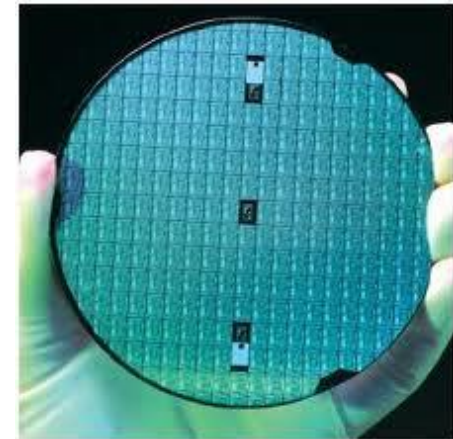
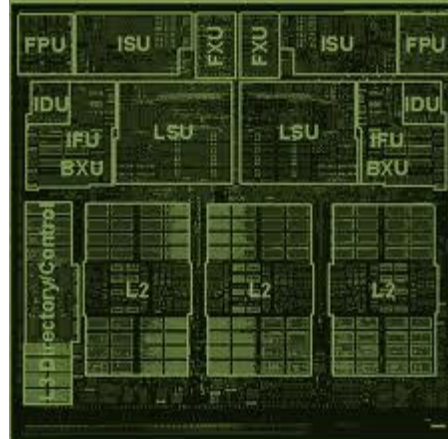
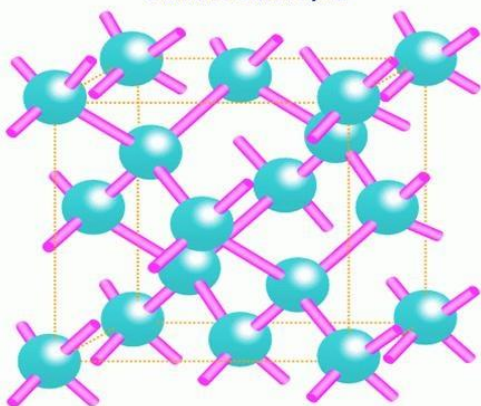


Structure of silicon crystal



ECE 225

High Speed Digital IC Design

Lecture 4

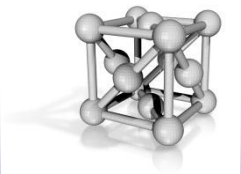
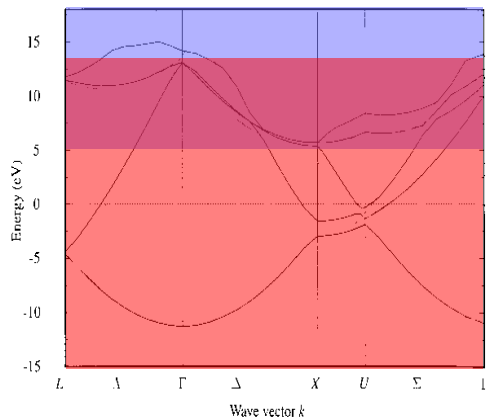
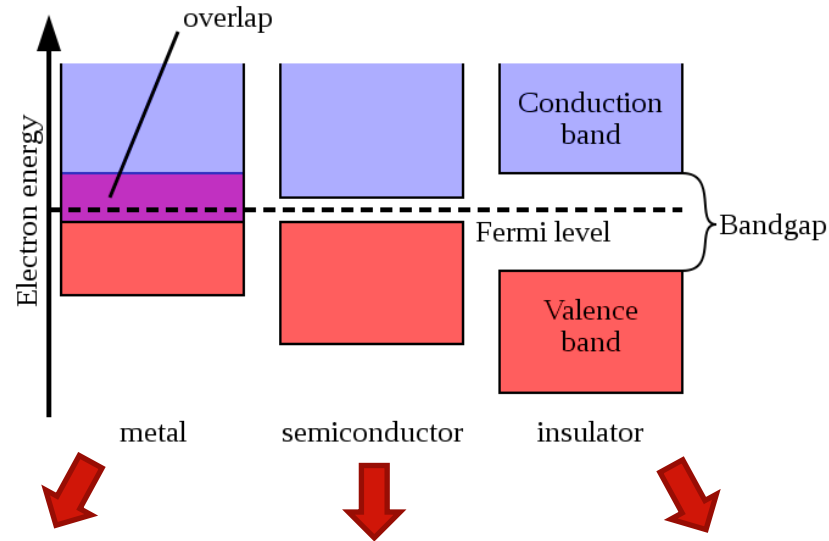
Semiconductor Physics (Review)

Prof. Kaustav Banerjee
Electrical and Computer Engineering
University of California, Santa Barbara
E-mail: kaustav@ece.ucsb.edu

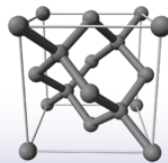
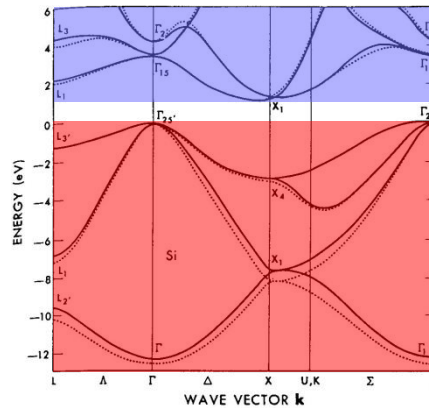
Outline

