ECE321 – Electronics I

Lecture 6: MOSFET I-V Characteristics

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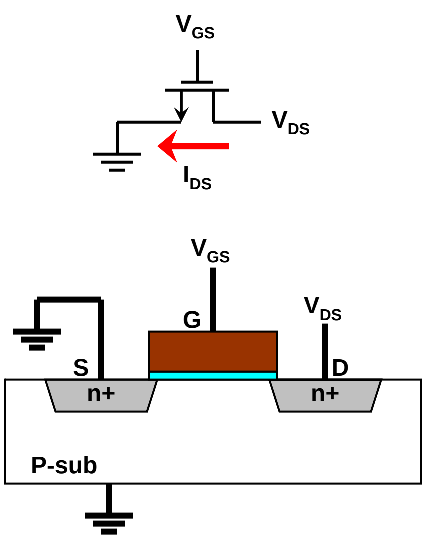
Review of Last Lecture

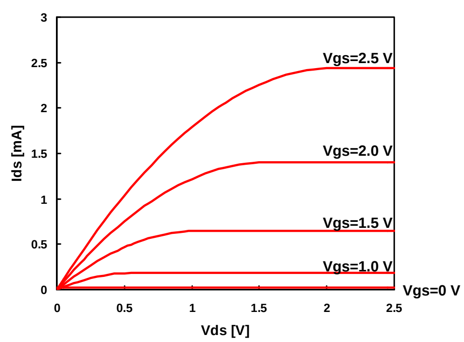
- ❑ **Basic MOS Transistor**
- ❑ **MOSFET Operations**
- ❑ **Cutoff, Linear, and Saturation Regions in MOSFET**
- ❑ **NMOS and PMOS Structures**

Today's Lecture

- ❑ Device Model for Linear Region
- ❑ Device Model for Saturation Region
- ❑ Channel Length Modulation

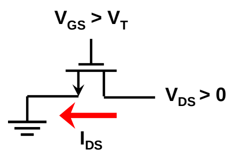
I-V Characteristic of MOSFET

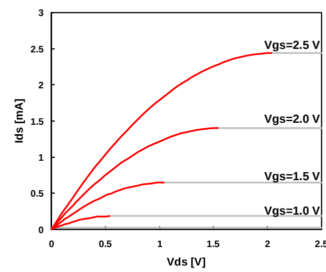


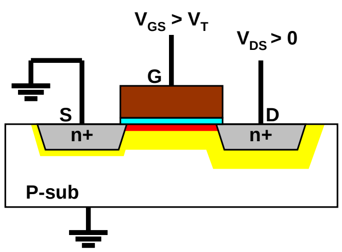


Device Operation: Linear (Ohmic) Region

- ❑ **Question: What is the MOS current equation in linear (or ohmic) region?**





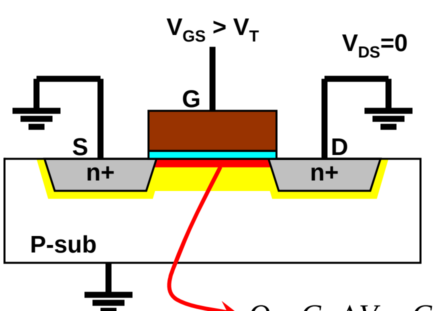


When: $V_{DS} < V_{GS} - V_T$

$$I_{DS} = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

?

Channel Charge Density Calculation



What is the drain current in this configuration?

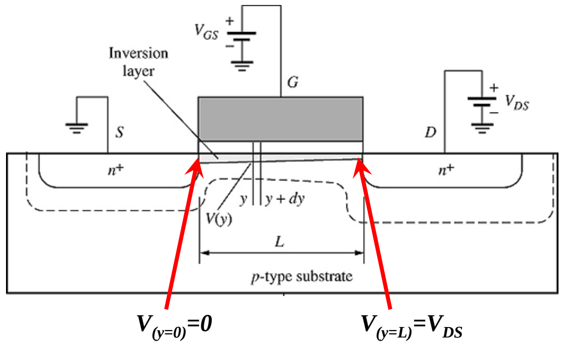
$$Q = C_{ox}\Delta V = C_{ox}(V_{GS} - V_T)$$

Gate oxide capacitance per unit area

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

Remember: V_T is the amount of gate voltage that you need to apply to "create" the channel.

