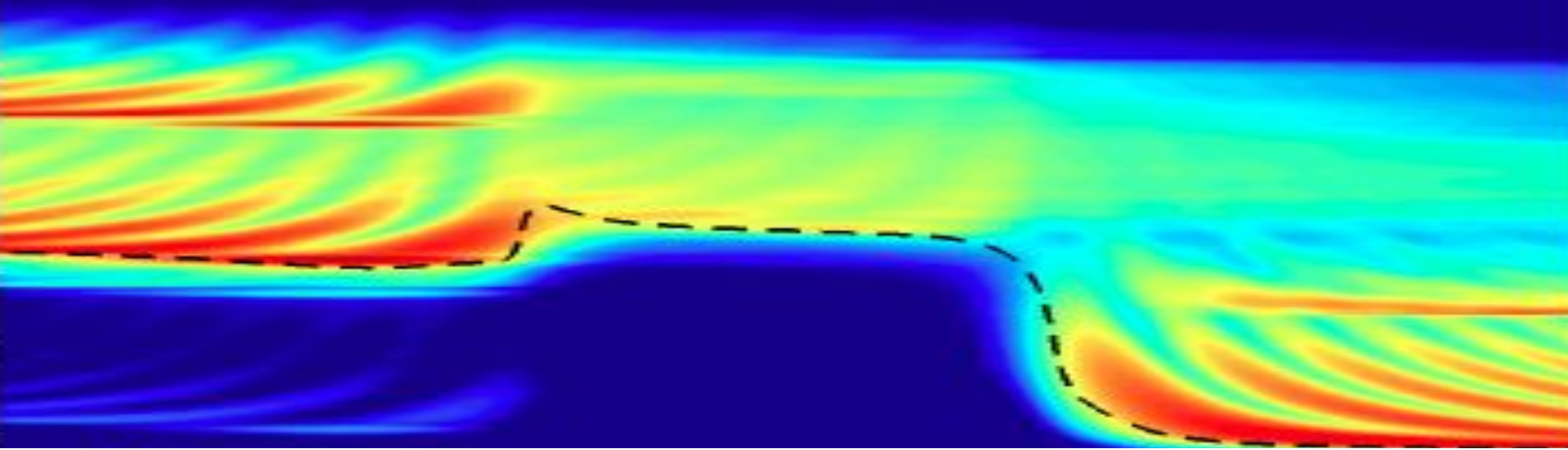

EECS 16B
Designing Information Devices and Systems II
Lecture 9

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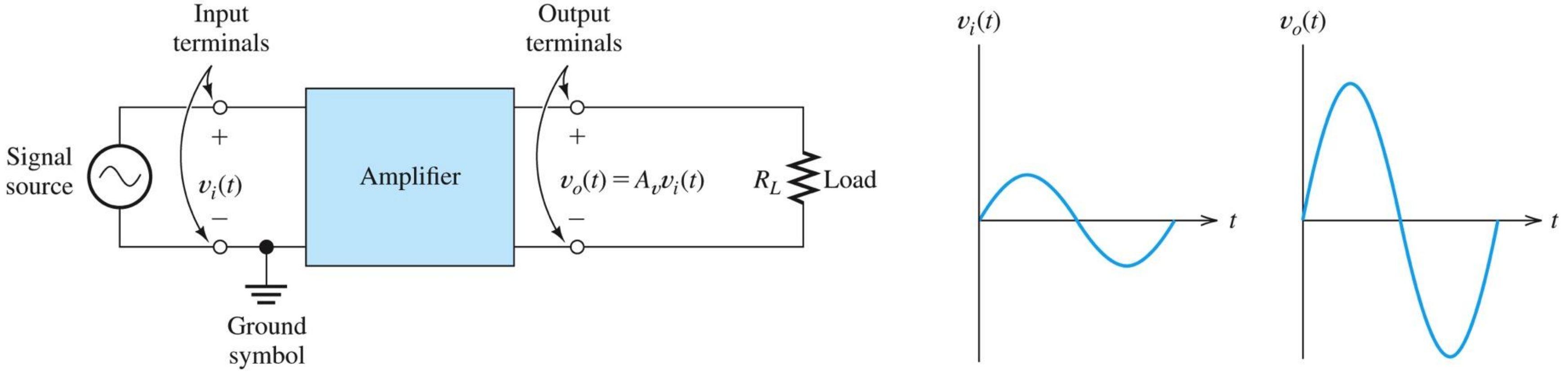
Devices

- Outline
  - Amplifiers and Devices

- Reading-slides

Active Devices



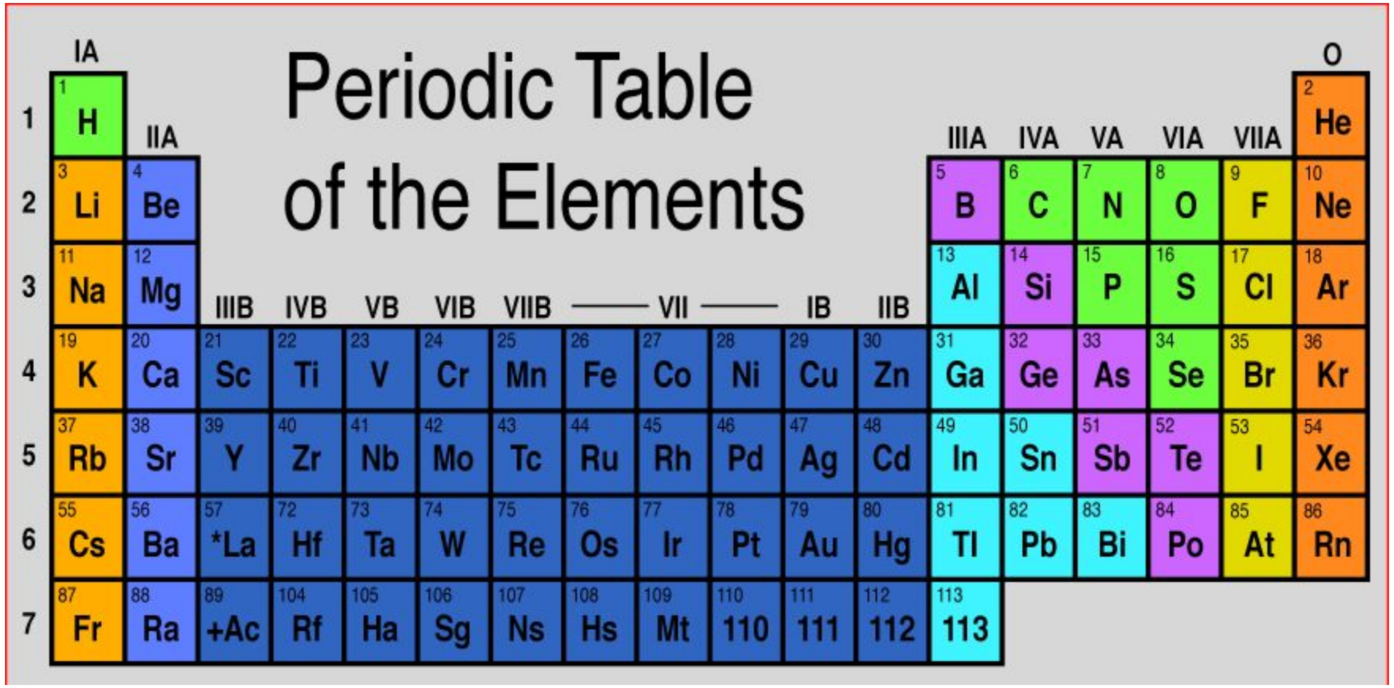
- Active devices are made of semiconductors
- Semi-conductors are materials whose resistance is in between a metal and insulator

Half

- More interestingly, one is able to change the resistance of the semiconductor materials by using external control such as voltage or current

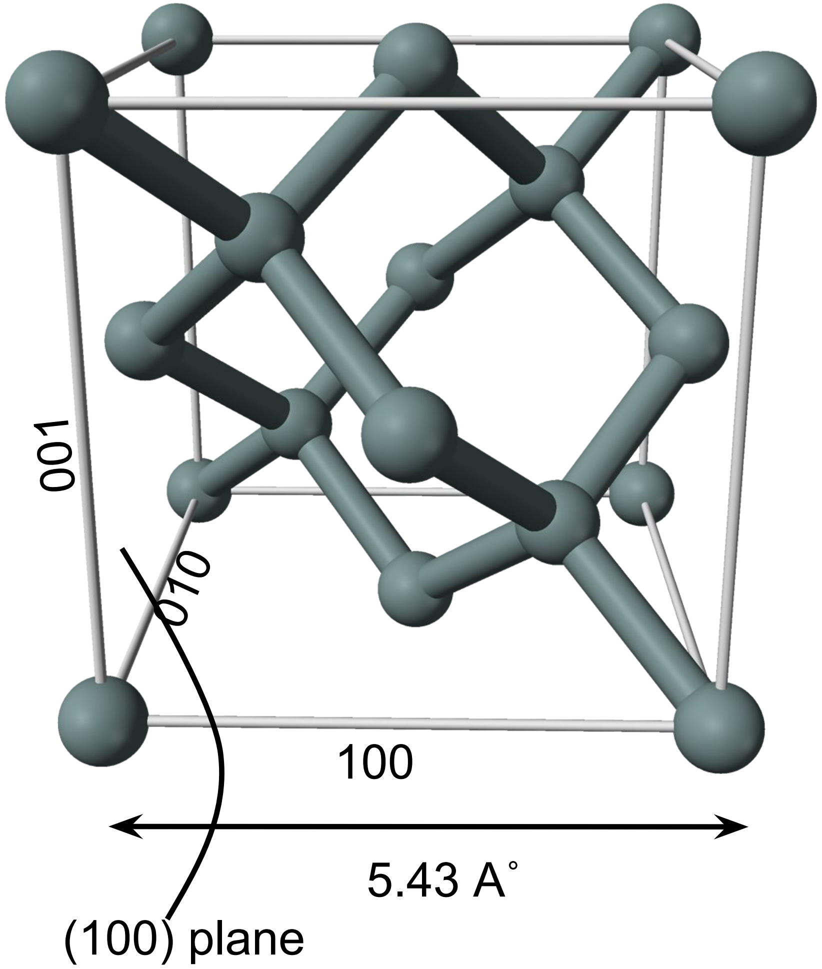
Semiconductors

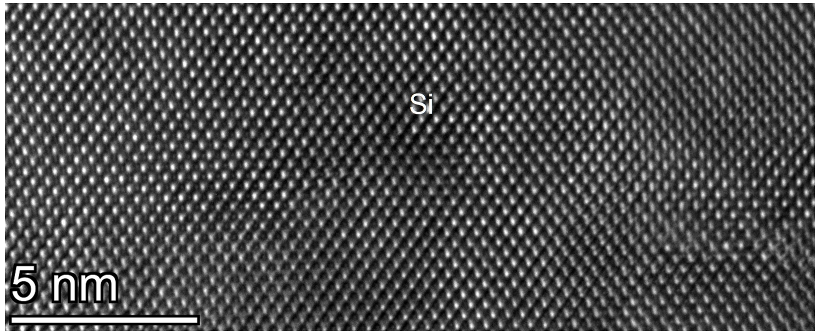
- Semiconductors are **usually** made of group IV elements- atoms that contain, on average, four valence electrons
- Most Common semiconductor used in electronic devices is **Silicon**



Crystal Structure of Si

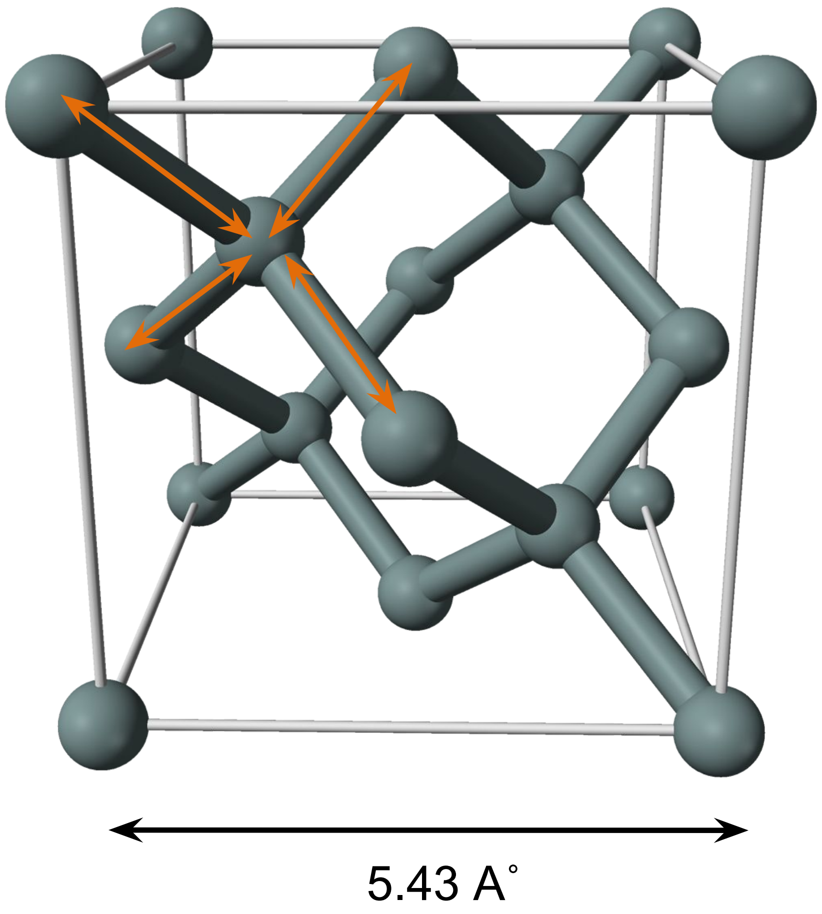
Often known as the diamond lattice





Transmission Electron Microscopy Image of Si taken at Lawrence Berkeley National Laboratorys

