

ECE321 – Electronics I

Lecture 6: MOSFET I-V Characteristics

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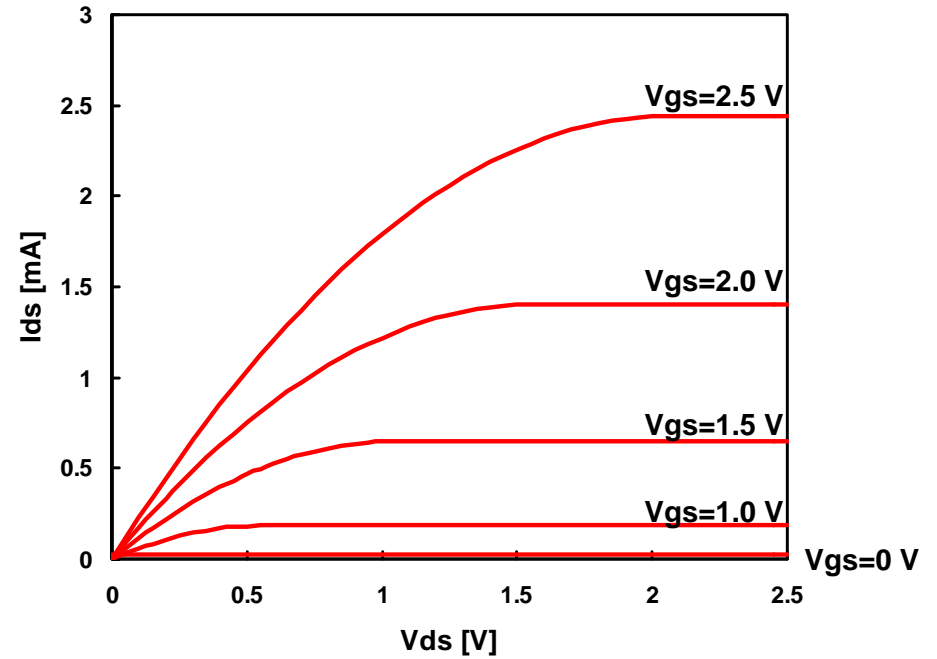
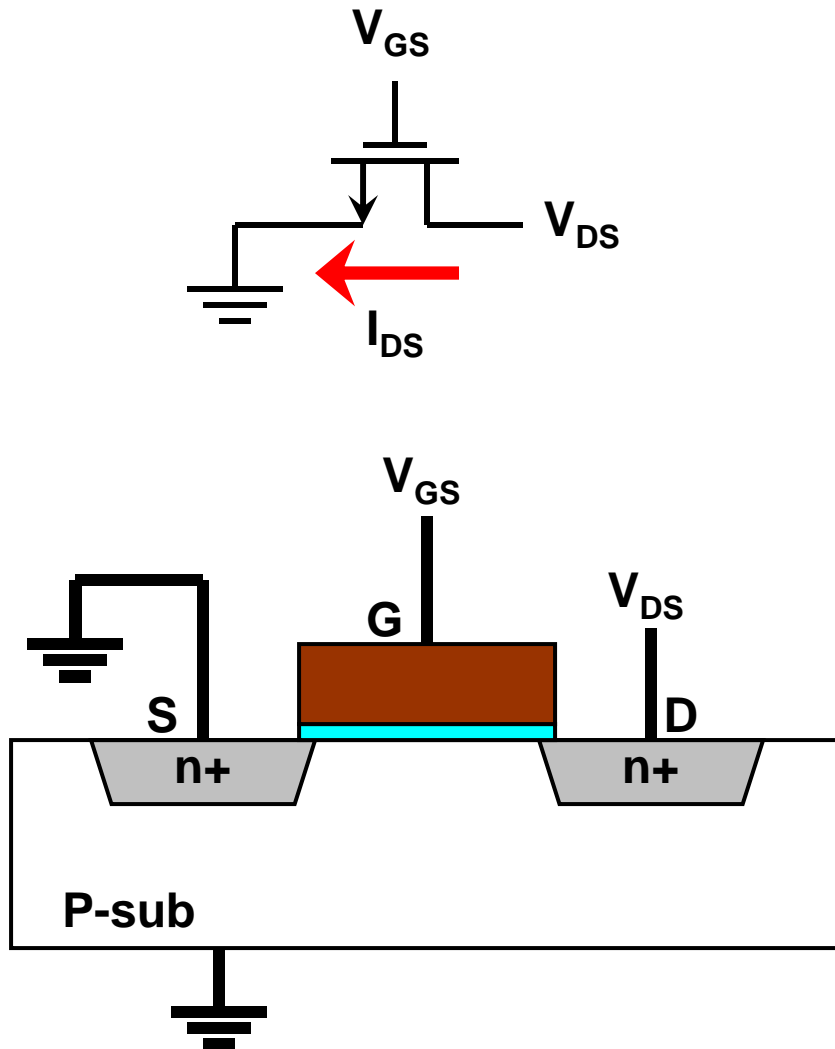
Review of Last Lecture

