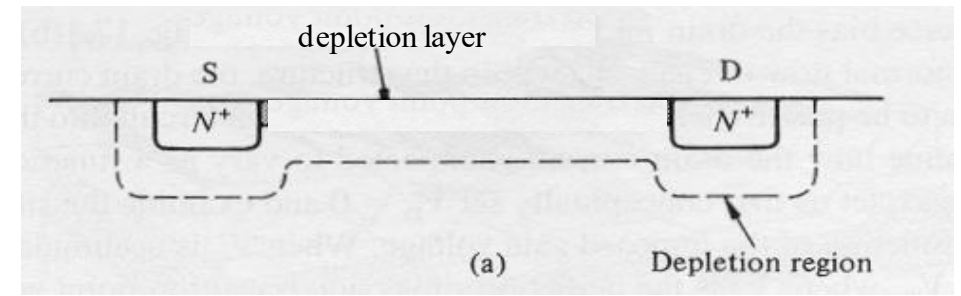
MOSFET As a Barrier-Controlled Device

- As we increase $V_{gs} > \text{_____}$ we have lowered the barriers to e- flow
- A significant # of carriers are able to cross from source to drain
- The device is now _____ with significant I_D



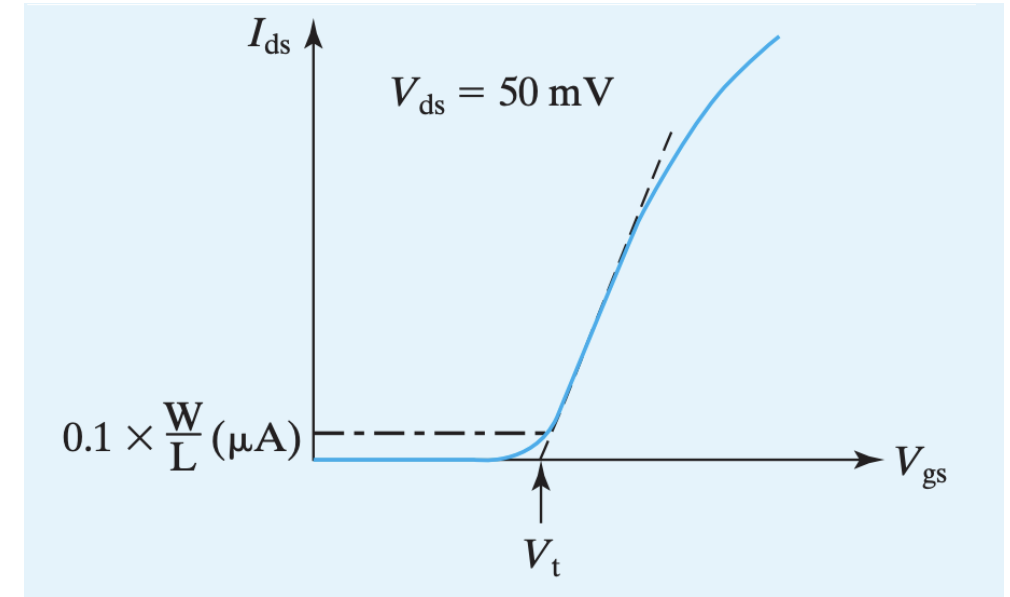
Recap: Theory of MOSFET (n-type)

- When $V_{GS} < V_T$ the channel is _____
- When $V_{GS} > V_T$ the channel is _____
- If small drain voltage ($V_{DS} > 0$) is applied _____
- Does sheet charge move by drift or diffusion?
 - Current \approx width x sheet charge x velocity
- What is the inversion charge? $|Q_{inv} (\frac{C}{cm^2})| =$ _____
- What is the drift velocity? $v =$ _____
- Note: in reality, carrier mobility will be lower than bulk mobility due to _____