Crystal Structure of Si



Each atom has 4 nearest neighbors

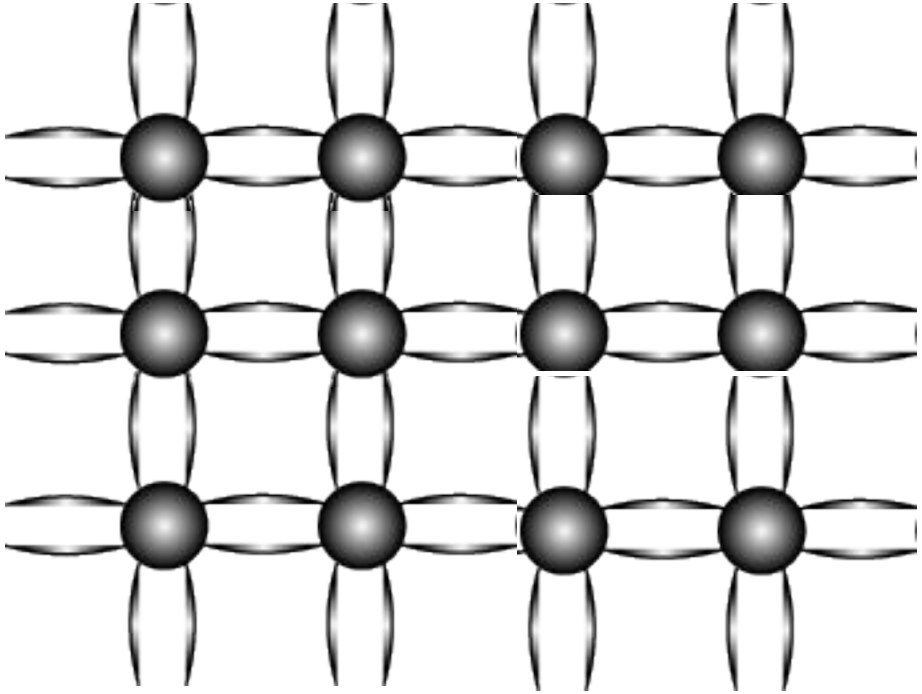
$Si(14) = 1S^2 2S^2 2P^6 3S^2 3P^2$

4 valence electrons

Each atom shares 2 electrons with 4 nearest neighbors to form a covalent bond

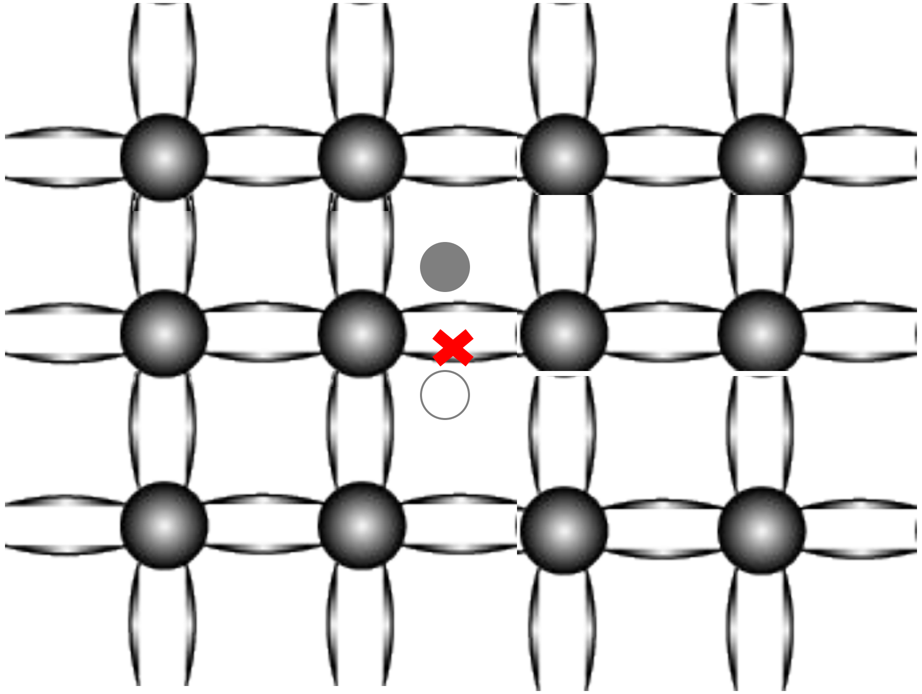
The Bond Model

Each atom shares 2 electrons with 4 nearest neighbors to form a covalent bond



At T=0K, all bonds are satisfied, there are no **free** carriers, no current flows, looks like an insulator

Intrinsic Si: The Bond Model: Electrons

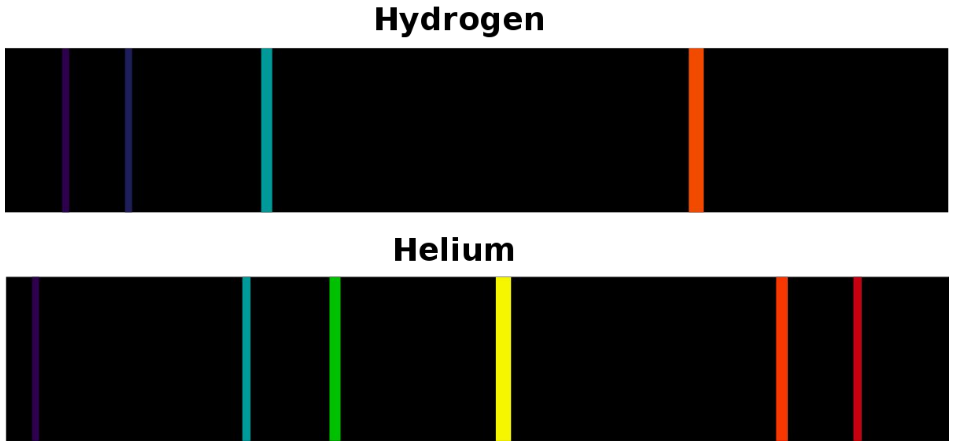


At finite temperature, an electron may gain enough energy to break the covalent bond, become **free** and move around.

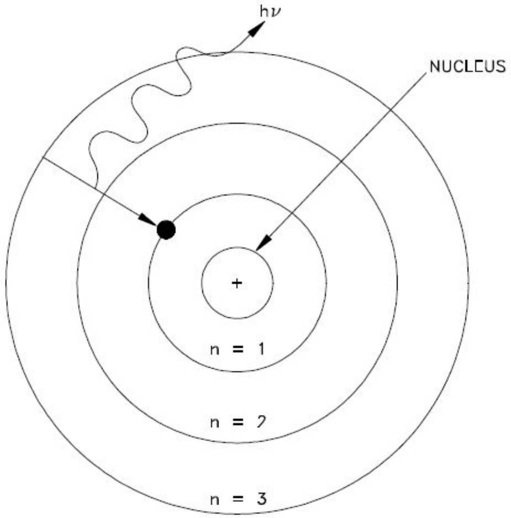
Energy Band Model

Electrons around nucleus

It was known from John Herschel's experiment in (1826) that heated gas emits a unique combination of colors

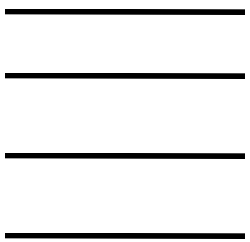


- In 1913 Niels Bohr proposed an atomic model that assumes electrons are orbiting around a positively charged nucleus in **specific shells**

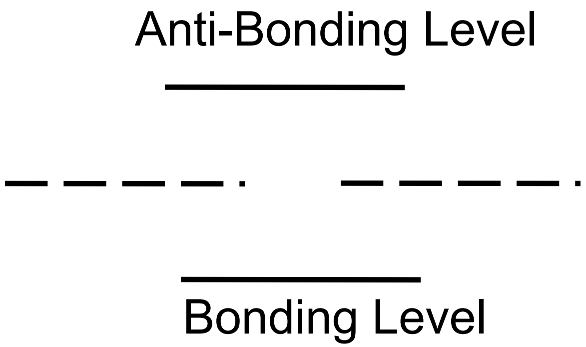


- When heated electrons can absorb the energy and go from shell 1 to 2. When cooling down, it comes down to 1, **emitting** the specific energy difference between 2 and 1 giving a specific color of light.

Energy Levels and Formation of a Molecule

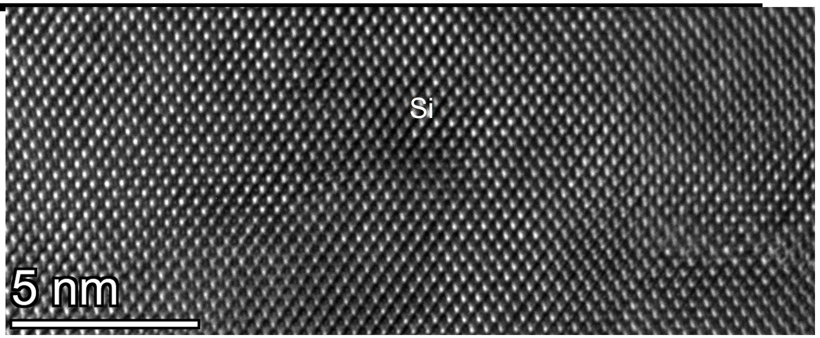


Discrete energy levels in an atom

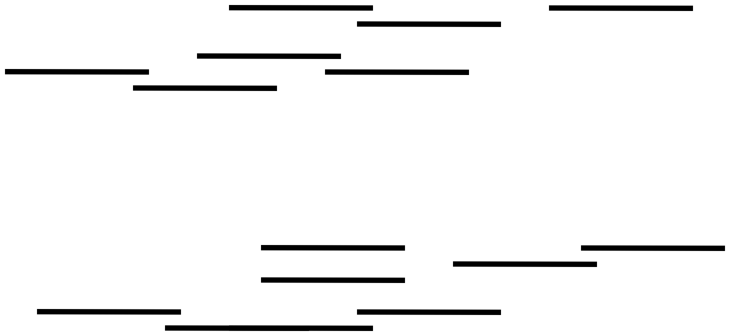


When energy levels of two atoms interact, they create one bonding and one anti-bonding level

Energy Bands

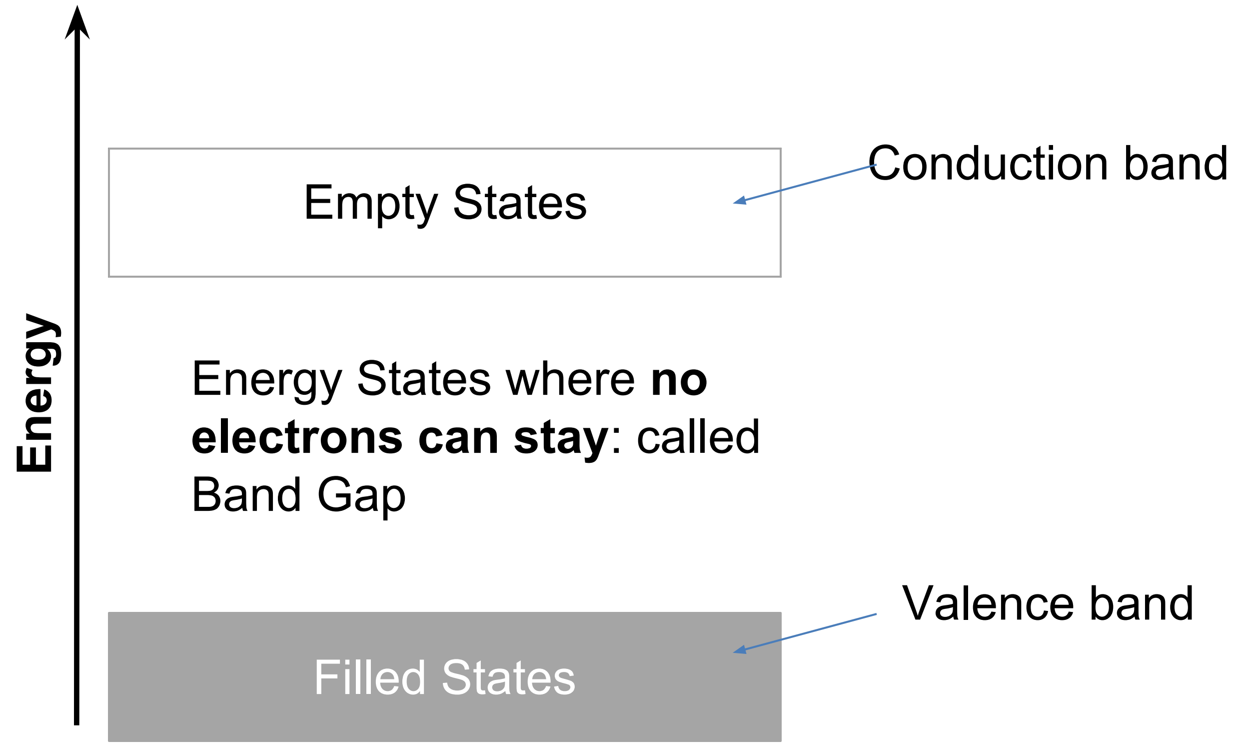


In a solid as many atoms are brought close to each other they create many many bonding and anti-bonding levels

