Metal Oxide Semiconductor Field Effect Transistors (MOSFETs)

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Announcements

- Pick up Midterm 1 if you haven't already!
- Two options: (1) from my office hours, or (2) ~~from lecture today~~ AFTER LECTURE FROM MY OFFICE
- MIDTERM SOLUTIONS ON BCOURSES

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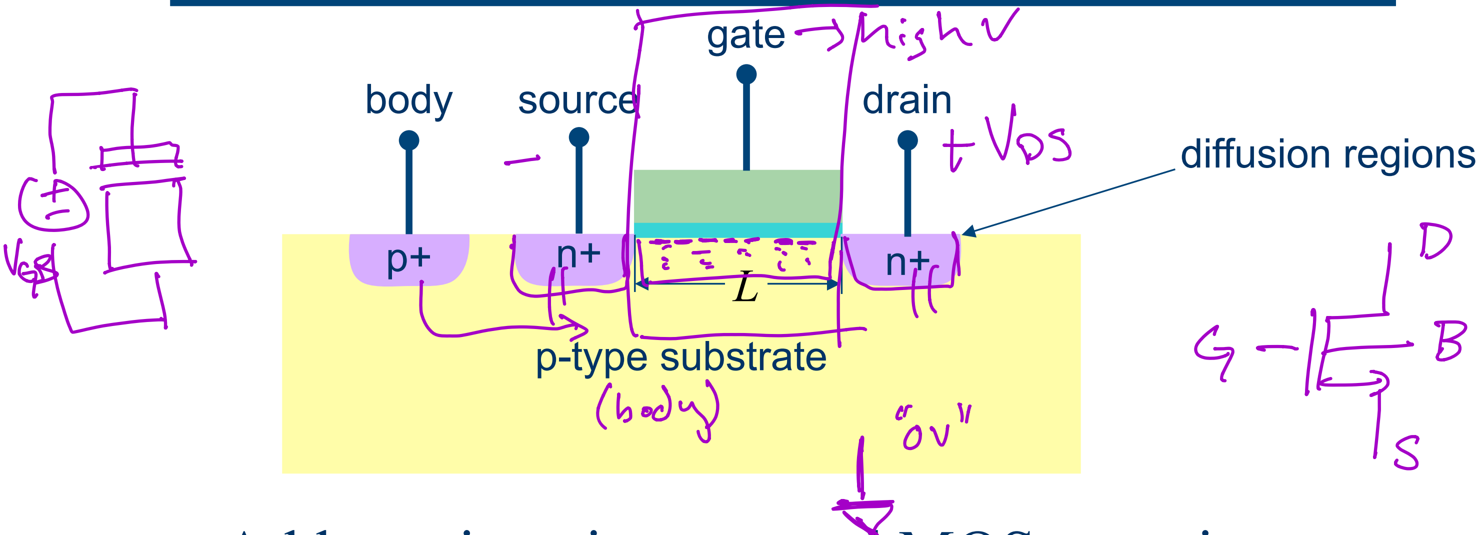
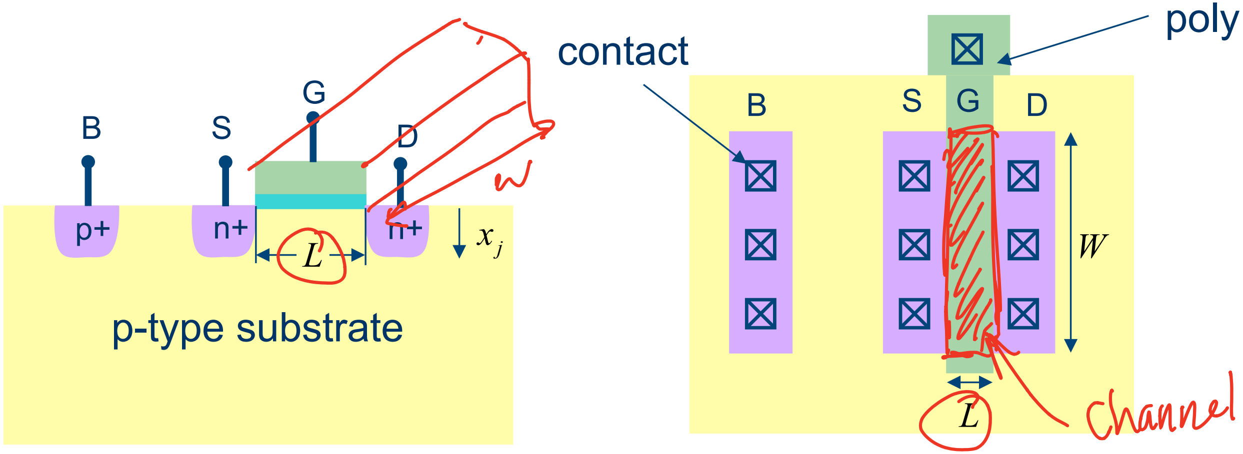
MOSFET Cross Section



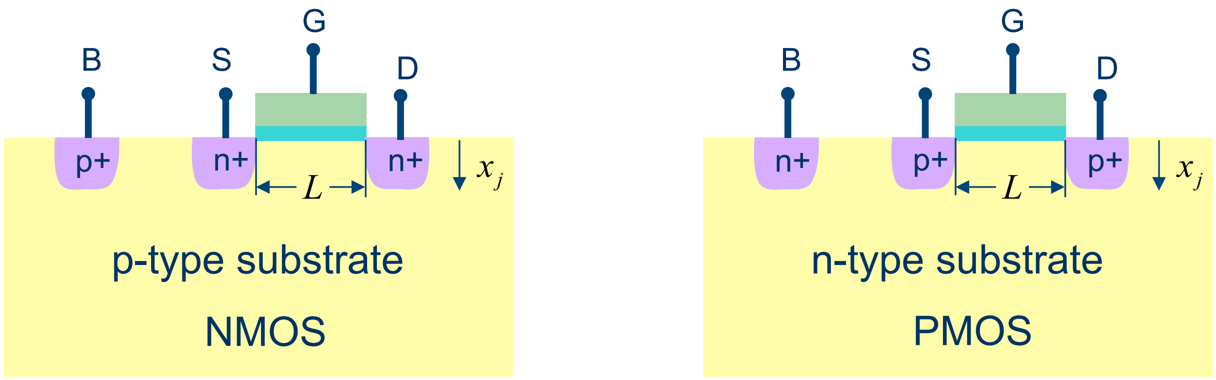
- Add two junctions around MOS capacitor
- The regions forms PN junctions with substrate
- MOSFET is a four terminal device
- The body is usually grounded (or at a DC potential)
- For ICs, the body contact is at surface

MOSFET Layout



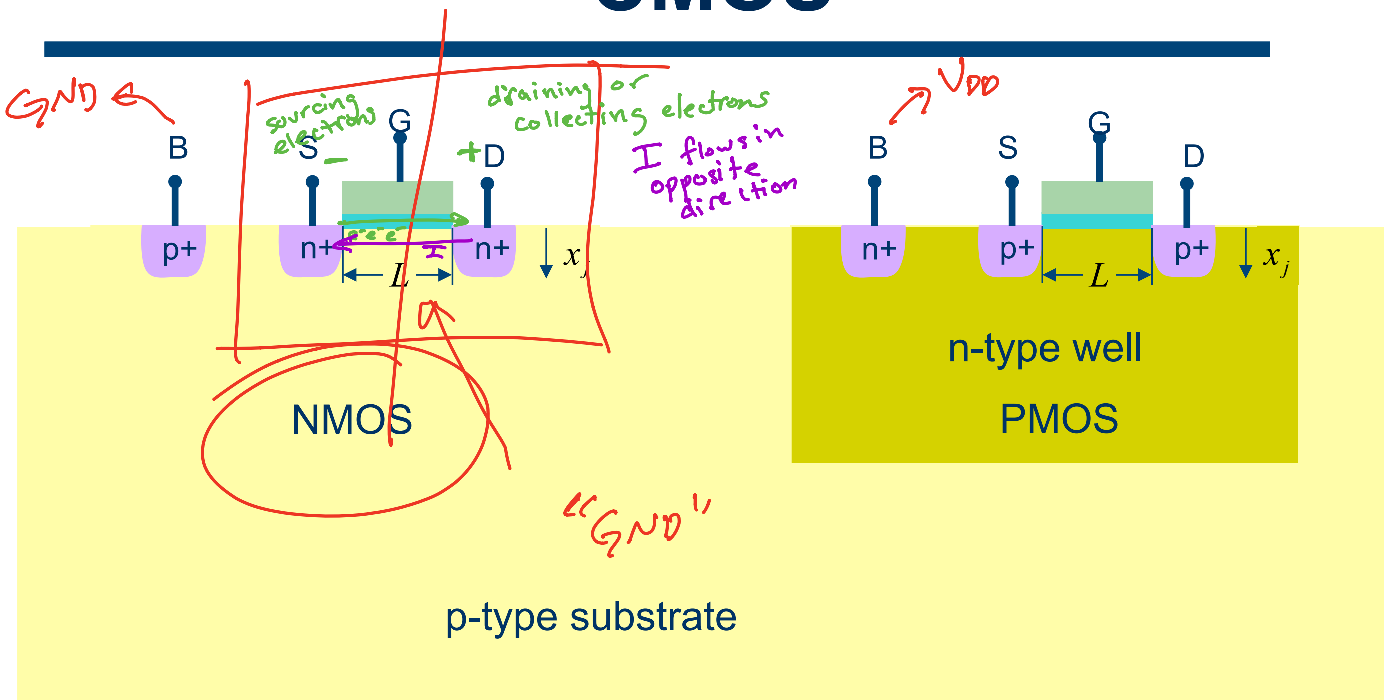
- Planar process: complete structure can be specified by a 2D layout
- Design engineer can control the transistor width W and L
- Process engineer controls t_{ox}, N_a, x_j, etc.