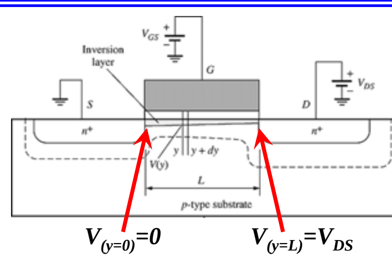
Device Operation: Linear Region



$$Q(y) = C_{ox}\Delta V(y) = C_{ox}\left(V_{GS} - V_T - V(y)\right)$$

$$0 < y < L$$

Device Operation: Linear Region



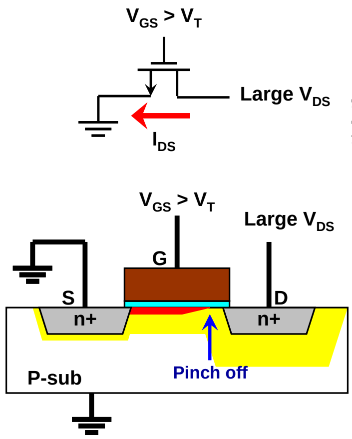
$$I_D = \mu_n Q(y) E(y) W = \mu_n C_{ox} W \left(V_{GS} - V_T - V(y)\right) E(y) = \mu_n C_{ox} W \left(V_{GS} - V_T - V(y)\right)\frac{dV}{dy}$$

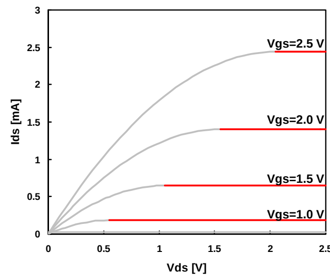
$$I_D dy = \mu_n C_{ox} W \left(V_{GS} - V_T - V(y)\right) dV \;\Rightarrow\; \int_0^L I_D dy = \int_0^{V_{DS}} \mu_n C_{ox} W \left(V_{GS} - V_T - V(y)\right) dV$$

$$I_D = \mu_n C_{ox} \frac{W}{L}\left(\left(V_{GS} - V_T\right)V_{DS} - \frac{V_{DS}^2}{2}\right)$$

Saturation Region

- Question: What is the MOS current equation in saturation region?





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

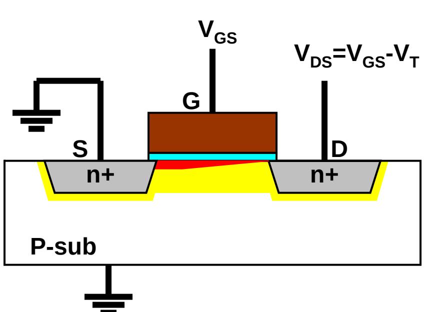
$$I_{DS} = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_T)^2$$

$$I'_{DS} = I_{DS}(1 + \lambda V_{DS})$$

?

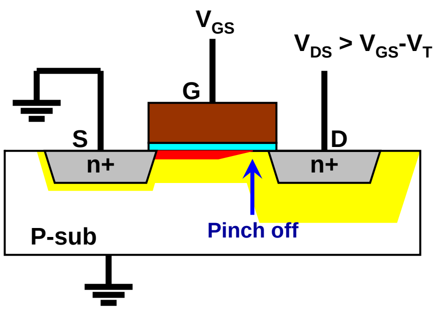
Device Operation: Saturation

- $V_{GD} = V_{GS} - V_{DS}$; so as V_{DS} increases V_{GD} will no longer exceed V_T, thus the charge density in the channel near the drain will decrease.
- If $V_{DS} = V_{GS} - V_T$ then $V_{GD} = V_T$. At this operating point the charge density in the channel would diminish to zero right at the drain.
- When $V_{DS} = V_{GS} - V_T$ the device is transitioning to saturation mode.