Metric: Threshold Voltage

- V_t (V): Threshold voltage, the minimum gate-to-source voltage (V_{GS}) that is needed to create a conducting path between the source and drain terminals and turn the device “on”
- Can be easily measured from the $I_D - V_{gs}$ transfer plot
- Extrapolate the steepest part of the measured V_{gs} curve back to _____
- Generally, lower V_t is _____ so high V_{gs} is not required for switching



Current in the Linear Region (Low V_{ds})

- At low V_{ds} , the inversion layer acts as a _____

$$I_D = W Q_{inv} v = W Q_{inv} \mu_n E = W Q_{inv} \mu_n \text{_____}$$

$$I_D = \mu \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_T) \cdot V_{DS} - \frac{1}{2} \cdot \mu \cdot C_{ox} \cdot \frac{W}{L} \cdot V_{DS}^2$$

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

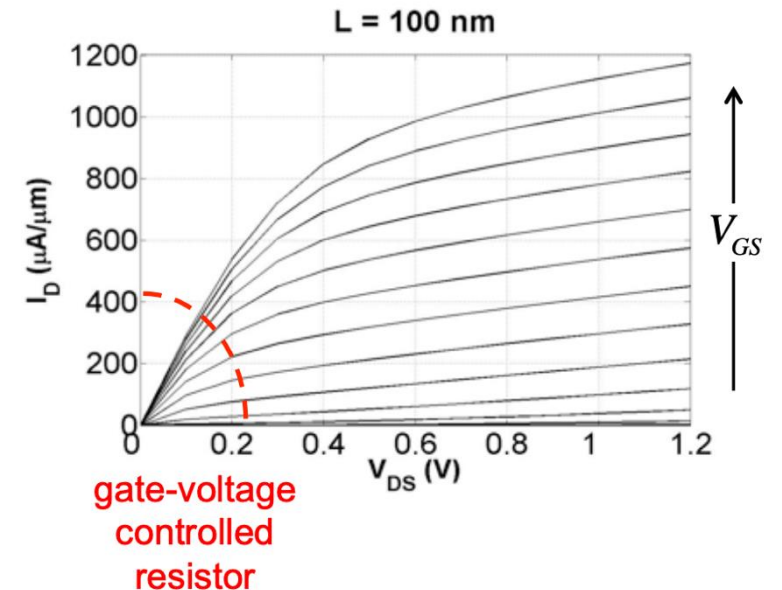
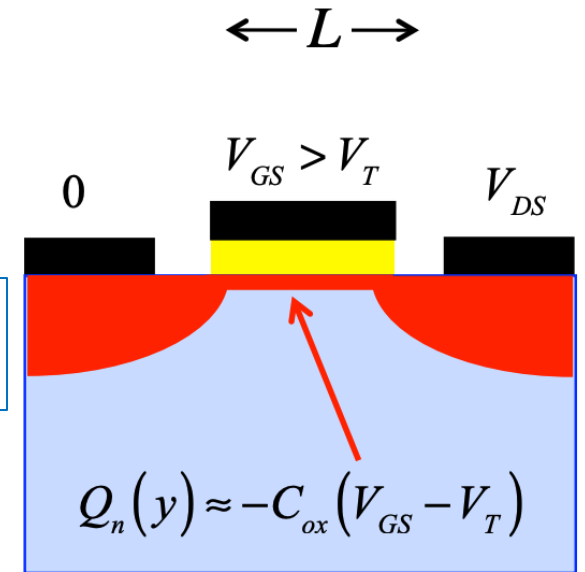
- First term represents _____, proportional to E-field
- Second term represents _____, which accounts for carrier gradients caused by the voltage drop _____ along the channel