PMOS & NMOS



- A MOSFET by any other name is still a MOSFET:
  - NMOS, PMOS, nMOS, pMOS
  - NFET, PFET
  - IGFET
  - Other flavors: JFET, MESFET
- CMOS technology: The ability to fabricate NMOS and PMOS devices simultaneously

CMOS



- Complementary MOS (CMOS): Both P and N type devices
- Create a n-type body in a p-type substrate through compensation. This new region is called a "well".
- To isolate the PMOS from the NMOS, the well must be reverse biased (p-n junction)

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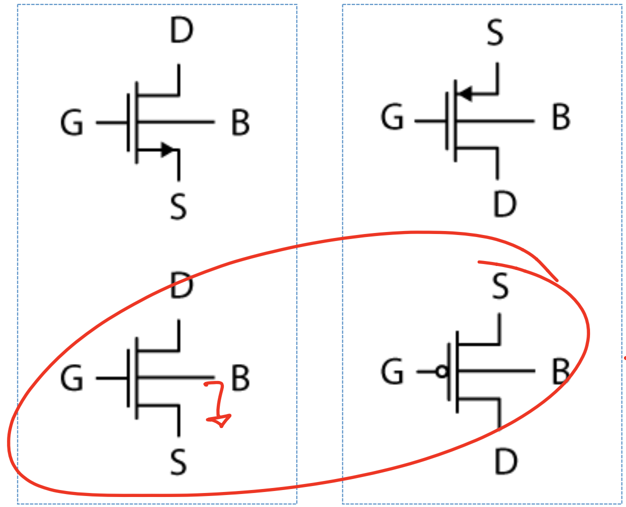
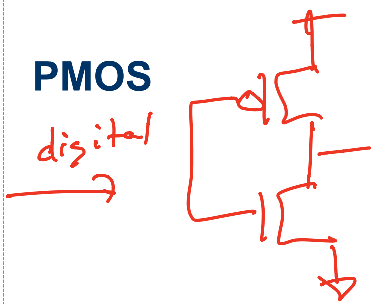
Circuit Symbols

NMOS

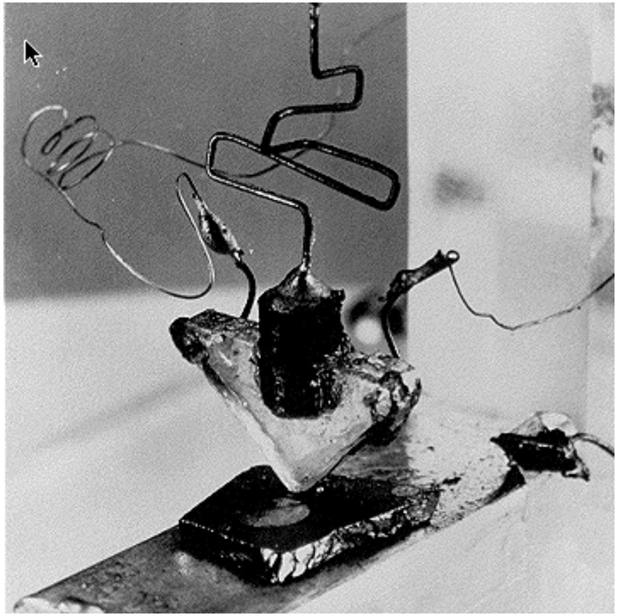


PMOS



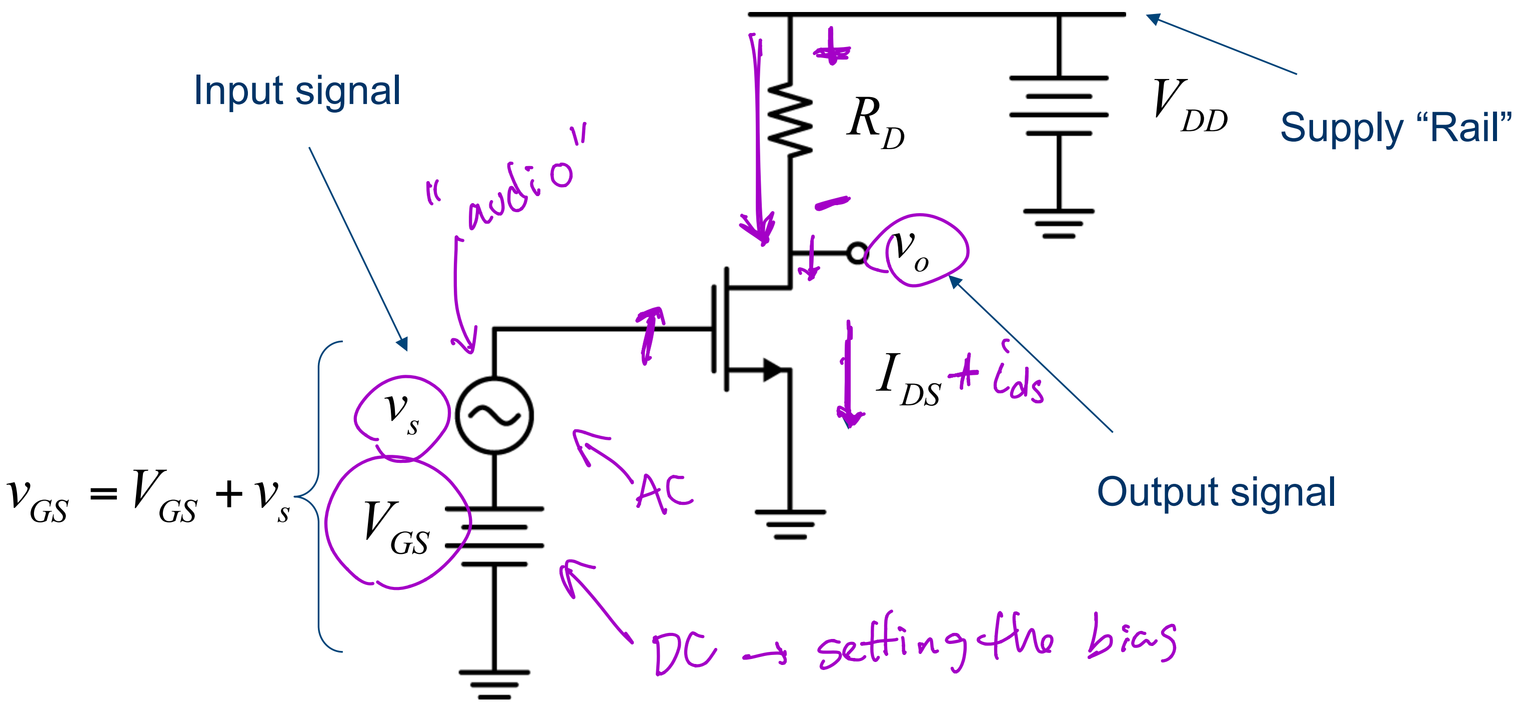
- The symbols with the arrows are typically used in analog applications
- The body contact is often not shown
- The source/drain can switch depending on how the device is biased (the device has inherent symmetry)

Circuits!