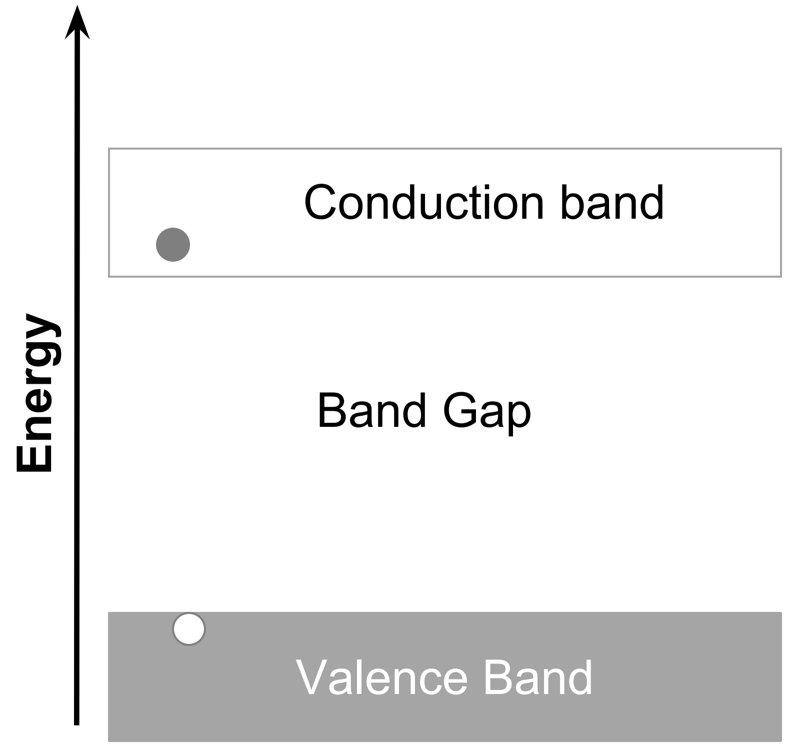


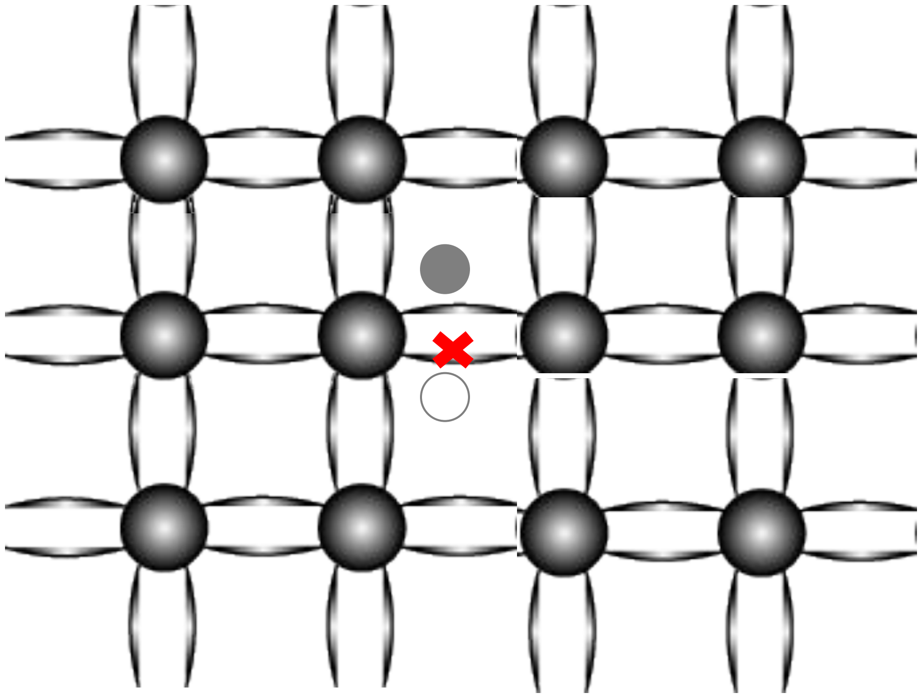
Energy Bands

Energy Bands

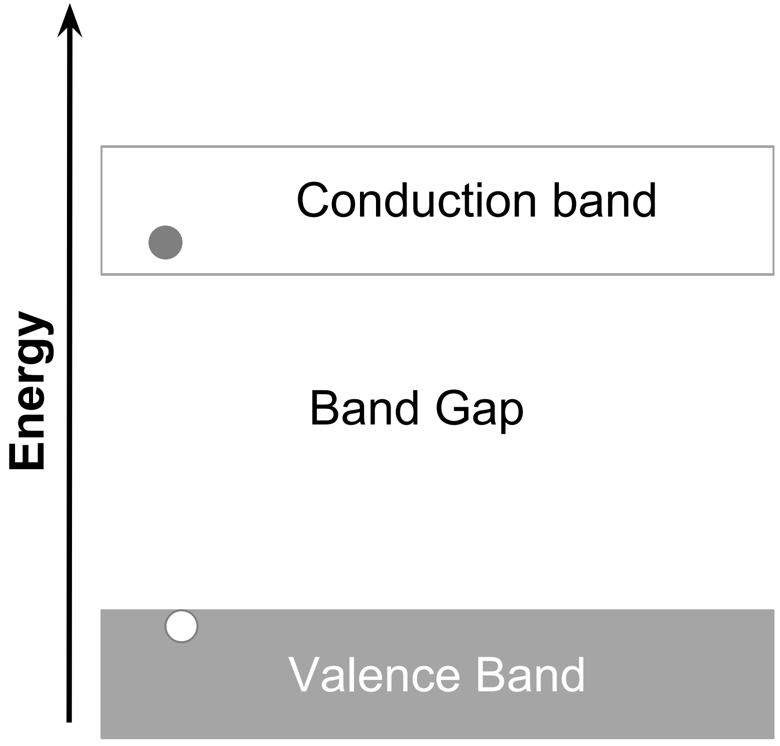


Energy Bands



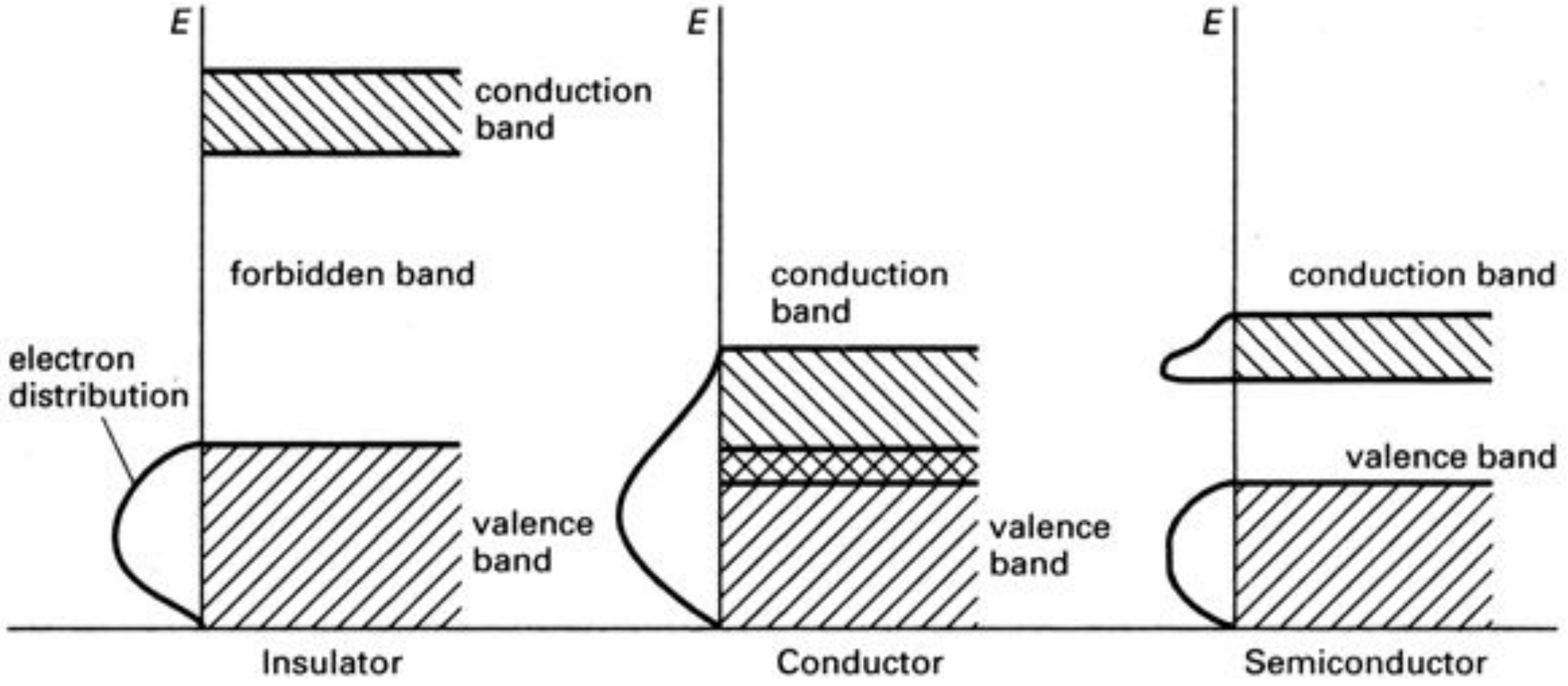


Probability of an electron being free



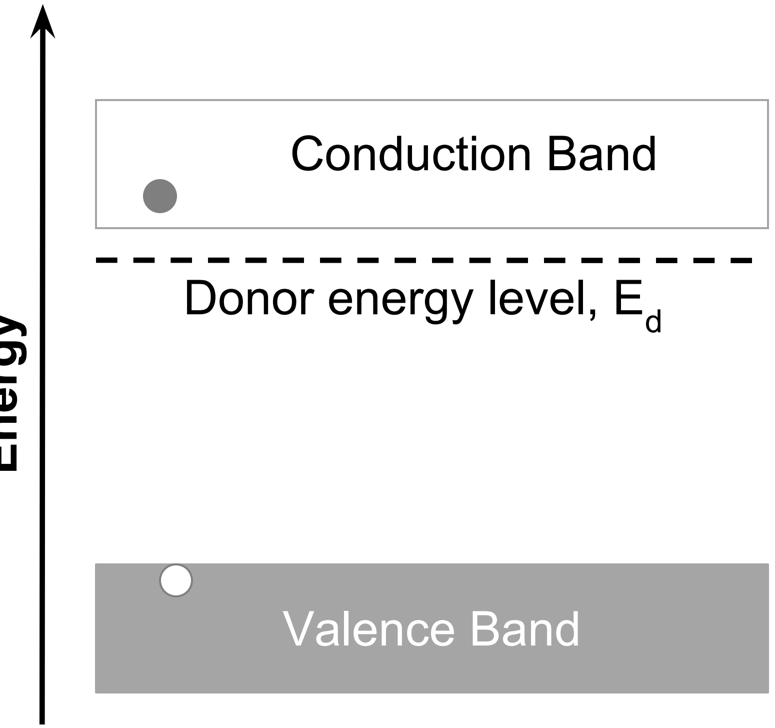
Probability of an electron being able to find itself in the conduction band becomes **exponentially smaller** with **increasing bandgap**

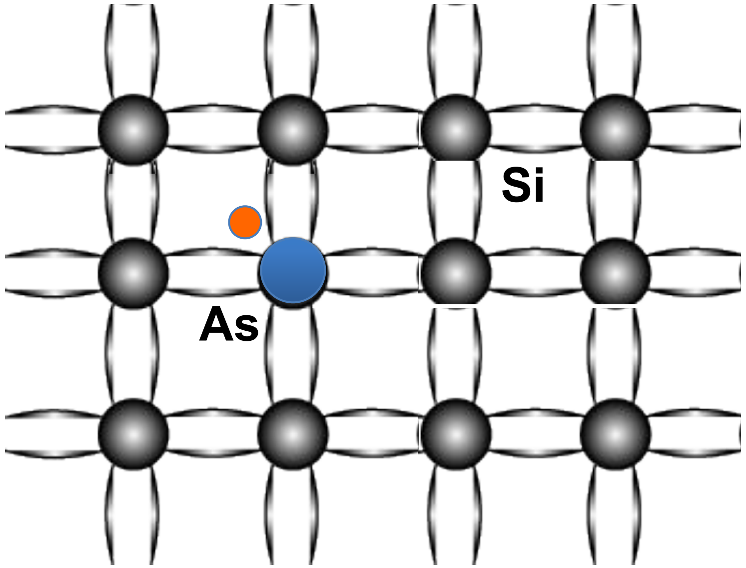
Semiconductors, Insulators and Conductors



✔Conductors have half filled bands
✔Semiconductors have lower energy gap compared to insulators and can be doped