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

Today's Lecture

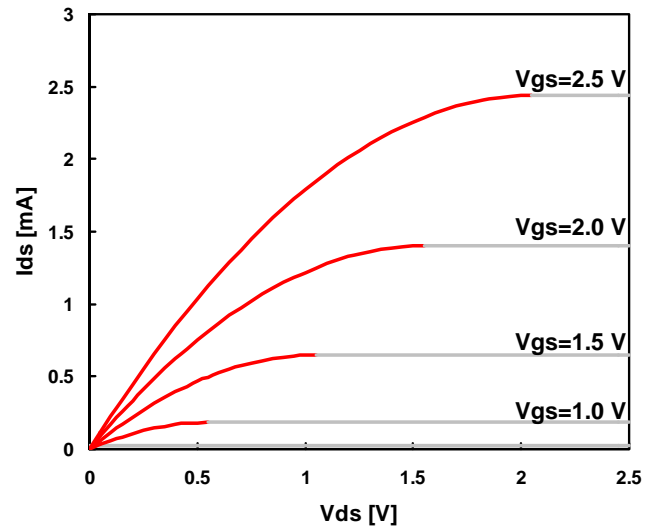
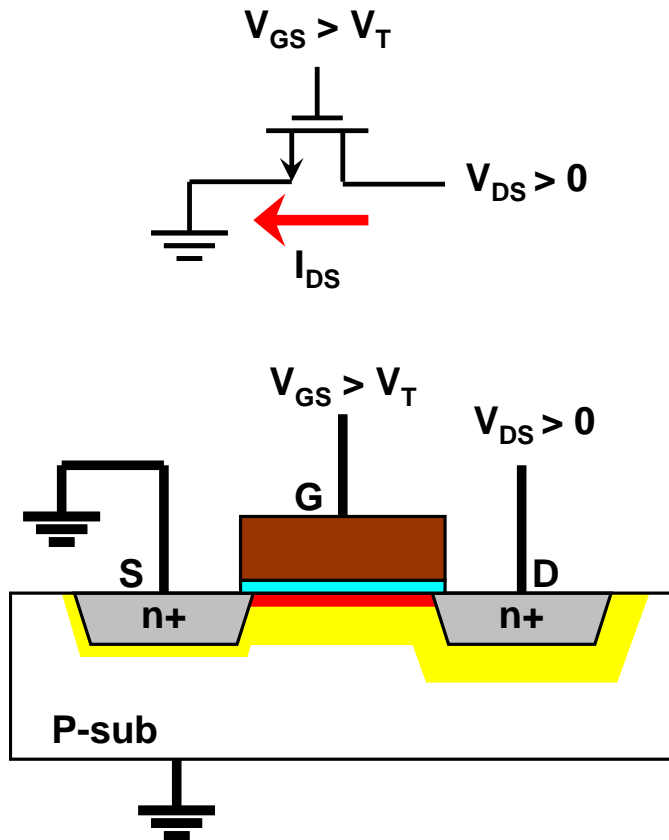
- Device Model for Linear Region**
- Device Model for Saturation Region**
- Channel Length Modulation**