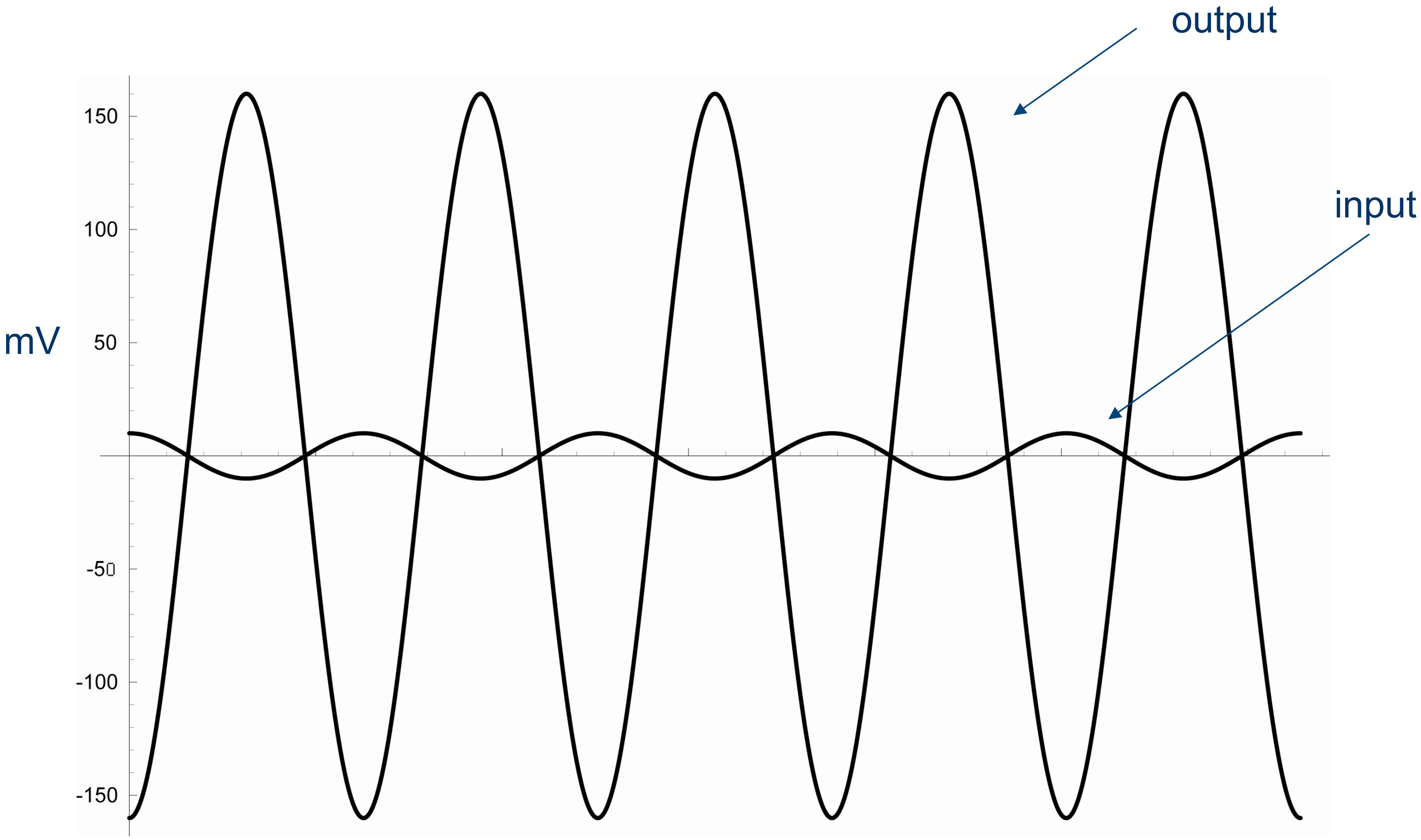


- When the inventors of the bipolar transistor first got a working device, the first thing they did was to build an audio amplifier to prove that the transistor was actually working!

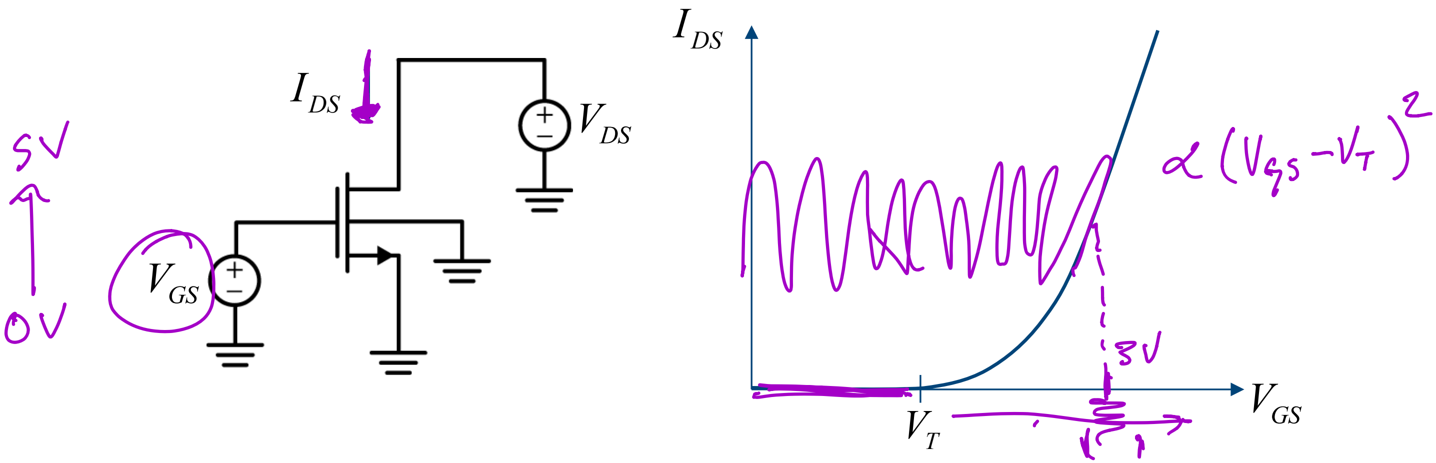
A Simple Circuit: An MOS Amplifier



Plot of Output Waveform (Gain!)