- ❑ Band Model
- ❑ Metal, Insulator and Semiconductor
- ❑ Electron / Hole Concentration
- ❑ Extrinsic Semiconductors
- ❑ P-N Junction
- ❑ MOS Capacitor

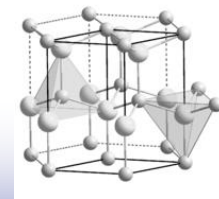
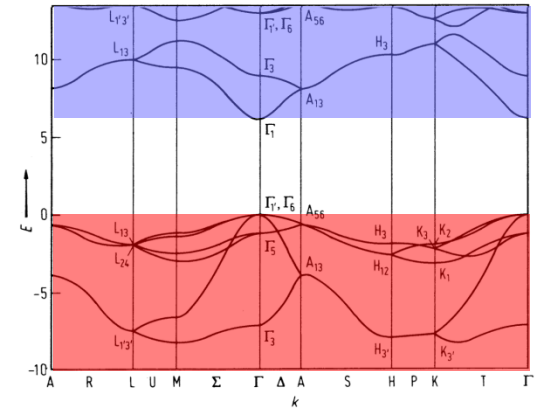
Classification of Solids from “Energy Bands”



Al



Si



AlN

Band Model of Solids

□ Electron Energy Levels (Bohr Model)

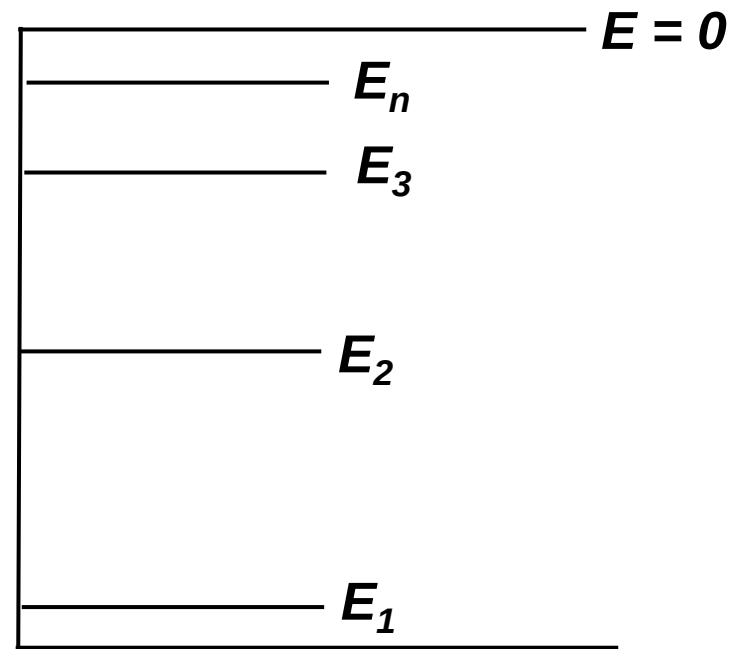
$$E_n = \frac{-Z^2 m_0 q^4}{8 \epsilon_0^2 h^2 n^2}$$

Z = # of protons in nucleus

q = charge of electron ($= -1.6 \times 10^{-19}$ C)

m_0 = free electron mass

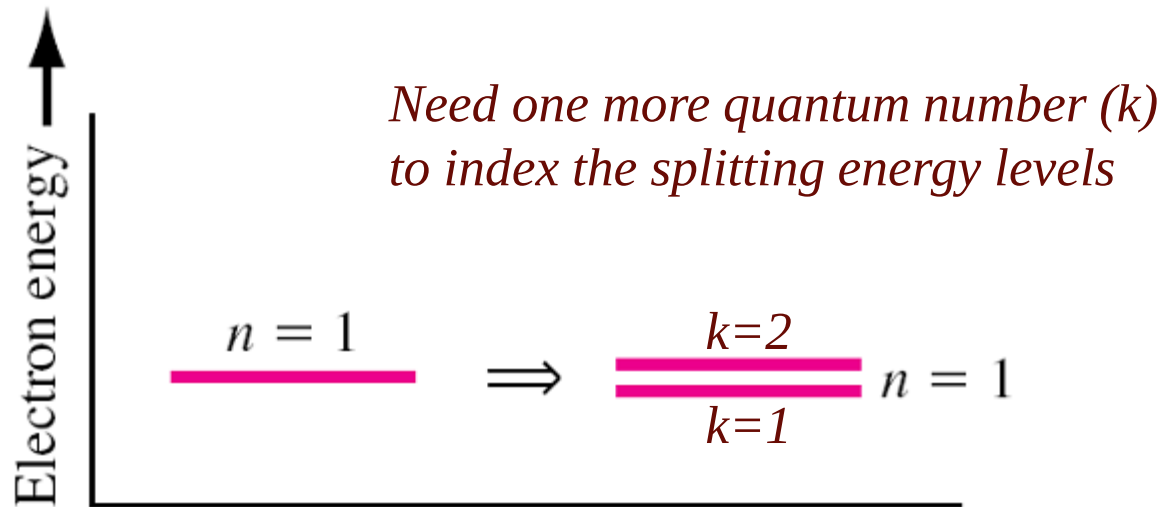
For Hydrogen atom, $Z=1$, $E_1 = -13.6$ eV