I-V Characteristic of MOSFET



Device Operation: Linear (Ohmic) Region

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

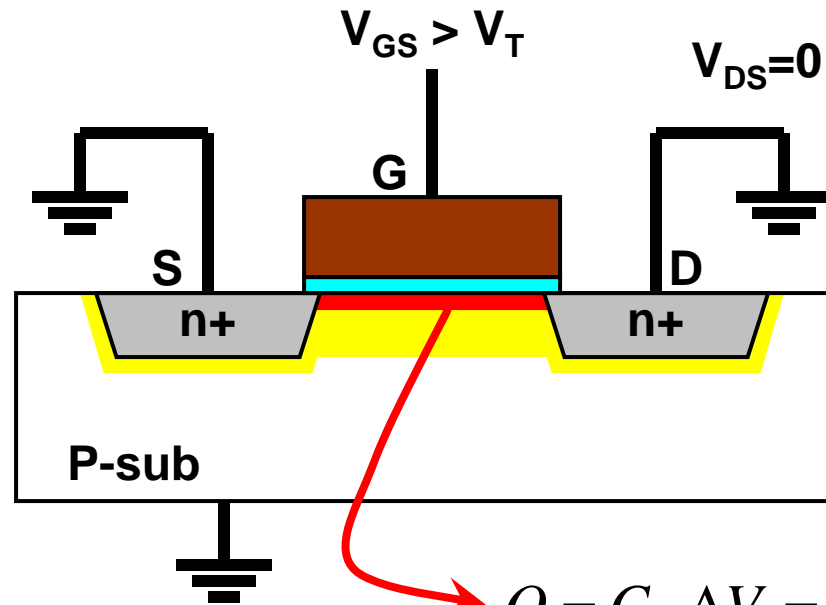


When: $V_{DS} < V_{GS} - V_T$

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

?

Channel Charge Density Calculation



What is the drain current in this configuration?

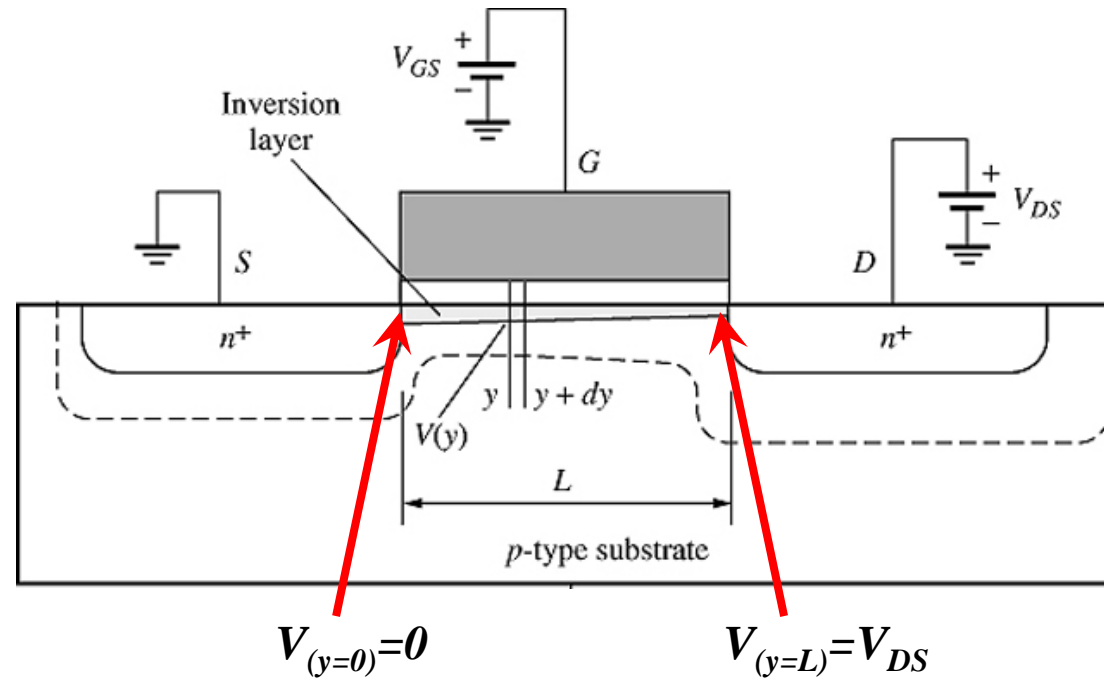
$$Q = C_{ox} \Delta V = C_{ox} (V_{GS} - V_T)$$