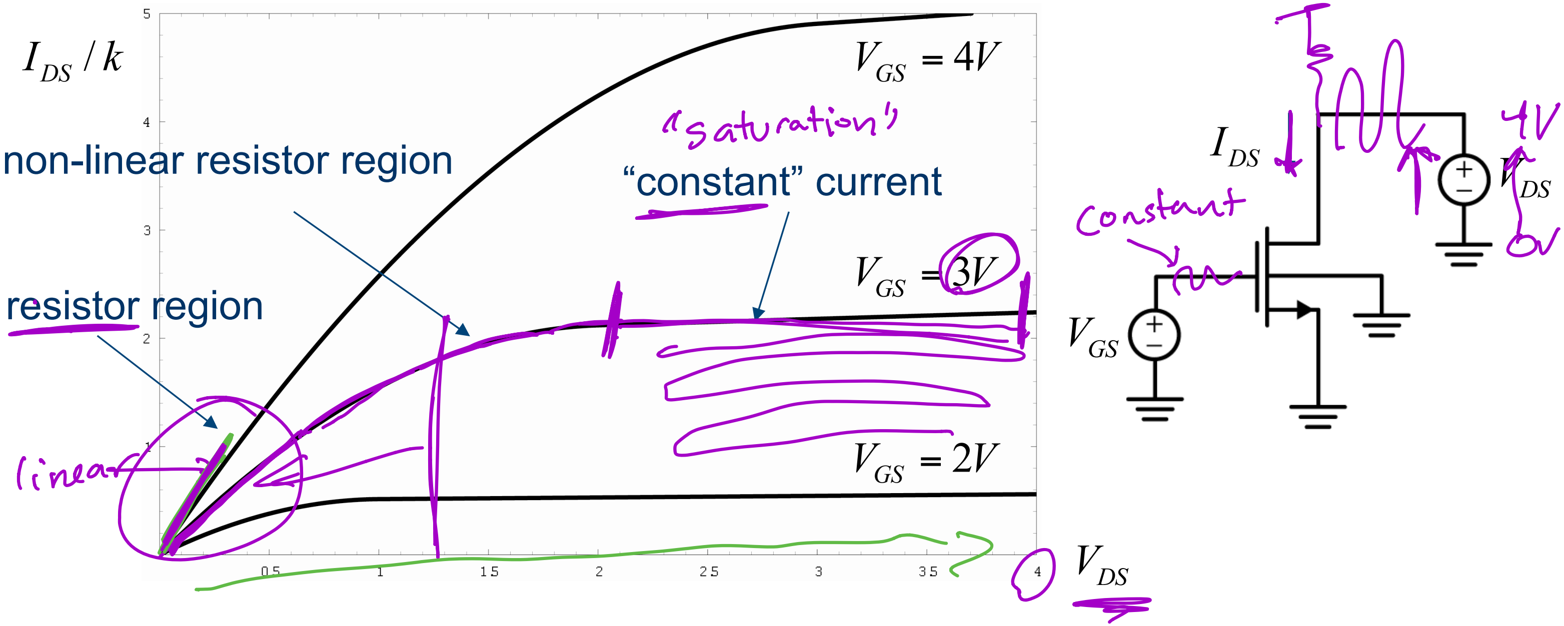


Observed Behavior: I_D-V_{GS}



- Current zero for negative gate voltage
- Current in transistor is very low until the gate voltage crosses the threshold voltage of device (same threshold voltage as MOS capacitor)
- Current increases rapidly at first and then it finally reaches a point where it simply increases ~~linearly~~ square

Observed Behavior: I_D-V_{DS}



- For low values of drain voltage, the device is like a resistor
- As the voltage is increases, the resistance behaves non-linearly and the rate of increase of current slows
- Eventually the current stops growing and remains essentially constant (current source)

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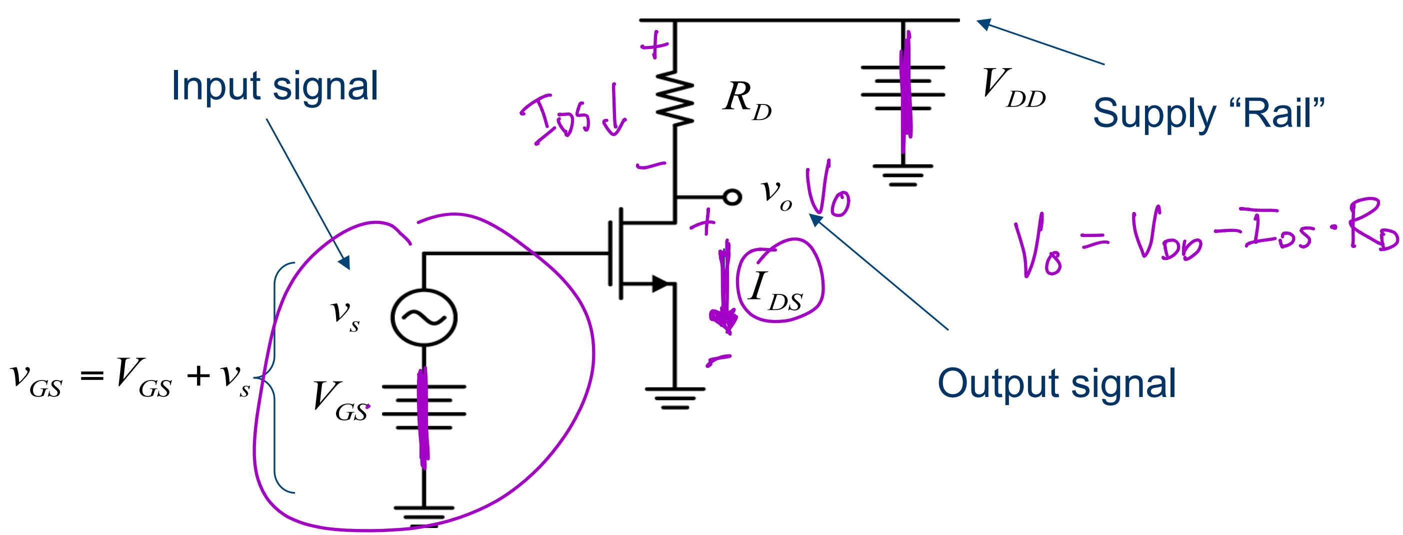
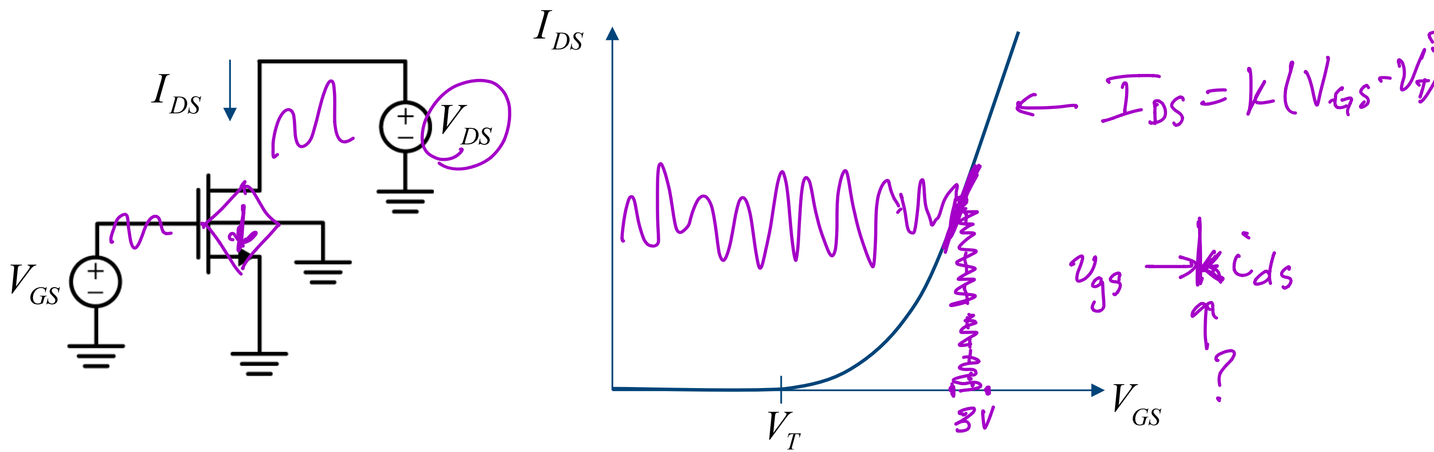
Operating Points



- Which bias voltages you operate the MOSFET at will make a big difference in how it functions.
- We will explore these regions of operation in this lecture.
- If we operate with a sufficiently high V_{GS} AND a sufficiently high V_{DS}, we can make a very good small-signal amplifier!

