Preliminaries and Device Physics

CSE562: Analog Integrated Circuits

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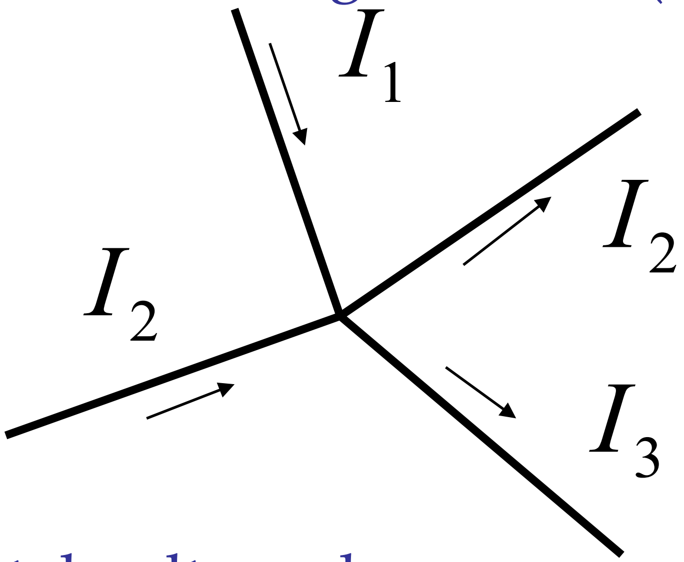
Fundamental Concepts in Electronics

- Flow of current is due to flow of charged particles (equivalently due to flow of electrons).
- Current always flows from higher potential (voltage) to a lower potential (voltage). In the absence of any potential difference, electrons (or any particle) flow from a higher concentration region to a lower concentration region.
- Conductors (e.g. Aluminum, Gold) can be assumed to be an infinite source of electrons.
- Static electric field cannot exist inside a good conductor. This implies static charge cannot exist inside the body of the conductor but can reside on the surface.

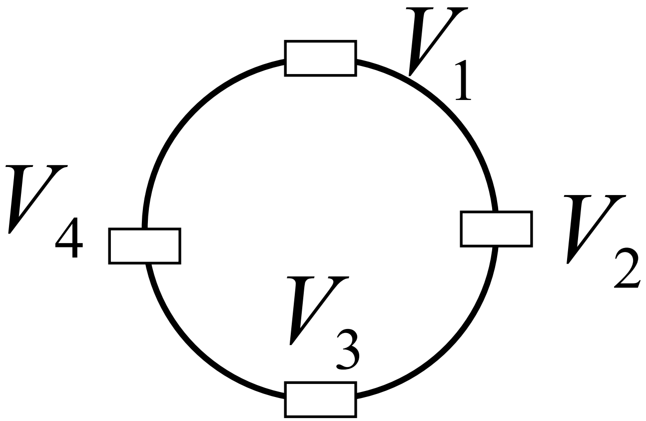
Conservation Laws

- Total current entering a node (conductor) is equal to total current leaving the node (Kirchoff's current law).



$$I_1 + I_2 = I_3 + I_4$$

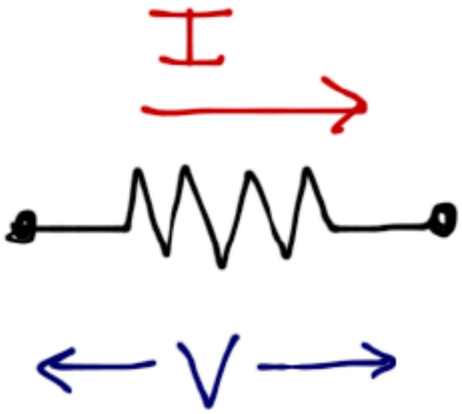
- Total voltage drop across a loop is equal to zero.



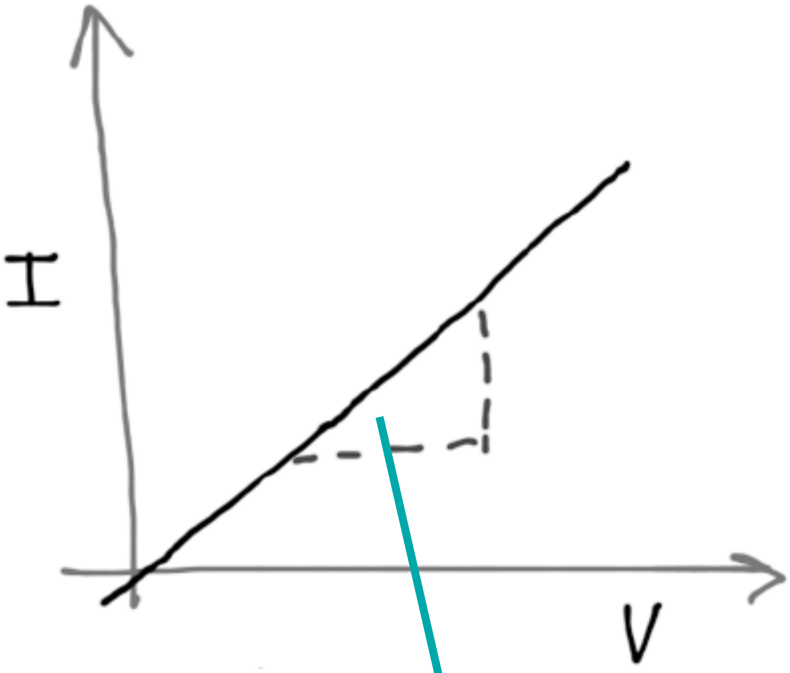
$$V_1 + V_2 + V_3 + V_4 = 0$$

Resistance and Ohms Law

- Current flowing through a linear resistor is linearly proportional to the voltage drop (potential difference) across it.



$$I \propto V$$



Slope is given by Transconductance

Transconductance

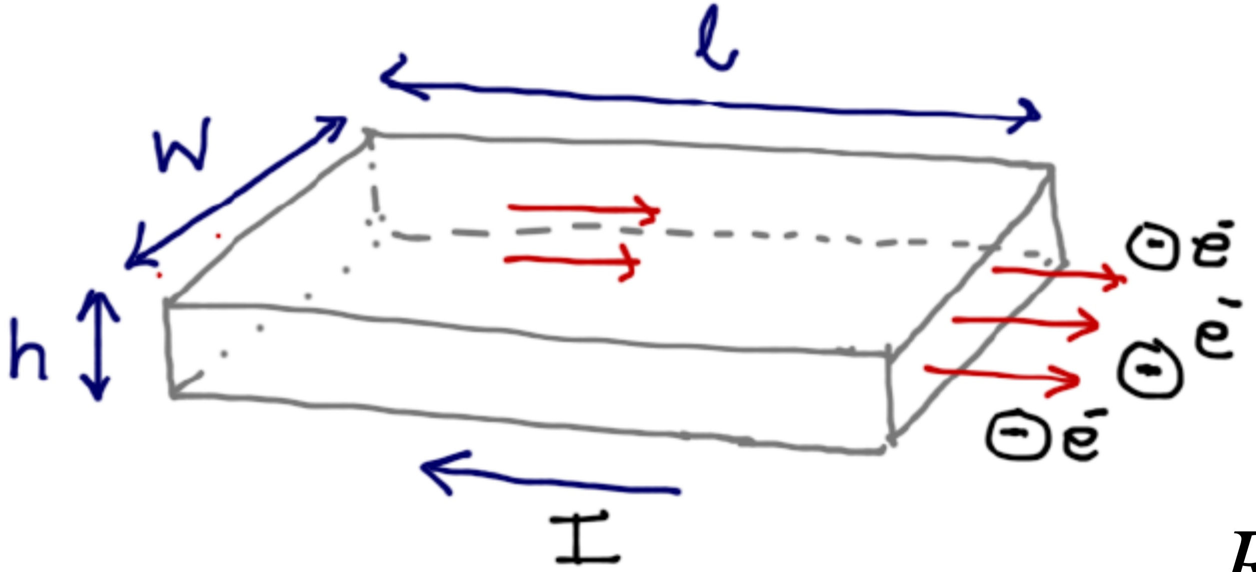
$$I = gV = \frac{1}{R}V$$

Resistance

Factors determining resistance

- Resistance is directly proportional to the length of the material.

- Resistance is inversely proportional to the cross-sectional area of the material



$$R \propto \frac{L}{Wh}$$

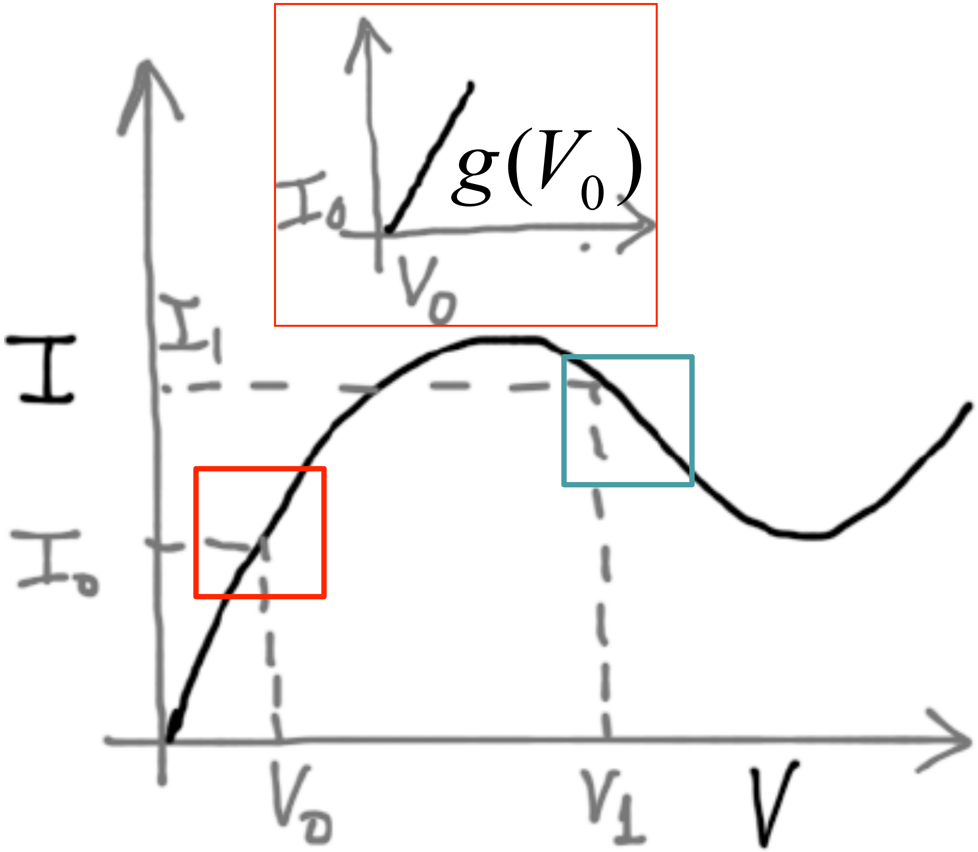
Resistivity

Silver: $1.6\text{x}10^{-8}$ ohms-m
Aluminum: $2.8\text{x}10^{-8}$ ohms-m
Silicon: $6.4\text{x}10^{2}$ ohms-m
Teflon: 10^{24} ohms-m

$$R = \rho \frac{L}{A}$$

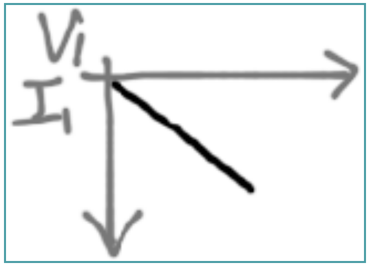
Non-linear Resistance and Ohms Law

- For a non-linear resistance, a useful concept is known as incremental resistance or conductance.



