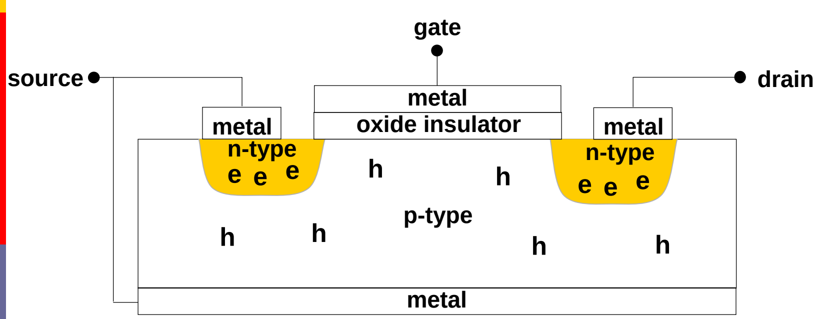
Lecture 17

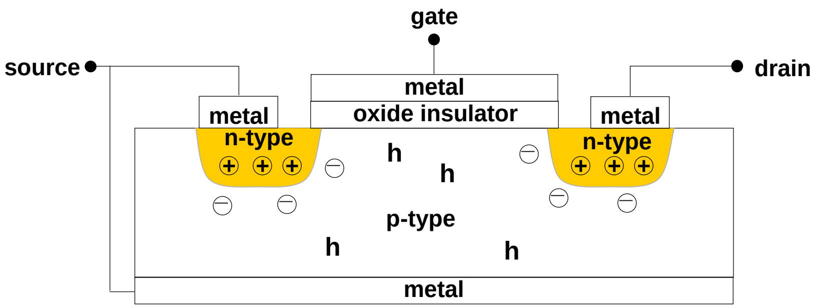
Today we will discuss

- Metal Oxide Semiconductor (MOS) Transistors
  - Physical structure
  - Physical operation
  - Circuit symbol and current/voltage designations
  - Modes of operation
  - I-V Relationship
  - Solution of MOS circuits

NMOS (N-Channel Metal Oxide Semiconductor) Transistor



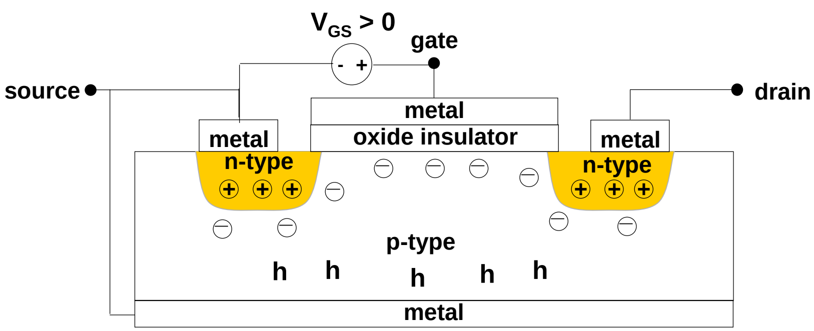
NMOS Transistor in Equilibrium



When the transistor is left alone, some electrons from the n-type wells diffuse into the p-type material to fill holes.

This creates negative ions in the p-type material and positive ions are left behind in the n-type material.

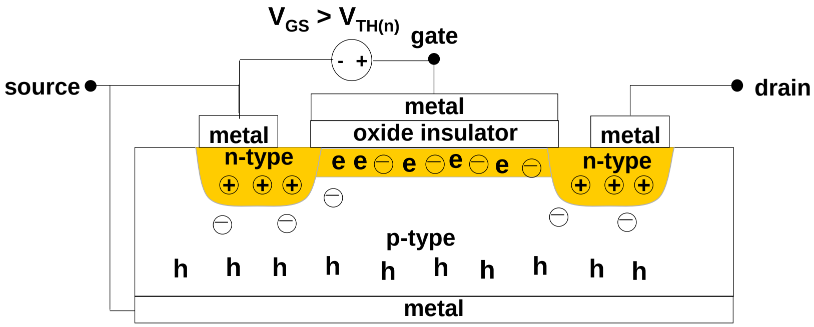
NMOS Transistor in Cutoff



When a small, positive V_{GS} is applied, holes "move away" from the gate.

Electrons from complete atoms elsewhere in the p-type material move to fill holes near the gate instead.