Band Model of Solids

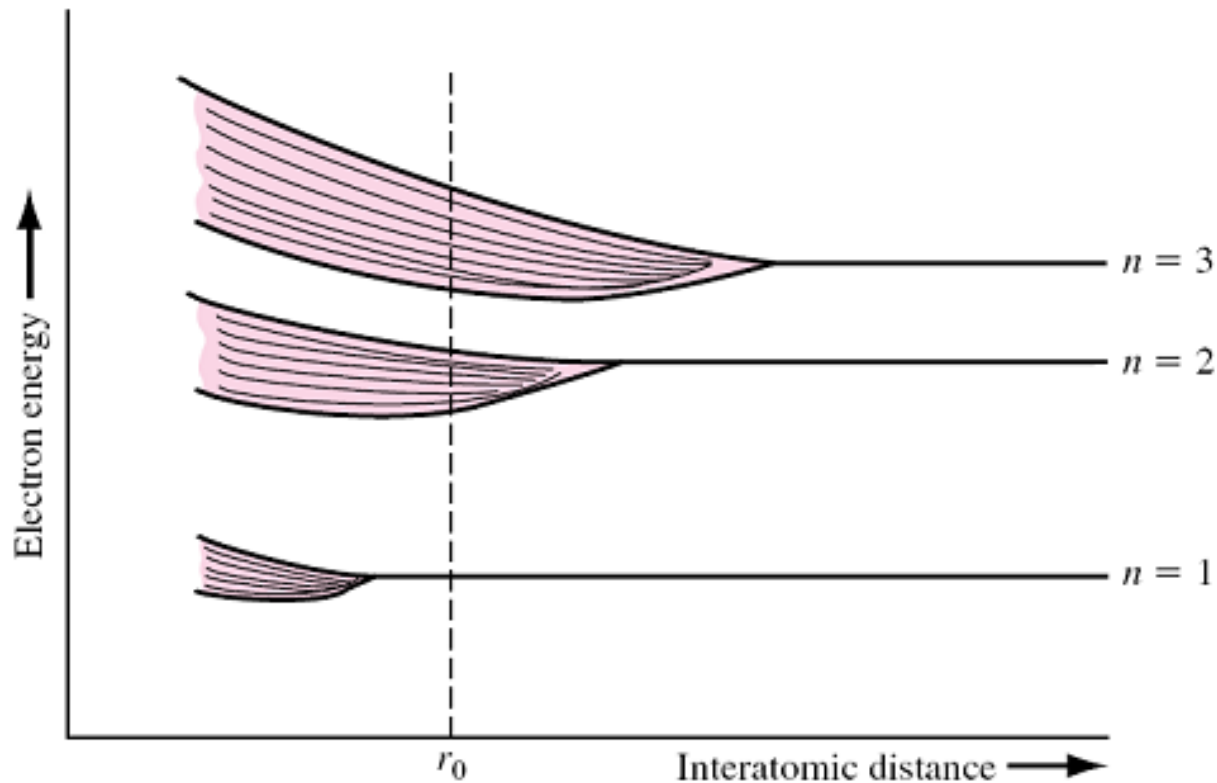
Pauli Exclusion Principle (PEP)

The splitting of the discrete states into two states in consistent with **the Pauli exclusion principle**.