$$\frac{dI}{dV} = g(V) = \frac{1}{R(V)}$$

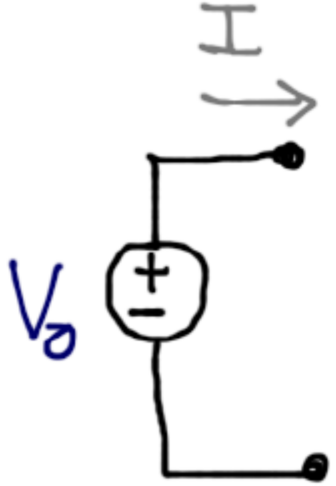
Resistance

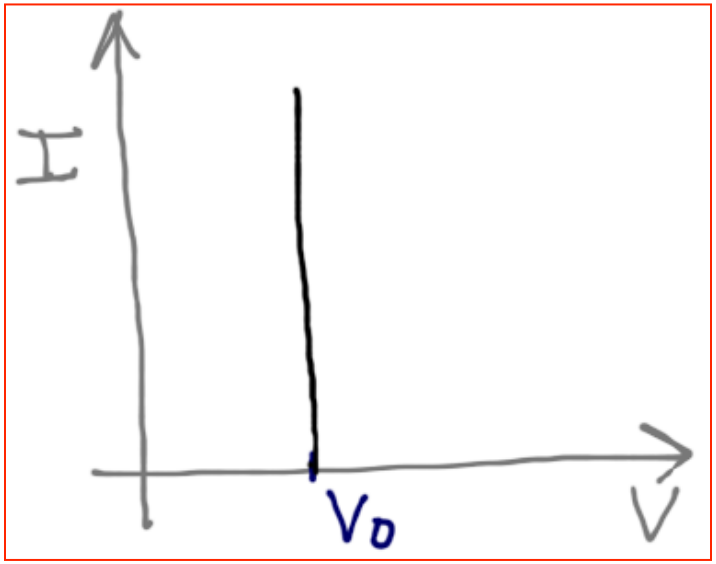


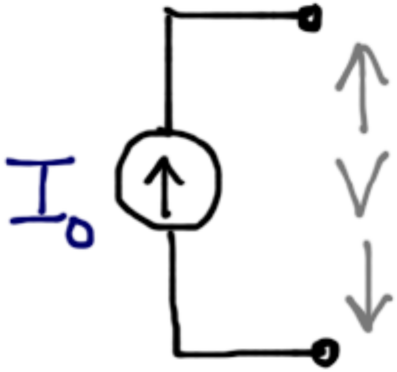
$g(V_1)$

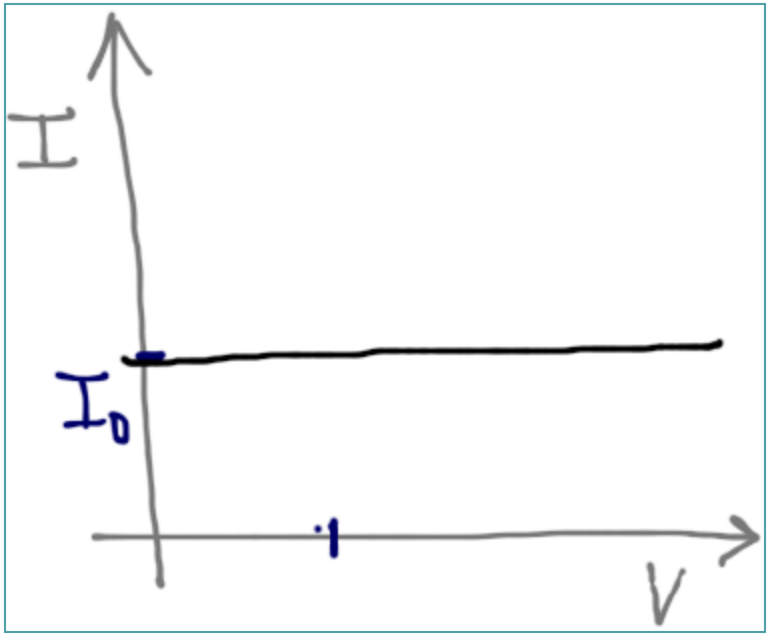
Ideal Voltage and Current Sources

- Ideal voltage source has zero internal resistance.
- Ideal current source has infinite internal resistance.

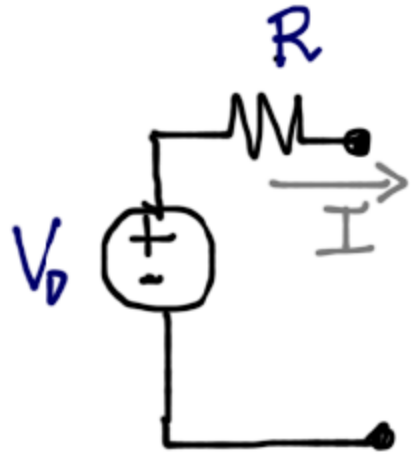


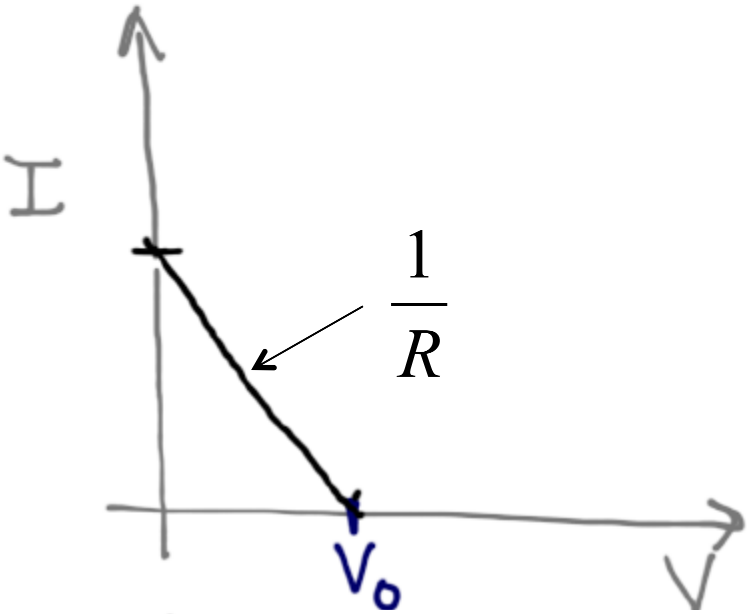






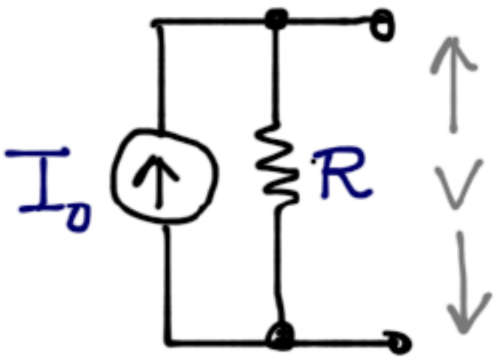
Non-ideal Voltage and Current Sources

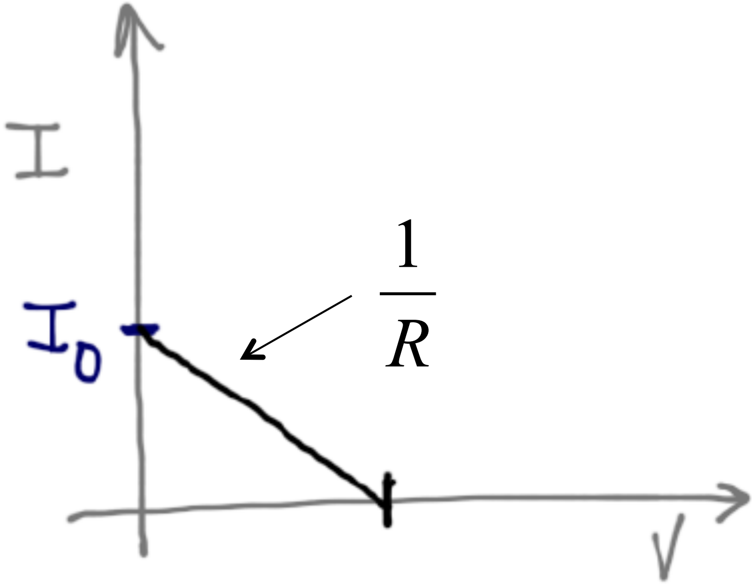




Non-ideal Voltage Source

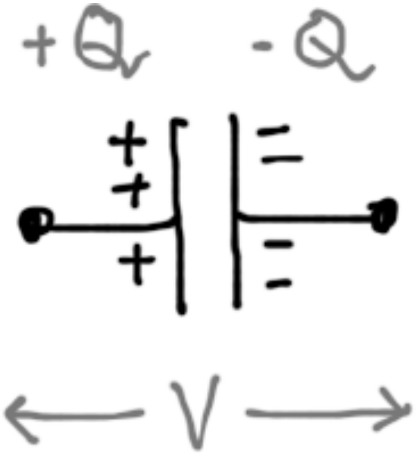
Non-ideal Current Source





Linear Capacitance

- Charge stored on a linear capacitor is directly proportional to voltage difference across its terminals.
- Each terminal stores equal but opposite charge.
- Voltage across a capacitor can not change instantaneously.



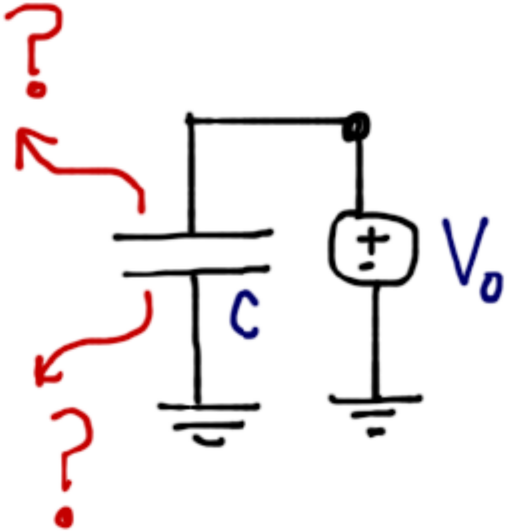
$$Q \propto V$$

Capacitance

$$Q = CV$$

$$\frac{\Delta Q}{\Delta t} = C\frac{\Delta V}{\Delta t}$$

$$\frac{1}{C}I = \frac{\Delta V}{\Delta t}$$

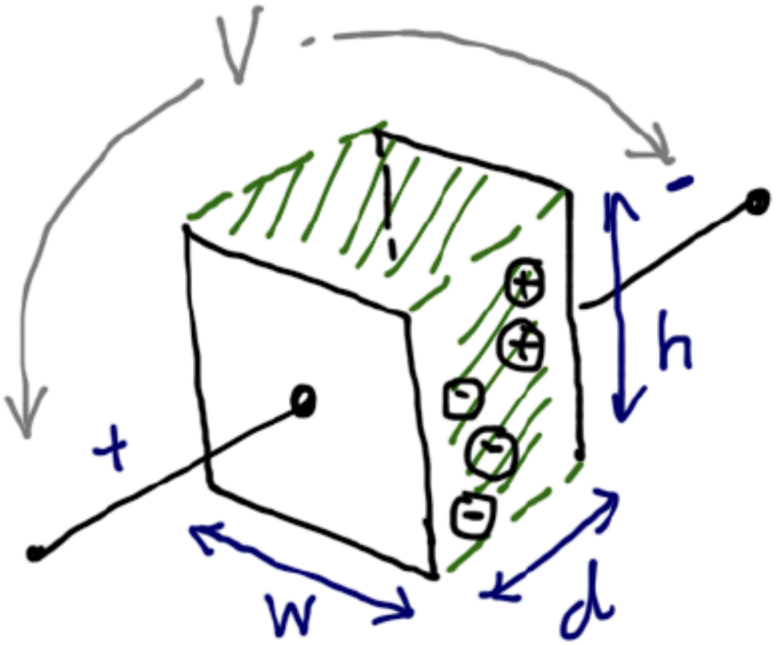


Voltage changes slowly proportional to charging current

Factors determining capacitance

- Capacitance is directly proportional to cross-sectional area.

- Capacitance is inversely proportional to distance between opposite plates.



$$C \propto \frac{A}{d}$$

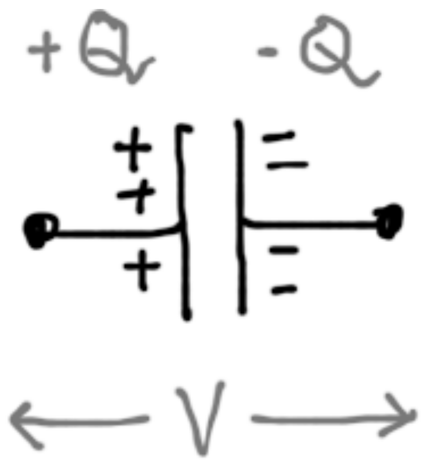
$$C = K_s \varepsilon_0 \frac{A}{d}$$

Relative permittivity

Permittivity of free space

Non-Linear Capacitance

- Capacitance is a function of the voltage. Occurs when charge distribution inside the dielectric is non-uniform.
- Each terminal stores opposite charge.
- Voltage across a capacitor can not change instantaneously.