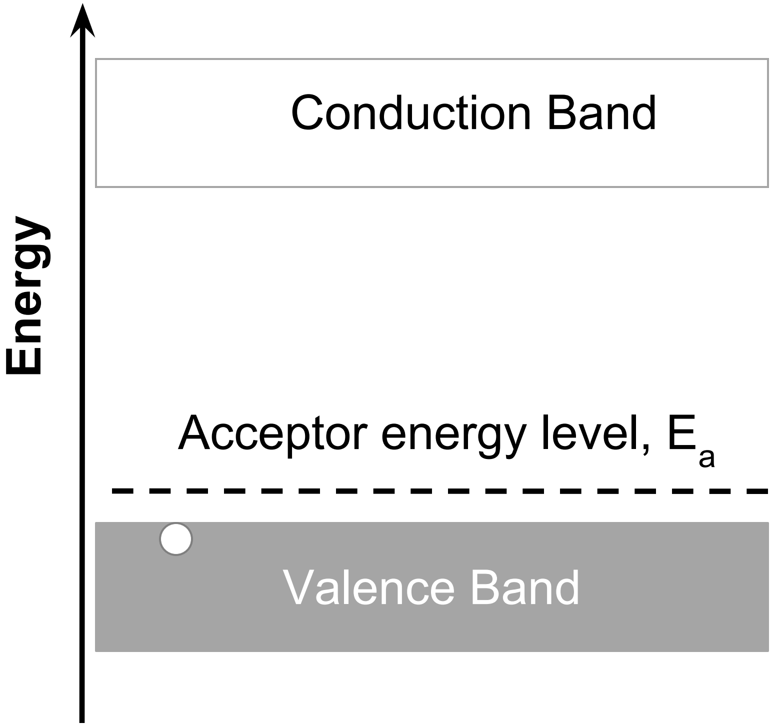
Doping

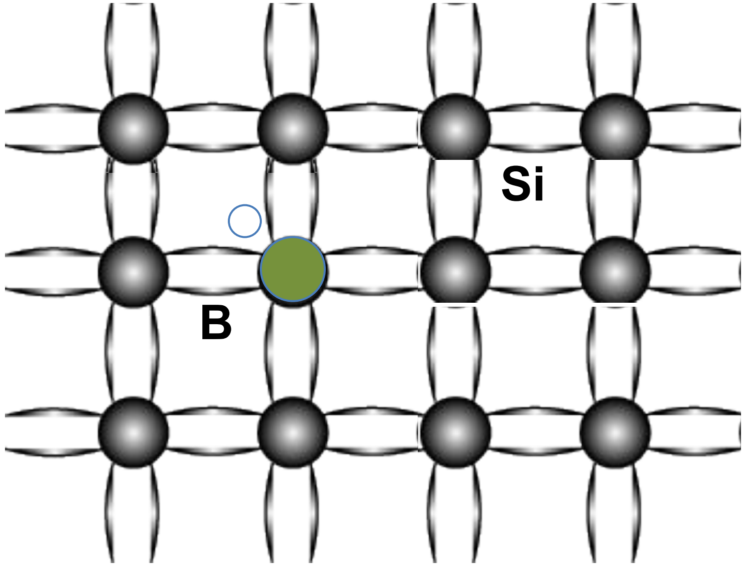




III	IV	V
Boron (B)	Carbon (C)	
Aluminum (Al)	Silicon (Si)	Phosphorous (P)
Galium (Al)	Germanium (Ge)	Arsenic (As)

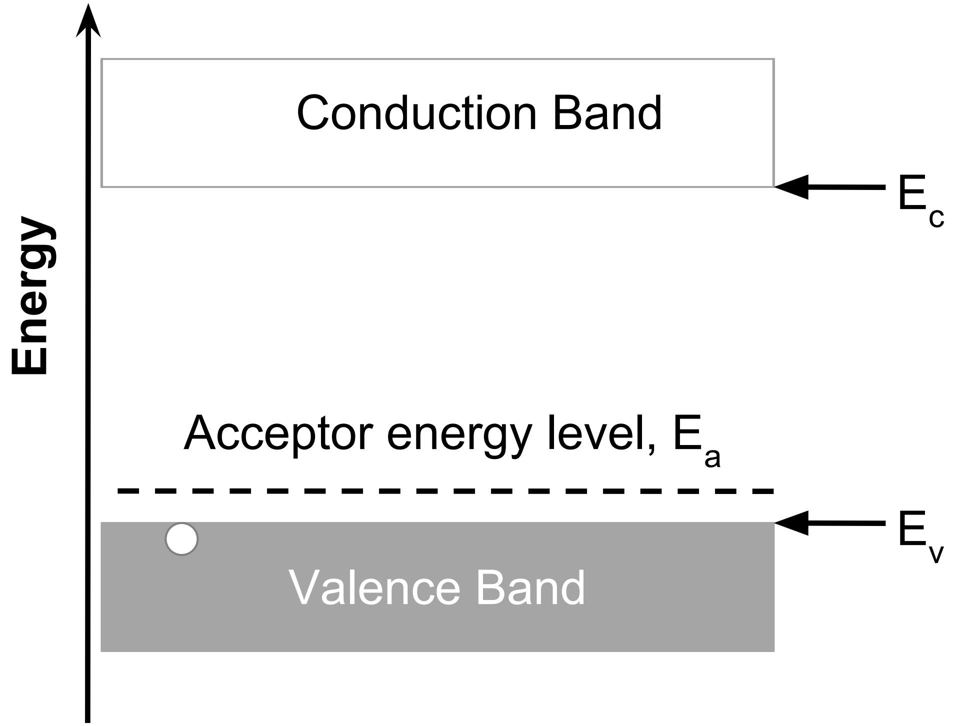
Doping





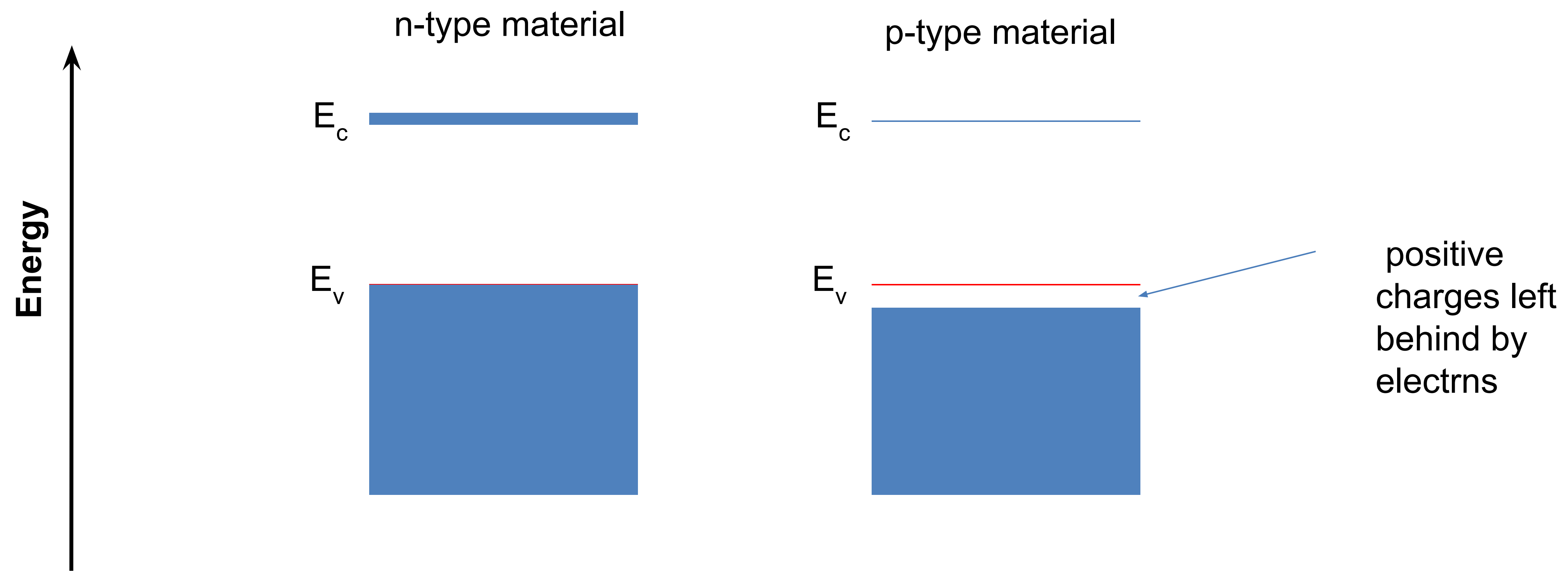
	III	IV	V	
	Boron (B)	Carbon (C)		
. . .	Aluminum (Al)	Silicon (Si)	Phosphorous (P)	. . .
	Galium (Al)	Germanium (Ge)	Arsenic (As)	
		. . .		

A convention about energy bands



Only the edge of the bands are shown where the difference between the two edges is the bandgap

N and P type Materials, Junctions and Devices

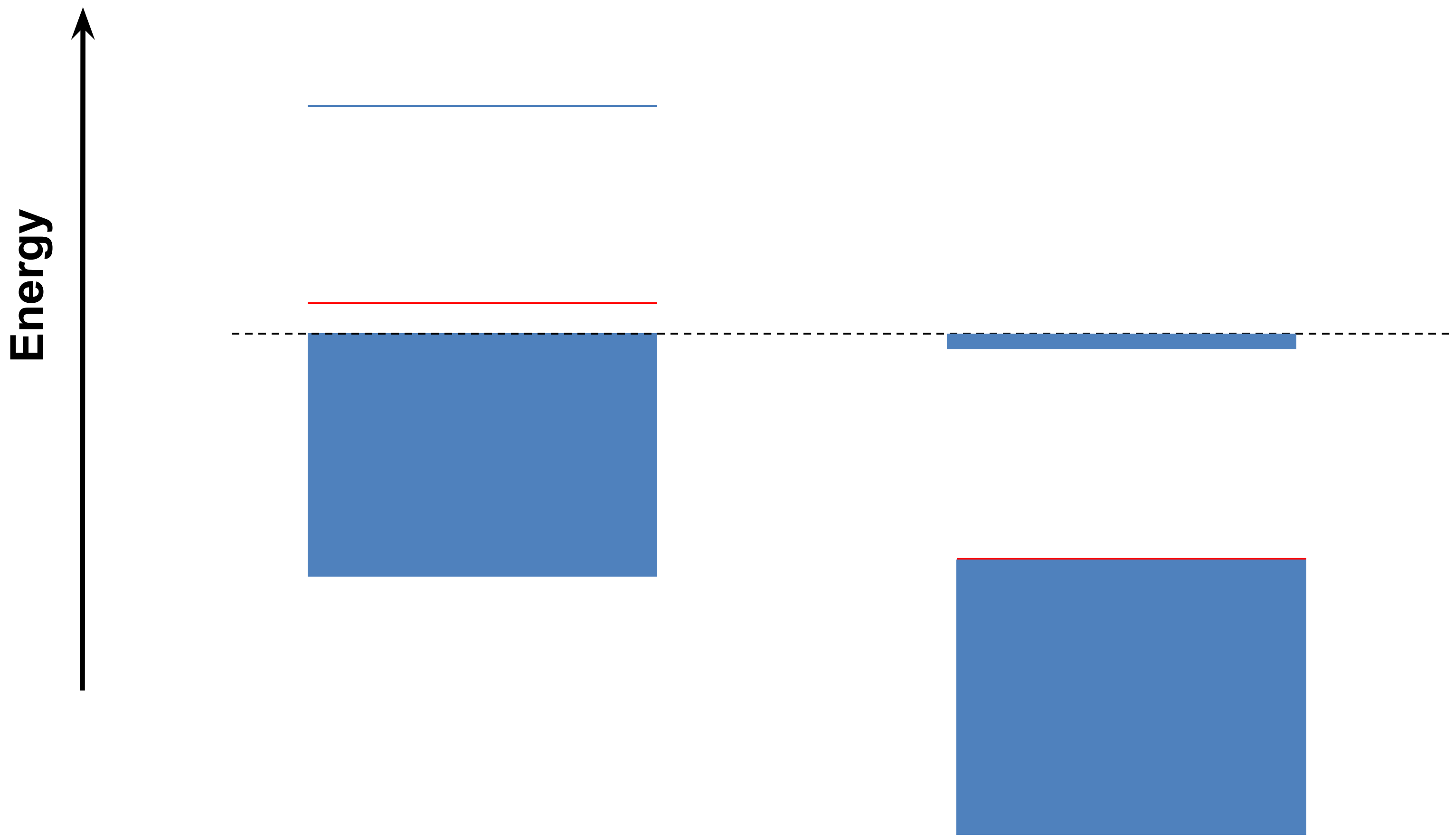


*Blue color indicates electrons

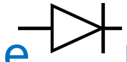
Combining N and P materials

N and P type Materials, Junctions and Devices

Qualitative Picture of a Junction Formation



- When a n and p are put together, they form a p-n junction diode
  Symbol:

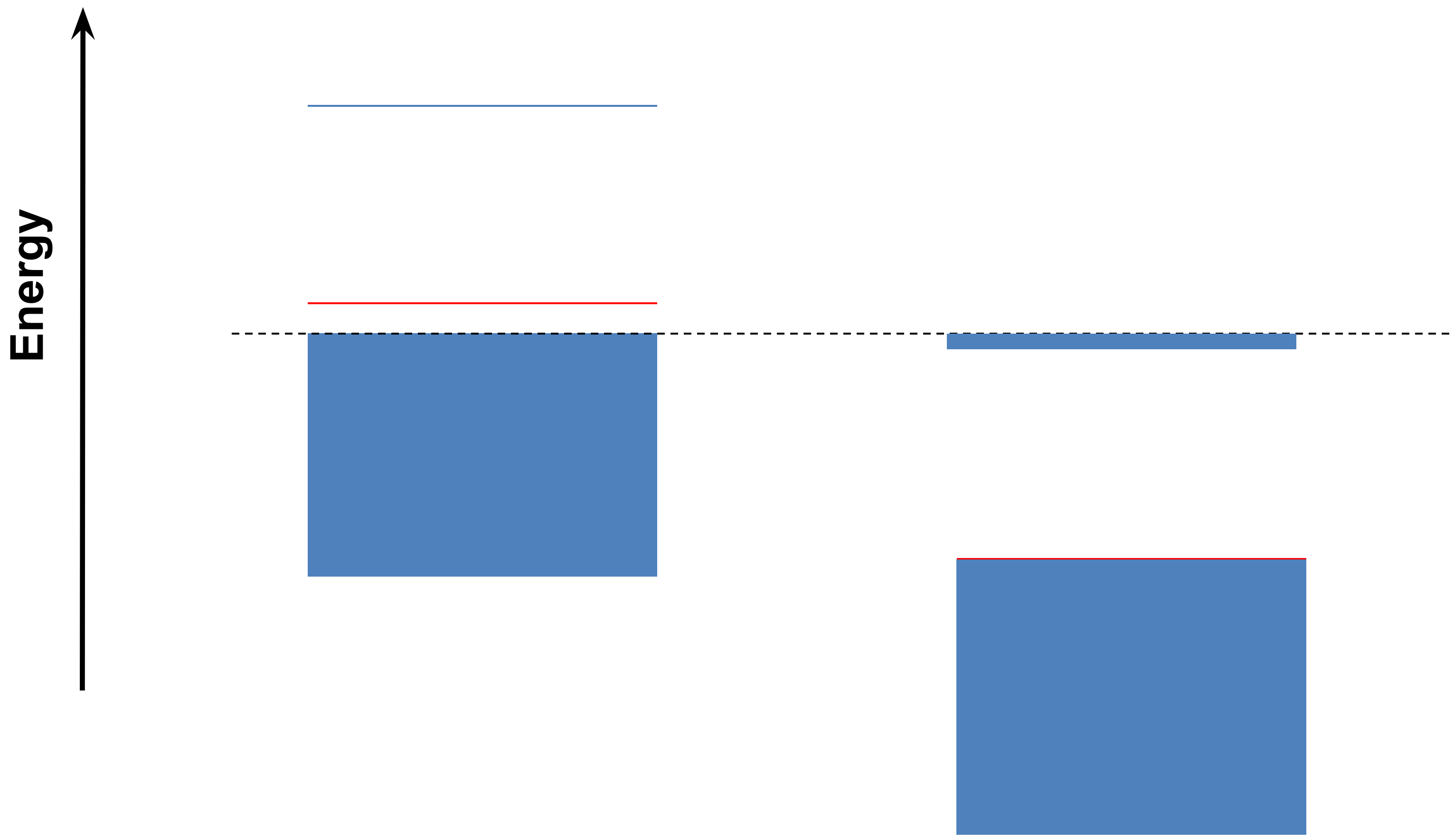
p-side  n-side

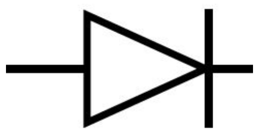
- Electron densities align in energy so that there is no difference in concentration

- Technically what aligns is the energy level where probability of finding an electron is ½ □to be discussed in more details in EE130

What does a voltage do?

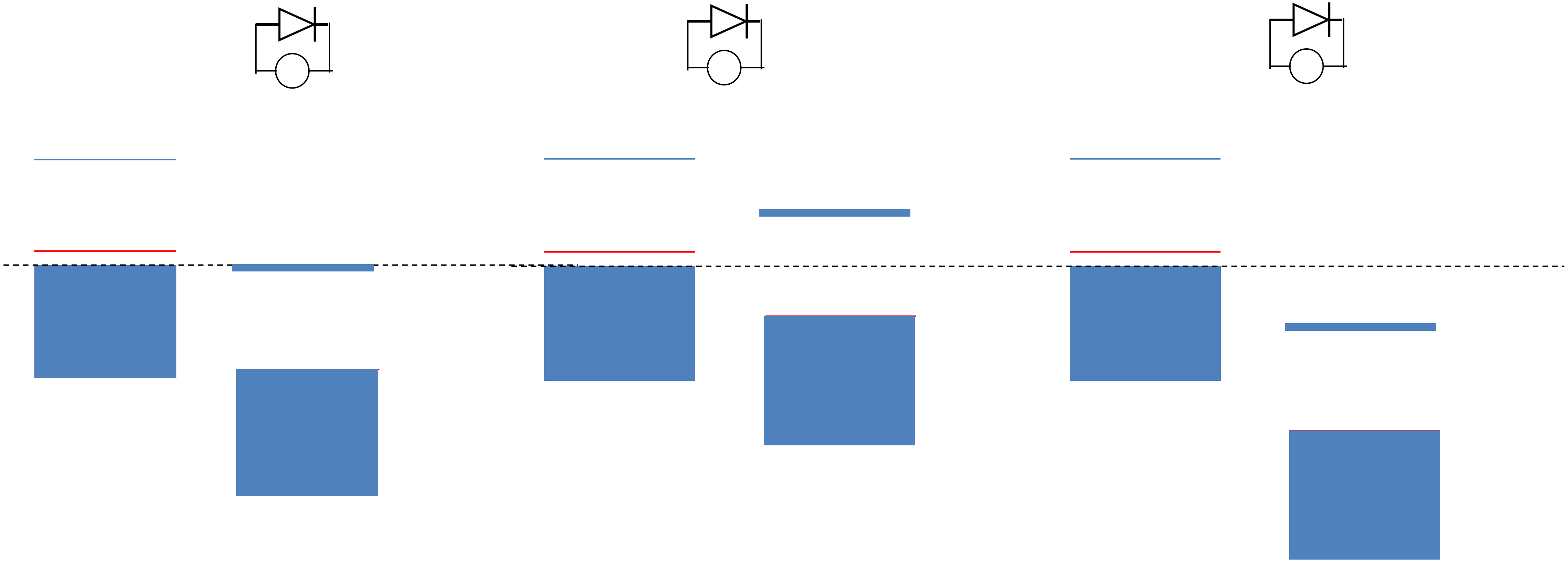
Qualitative Picture of a Junction Formation





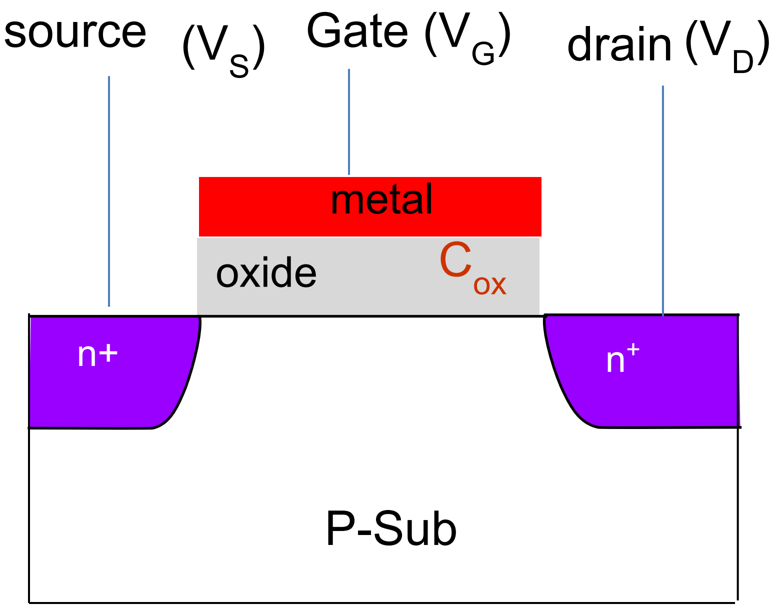
Negative terminal of a battery brings electrons and thereby **increases energy.**

N and P type Materials, Junctions and Devices

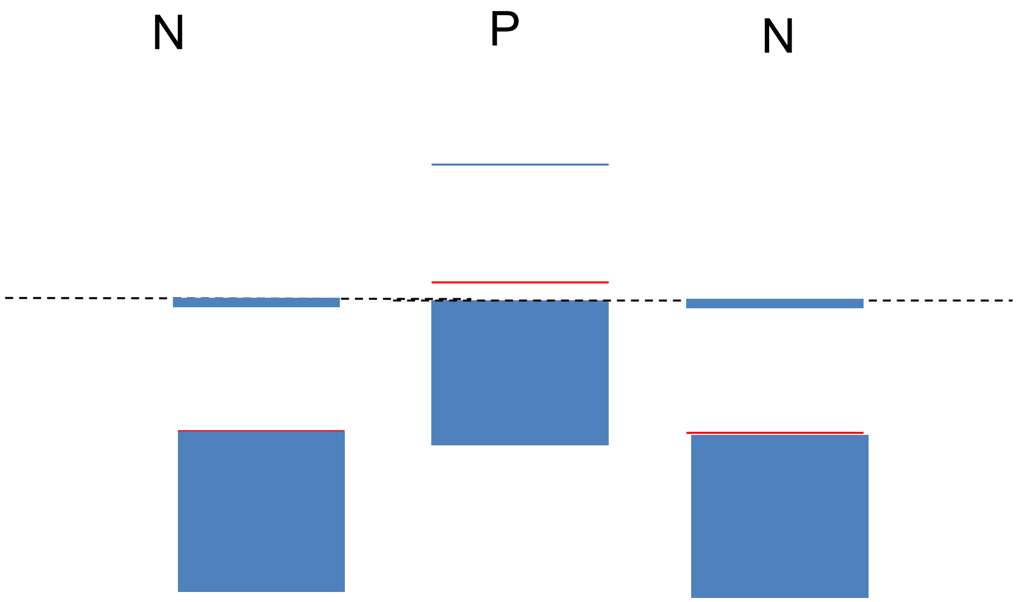


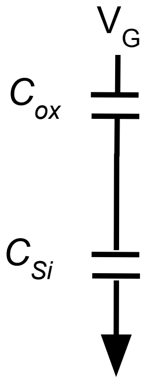
I-V of a PN junction Diode

Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)



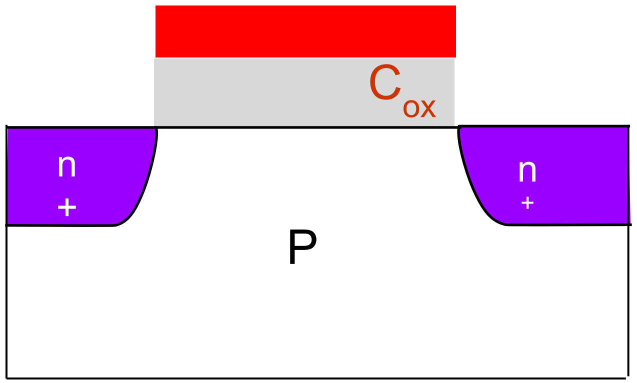
- + or – in the name of n or p type material indicates extent of doping. N+ means doped **heavily** to n type.
- In common MOSFET source and drain voltages are interchangeable

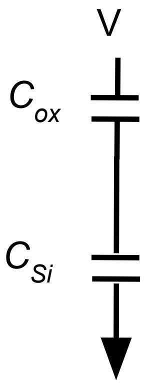


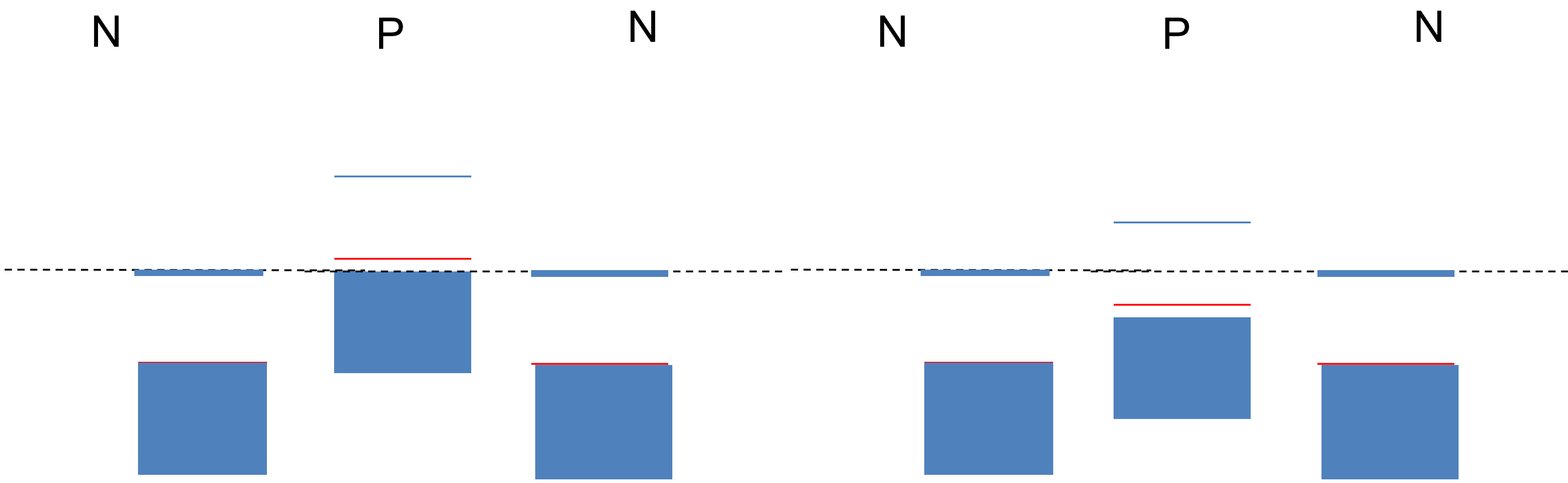


P-type semiconductor in the middle with little to no electrons on the conduction band acts like an insulator