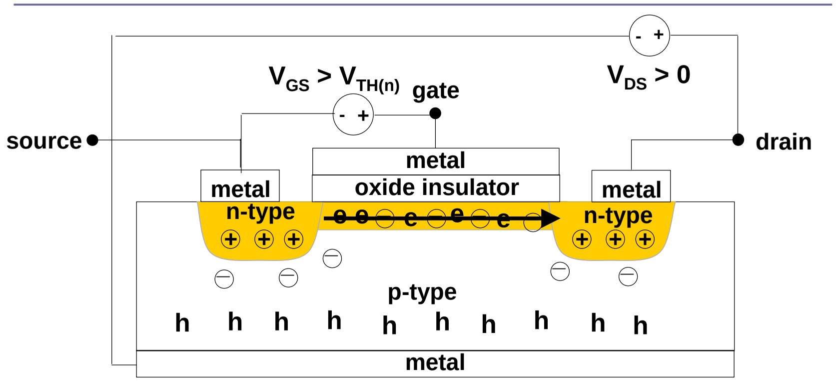
NMOS Transistor Channel



When V_{GS} is larger than a **threshold** voltage $V_{TH(n)}$, the attraction to the gate is so great that free electrons collect there.

The applied V_{GS} creates an **induced n-type channel** under the gate (an area with free electrons).

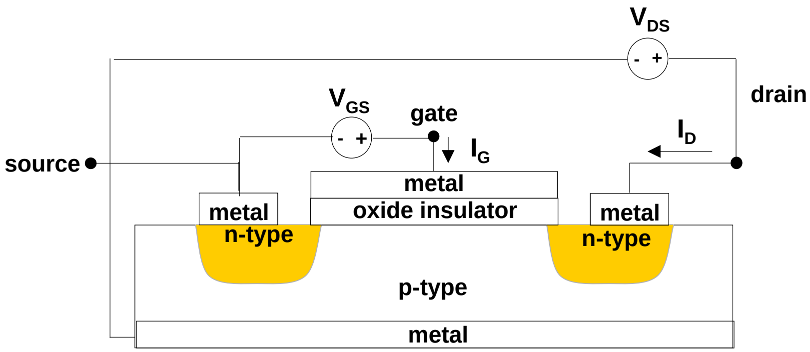
NMOS Transistor Drain Current

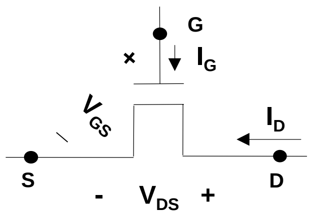


When a positive V_{DS} is applied, the free electrons flow from the source to the drain. (Positive current flows from drain to source).

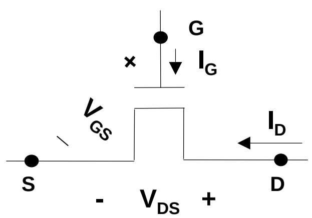
The amount of current depends on V_{DS}, as well as the number of electrons in the channel, channel dimensions, and material.

NMOS Transistor Circuit Symbol



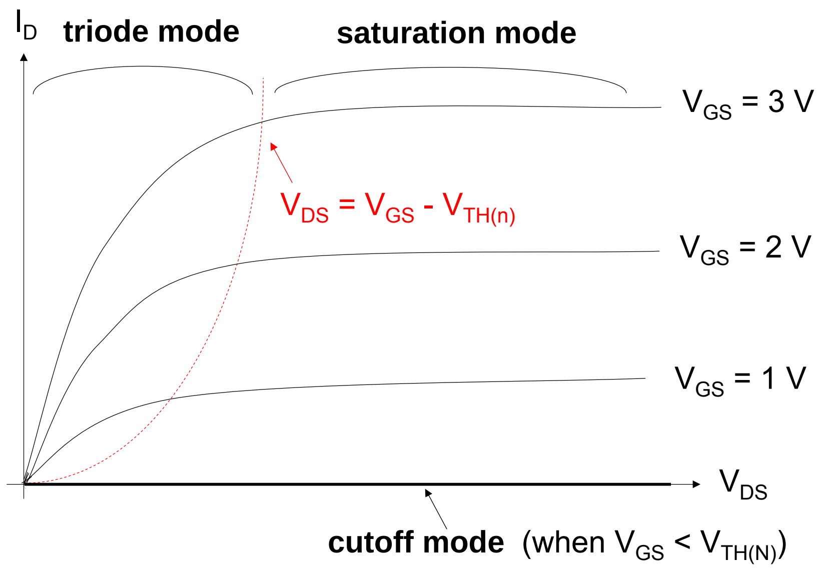


NMOS I-V Characteristic



- Since the transistor is a 3-terminal device, there is no single I-V characteristic.
- Note that because of the insulator, I_G = 0 A.
- We typically define the MOS I-V characteristic as I_D vs. V_{DS} for a fixed V_{GS}.
- The I-V characteristic changes as V_{GS} changes.