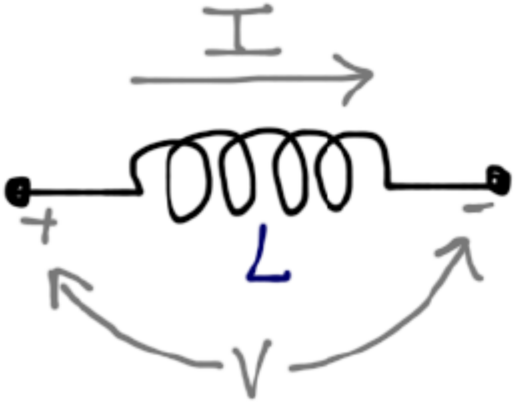
$$\frac{dQ}{dV} = C(V)$$

Non-linear Capacitance

$$\frac{\Delta Q}{\Delta t} = C(V)\frac{\Delta V}{\Delta t}$$

Inductance

- Magnetic flux stored on a linear inductor is directly proportional to the current flowing through the inductor.
- Current through an inductor can not change instantaneously.



Magnetic Flux

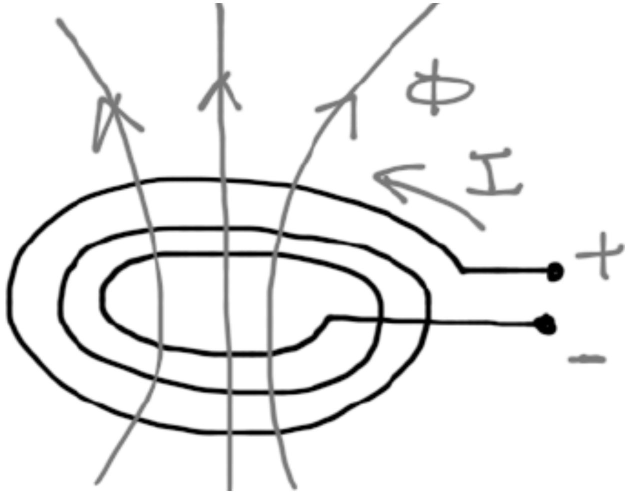
Inductance

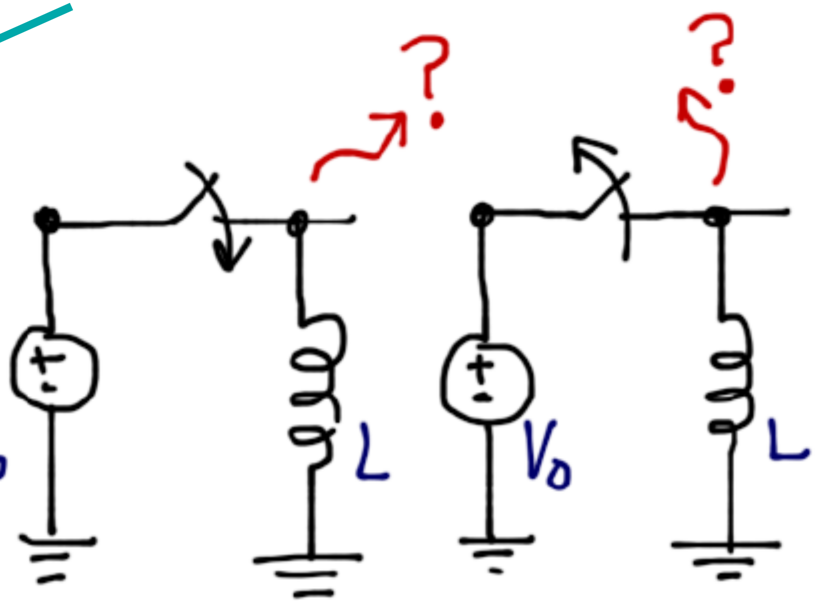
$$\Phi \propto I$$

$$\Phi = LI$$

$$\frac{\Delta\Phi}{\Delta t} = L\frac{\Delta I}{\Delta t}$$

$$\frac{1}{L}V = \frac{\Delta I}{\Delta t}$$

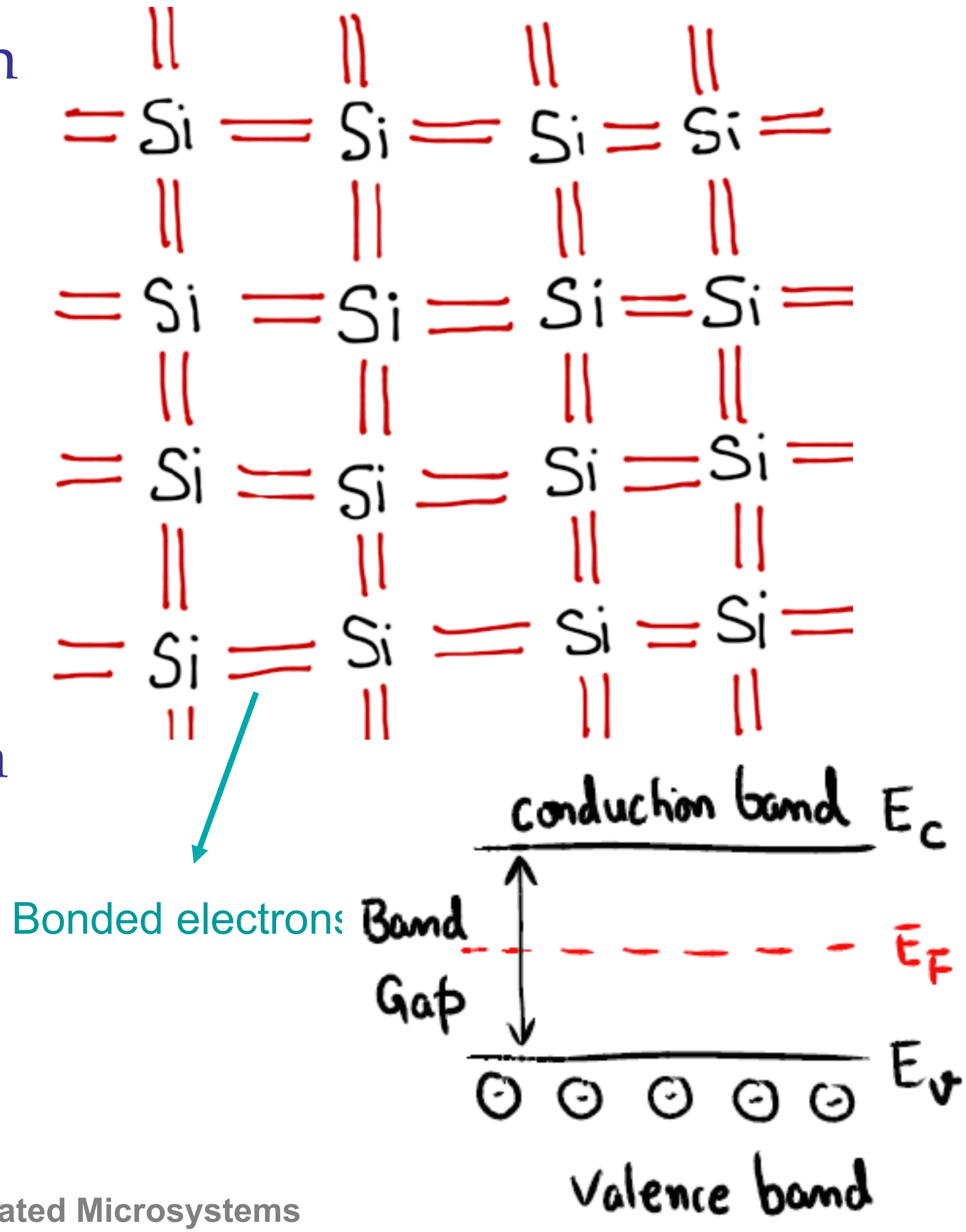




Current changes slowly proportional to applied voltage

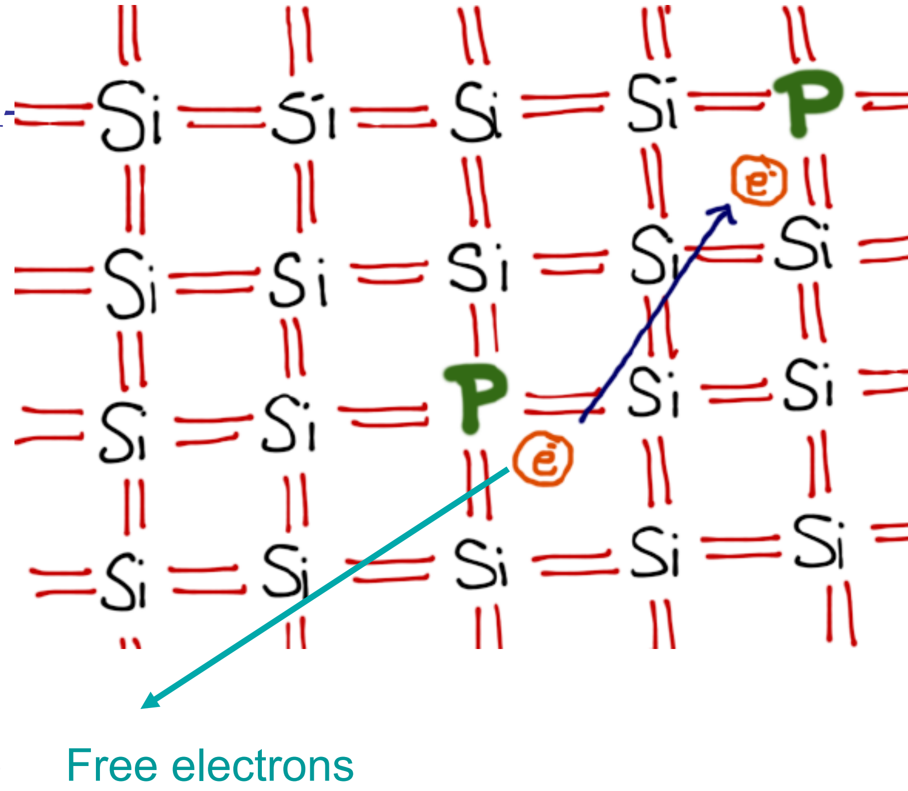
Electronic properties of pure (instrinsic) silicon

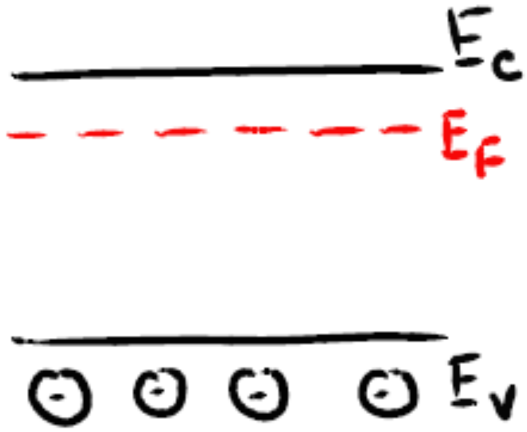
- A silicon atom has 4 electrons in the outer shell
- In a silicon lattice each silicon atom bonds with 4 neighboring silicon atoms by sharing 4 of its electrons.
- No electron is free (at zero temperature).
- For flow of electrons in a silicon lattice, energy (electrical or thermal) has to be supplied to break the bonds and release electrons.