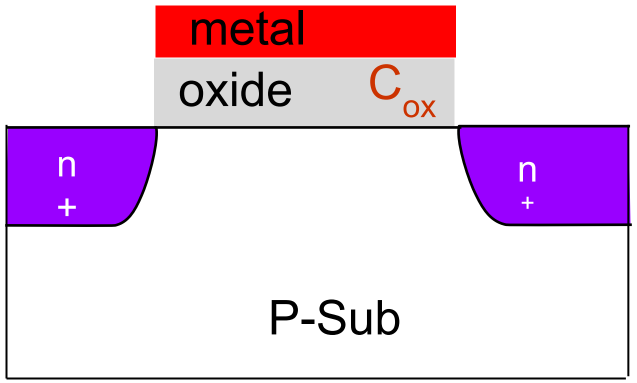
MOSFET

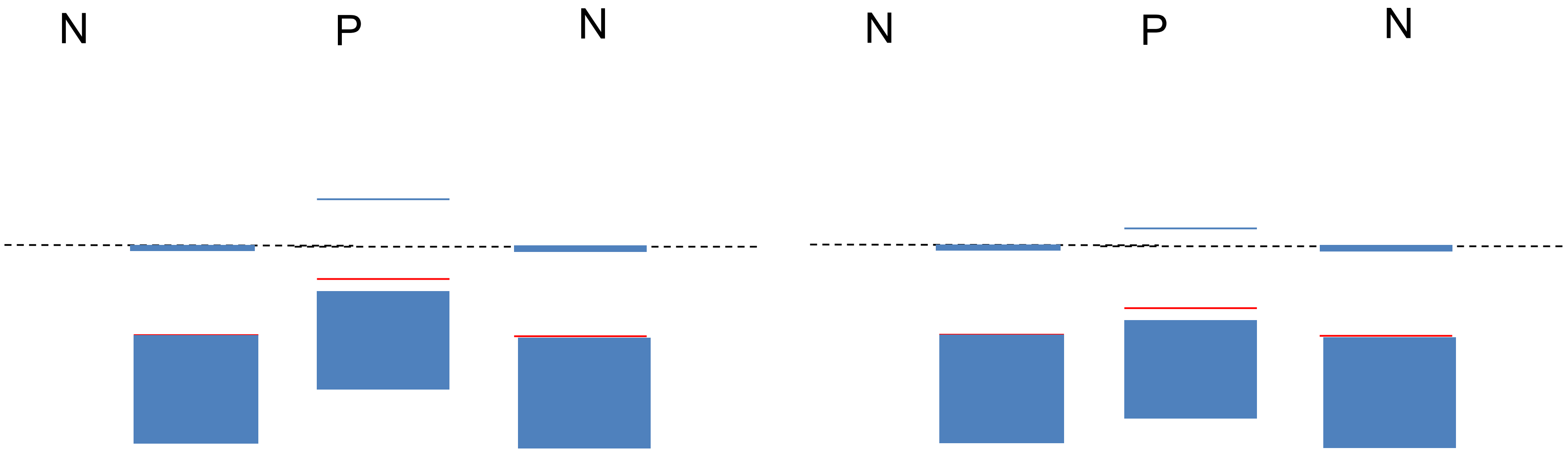


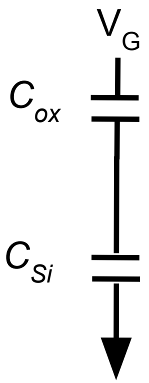




MOSFET

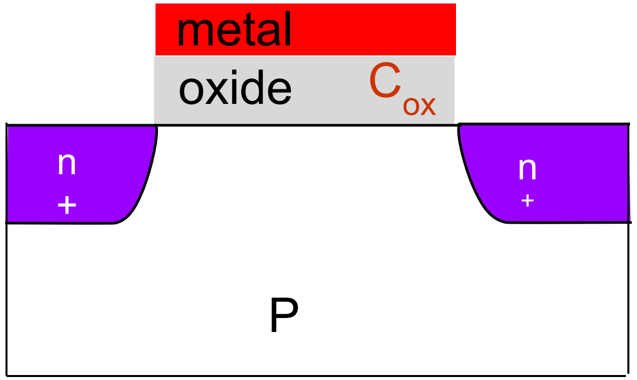


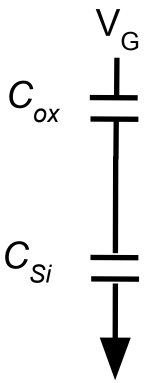


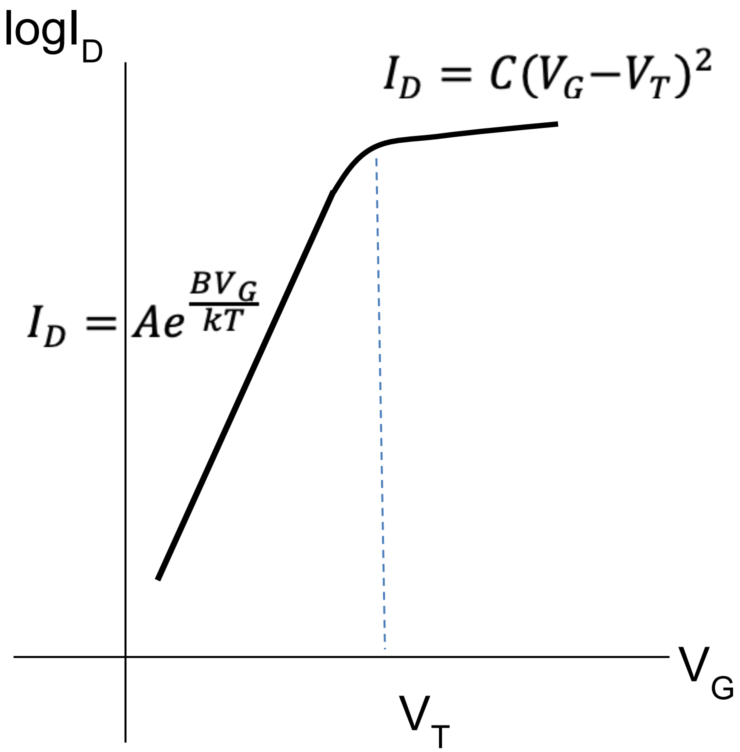


At large gate voltages, one reaches close to maximum charge density achievable in Si. So rate of change in increase in electron density with gate voltage slows down