Small Signal vs. Large Signal



- We observe I_{DS} vs. V_{GS} to be quadratic for $V_{GS} > V_T$
- Large changes in v_{GS} result in quadratic changes at the output
- However, for small changes in v_{GS} (denoted as v_{gs}) will produce linear changes at the output!
- We can show this using Taylor series expansion:

$$i_{DS} = k(v_{GS} - V_T)^2 ; v_{GS} = V_{GS} + v_{gs}$$

$$TS : i_{DS}(v_{GS})\big|_{V_{GS}} = k(V_{GS} - V_T)^2 + 2k(V_{GS} - V_T)v_{gs} + kv_{gs}^2$$

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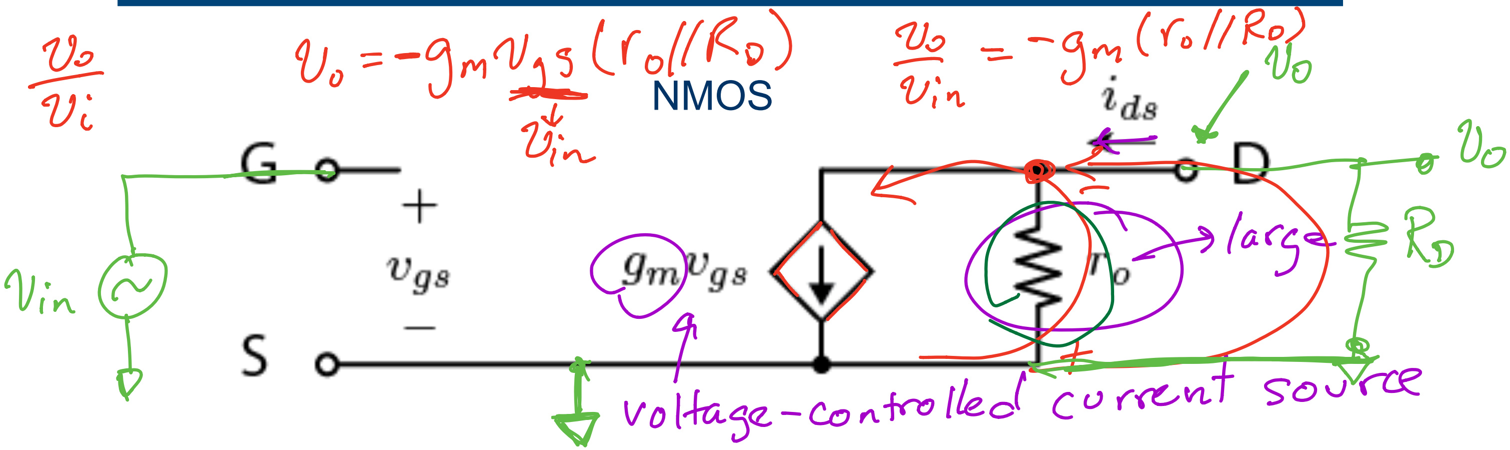
Simple Small Signal Model for MOSFET

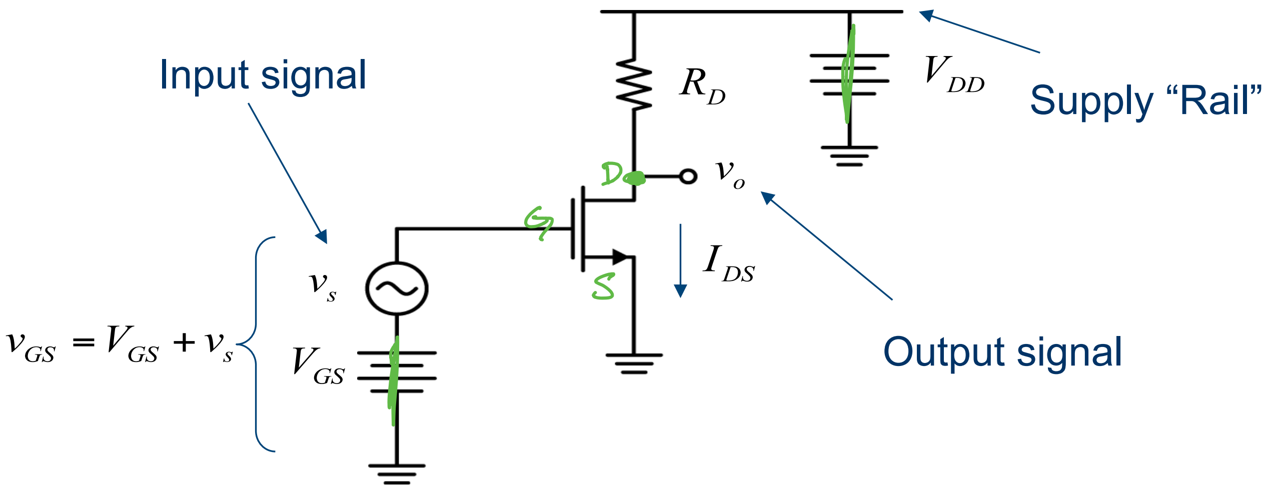


- This is a simplified, 3-terminal small-signal model for a MOSFET
- In later lectures we will develop a more complete model
- g_m = transconductance
  - defined as di_{ds}/dv_{gs}, units $[\text{Ohms}]^{-1}$
- r_o = output resistance
  - defined as $[di_{ds}/dv_{ds}]^{-1}$, units Ohms

$v_{gs} \cdot g_m = i_{ds}$

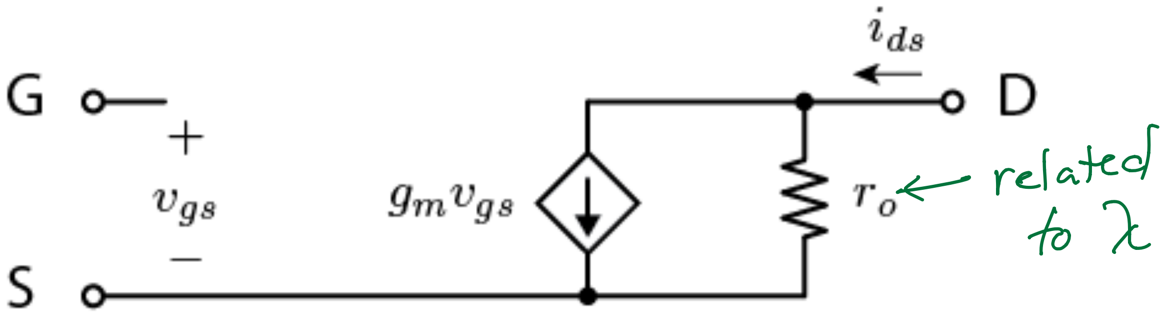
→ Siemens = $\frac{1}{\Omega}$

Small Signal Gain Example



- Steps to analyze small signal amplifiers:
- 1. Calculate bias points using DC sources
  - As you will see in later lecture, you will use these bias points to determine the MOSFET region of operation as well as to calculate small-signal parameters
- 2. Turn off DC sources
- 3. Plug in the small-signal model for a MOSFET

Small Signal Gain Example



- 4. Calculate the gain (v_{out}/v_{in}) of the circuit

MOSFET Large Signal Models and Regions of Operation

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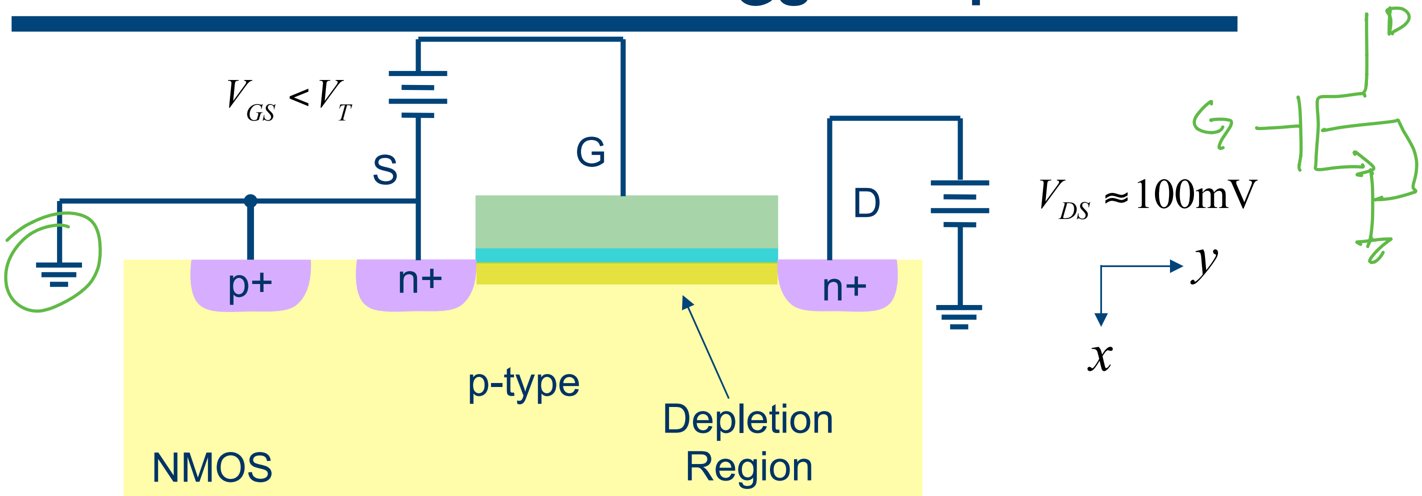
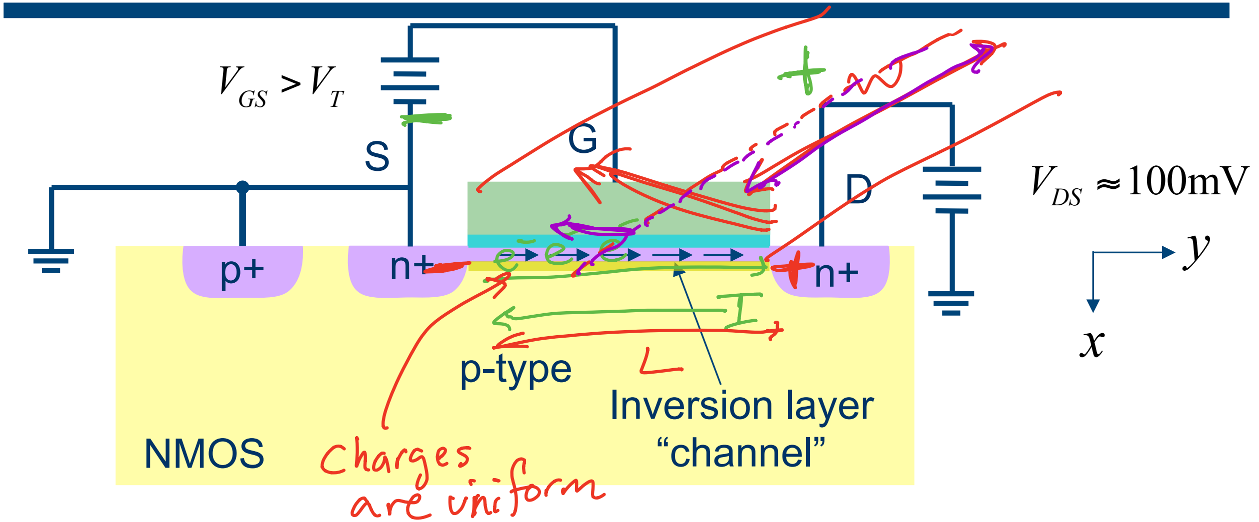
Cut-off, $V_{GS} < V_T$