n-doped silicon

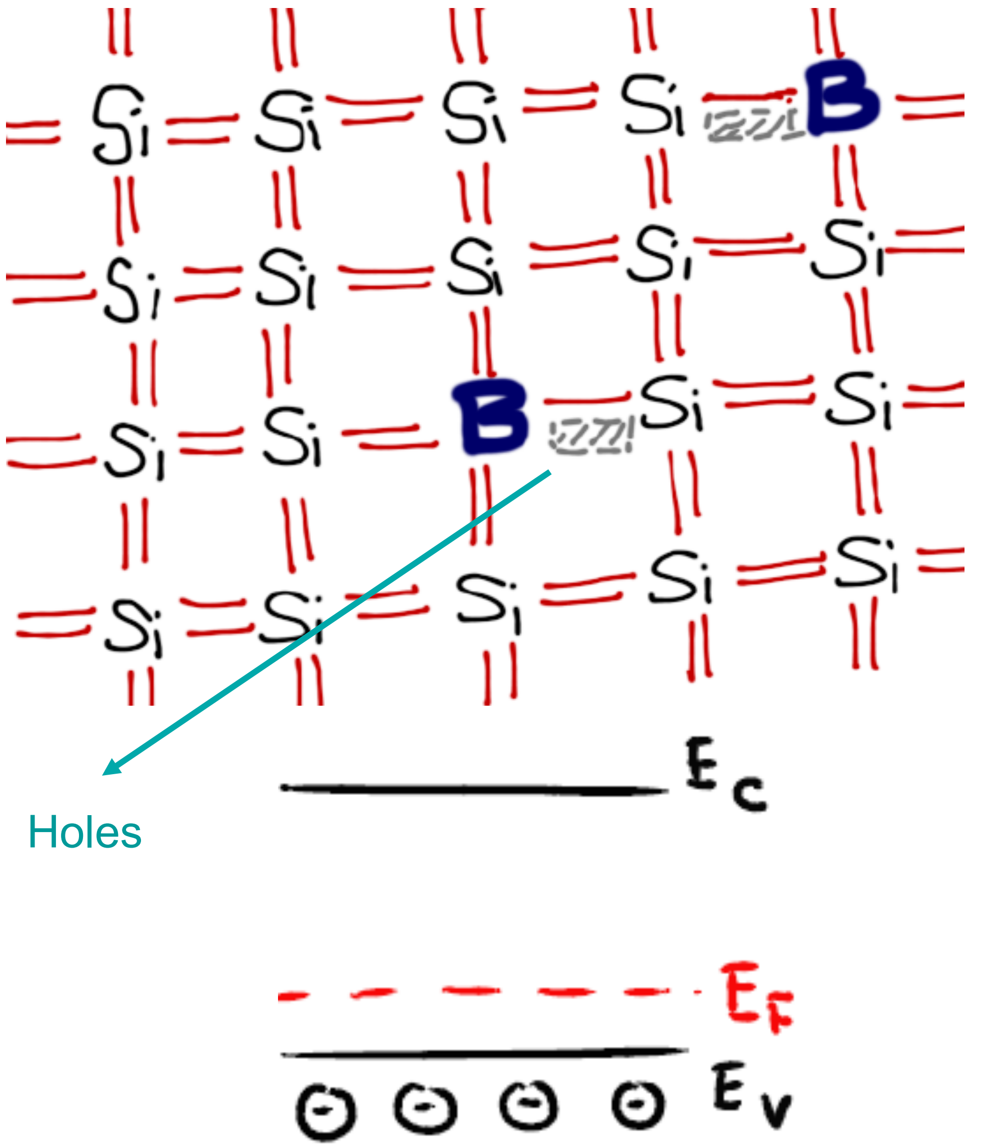
- Doping is a process of intentionally replacing silicon atoms by electron rich (n-type doping) or electron deficient (p-type doping) atoms.
- For example in n-type silicon, phosphorous (P) atoms which has 5 electrons in its outer shell, could be used.
- 4 of its electrons are used for bonding with 4 of its silicon neighbors.
- 1 electron is free to move. When a voltage difference is applied the free electron moves through the lattice leading to a flow of current.
- n^- means lightly doped (lower conductivity) silicon and n^+ means heavily doped (higher conductivity) silicon.



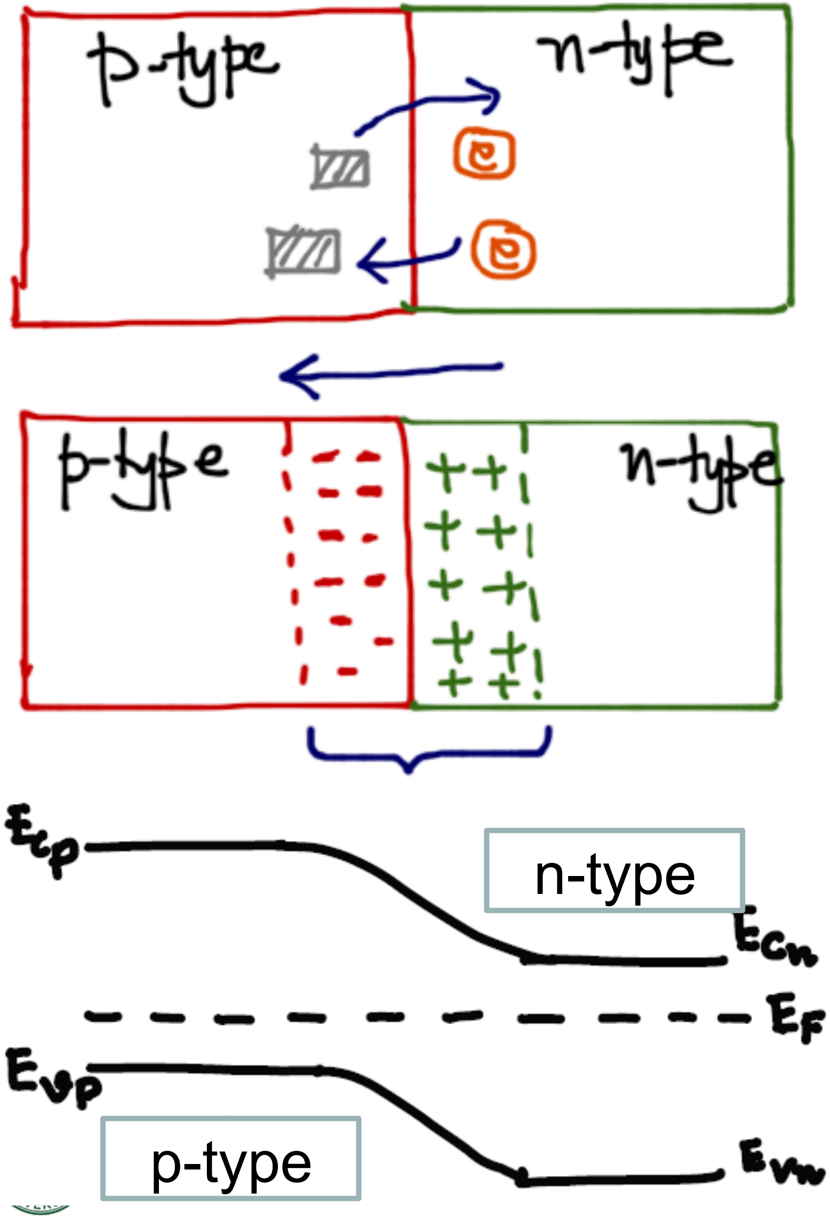


p-doped silicon

- In p-type doping, electron deficient atoms like Boron (B) are used to replace silicon atoms.
- Boron has 3 electrons in its outer shell
- Leads to an absence of one electron called a hole.
- Hole can move through the lattice by stealing electrons from neighboring bonds.
- Similar properties as a positively charged particle.
- Note: Both n-type and p-type silicon are electrically neutral.



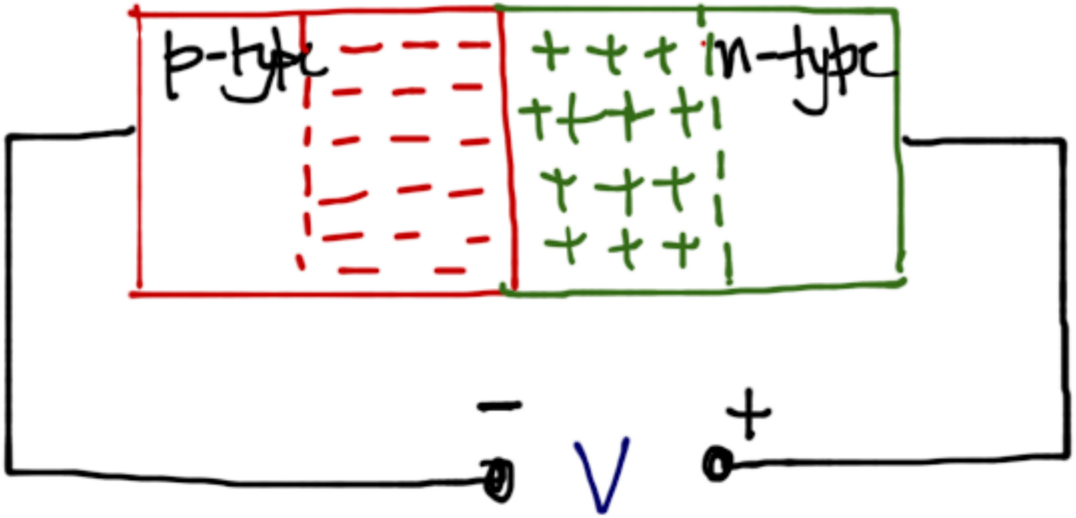
Connecting p-type and n-type silicon



- Remember: In the absence of any applied voltage, particles will move from higher concentration to a lower concentration region.
- Electrons diffuse from n-type Si to p-type Si.
- Movement of charged particles creates charge separation and hence an electric field.
- Region is called depletion region (acts as a capacitance) with a voltage called built-in potential across it.

Worksheet

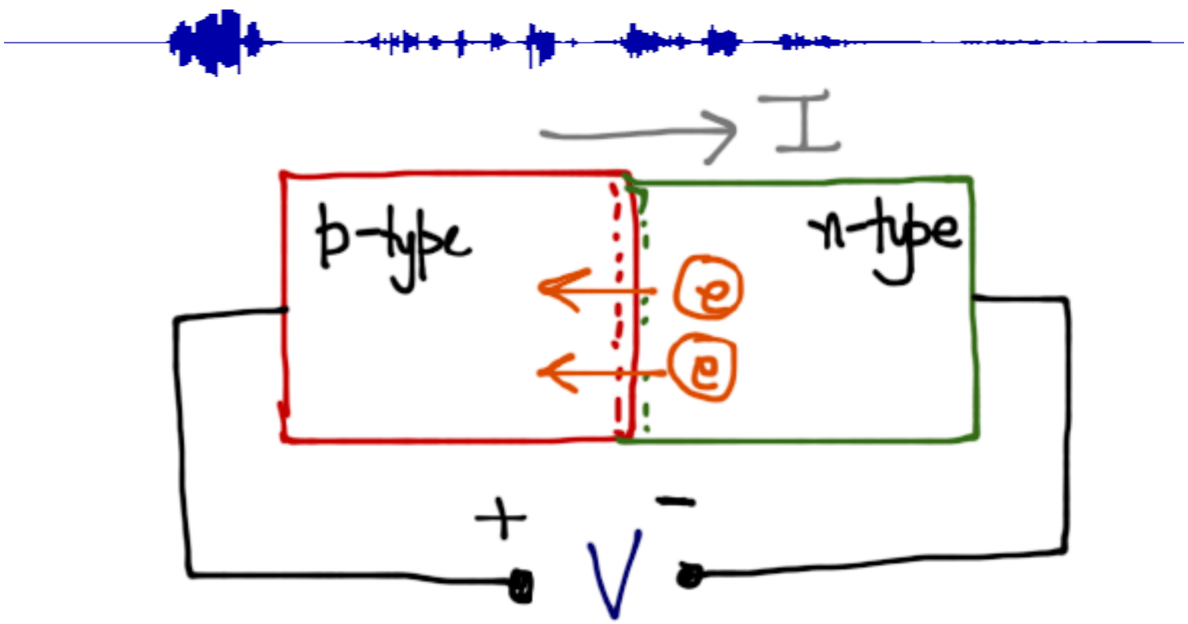
Non-linear capacitor



- Apply negative potential to the p-type, supplies more electrons.
- Depletion width increases which means more charge is now stored.
- The amount of charge is a non-linear function of the applied voltage – voltage controlled capacitance (Varactor).

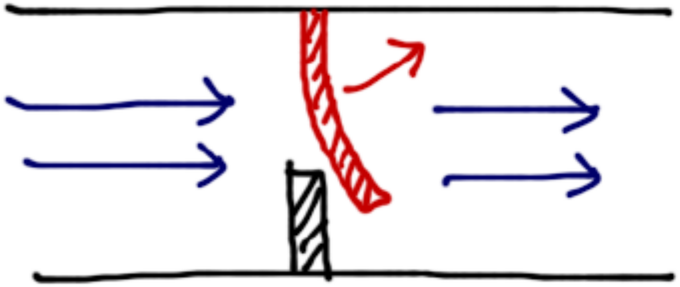
$$C_j = \frac{C_{jo}}{(1 + \frac{V_R}{\Phi_0})^{1/2}}$$

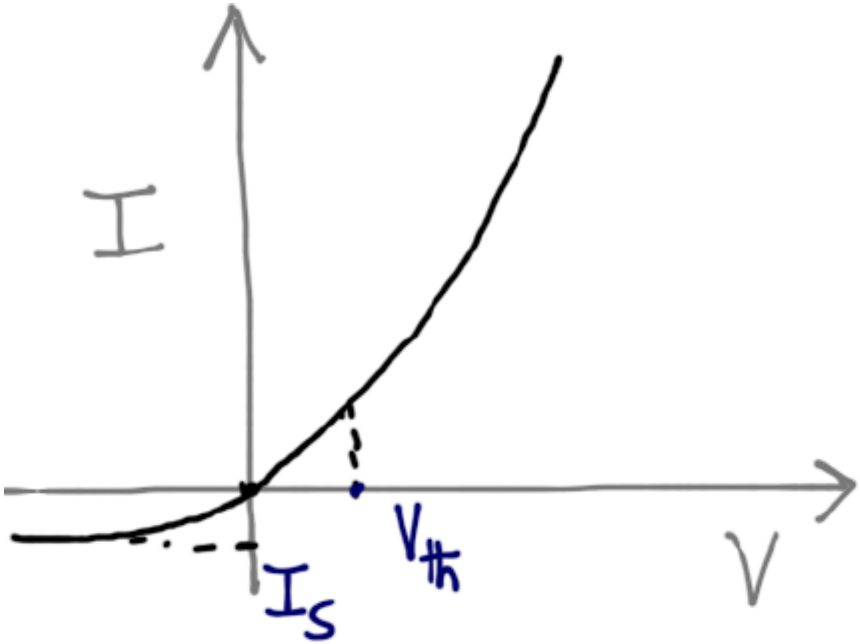
p-n Diode



- Apply negative potential to the n-type, supplies more electrons into the n-type region.
- Depletion width decreases. Depletion width goes to zero when voltage difference is 0.7V or the threshold voltage.
- Further increase in voltage leads to an exponential increase in current.