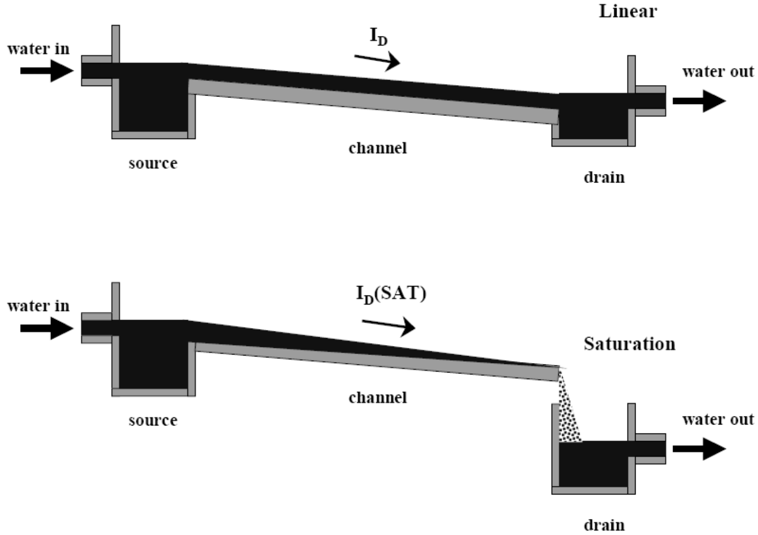


Device Operation: Saturation

- As V_{DS} increases beyond $V_{GS} - V_T$ the charge density in the channel reaches zero prior to reaching the drain. At this point mobile charges are injected into the depletion region and swept to the drain.
- The early termination of the channel is termed "pinch off".
- I_{DS} stops increasing with V_{DS}, and the device is said to be "saturated".



Saturation Region Analogy

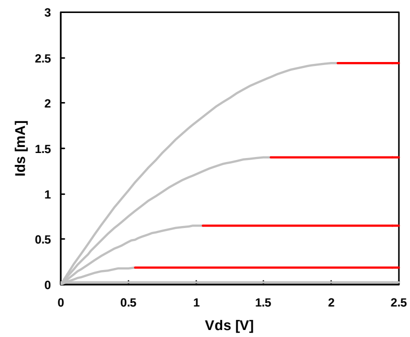


Device Current in Saturation Region

- Since I_{DS} does not increase with increasing V_{DS} beyond $V_{DS} = V_{GS}-V_T$ one can find the equation for I_{DS} in saturation by substituting $V_{DS} = V_{GS}-V_T$ into the I_{DS} equation for linear mode:

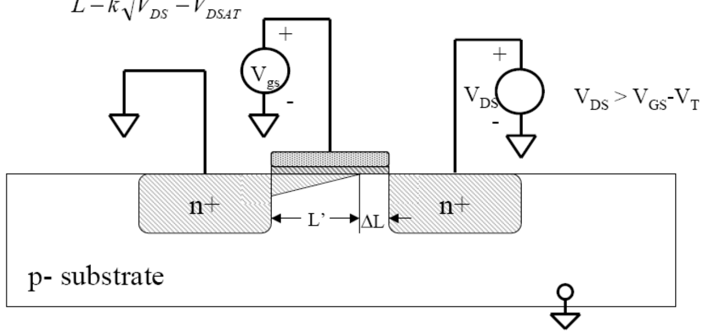
$$I_{DS} = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS}-V_T)(V_{GS}-V_T) - \frac{(V_{GS}-V_T)^2}{2}\right]$$

$$I_{DS} = \mu_n C_{ox} \frac{W}{2L}(V_{GS}-V_T)^2$$



Channel Length Modulation

- Our previous view of saturation is too simple. I_{DS} *will* still have some V_{DS} dependence for V_{DS} values greater than $V_{GS}-V_T$
- As V_{DS} increases beyond $V_{GS}-V_T$ more and more of the channel becomes "pinched off". Thus the effective channel length (L') is reduced by ΔL.
- This ΔL is proportional to: $\sqrt{V_{DS}-V_{DSAT}}$; However one will discover that $\frac{1}{L-k\sqrt{V_{DS}-V_{DSAT}}}$ is a fairly linear function. Therefore …

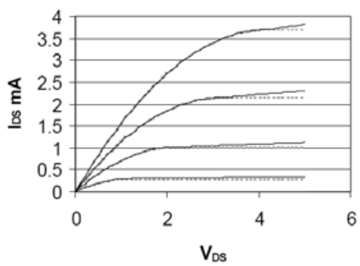


Channel Length Modulation

- The effect of channel length modulation is typically modeled with an empirical linear factor λ.
- Thus the equation for I_{DS} in saturation becomes:

$$I_{DS} = \mu_n C_{ox} \frac{W}{2L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

where λ = “channel length modulation factor”



Device Operation: I-V curves

$$I_{DS} = K_n' \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right](1 + \lambda V_{DS})$$

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

$$I_{DS} = \frac{K_n'}{2}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

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

$$K_n' = \mu_n C_{ox}$$