- This structure should look familiar! It is an MOS capacitor with two n+ diffusion regions on each side.
- When $V_{GS} < V_T$, the device is either in accumulation or in depletion.
- Since there are no (or few) inversion charges at the surface, therefore no current will flow regardless of the value of V_{DS}.

"Linear" Region Current



- If the gate is biased above threshold, the surface is inverted
- This inverted region forms a channel of inversion charges (in this case electrons) that connects the drain and source – inversion charges originate from n+ diffusion
- If a drain-source voltage (V_{DS}) is applied positive, electrons will flow from source to drain
- *Note: electrons flow S → D, current flows D → S*

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MOSFET “Linear” Region

- The current in this channel is given by

$$I_{DS} = -W v_y Q_N$$

- The charge proportional to the voltage applied across the oxide over threshold

$$Q_N = C_{ox}(V_{GS} - V_{Tn})$$

$$I_{DS} = -W v_y C_{ox}(V_{GS} - V_{Tn})$$

- If the channel is uniform density, only drift current flows

$$v_y = -\mu_n E_y \qquad E_y = -\frac{V_{DS}}{L}$$

$$I_{DS} = \frac{W}{L}\mu_n C_{ox}(V_{GS} - V_{Tn})V_{DS} \qquad V_{GS} > V_{Tn} \qquad V_{DS} \approx 100\text{mV}$$

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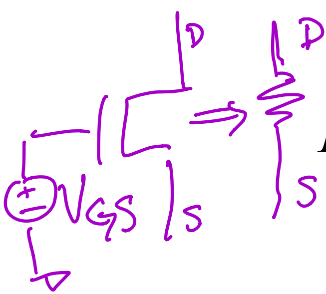
MOSFET: Variable Resistor

- Notice that in the linear region, the current is proportional to the voltage

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

- Can define a voltage-dependent resistor



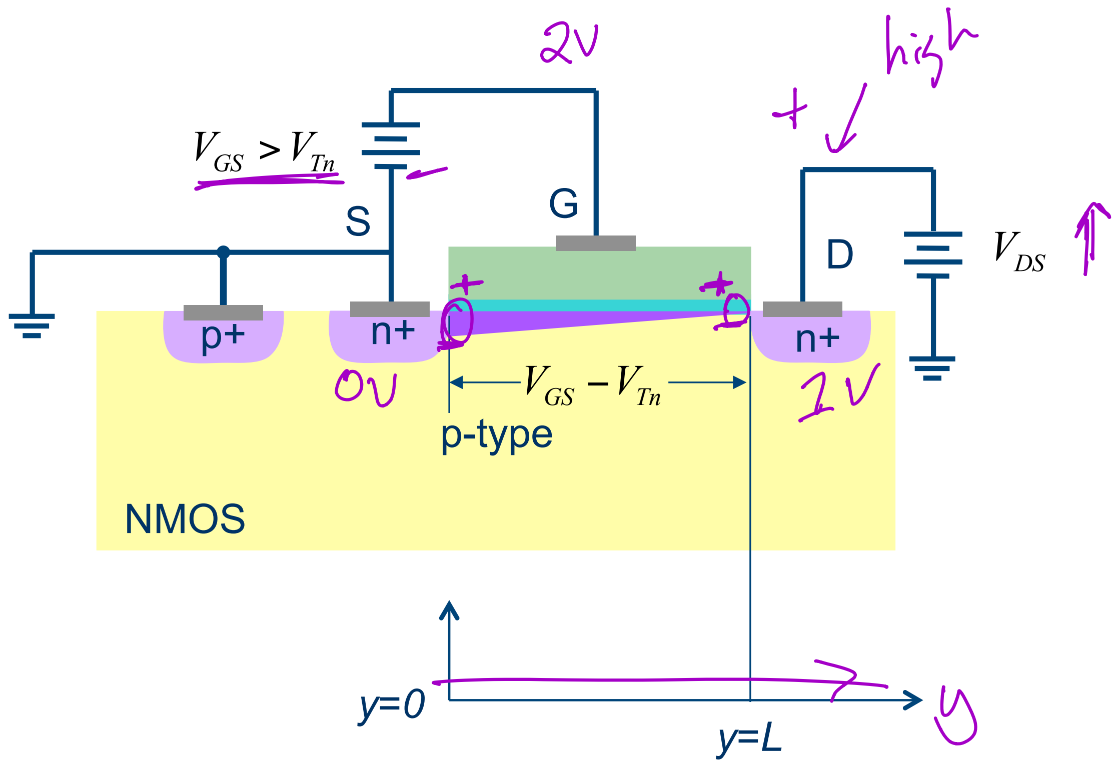
$$R_{eq} = \frac{V_{DS}}{I_{DS}} = \frac{1}{\mu_n C_{ox}(V_{GS} - V_{Tn})}\left(\frac{L}{W}\right) = R_W(V_{GS})\frac{L}{W}$$

Rw

- This is a nice variable resistor, electronically tunable!