Model of a p-n Diode





Current through the diode

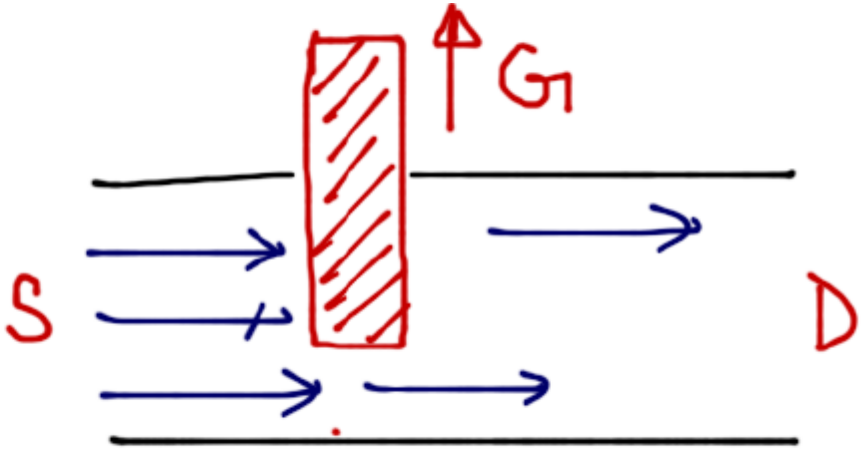
$$I_d = I_s \exp\left(\frac{V_d}{V_T}\right)$$

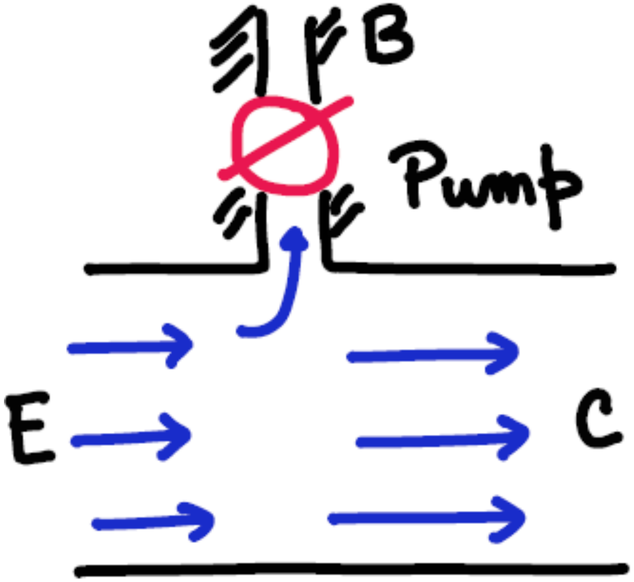
Diode voltage

Scale current proportional to diode structure

Transistor

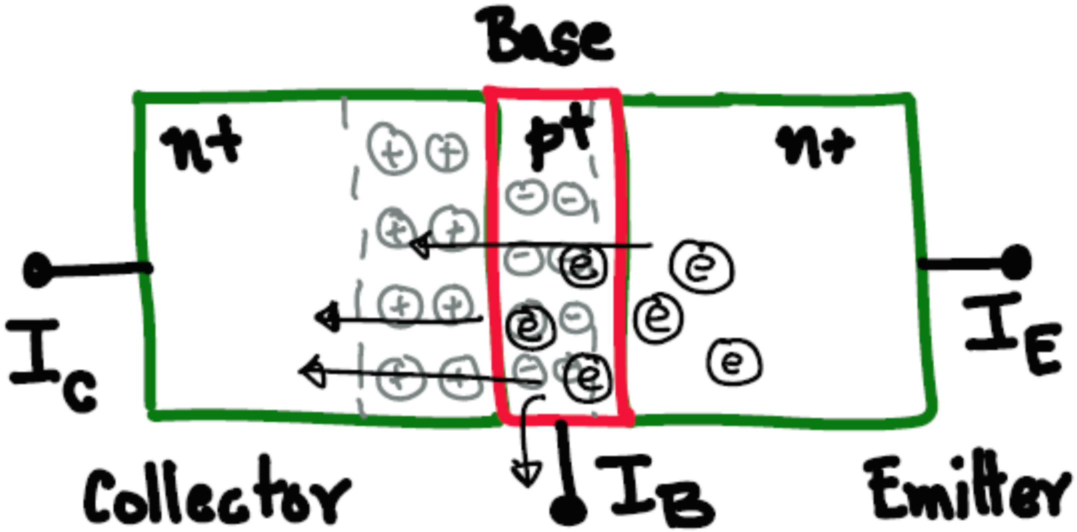
- What is a transistor ?
- Current between two terminals is controlled by a third terminal (analogy: water faucet).
- Two popular types: Current controlled - Bipolar transistor. Voltage or charge controlled - Metal-oxide semiconductor field effect transistor (MOSFET).

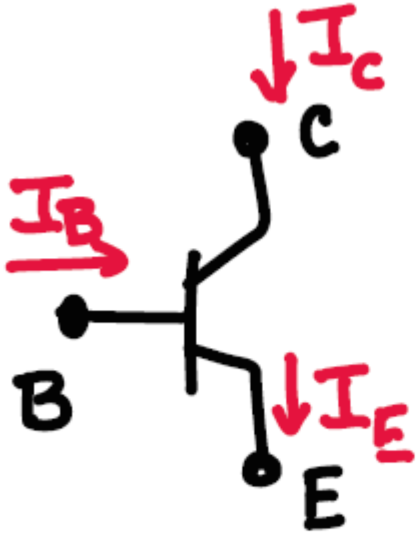




Bipolar Transistor

- Current controlled.
- When the base terminal is forward biased electrons flow in (out of) the base.
- Base cross-sectional area is designed to be small (high-current-gain bipolar) – Most of the electrons enter the base-collector depletion region and get collected.

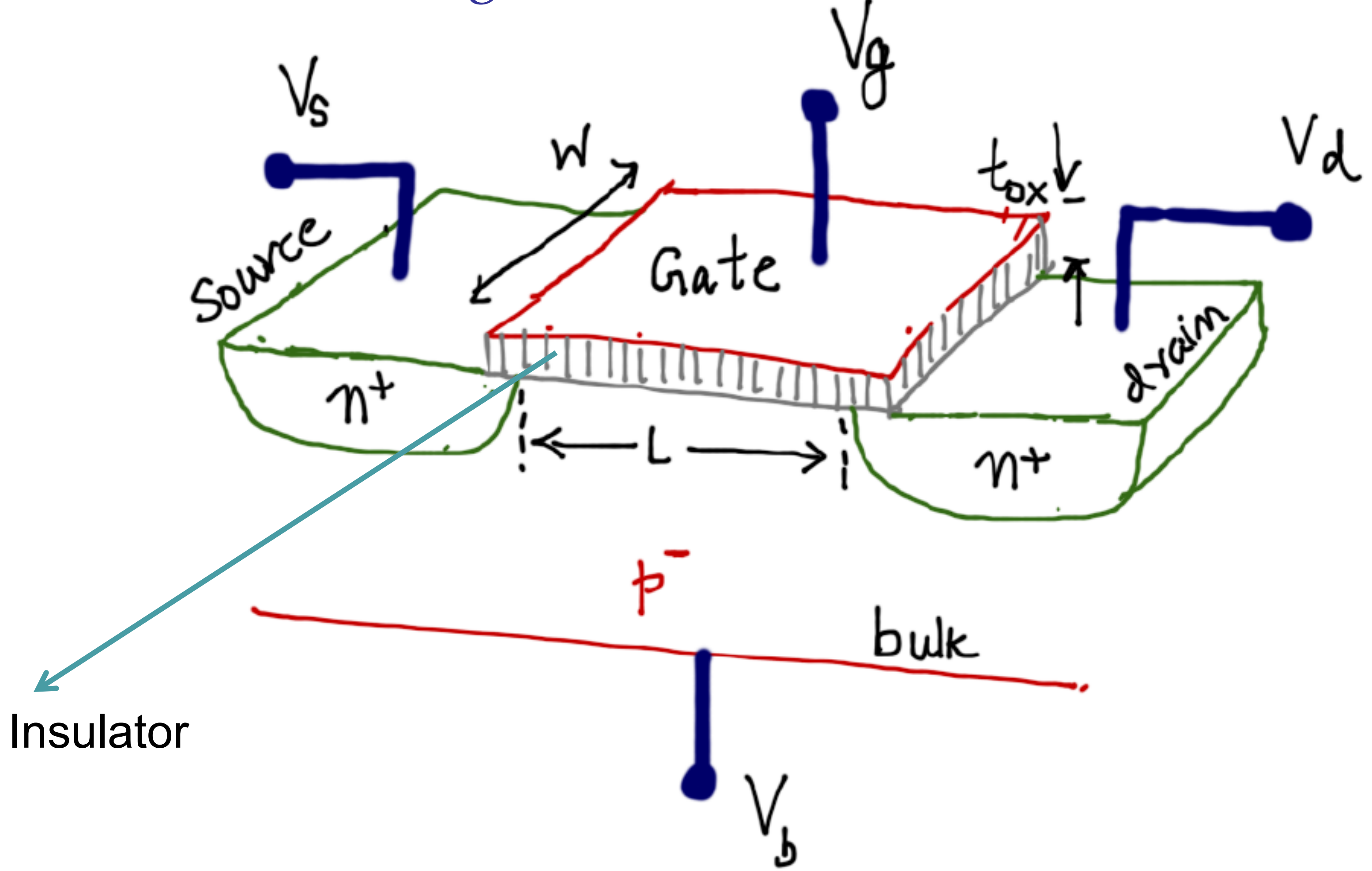




Structure of a MOSFET

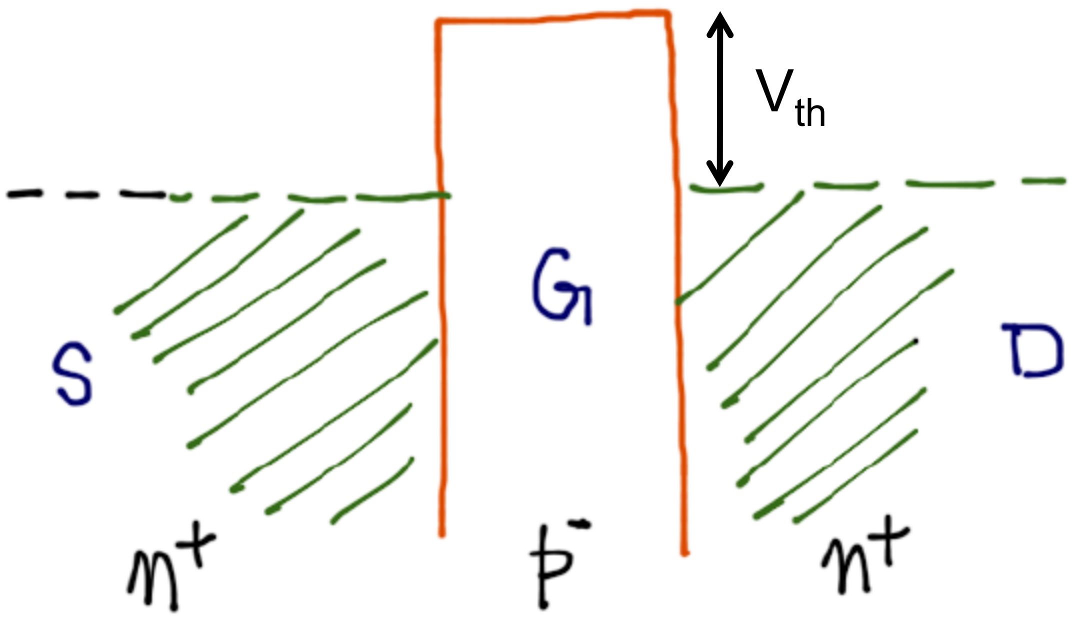
- Source and drain are the terminals through which the current flows.