Gate oxide capacitance
per unit area

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

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

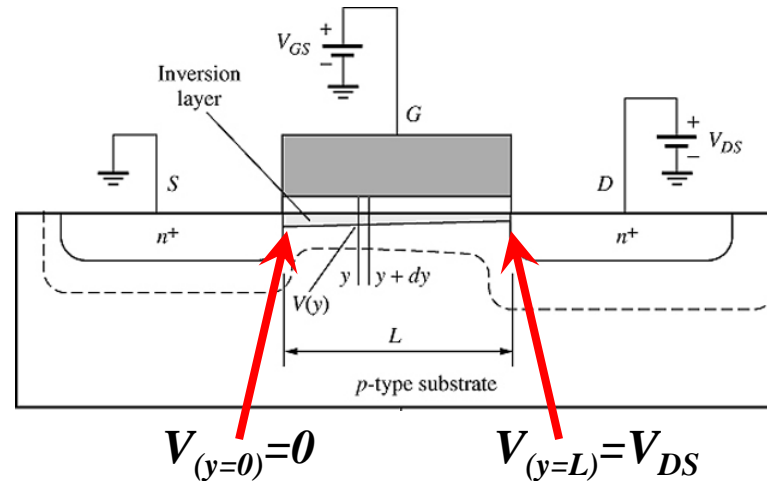
Device Operation: Linear Region



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

$$0 < y < L$$

Device Operation: Linear Region



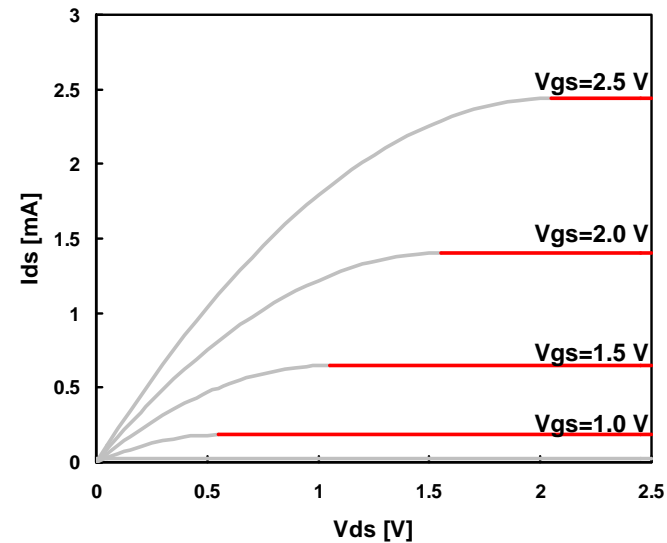
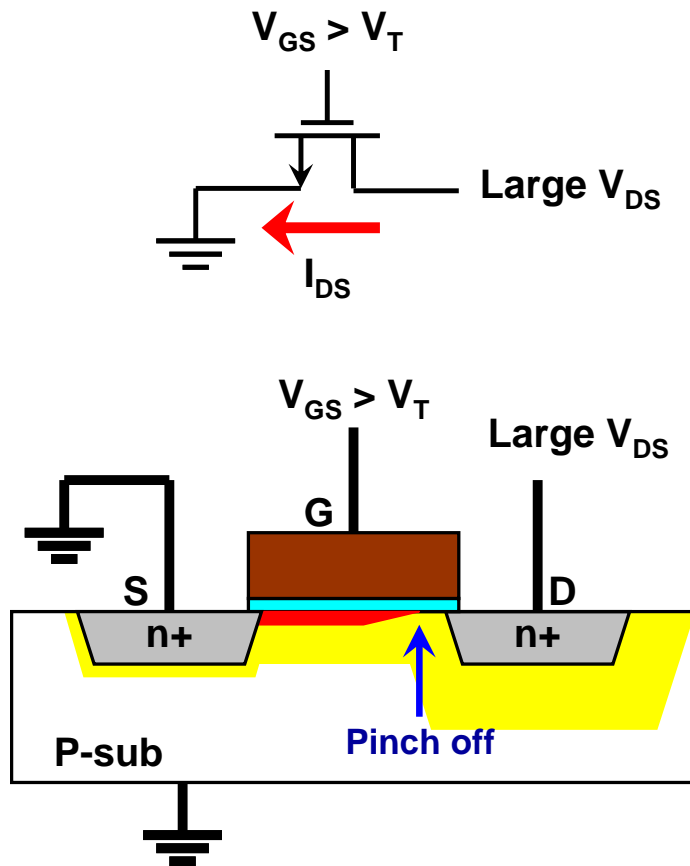
$$I_D = \mu_n Q(y) E(y) W = \mu_n C_{ox} W (V_{GS} - V_T - V(y)) E(y) = \mu_n C_{ox} W (V_{GS} - V_T - V(y)) \frac{dV}{dy}$$