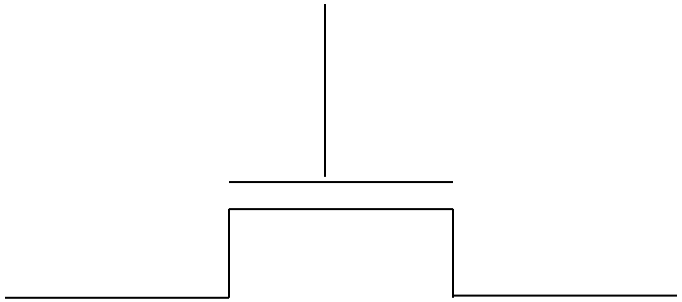
MOSFETs

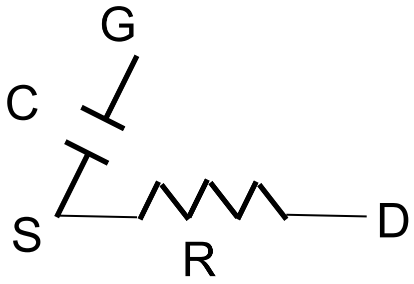






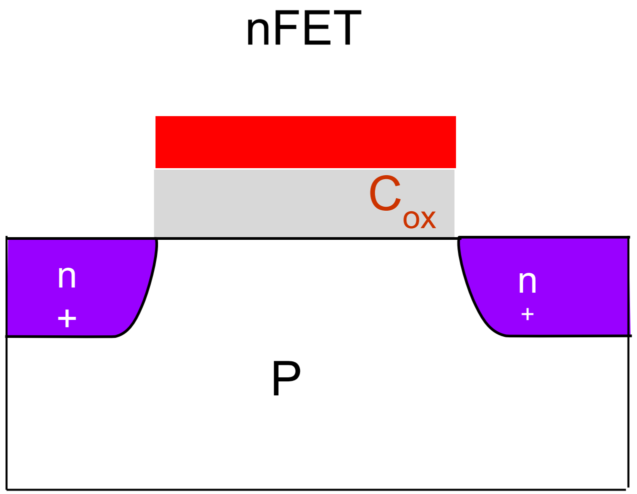
Assuming large V_{DS} is present

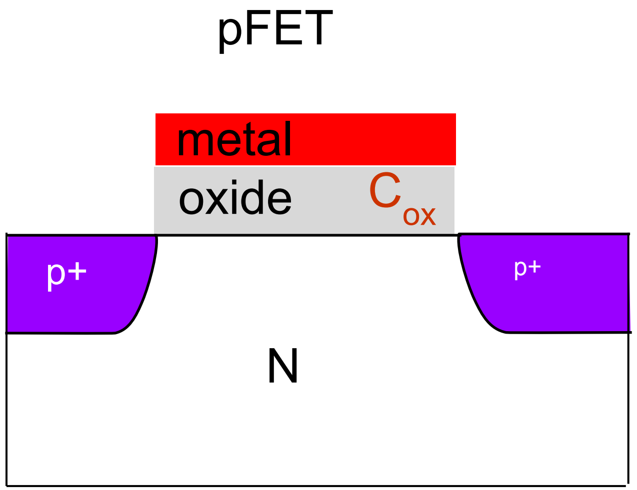




- C is the series combination of Cox and Csi
- $R = I_{DS}/V_{DS}$

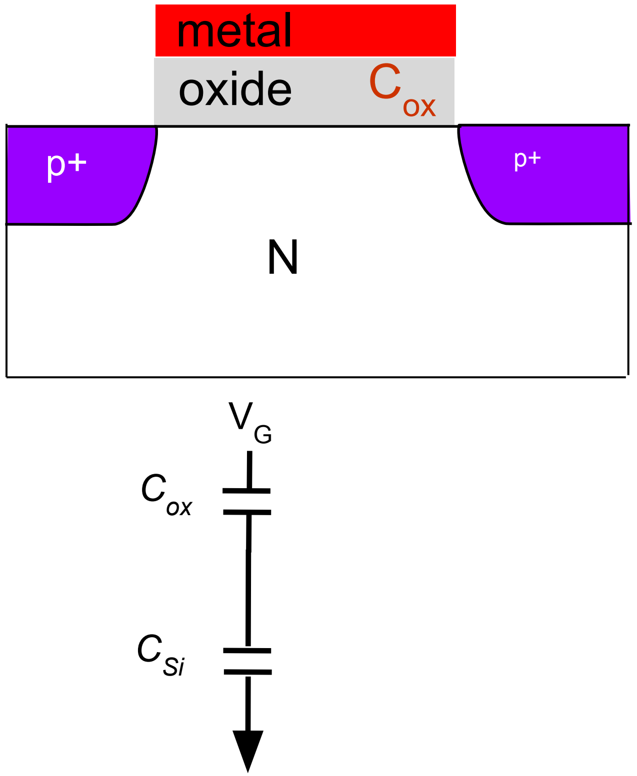
nFET vs pFET

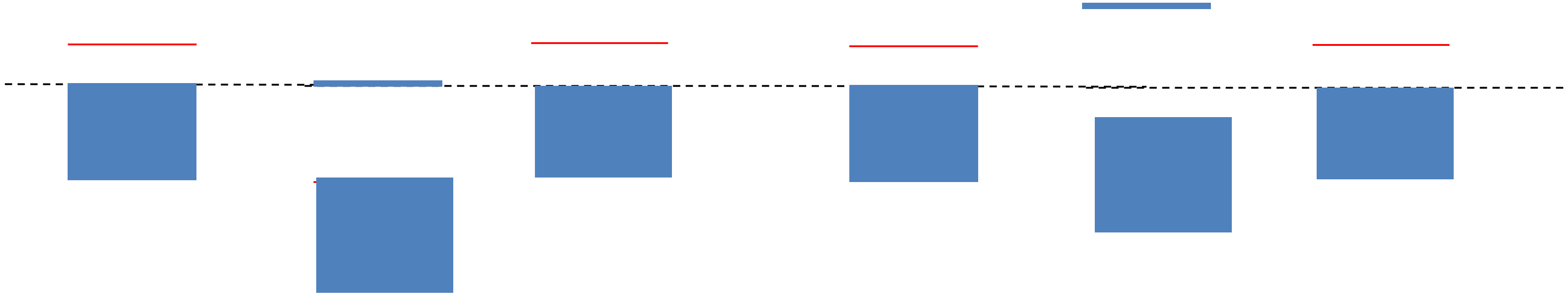




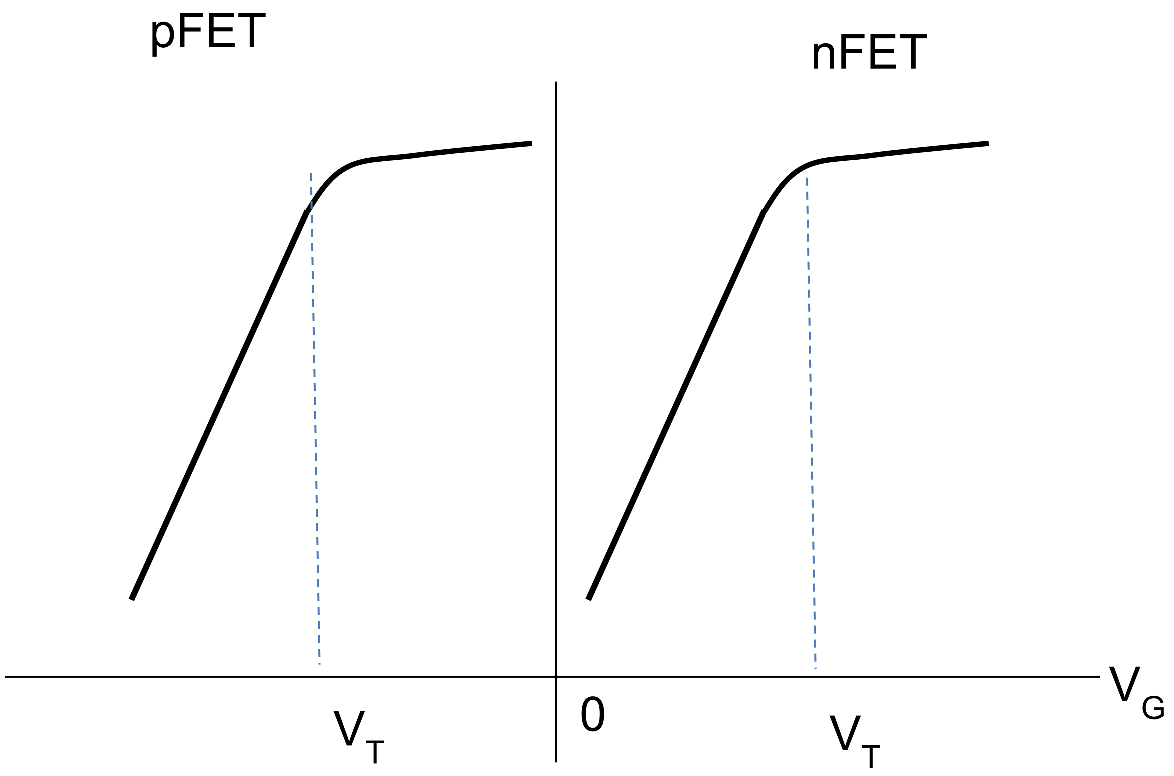
nFET vs pFET

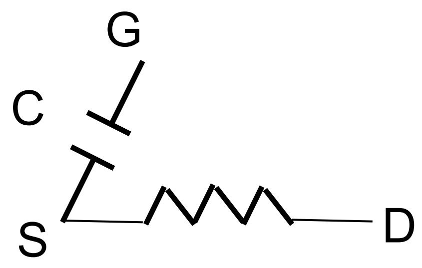
pFET





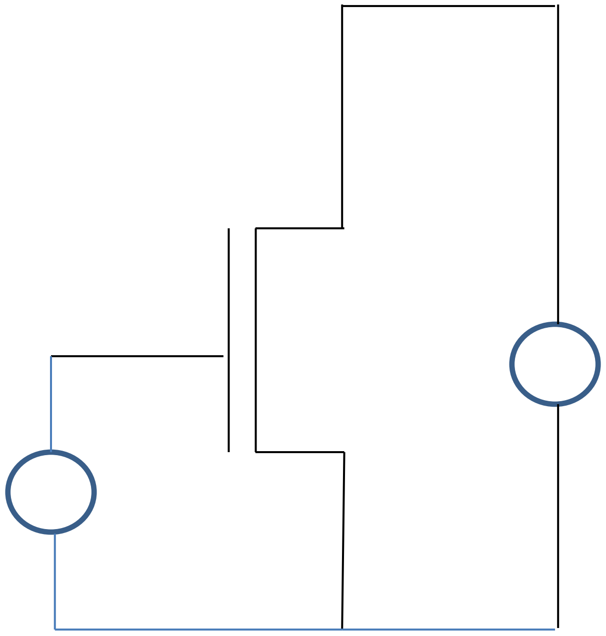
nFET vs pFET





- nFET, V_{GS} and V_T are positive
- pFET, V_{GS} and V_T are negative

FET as an analog amplifier



When $V_{GS}<V_T$

$$I_D = Ae^{\frac{BV_G}{kT}}$$

Small change in V_{GS} changes I_D exponentially

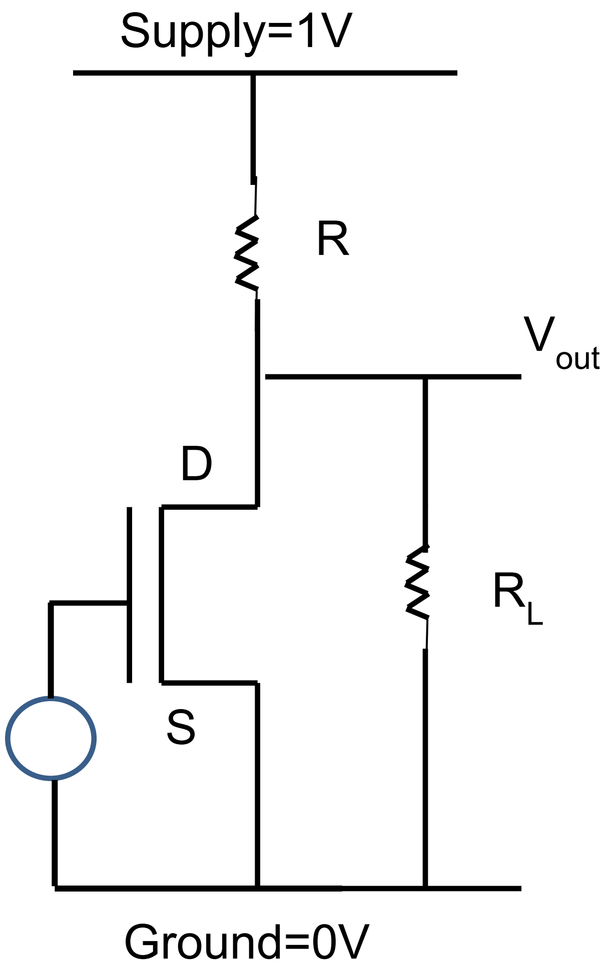
When $V_{GS}>VT$

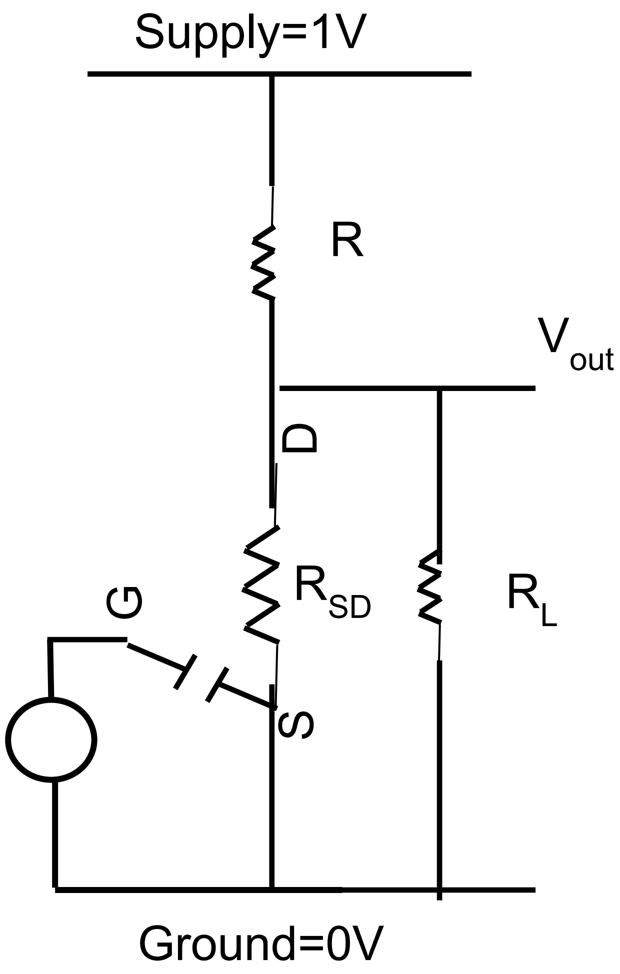
$$I_D = C(V_G - V_T)^2$$

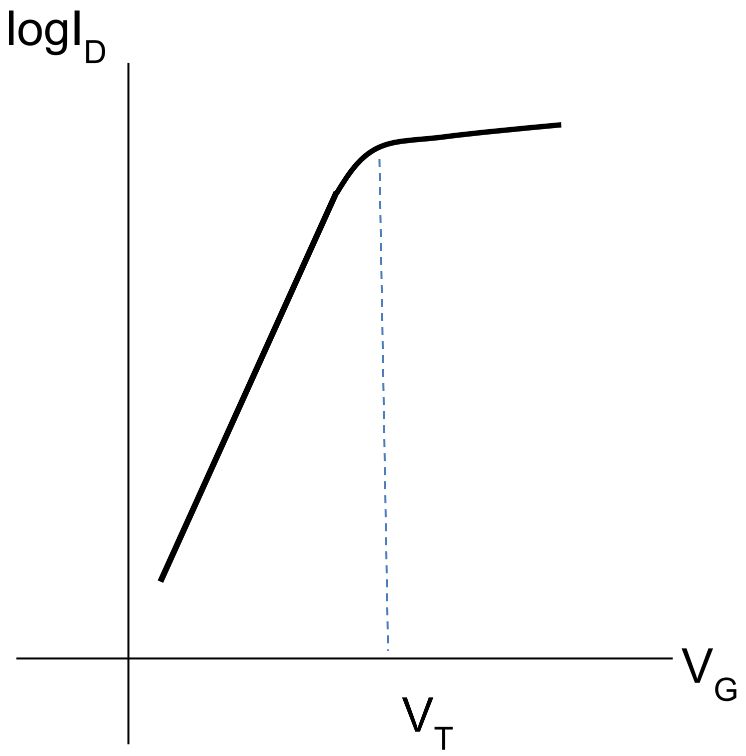
Small change in V_{GS} changes I_D quadratically

Overall, Large changes in the Drain current can be achieved by changing Gate Voltage