NMOS I-V Curves



Modes of Operation

- For small values of V_{GS}, $V_{GS} \leq V_{TH(n)}$, the n-type channel is not formed. No current flows. This is **cutoff mode**.
- When $V_{GS} > V_{TH(n)}$, current I_D may flow from drain to source, and the following modes of current flow are possible.
  - The mode of current flow depends on the propelling voltage, V_{DS}, and the channel-inducing voltage, $V_{GS} – V_{TH(n)}$.
  - When $V_{DS} < V_{GS} – V_{TH(n)}$, current is starting to flow. I_D increases rapidly with increased V_{DS}. This is **triode mode**.
  - When $V_{DS} \geq V_{GS} – V_{TH(n)}$, current is reaching its maximum value. I_D does not increase much with increased V_{DS}. This is called **saturation mode**.

Faucet Analogy

Imagine the faucet on your kitchen sink.

- To make water flow, the water supply has to be connected to the faucet. This establishes a path for water to flow.
- Setting V_{GS} above the threshold voltage is like connecting the water supply.
- **Cutoff = water supply disconnected (no path for current flow)**
- Setting V_{GS} to a larger value is like connecting a high-pressure water supply—more flow can potentially occur.

Faucet Analogy

- The faucet itself is used to adjust water flow. You can turn the flow up and down.
- V_{DS} is like the faucet. It controls the amount of flow.
- There is, of course, a saturation point. If you keep turning the faucet control, eventually you won't get any more flow.
- **Triode = faucet in "normal range", controls flow**
- **Saturation = faucet turned up to (or past) point for maximum flow**

NMOS Equations

Cutoff Mode

Occurs when $V_{GS} \le V_{TH(n)}$

$$I_D = 0$$

Triode Mode

Occurs when $V_{GS} > V_{TH(n)}$ and $V_{DS} < V_{GS} - V_{TH(n)}$

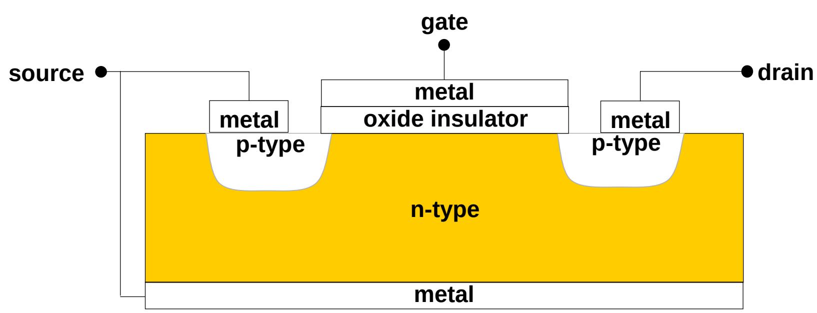
$$I_D = \frac{W}{L}\mu_n C_{OX}\left(V_{GS} - V_{TH(n)} - (V_{DS}/2)\right)V_{DS}$$

Saturation Mode

Occurs when $V_{GS} > V_{TH(n)}$ and $V_{DS} \ge V_{GS} - V_{TH(n)}$

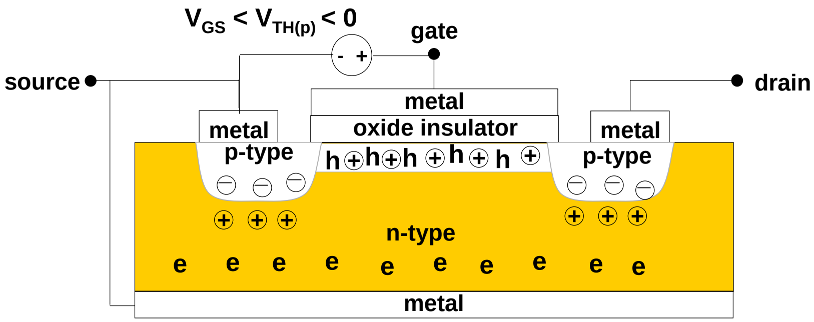
$$I_D = \frac{W}{L}\mu_n C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(n)}\right)^2\left(1 + \lambda_n V_{DS}\right)$$