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

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

Saturation Region

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



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

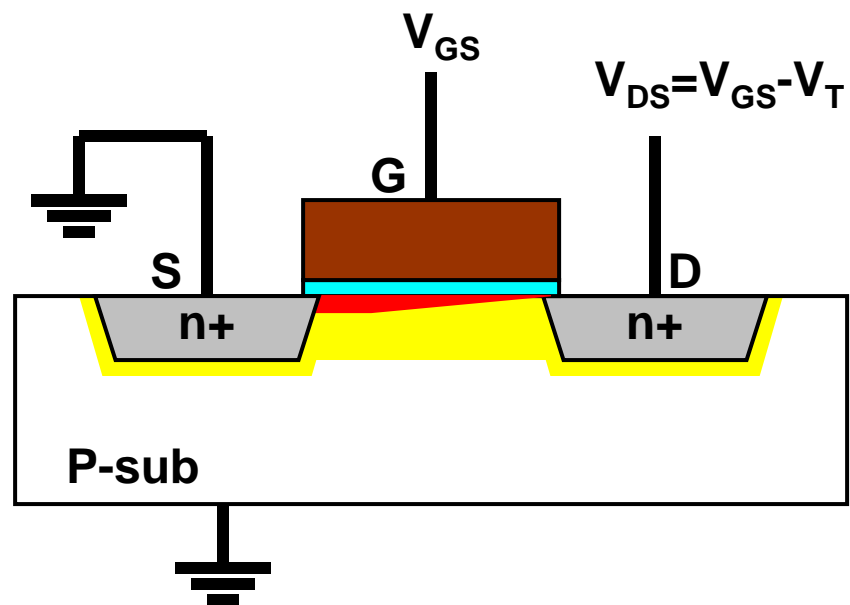
$$I_{DS} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2$$

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

?