Finding $I_D = f\,(V_{GS}, V_{DS})$

- Approximate inversion charge $Q_N(y)$: drain voltage is higher than the source → less charge at drain end of channel



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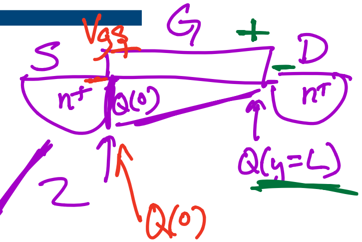
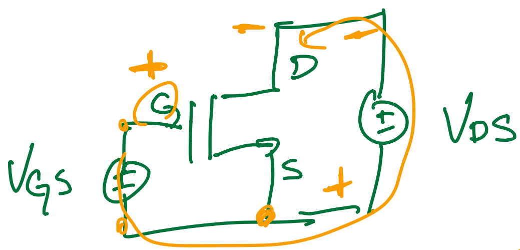
Inversion Charge at Source/Drain



$$Q_N(y) \approx Q_N(y=0) + Q_N(y=L)$$

$$Q_N(y=0) = -C_{ox}(V_{GS} - V_{Tn})$$

$$Q_N(y=L) = -C_{ox}(V_{GD} - V_{Tn})$$



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

Average Inversion Charge

Source End Drain End

$$Q_N(y) \approx -\frac{C_{ox}(V_{GS}-V_T)+C_{ox}(V_{GD}-V_T)}{2}$$

$$Q_N(y) \approx -\frac{C_{ox}(V_{GS}-V_T)+C_{ox}(V_{GS}-V_{DS}-V_T)}{2}$$

$$Q_N(y) \approx -\frac{C_{ox}(2V_{GS}-2V_T)-C_{ox}V_{DS}}{2} = -C_{ox}(V_{GS}-V_T-\frac{V_{DS}}{2})$$

- Charge at drain end is lower since the vertical field is lower at that point

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Drift Velocity and Drain Current

Use mobility to find velocity v

$$v(y) = -\mu_n E(y) \approx -\mu_n(-\Delta V / \Delta y) = \frac{\mu_n V_{DS}}{L}$$

same as linear region

Substituting:

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

only term that's different

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

standard format

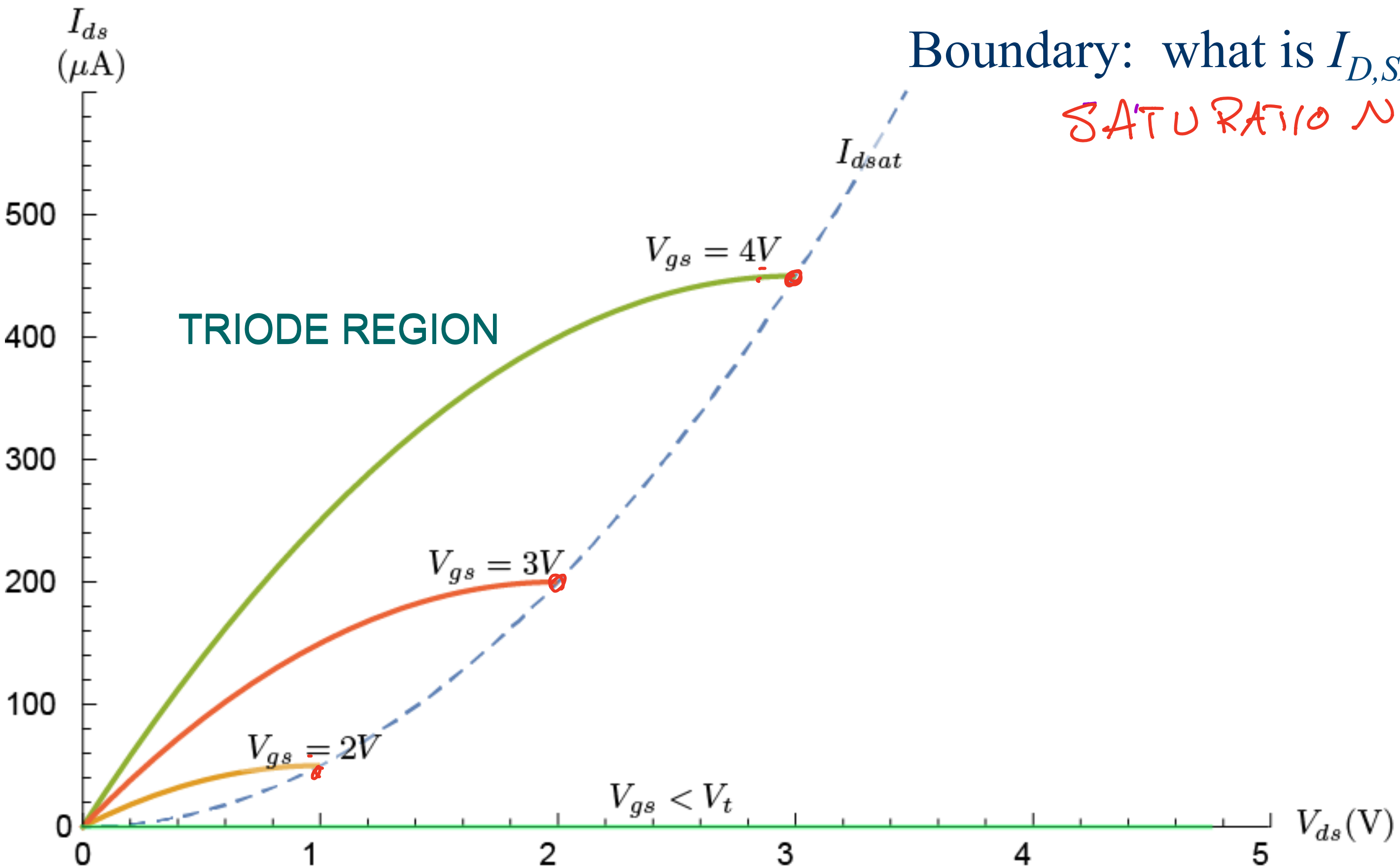
Family of Inverted Parabolas

if V_{DS} is small, this term goes away → becomes linear eq.

Square-Law Characteristics

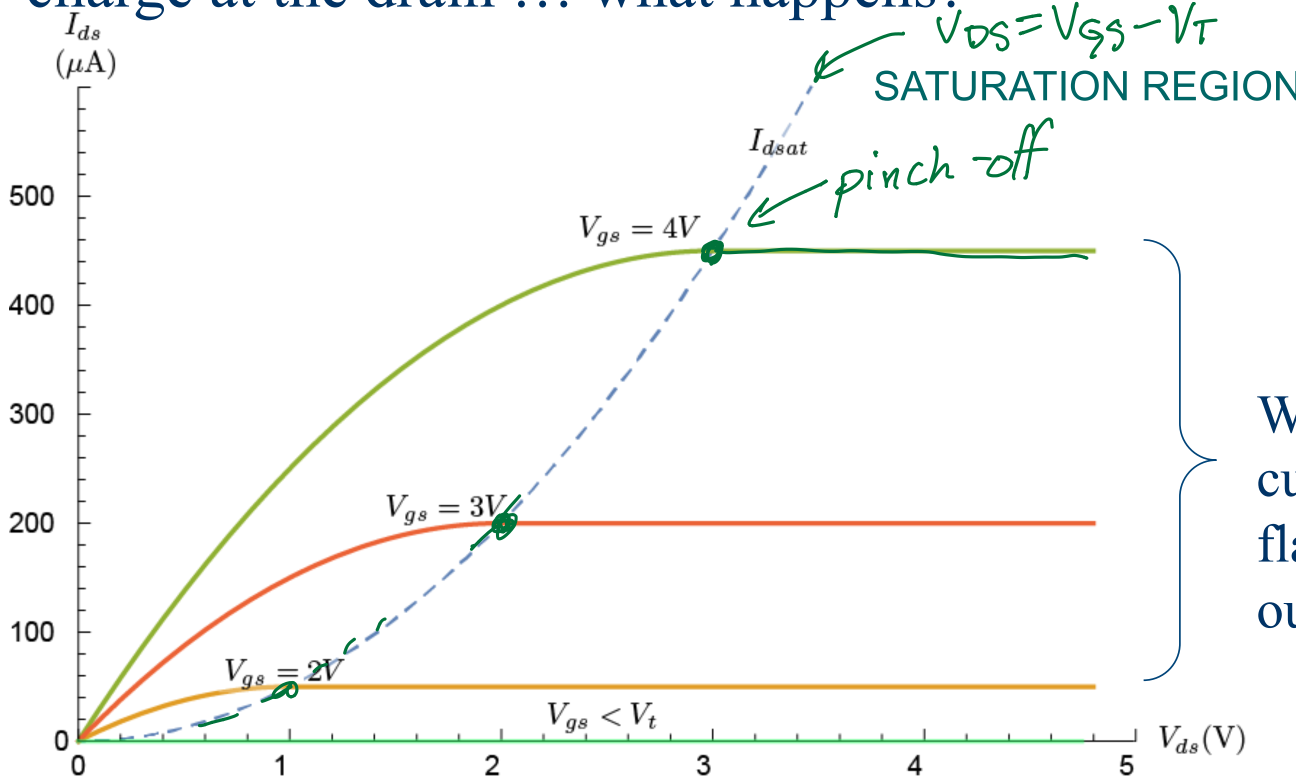
Boundary: what is $I_{D,SAT}$?