FET in digital logic



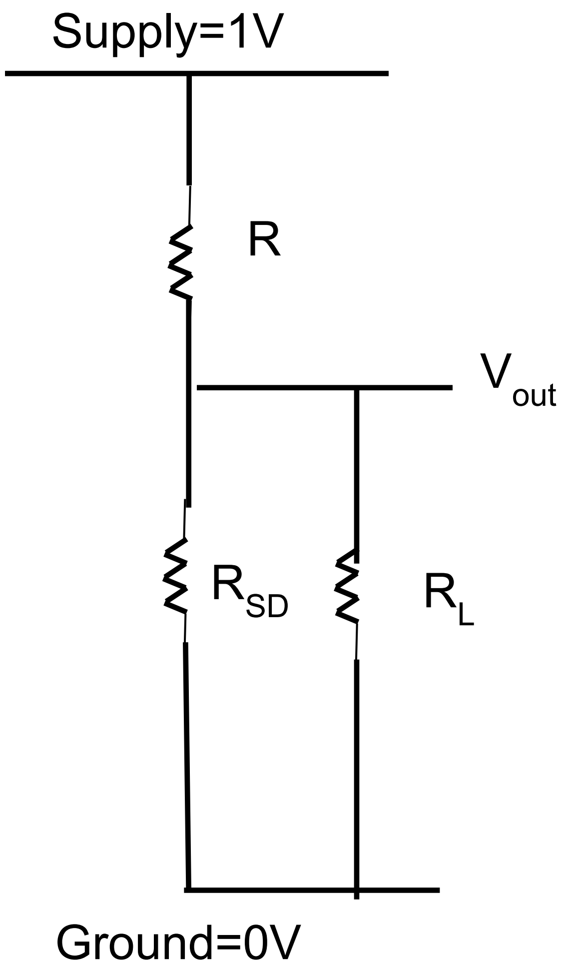


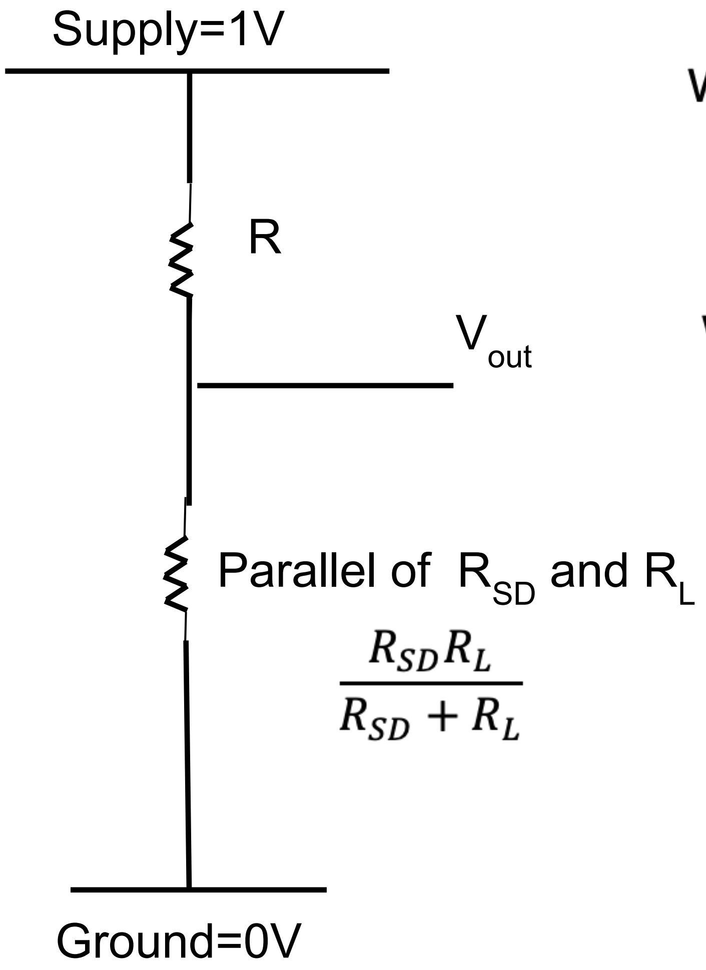


When V_{GS} is High, R_{SD} is low

When V_{GS} is Low, R_{SD} is High

FET in digital logic



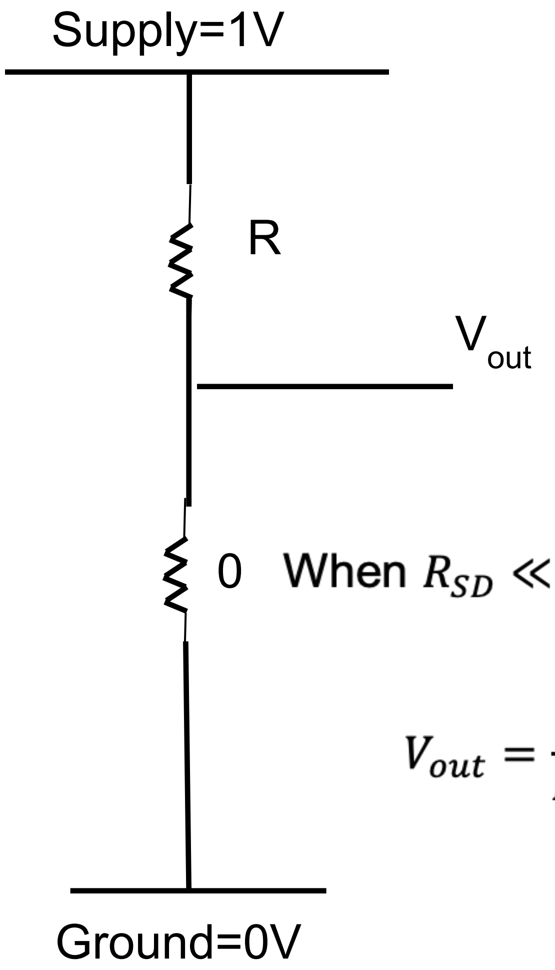


$$\frac{R_{SD}R_L}{R_{SD}+R_L}$$

When $R_{SD} \ll R_L$; $\frac{R_{SD}R_L}{R_{SD}+R_L} \approx \frac{R_{SD}}{R_L} \approx 0$

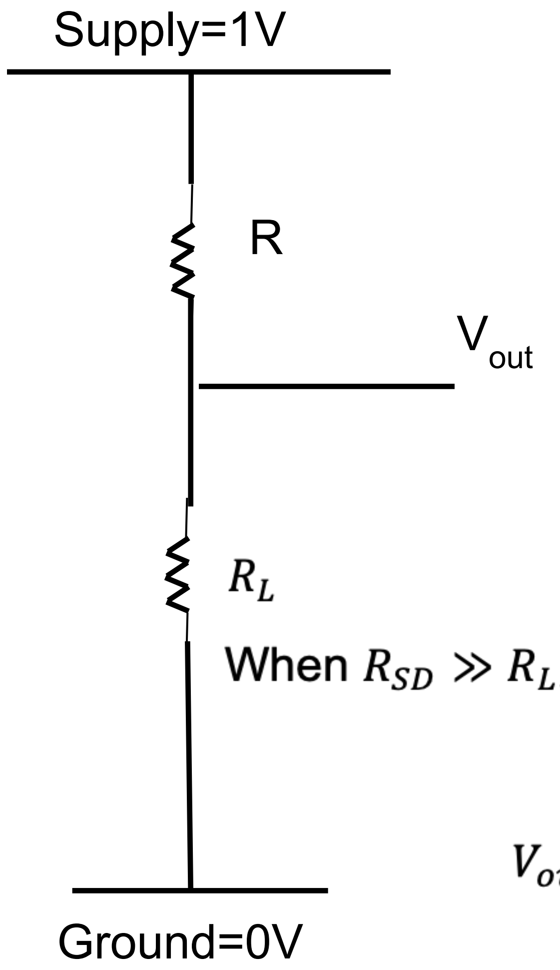
When $R_{SD} \gg R_L$; $\frac{R_{SD}R_L}{R_{SD}+R_L} \approx R_L$

FET in digital logic



When $R_{SD} \ll R_L$ $i.e., V_{GS}$ $is\ high$

$$V_{out} = \frac{0}{R+0} = 0$$

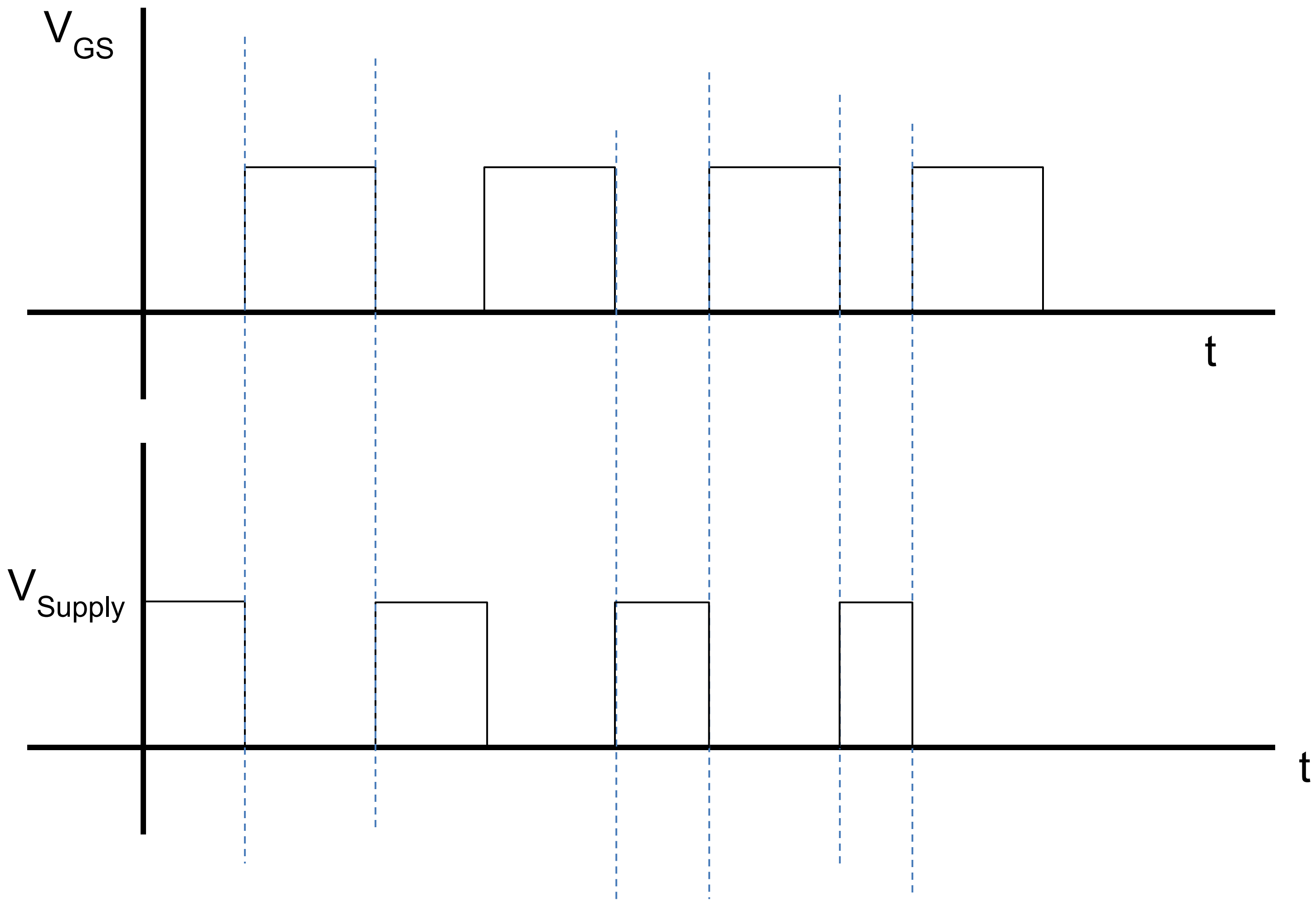


When $R_{SD} \gg R_L$; when V_{GS} $is\ low$

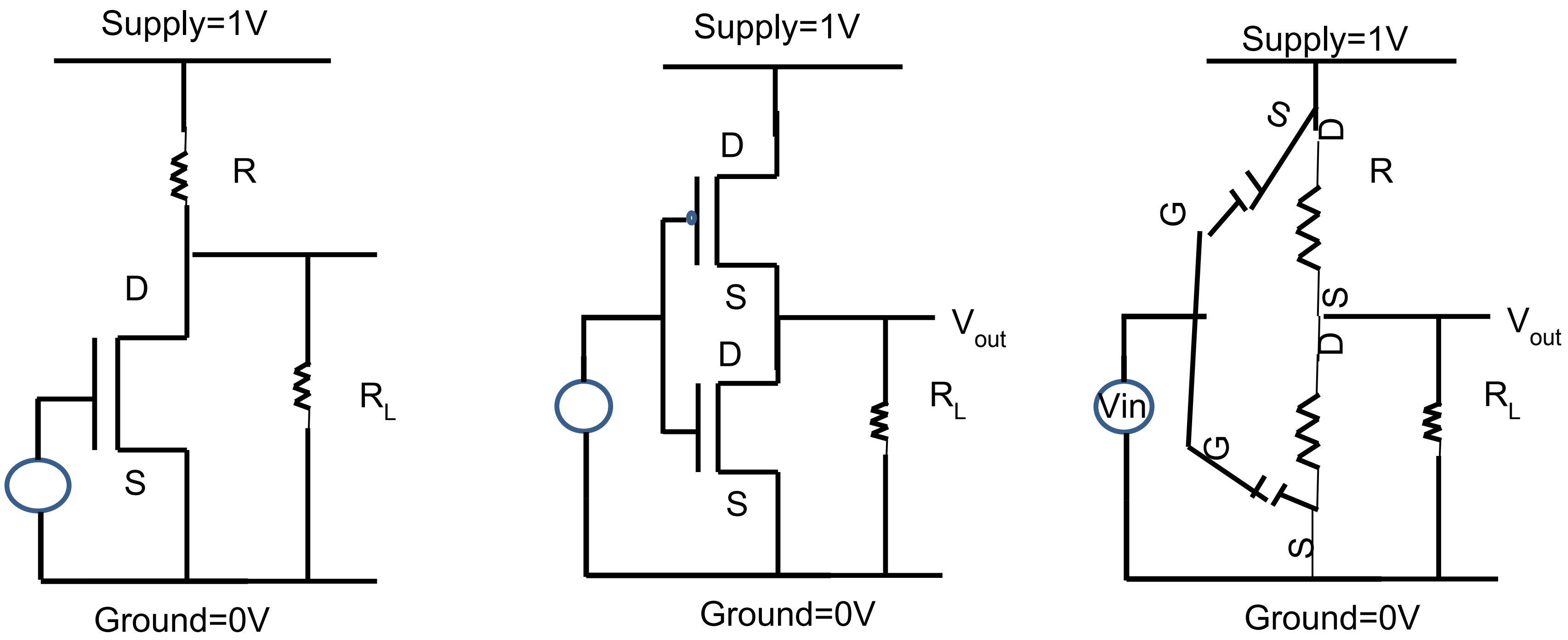
$$V_{out} = \frac{R_L}{R+R_L} V_{supply}$$

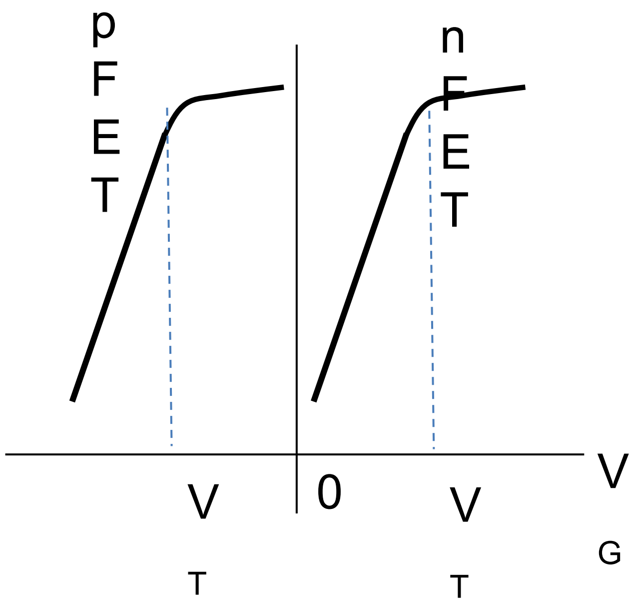
$$\approx V_{supply}\ if\ we\ design\ R \ll R_L$$

FET in digital logic



CMOS





Vin=1V

V_{GS} for nFET is HIGH□ R_{SD} is LOW

V_{GS} for pFET is LOW□ R_{SD} is high

Vin=0 V

V_{GS} for nFET is LOW□ R_{SD} is HIGH

V_{GS} for pFET is HIGH **NEGATIVE**□ R_{SD} is LOW