- Gate and bulk voltages controls the current.



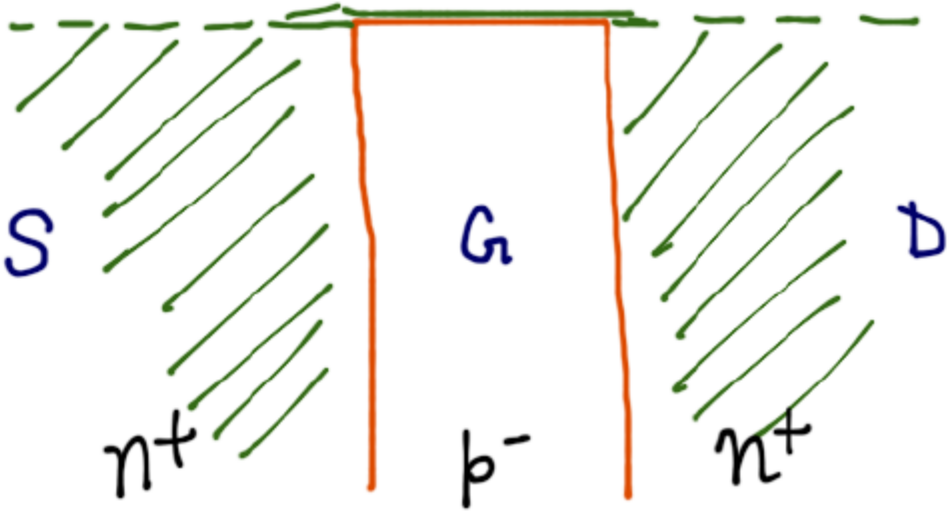
Conceptual Operation of a n-type MOSFET

- Source and Drain (n^+ regions) – infinite source of electrons, separated by a barrier formed by a p^- region (bulk).
- The height of the barrier is called threshold voltage V_{th}.



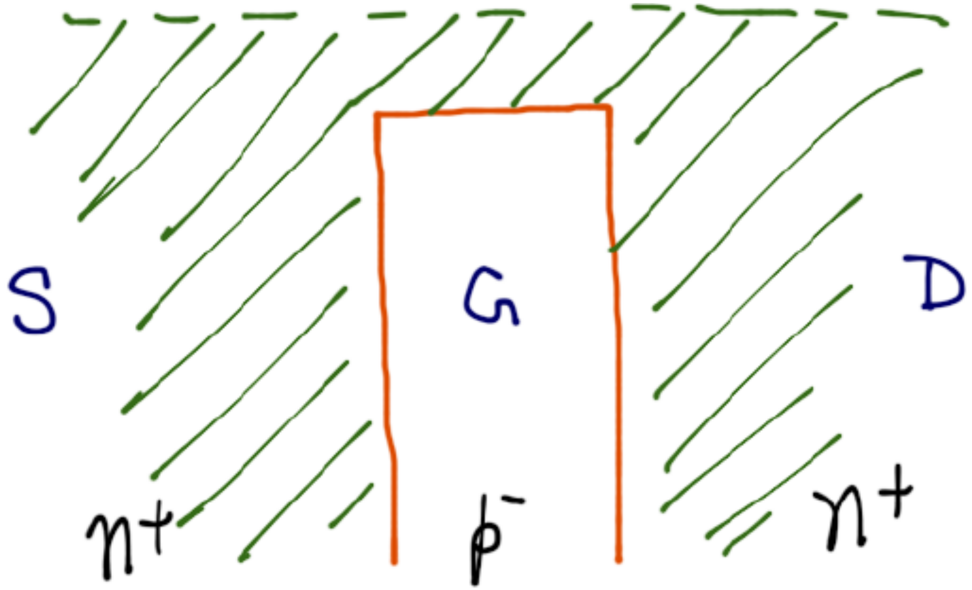
Conceptual Operation of a n-type MOSFET

- Reduce the barrier by controlling the voltage at the gate terminal.
- Source and drain connected by a channel of electrons when $V_g - V_s = V_{th}$.



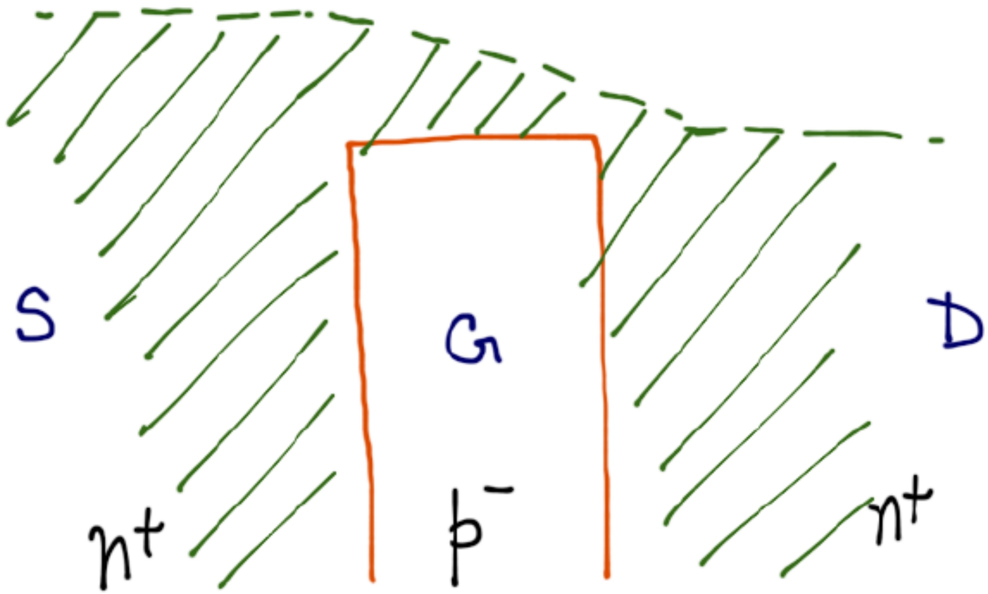
Conceptual Operation of a p-type MOSFET

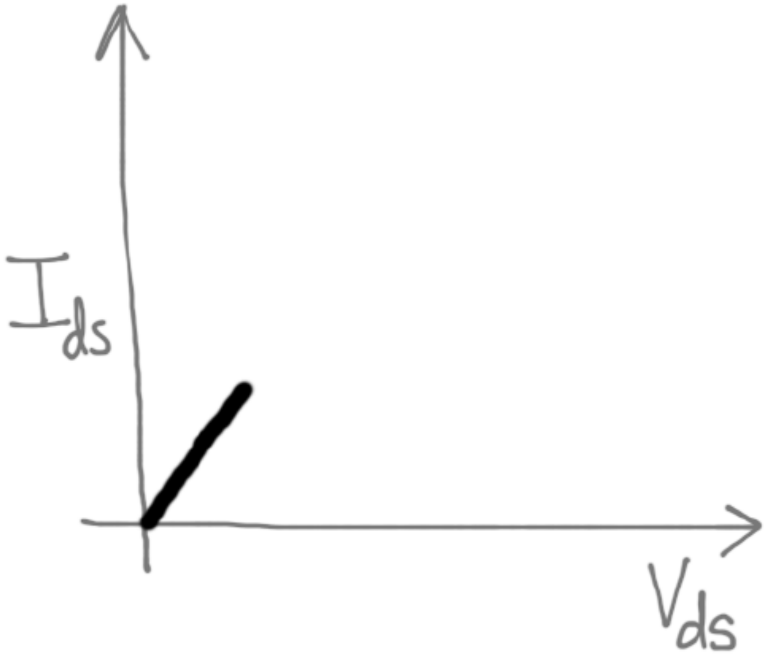
- Decrease the barrier further which connects the source and drain with a thicker channel of electrons.
- Source and Drain levels are the same – so no flow of electrons.



Conceptual Operation of a n-type MOSFET

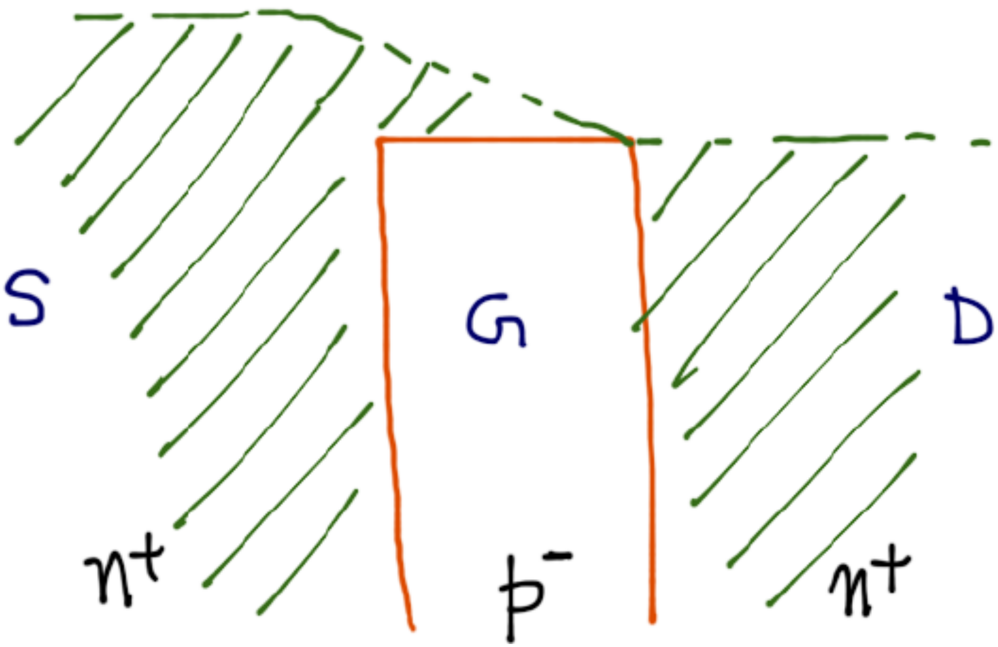
- Reduce the drain level by increasing the drain voltage.
- Electron starts flowing between the source and the drain and the flow is controlled by the drain level (voltage) – Triode region.