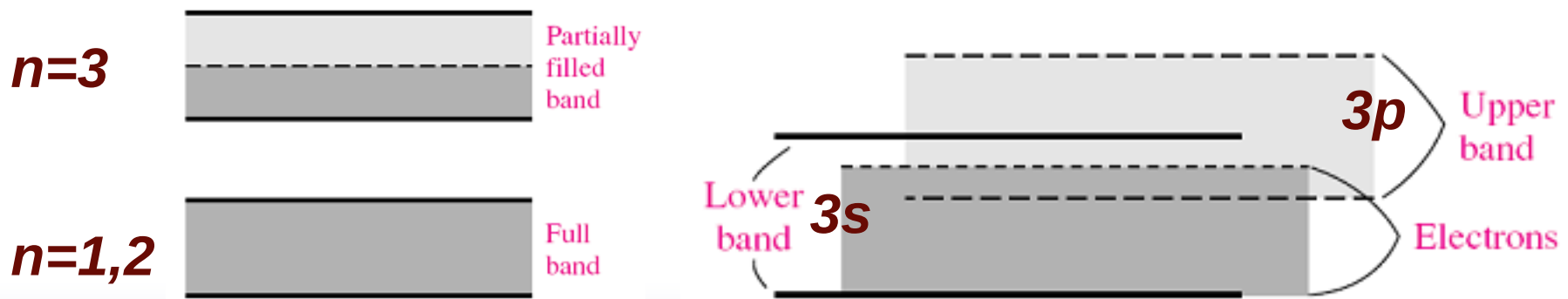
Band Model of Solids

□ The allowed/forbidden energy band



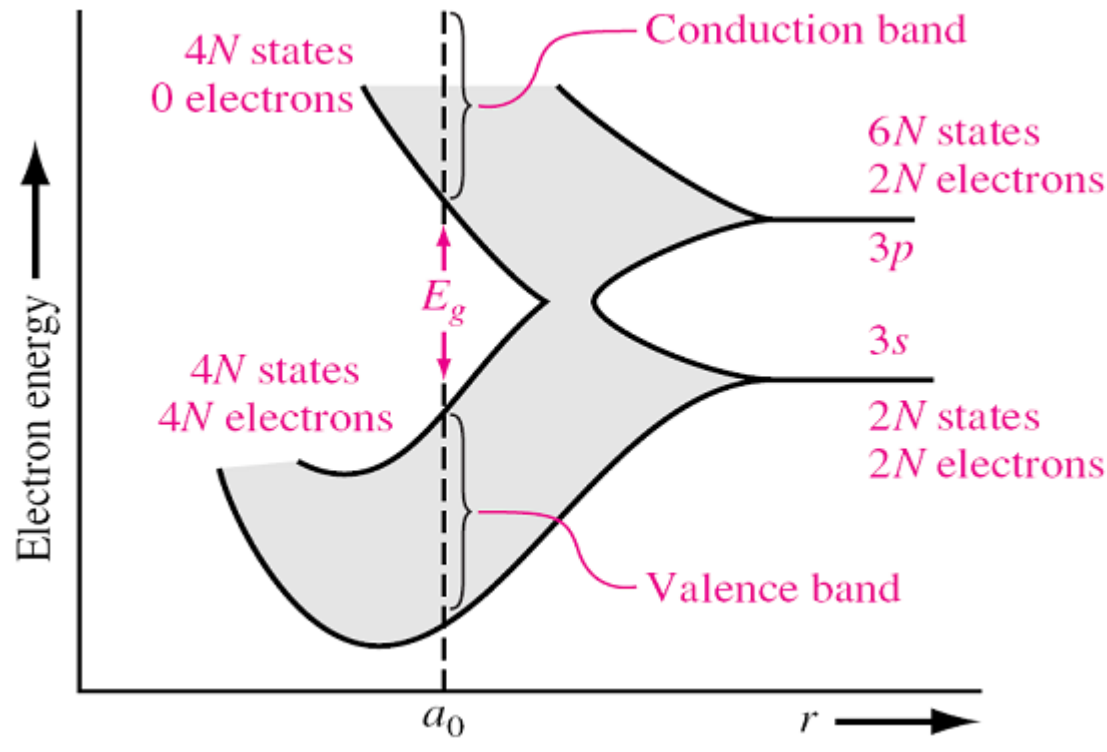
Metals, Semiconductors and Insulators

- Metallic Conduction happens if one band is **neither empty nor full**
- Consider N sodium atoms ($1s^2 2s^2 2p^6$ **$3s^1$**)
 - Total number of available states = $2N$
 - **N** conduction electrons



Metals, Semiconductors and Insulators

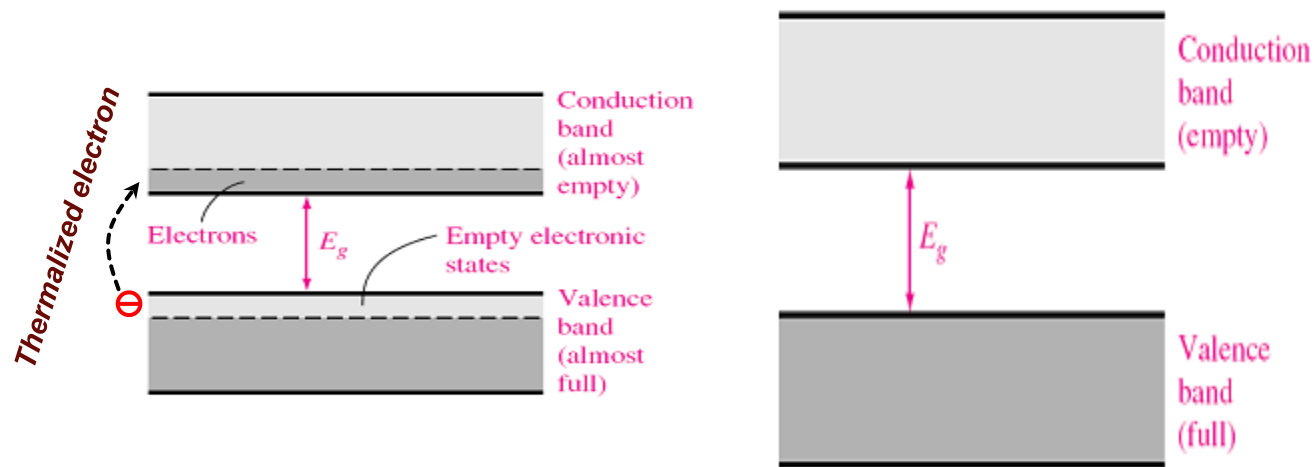
- ❑ Silicon: The 14 electrons are placed into the following 3 energy levels and 5 orbitals: $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$
- ❑ The splitting of the 3s and 3p states of Si into the allowed and forbidden bands



Metals, Semiconductors and Insulators

➤ insulators vs. semiconductors?