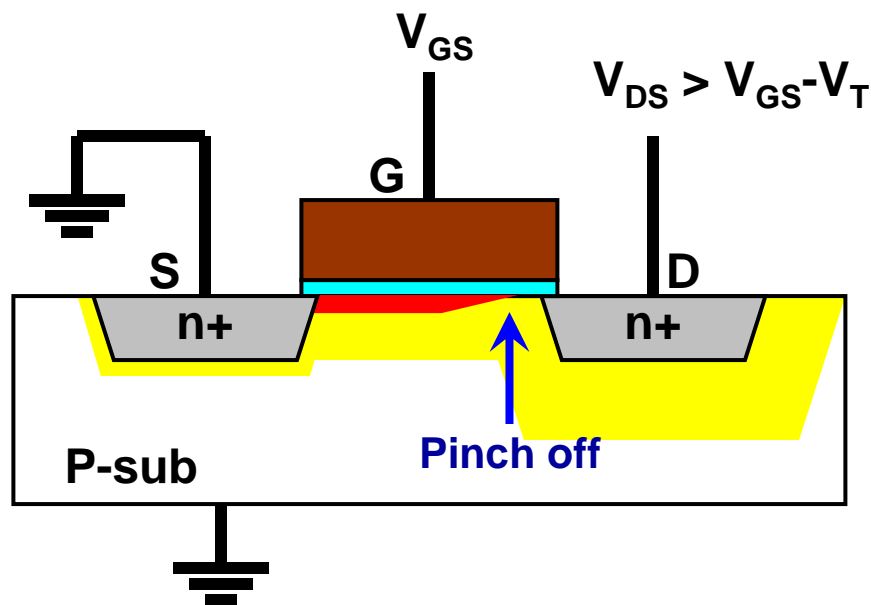
Device Operation: Saturation

- $V_{GD} = V_{GS} - V_{DS}$; 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.

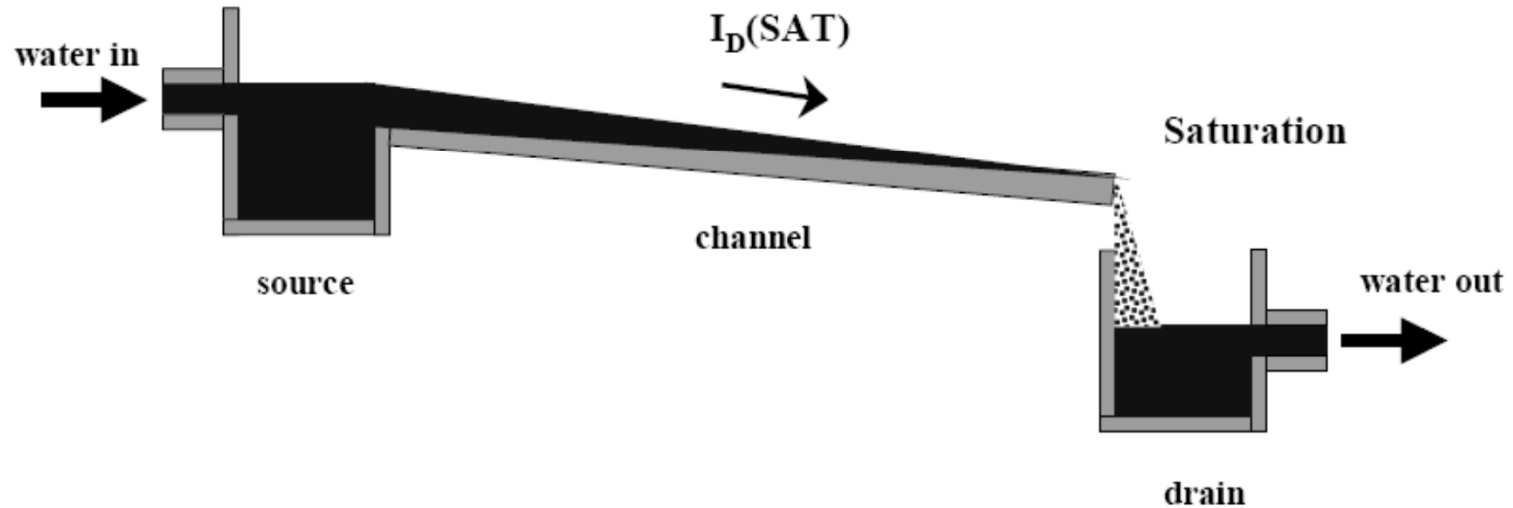
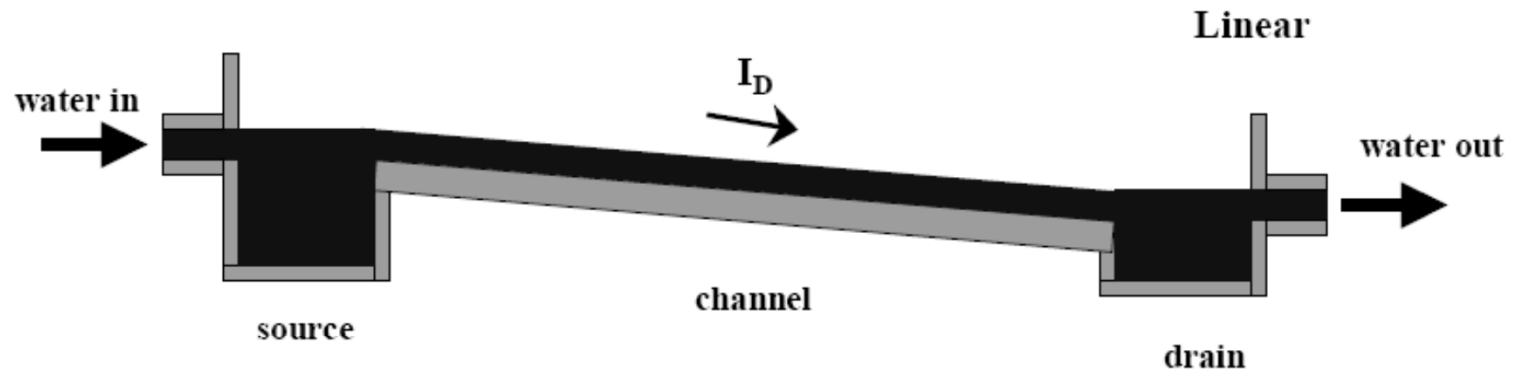