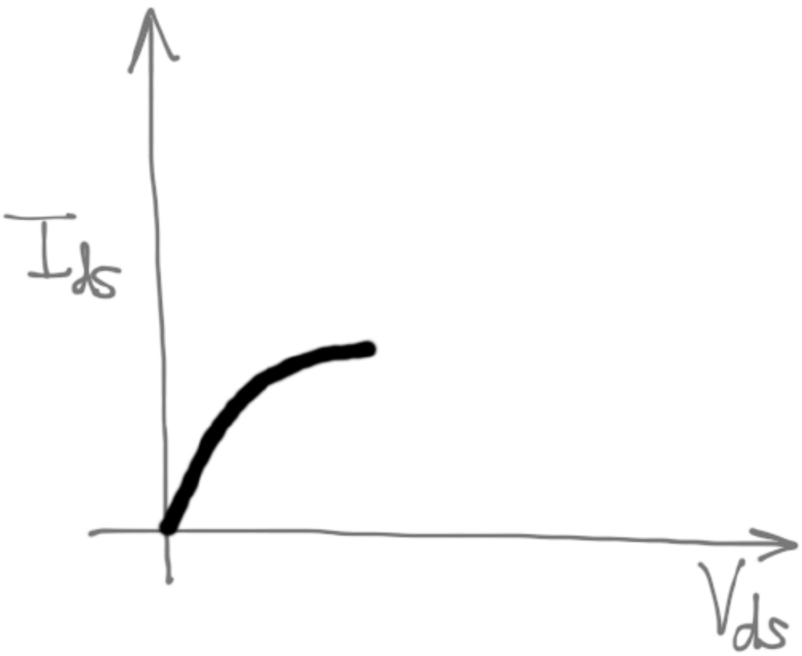




Conceptual Operation of a n-type MOSFET

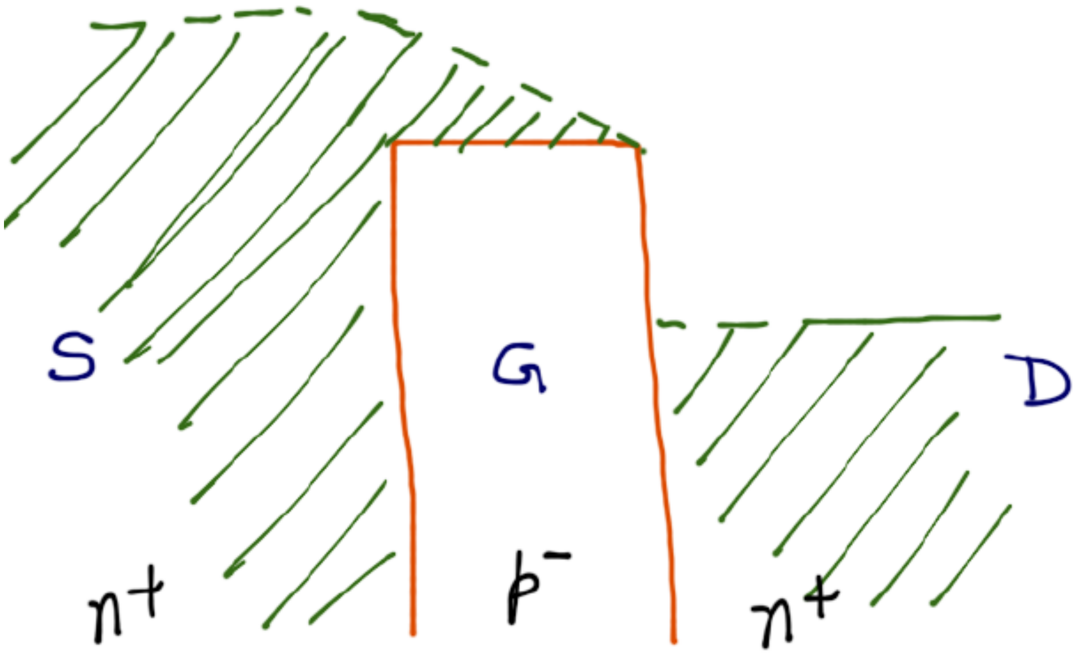
- Drain level (voltage) decreased (increased) further the electron channel gets pinched off.
- The flow of electrons becomes less sensitive to the drain level (voltage).

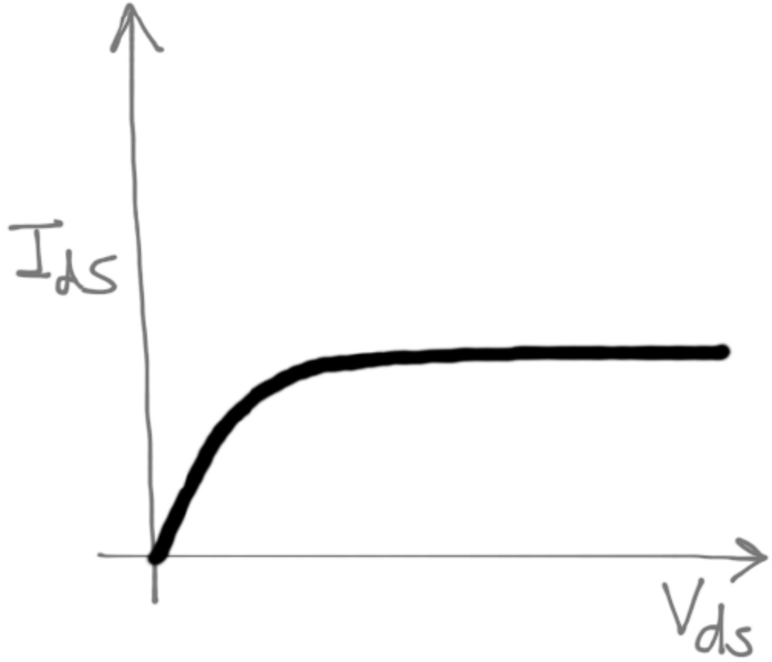




Conceptual Operation of a p-type MOSFET

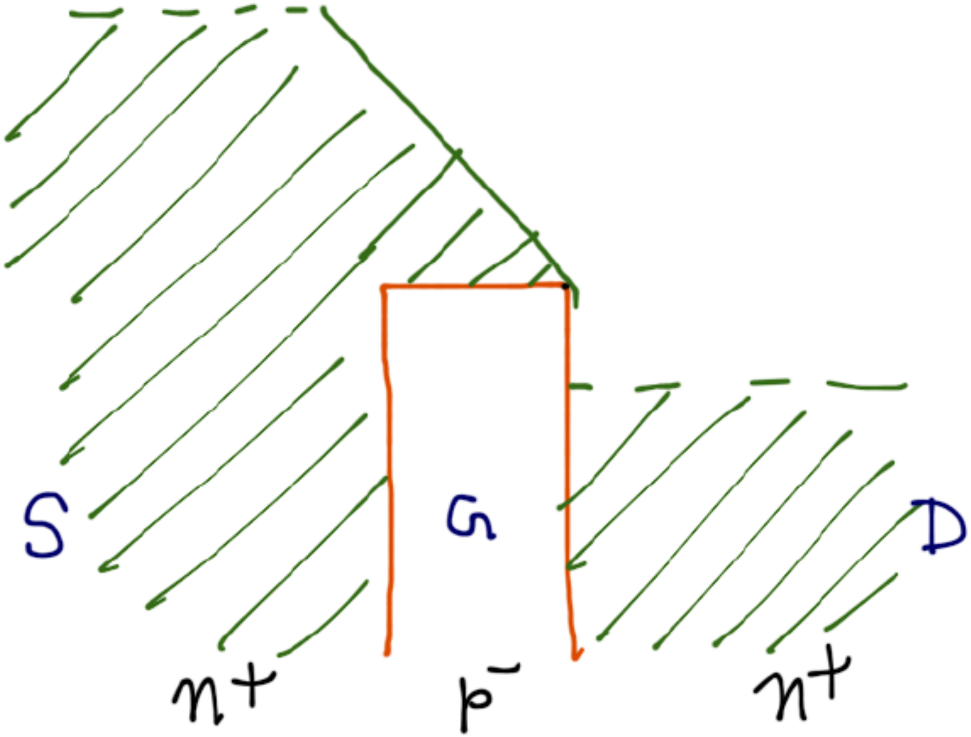
- Reduce the drain level (voltage) further the channel remains pinched.
- The flow of electrons remains independent of the drain level (voltage) – current saturates.

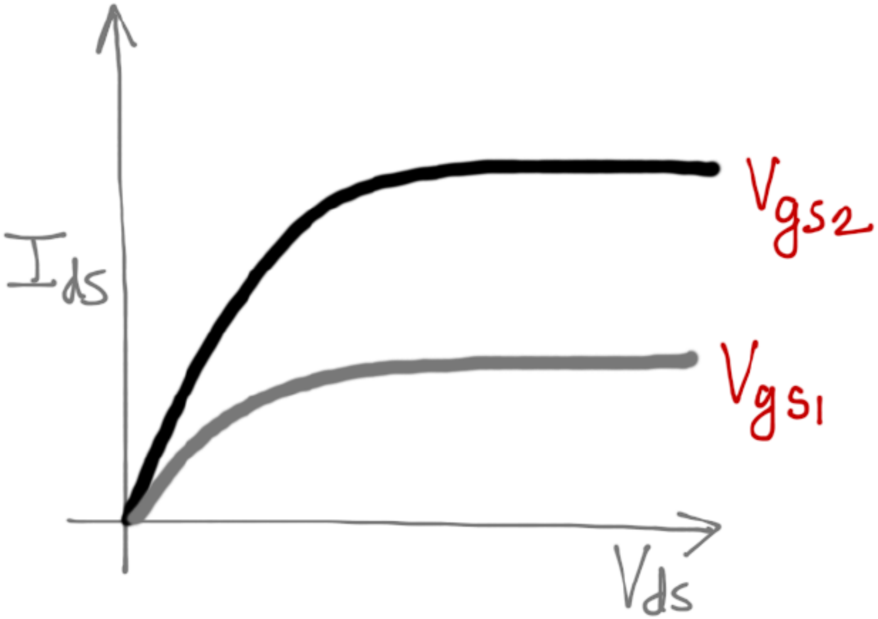




Conceptual Operation of a n-type MOSFET

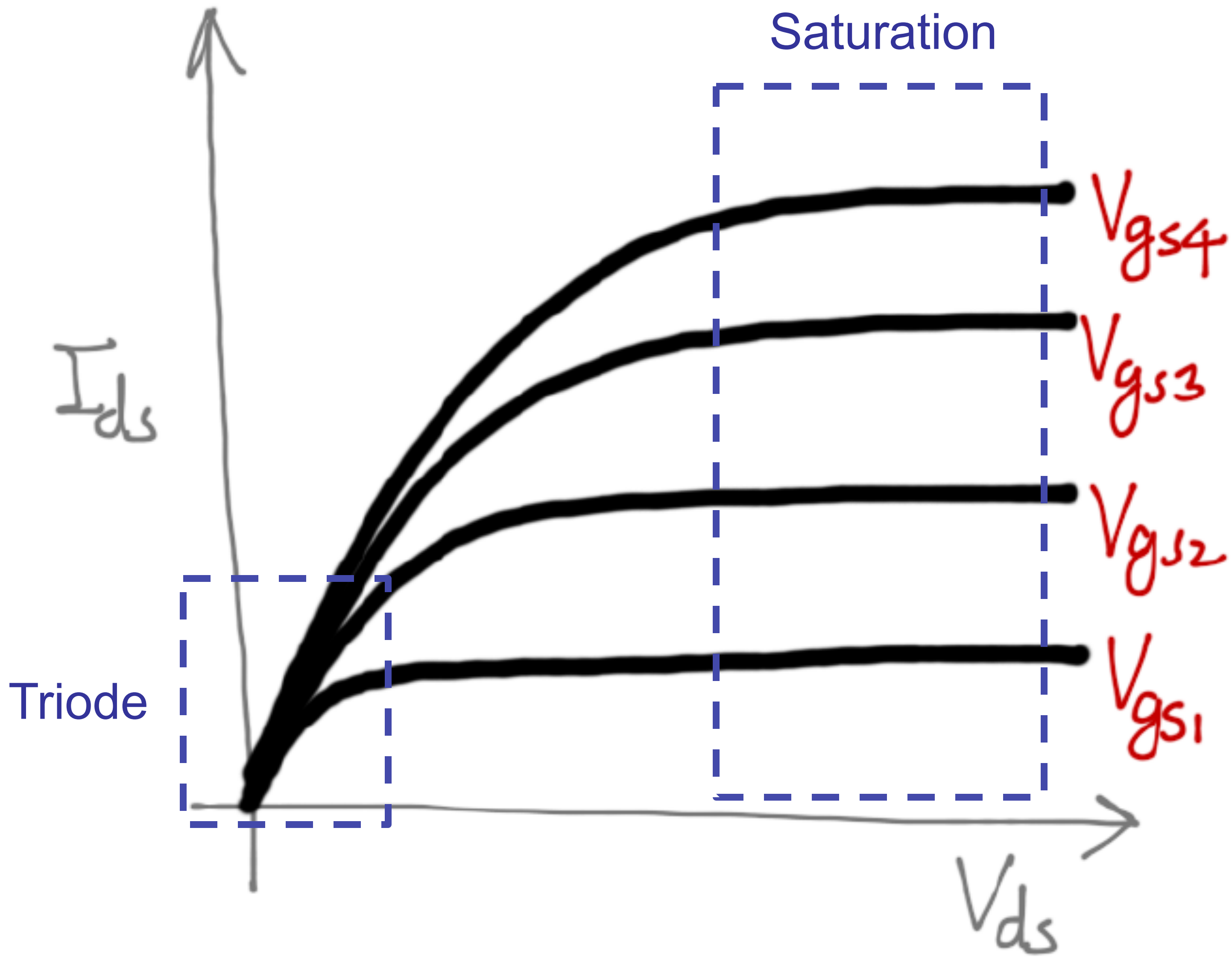
- If the barrier is further reduced (by increasing the gate voltage) the channel becomes thicker.
- Gate voltage controls the flow of electrons even in saturation.