- W is the channel width (channel dimension _____ to the page), L is the channel length (_____ to page)
- Summary of relevant equations:

$$|Q_{inv}| = C_{ox} (V_{gs} - V_t)$$

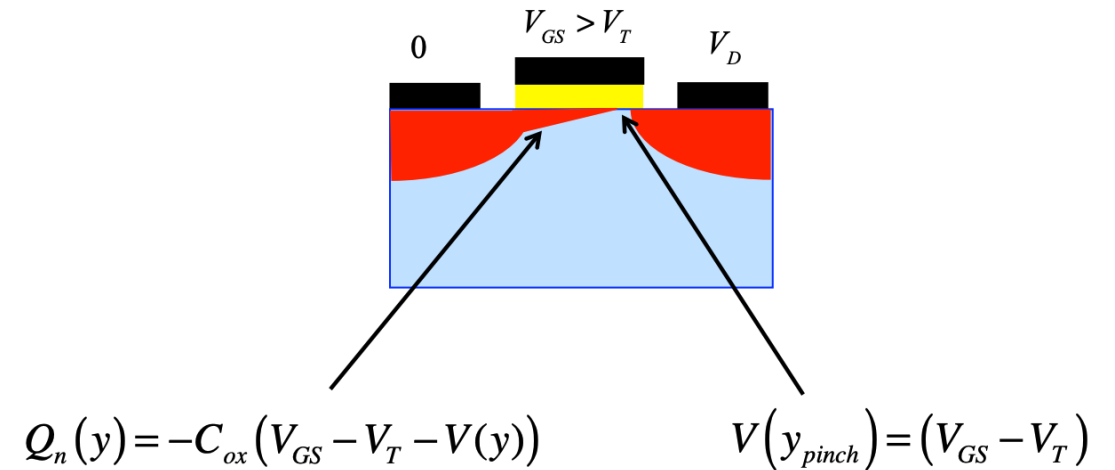
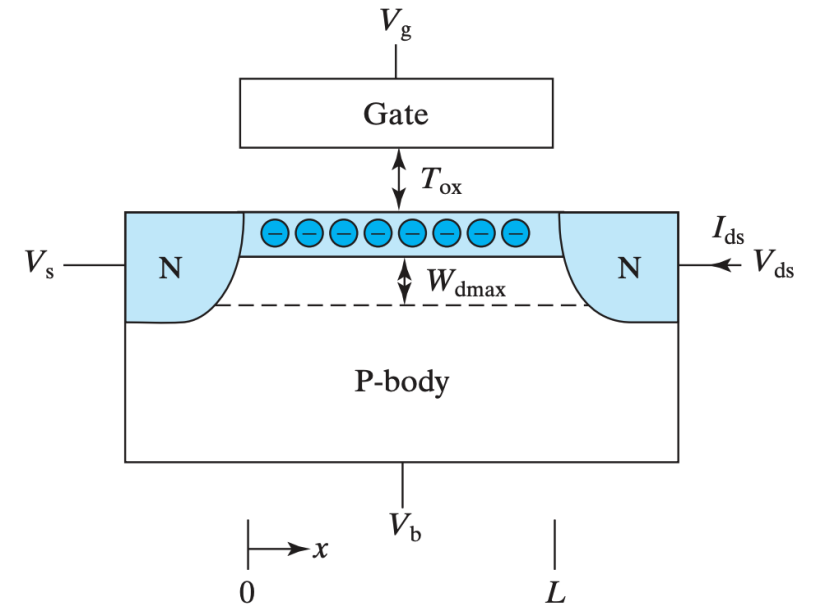
$$|E| = \frac{V_{ds}}{L}$$

$$v = \mu E$$



Channel Pinch-Off

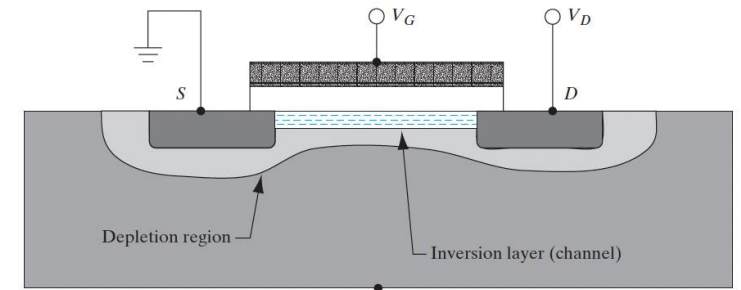
- At higher V_{ds} , we must take into account variation in potential along the channel, $0 < V_c(x) < V_{ds}$
- Let $V_c = V_s$ at $x = 0$ and $V_c = V_d$ at $x = L$
- In the middle of the channel, $V_c\left(\frac{L}{2}\right) > V_s$
- Therefore, the total voltage across the capacitor will be less closer to the drain, so Q is less, and fewer e^- in the inversion layer!
 - Recall: $C =$
- $|Q_{inv}(x)| = C_{ox}(V_{gs} - V_t - V_c(x))$
- Eventually, the channel becomes completely pinched-off on the _____ side at a point denoted $V_{d,sat} = V_{gs} - V_t$
- The E-field is very _____ in the pinch-off region