- Si with $E_G = 1.12$ eV is a semiconductor
- SiO_2 with $E_G \sim 5$ eV is an insulator
- **Finite temperature makes the difference**

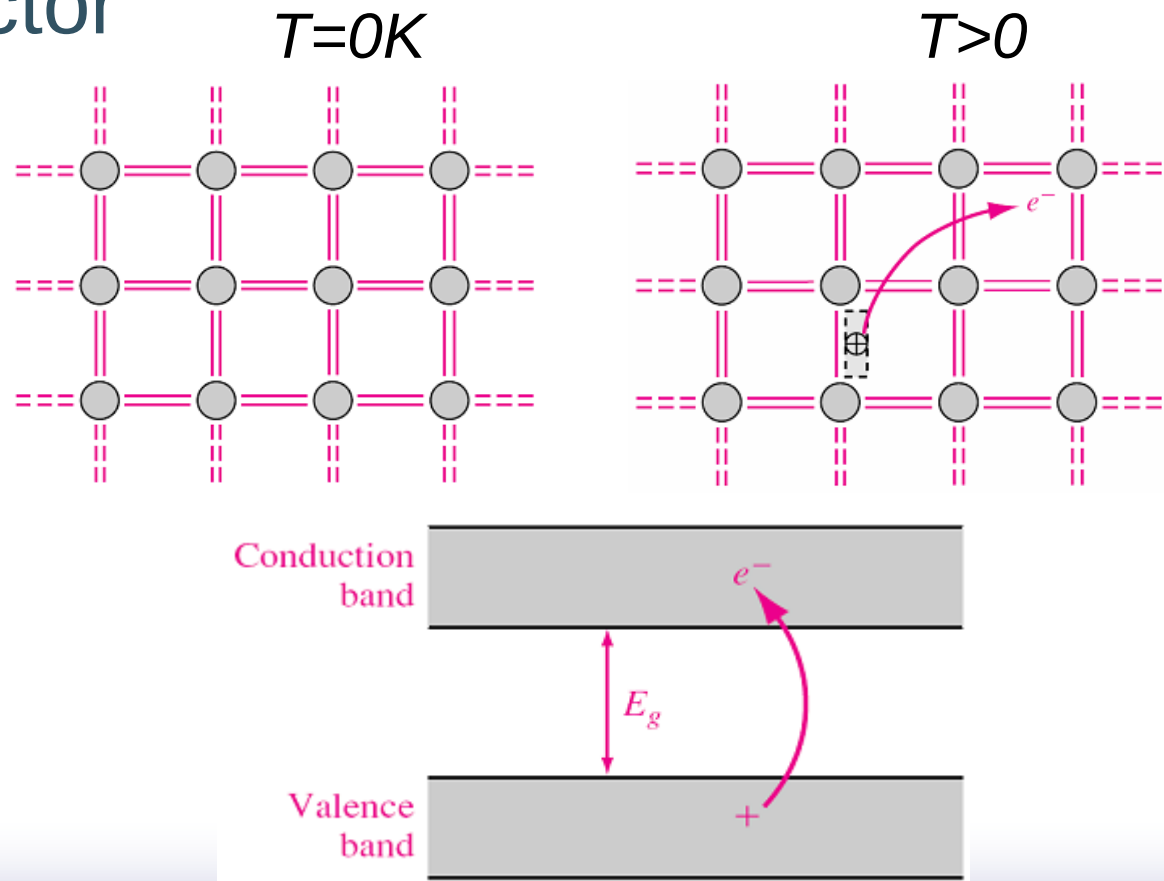


- *Ref.: Charles Kittel, 'Introduction to Solid State Physics', 7th edition*

Charge Carriers in Semiconductor

□ Two types of charged particles exist in a semiconductor

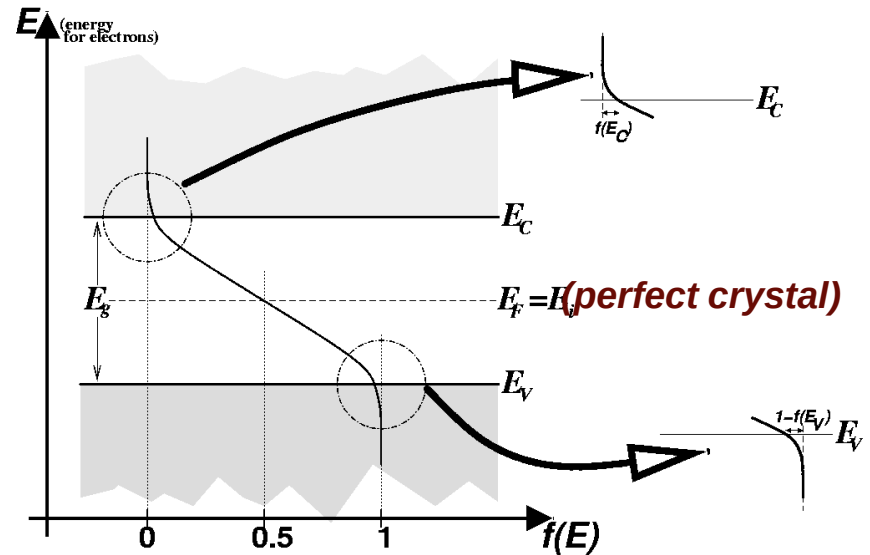
- Electron
- Hole



Fermi-Dirac Occupation Function

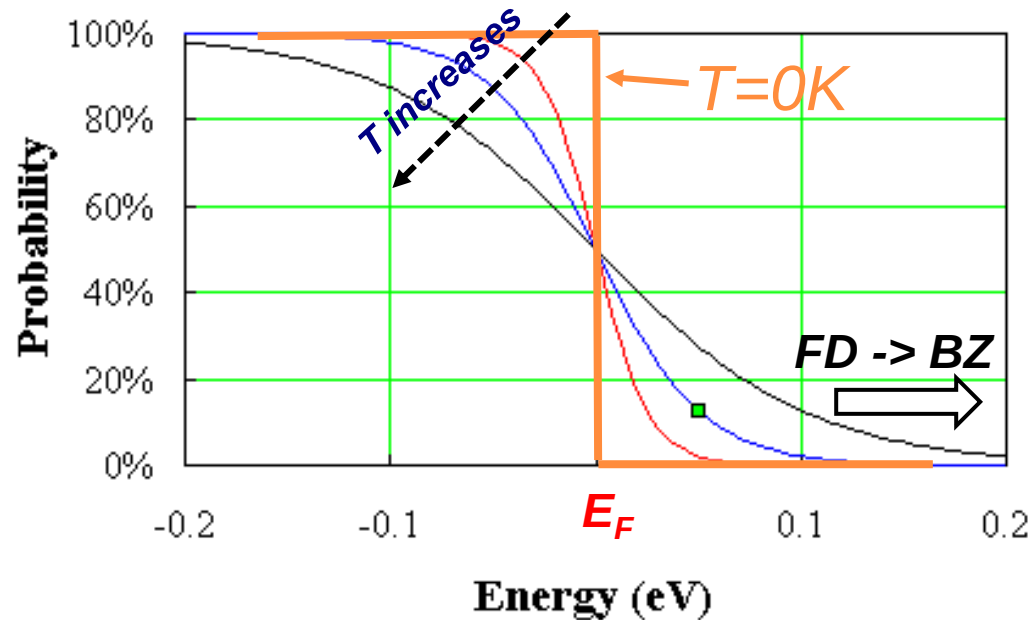
$$f_D(E) = \frac{1}{1 + e^{\frac{-(E_F - E)}{k_B T}}}$$

E_F is the **Fermi level**



- $f_D(E)$ = probability of occupation of a state of energy E , given that such a state exists.
- $f_D(E) = 0.5$ at $E = E_F$
- Probability of a hole in a state of energy E is $(1 - f_D(E))$

Fermi-Dirac vs. Boltzmann Distributions



At non-zero temperatures, & $(E-E_F) \gg kT$

Fermi-Dirac (FD) distribution function reduces to the Boltzmann (BZ) distribution function: $f(E) = \exp(-(E-E_F)/kT)$

Electron and Hole Concentrations

$$n = \int_{E_C}^{\infty} DOS_e(E) f_D(E) dE \quad p = \int_{-\infty}^{E_V} DOS_h(E) (1 - f_D(E)) dE$$

DOS_e and DOS_h are *density of states* of electrons and holes, specifically number of states per eV per cm^3