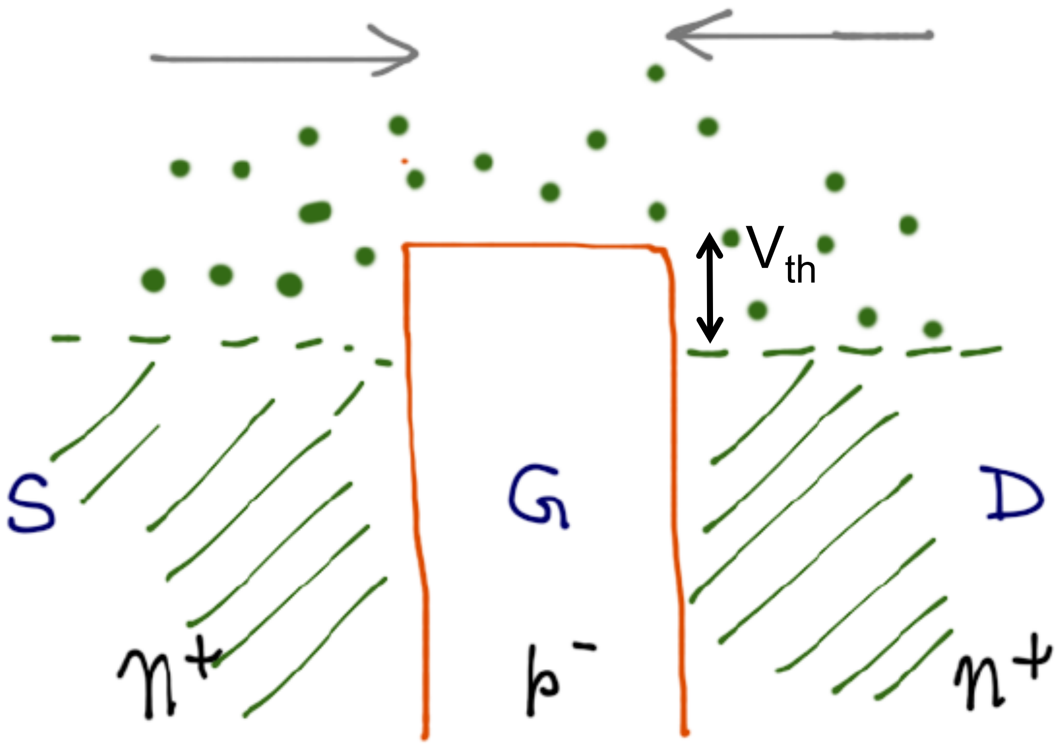
nMOS I-V Characteristics

- For current to flow: (a) Electron channel has to be formed $V_{gs} > V_{th}$; and (b) Potential/Flow gradient across the terminals $V_{ds} > 0$.



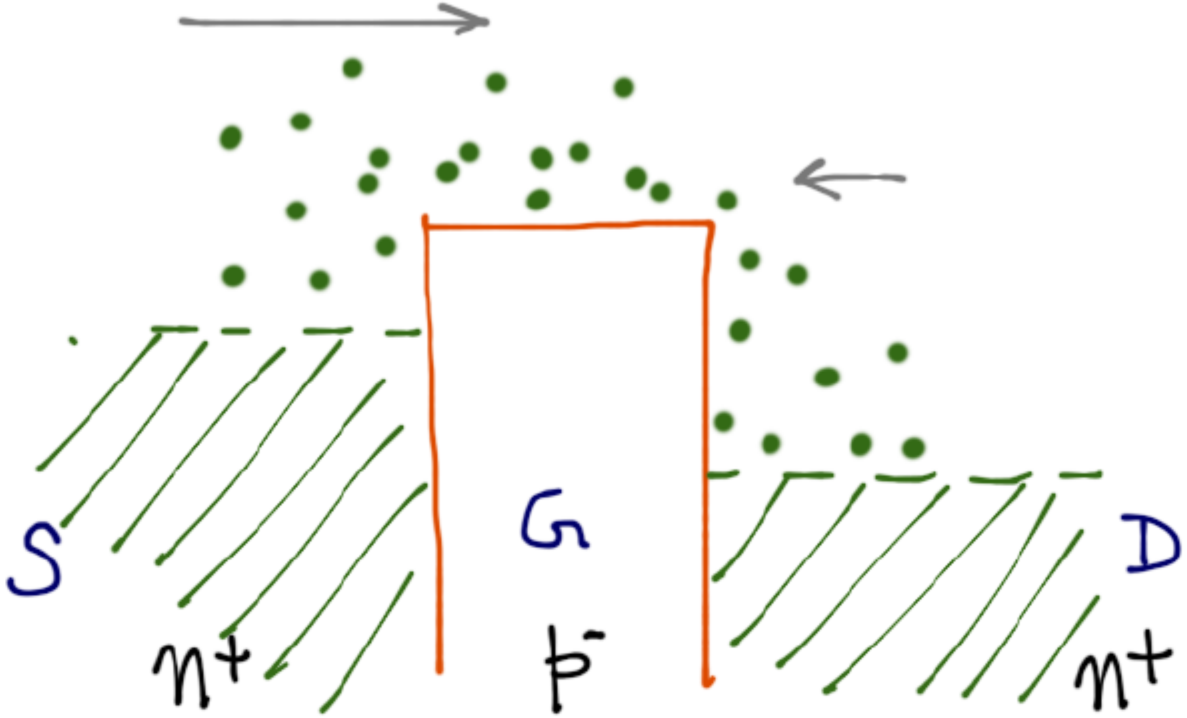
What happens below the threshold ?

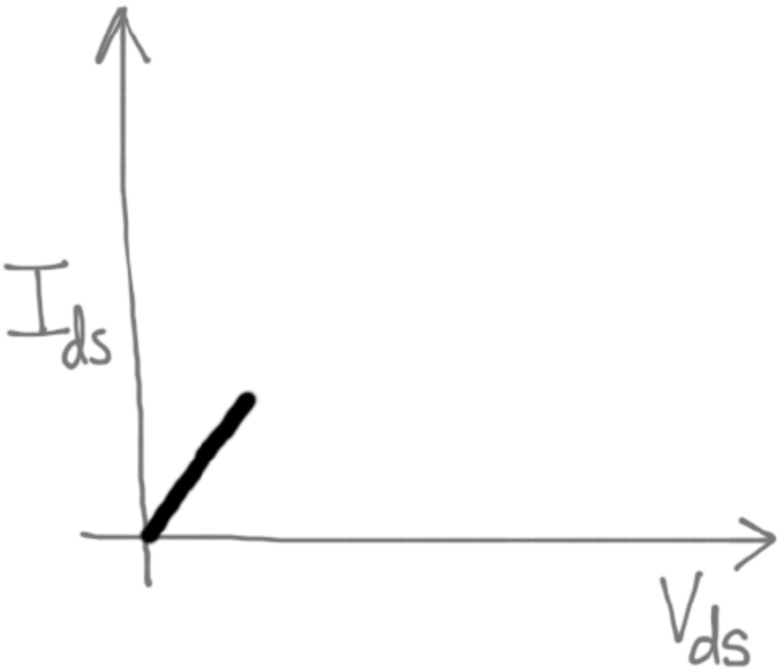
- At room temperature, electrons gain thermal energy (like water vapor) and diffuse over the barrier.
- Source and drain levels are the same – diffusion rate in both directions are the same – current = 0.



What happens below threshold ?

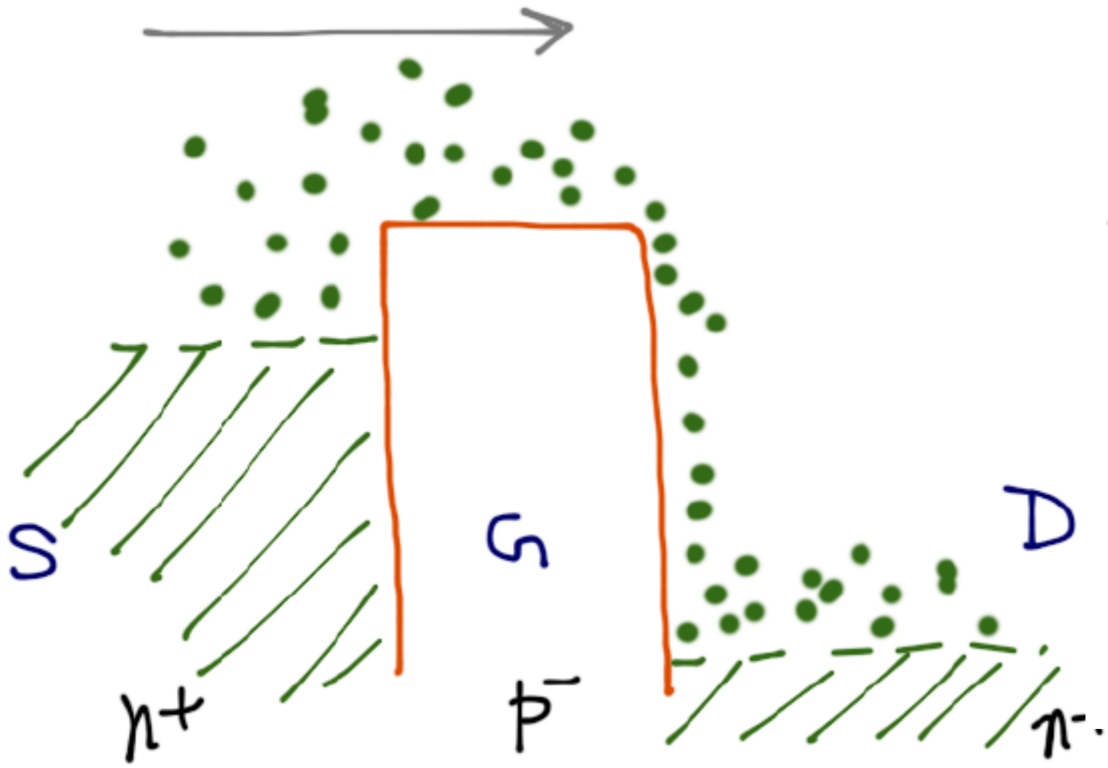
- Drain level (voltage) reduces (increases), the diffusion of electrons from the drain to the source reduces.
- Electron flow is controlled by the drain level (sub-threshold triode).

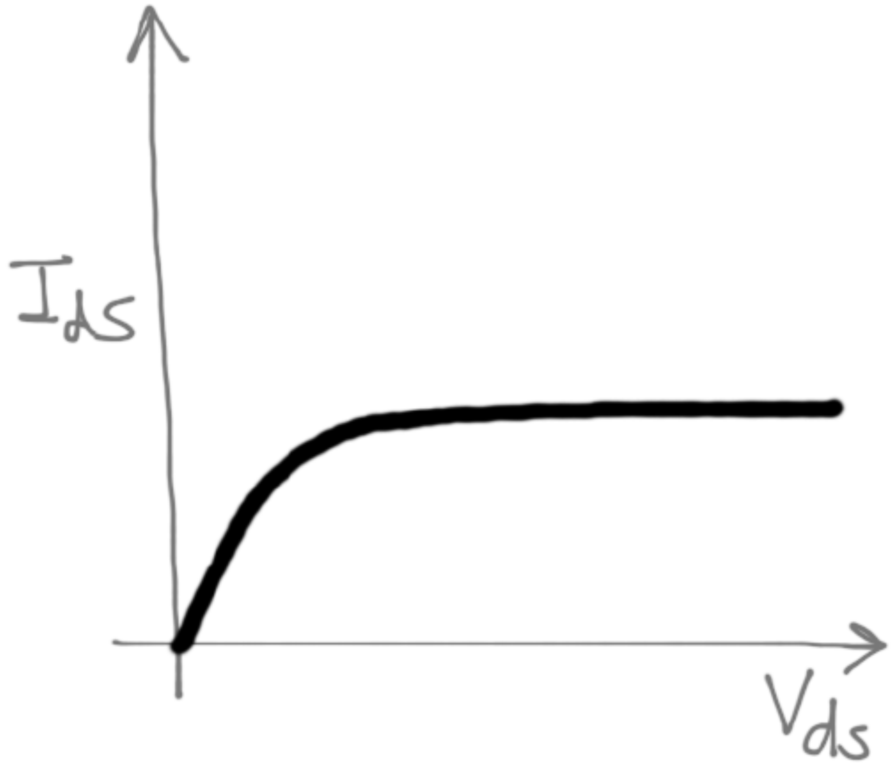




What happens below threshold

- When the drain level is reduced further, the diffusion of electrons from drain to source reduces to zero.
- Electron flow becomes independent of the drain level (voltage) and is controlled by the source level and the barrier level (gate voltage)





Operating regions of nMOS

- Weak inversion or sub-threshold – Flow of electrons is due to diffusion.
- Moderate inversion – Flow of electrons is due to diffusion and drift (flow gradient).
- Strong inversion or above-threshold – Flow of electrons is due to drift.