Device Operation: Saturation

- 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

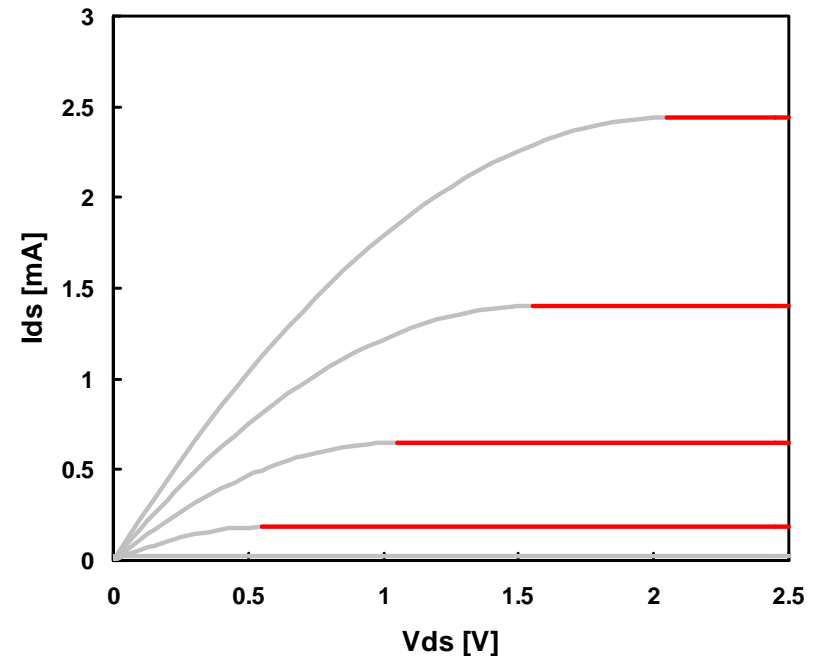


Device Current in Saturation Region

- 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:

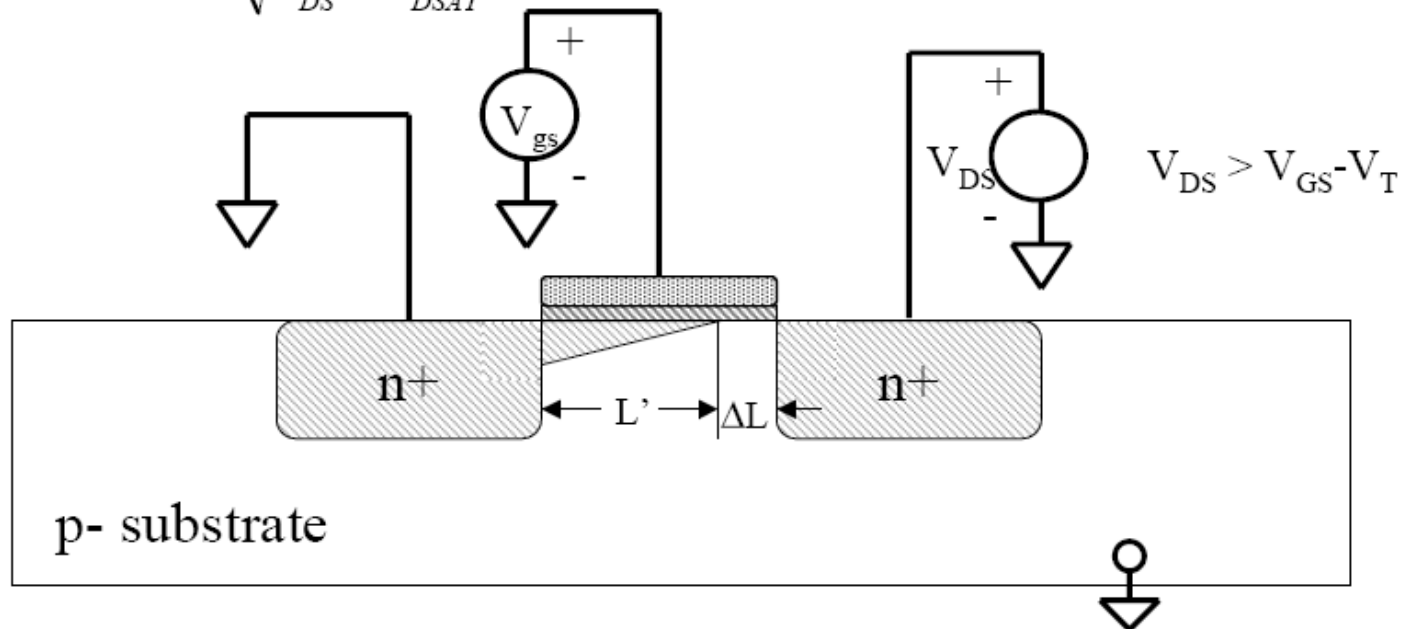
$$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_T)(V_{GS} - V_T) - \frac{(V_{GS} - V_T)^2}{2} \right]$$

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



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 ...

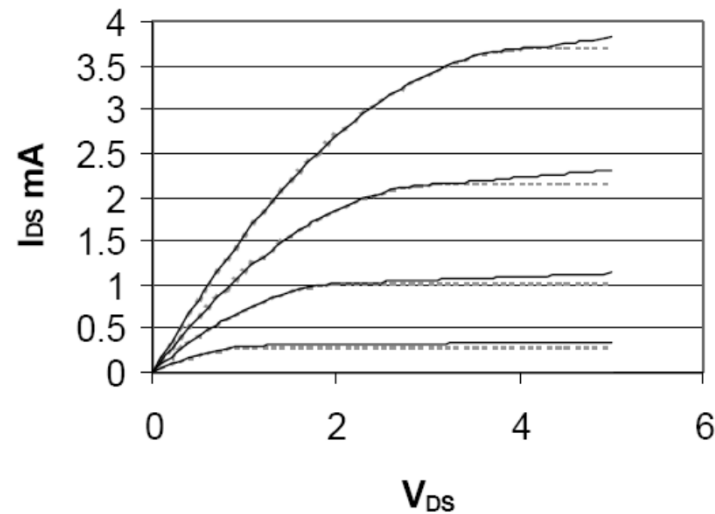


Channel Length Modulation

- 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

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

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

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

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

$$K'_n = \mu_n C_{ox}$$