➤ Boltzmann Approximation & Integration :

$$n_0 = N_C e^{\frac{(E_F - E_C)}{k_B T}} \quad p_0 = N_V e^{\frac{(E_V - E_F)}{k_B T}}$$

N_C and N_V are called the “*effective density of states*”, Number of states per cm^3

Electron and Hole Concentrations in Intrinsic Si

- Exercise: calculate n_0 for intrinsic (undoped, pure) Si at 300K
 - $N_c = 3.2 \times 10^{19} \text{ cm}^{-3}$
 - $E_F - E_V = 0.5506 \text{ eV}$
 - $E_g = 1.11 \text{ eV}$
- Result: $n_i = 1.45 \times 10^{10} \text{ cm}^{-3} = p_i$

Extrinsic Semiconductors

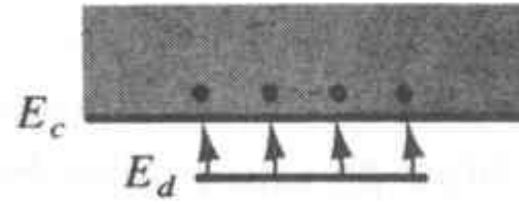
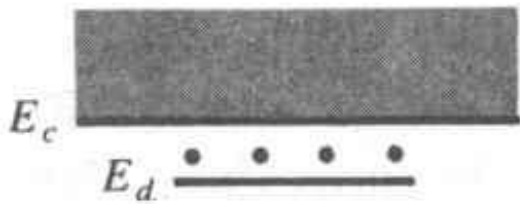
- To increase conductivity, *doping* adds impurities to silicon crystal
- Two types of impurities:
 - Donors
 - Acceptors
 - Impurities are ionized when they donate or accept an electron

N-Type Semiconductors

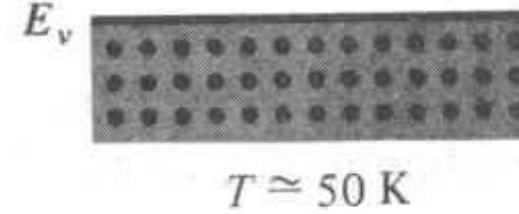
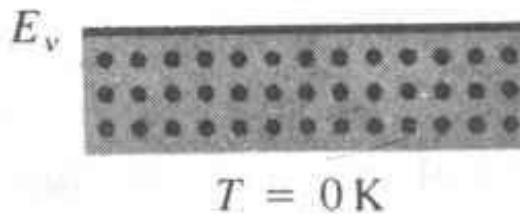
- **N-Type**: Large concentration of electrons in conduction band
- **Created by donor impurities**
 - One extra electron than Silicon
 - Silicon: periodic table column IV
 - Donors: periodic table column V
 - Phosphorus (P)
 - Arsenic (As)
 - Antimony (Sb)
- **Doping concentration**: N_D (atoms/cm³)