SATURATION



The Saturation Region

When $V_{DS} > V_{GS} - V_{Tn}$, there isn't any inversion charge at the drain … what happens?



Why do curves flatten out?

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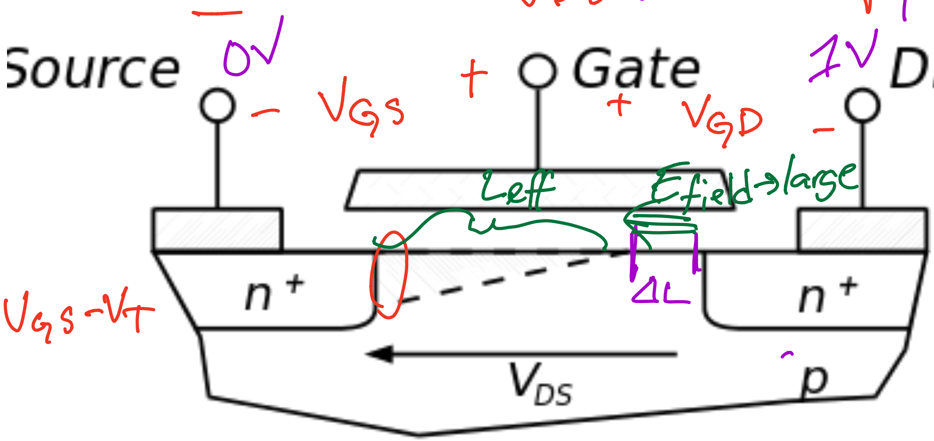
Why does current saturate?

- The charge at drain end goes to zero once $V_{GD} < V_T$
- We say that the drain end is "pinched off"
  - If you pinch a hose, water flow stops !
  - But then how does current flow?



$V_T = 0.5V$

$2V \rightarrow V_{GD} = 0$

$V_{DS} = 1.5V$

$Q \propto V_{GS} - V_T$

$Q \propto V_{GD} - V_T$

$\propto V_{GS} - V_{DS} - V_T$

$2V - 1.5V - .5V = 0$

$V_{GS} - V_{DS} - V_T = 0$

OR

pinch-off $\rightarrow$ $V_{GS} - V_T = V_{DS}$

saturation → $V_{GS} - V_T \leq V_{DS}$

Pinch Off

- Excess field beyond E_{dsat} drops across tiny region between drain and channel
  - Huge field means that electrons flow at very high velocity across the "high field" region.
  - They are injected from source end and are collected at the drain end
- Increasing the drain voltage does not increase current (appreciably) because the current is limited by the supply of electrons from channel side

Square-Law Current in Saturation

Current stays at maximum (where $V_{DS} = V_{GS} - V_{Tn} = V_{DS,SAT}$)

no ΔV across G–D

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

$$I_{DS,sat} = \frac{W}{L}\mu C_{ox}(V_{GS} - V_T - \frac{V_{GS} - V_T}{2})(V_{GS} - V_T)$$

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

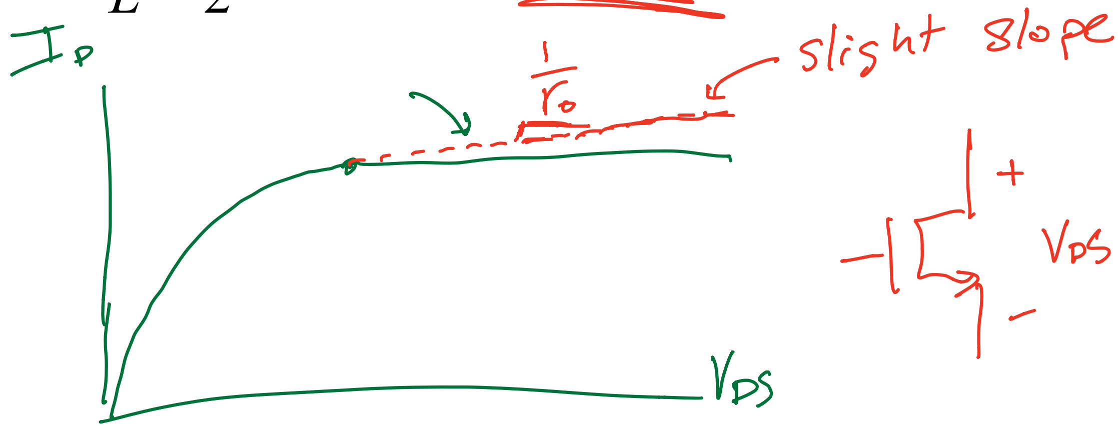
standard form

"square law"

Actual Saturation Current

- Measurement: I_D increases slightly with increasing V_{DS}:
- The physics is complicated, but a simple way to see this is that the channel is getting shorter as the drain voltage depletes away more electrons from the drain end
- We model this with an additional linear factor:

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



Channel Length Modulation

- When $v_{DS} = v_{GS}-V_T$, the channel pinches off near the drain. With further increase in v_{DS}, the pinch-off point moves toward the source, effectively reducing the channel length from L to L-ΔL.

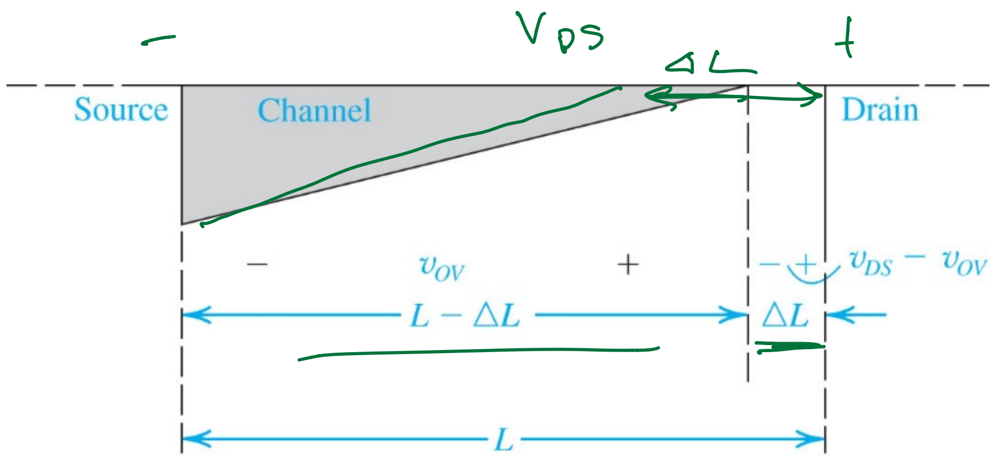
L that we drew

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

changes with V_{DS}

The continual increase of I_D with V_{DS} is modeled by

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



Summary: Regions of Operation

- Cut-off: $V_{GS} < V_T$
  - $I_{DS} = 0$
  - *Note: this is an approximation we will make in EE105, in later courses you will learn about sub-threshold conduction*
- Linear: $V_{GS} > V_T$, $V_{DS} << V_{GS} - V_T$

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

- Triode: $V_{GS} > V_T$, $V_{DS} < V_{GS} - V_T$

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

- Saturation: $V_{GS} > V_T$, $V_{DS} > V_{GS} - V_T$

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

PMOS Device

- So far, we've derived all of our equations for an NMOS device
- PMOS devices work exactly the same way, but with an n-type body and a channel made of positive charges (holes)
- The direction of the voltages and currents are inverted, for example:

$$I_{SD,sat} = \frac{W}{L}\frac{\mu C_{ox}}{2}(V_{SG} - V_{Tp})^2(1+\lambda V_{SD})$$

μ_n λ_n

μ_p λ_p

V_{Tn} vs V_{Tp}

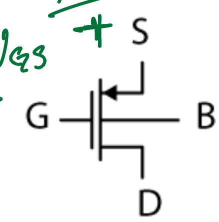
same

threshold is negative

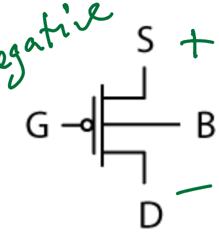
tox is same thickness across wafer

PMOS

negative → V_{GS} OR V_{SG}



V_{DS} is negative OR V_{SD}



Next Lecture

- In the next lecture we will learn how to analyze small-signal amplifiers, including
  - Computation of bias points
  - How to derive and compute small signal model parameters (g_m, r_o)
  - How to calculate small signal gain