PMOS (P-Channel Metal Oxide Semiconductor) Transistor



Same as NMOS, only p-type and n-type switched

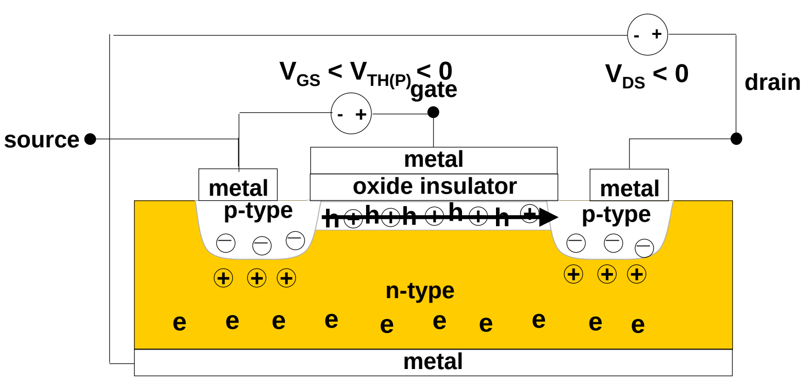
PMOS Transistor Channel



When V_{GS} is more negative than a **threshold** voltage $V_{TH(p)}$, the gate attracts many positive ions and holes (repels electrons)

Thus the applied V_{GS} creates an **induced p-type channel** under the gate (an area with positive ions).

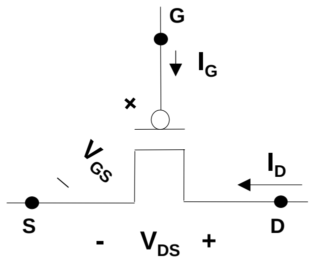
PMOS Transistor Drain Current



When a negative V_{DS} is applied, the positive ions flow from the source to the drain. (Positive current flows from source to drain).

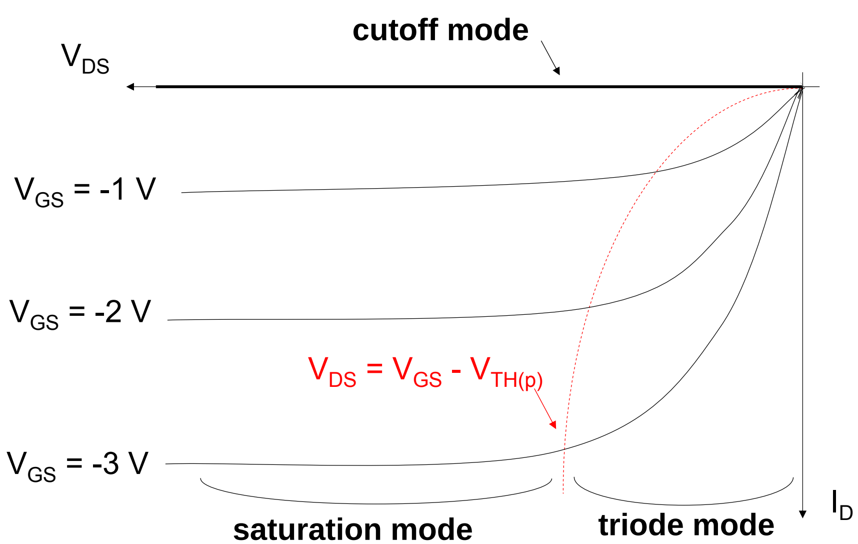
The amount of current depends on V_{DS}, as well as the number of ions in the channel, channel dimensions, and material.

PMOS Transistor Circuit Symbol



- Symbol has “dot” at gate. NMOS does not.
- I_D, V_{GS}, V_{DS}, and $V_{TH(p)}$ are all negative. These values are positive for NMOS.
- Channel formed when $V_{GS} < V_{TH(p)}$. Opposite for NMOS.
- Saturation occurs when $V_{DS} \leq V_{GS} - V_{TH(p)}$. Opposite for NMOS.

PMOS I-V Curves



PMOS Equations

Cutoff Mode

Occurs when $V_{GS} \geq V_{TH(p)}$

$$I_D = 0$$

Triode Mode

Occurs when $V_{GS} < V_{TH(p)}$ and $V_{DS} > V_{GS} - V_{TH(p)}$

$$I_D = -\frac{W}{L}\mu_p C_{OX}\left(V_{GS} - V_{TH(p)} - (V_{DS}/2)\right)V_{DS}$$

Saturation Mode

Occurs when $V_{GS} < V_{TH(p)}$ and $V_{DS} \leq V_{GS} - V_{TH(p)}$

$$I_D = -\frac{W}{L}\mu_p C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(p)}\right)^2\left(1 + \lambda_p V_{DS}\right)$$

Solving Transistor Circuits

- Guess the transistor mode (for each transistor).
  - Sometimes you can make educated guess
- Write down the I-V relationships that go with those modes: 1 equation, 3 unknowns (I_D, V_{DS}, V_{GS}) for each transistor
- Write down KVL and KCL equations (enough so that we can solve for the 3 unknowns)
- Check values of I_D, V_{DS}, V_{GS} – do they agree with mode?
- If yes, done. Else, start over with new guess.