N-Type Semiconductors (2)

- Donor impurities create “donor level” in energy band diagram



Effective donor impurities can be fully ionized at room temperature, i.e. $n \approx N_D$

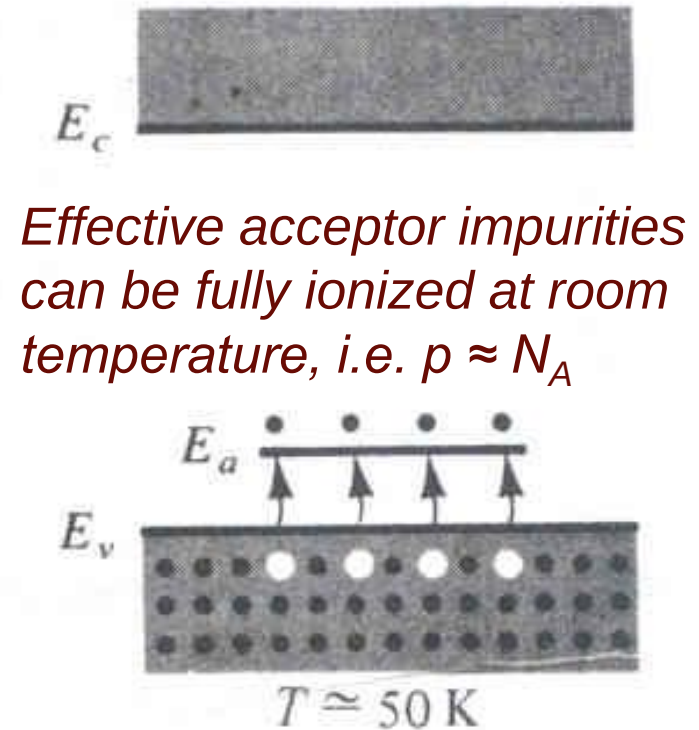
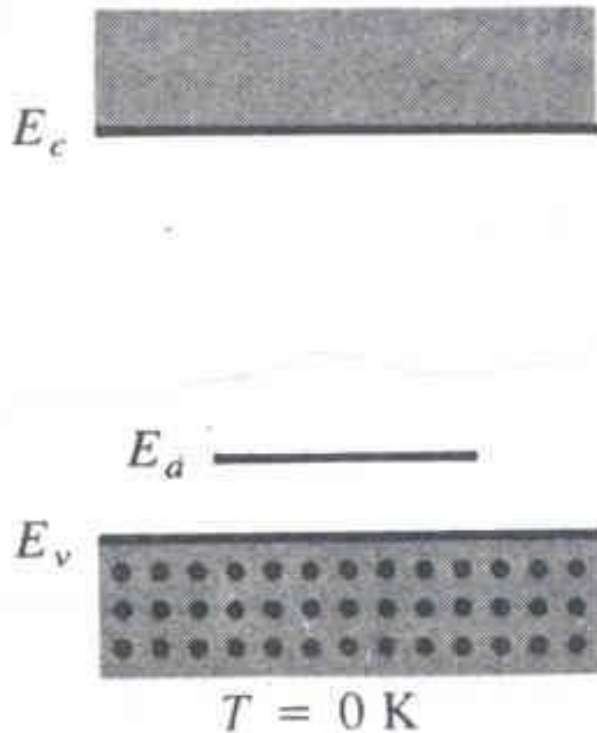


P-Type Semiconductors

- *P-Type: Large concentration of holes in valence band*
- *Created by acceptor impurities*
 - *Acceptors: one fewer electron than Silicon*
 - *Silicon: periodic table column IV*
 - *Acceptors: periodic table column III*
 - *Boron (B)*
 - *Aluminum (Al)*
 - *Gallium (Ga)*
- *Doping concentration: N_A*

P-Type Semiconductors (2)

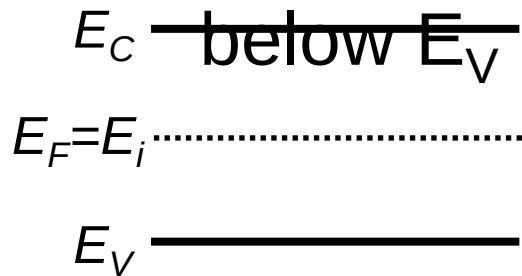
- *Acceptor impurities* create “*acceptor level*” in energy band diagram



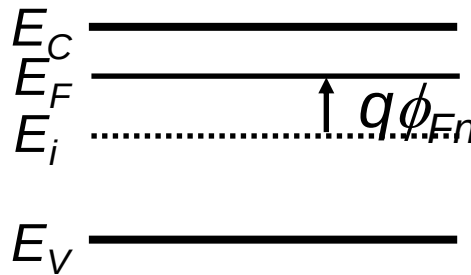
Effective acceptor impurities can be fully ionized at room temperature, i.e. $p \approx N_A$