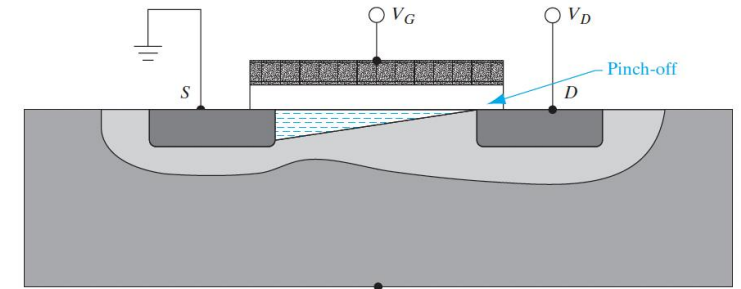
Channel Pinch-Off and Saturation

- What happens if we increase V_{ds} beyond $V_{ds,sat}$?
- The channel gets pinched off more and more!
- But how do carriers travel across the pinched-off region?
 - Due to high longitudinal _____, e- in channel are pulled into pinch-off region
 - They travel at drift saturation velocity, _____
- So now, we have 2 competing effects. Any increase in V_{ds}
 - Reduces the amount of inversion charge, but...
 - Increases the lateral field (charge velocity)
- The two effects _____ so that the current _____ to a value only dependent on V_{gs} (i.e. charge)
- I_d does not increase significantly with increasing V_{ds} beyond $V_{ds,sat}$
- But in reality I_d does increase a little. More on that in a minute.

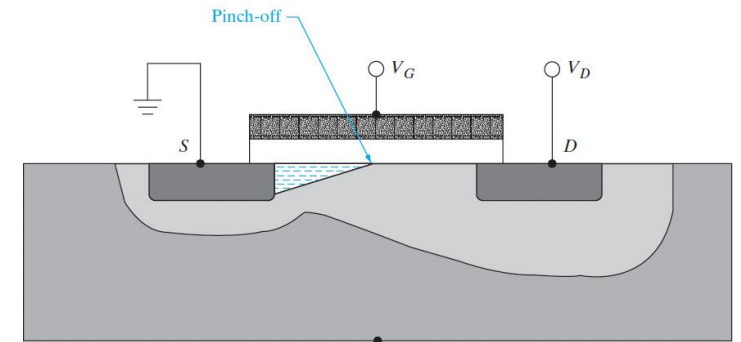
n-channel MOSFET



(a) linear region for $V_g > V_t$ and $V_{ds} < (V_g - V_t)$



(b) onset of saturation at pinch-off, $V_g > V_t$ and $V_{ds} = (V_g - V_t)$



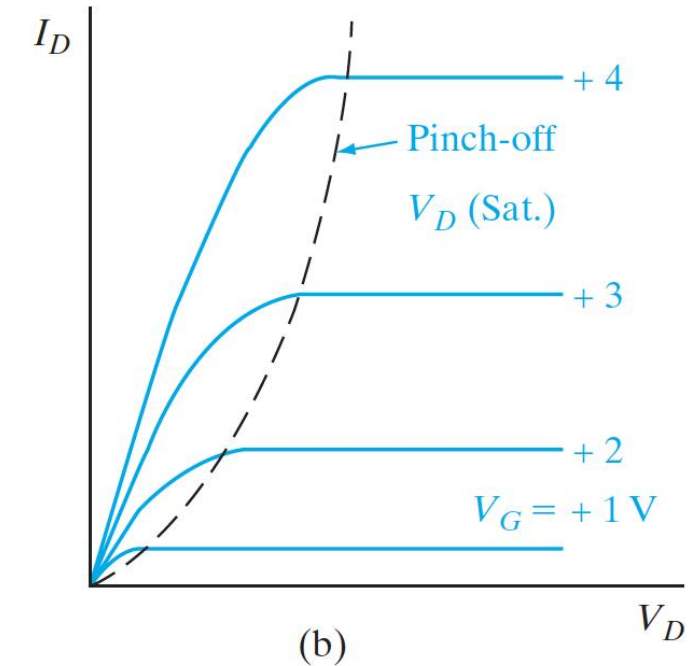
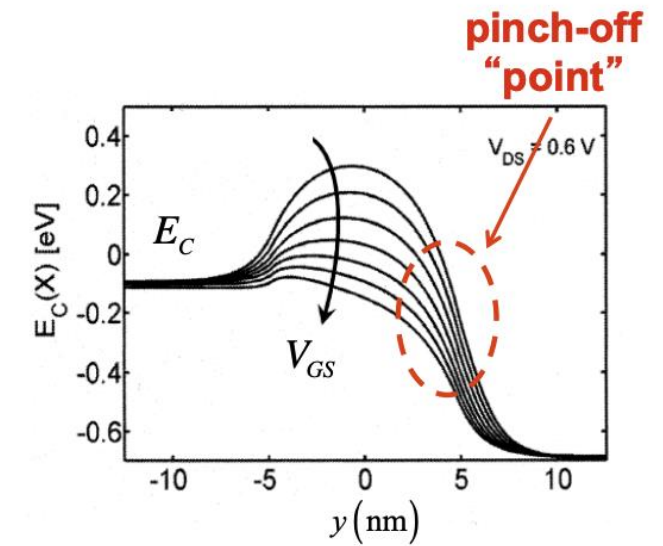
(c) strong saturation, $V_g > V_t$ and $V_{ds} > (V_g - V_t)$

Metric: Pinch-off/Saturation Voltage

- So the recap, we've found that channel pinch-off occurs at the saturation or pinch-off voltage

$$V_{d,sat} = V_{gs} - V_t$$

- This point represents the transition from the linear to saturation region
- We can easily find $V_{d,sat}$ from the output characteristics
- For each _____, there is a different $V_{d,sat}$



Long Channel: Current in the Saturation Region (High V_{ds})

- Now that we know our variation of the inversion charge with channel distance x ,

$$|Q_{inv}(x)| = C_{ox}(V_{gs} - V_t - V_c(x))$$

- We can describe our current across a differential element dx at any point x as

$$I_d dx = \mu_n W |Q_{inv}(x)| dV_c$$

- If we integrate from source to drain, we get

$$\int_0^L I_d dx = \mu_n W C_{ox} \int_0^{V_{ds}} ((V_{gs} - V_t - V_c(x))) dV_c$$

$$I_d = \frac{\mu_n W C_{ox}}{L} [(V_{gs} - V_t)V_{ds} - \frac{1}{2} V_{ds}^2]$$

- Since I_d is essentially constant in saturation, we can substitute in _____ = $V_{gs} - V_t$, and we finally get:

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

Metric: Transconductance

- g_m (S or $\frac{S}{\mu m}$): Transconductance, change in drain current with change in gate-source voltage

$$g_m \equiv dI_{ds}/dV_{gs}|_{V_{ds}}$$

- And can be easily obtained in the saturation region by differentiating our drain current eq. on previous slide w.r.t. gate voltage:

$$g_m(sat) = \frac{W}{L} \mu_n C_{ox} (V_{gs} - V_t)$$

- A measure of a transistor's sensitivity to the input voltage.
- In general, we want a large g_m (e.g. high _____)
- We can plot $g_m - V_{gs}$
- The peak value is denoted $g_{m,max}$
- *Note: It is common to normalize the transconductance to channel width