Extrinsic Energy Band Diagram

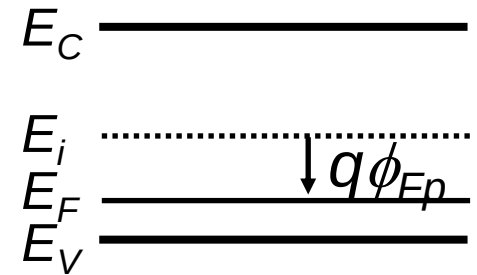
- Effect of doping on Fermi level E_F
 - N-Type: Fermi level moves up
 - P-Type: Fermi level moves down
 - Degenerate doping can move E_F above E_C or



Intrinsic



N-type



P-type

$$q\phi_F = E_F - E_i$$

ϕ_F is called the Fermi potential

$\phi_F: V$ $q \phi_F: eV$

Extrinsic Energy Band Diagram (2)

- Reorganize n_0 , p_0 expressions:

$$n_0 = n_i e^{(E_F - E_i)/kT}$$

$$p_0 = n_i e^{(E_i - E_F)/kT}$$

- New position of E_F can be found for any doping levels, by assuming $n_0 \approx N_D$ & $p_0 \approx N_A$

$$n_0 p_0 = n_i^2$$

Valid for all
semiconductors,
intrinsic or extrinsic

Extrinsic Energy Band Diagram (3)

For n-type semi

$$n_0 = N_D = n_i e^{(E_F - E_i)/kT}$$

$$E_F - E_i = kT \ln \frac{N_D}{n_i}$$

$$q\phi_{Fn} = kT \ln \frac{N_D}{n_i}$$

For p-type semi

$$p_0 = N_A = n_i e^{(E_i - E_F)/kT}$$

$$E_i - E_F = -kT \ln \frac{n_i}{N_A}$$

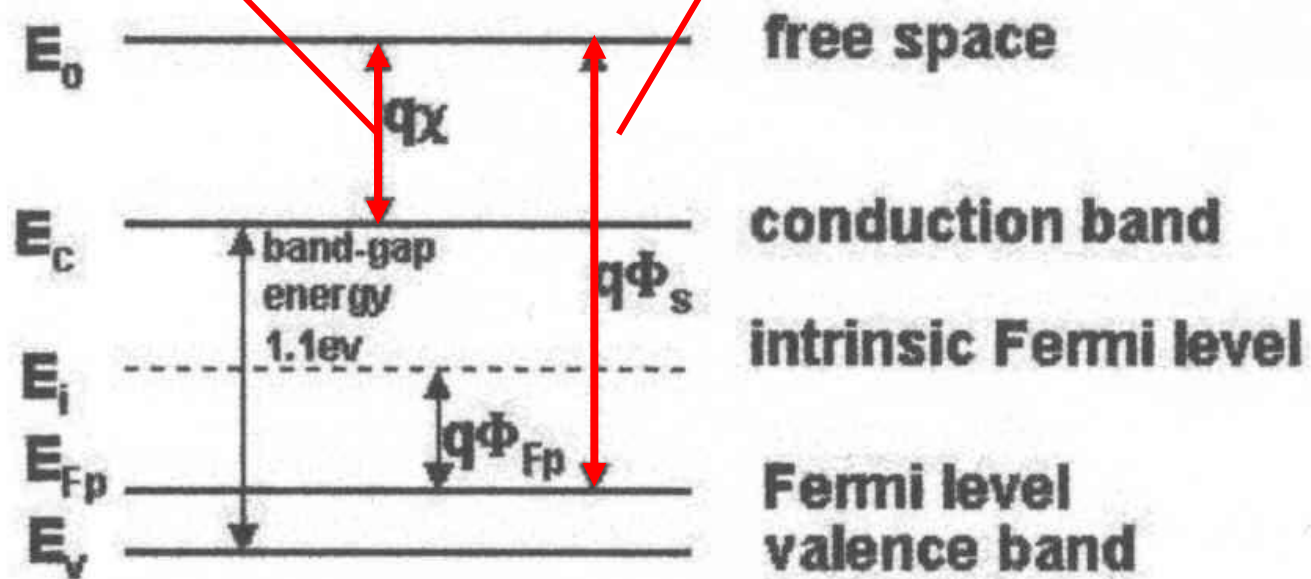
$$q\phi_{Fp} = kT \ln \frac{n_i}{N_A}$$

➤ *Example:* find the position of E_F in Si with a doping of 10^{16} As atoms/cm³

More about Semiconductor

*Electron affinity:
energy to move
electron from
conduction band to
free space*

*Work function:
energy to move
electron from Fermi
level to free space*



Energy band diagram of a p-type silicon

Electron Currents

- Two types of current in semiconductors
 - Drift current: Electron motion due to electric field
 - Diffusion current: Electron motion due to differences in carrier concentration

Drift Current

- Without external electric field applied, electrons moves randomly (thermal process), no net current
- With electric field, there is net force on each electron, causing acceleration
- Acceleration causes collisions, which balance electric field
- Force on electron: $F_x = -qE_x$
- Average net velocity:

$$\langle v_x \rangle = -\frac{q\bar{t}}{m_n^*} E_x$$

Drift Current (2)

- Define μ_n = *electron mobility*: ease with which electrons drift in a material

$$\mu_n = \frac{q\bar{t}}{m_n^*} \quad \langle v_x \rangle = \mu_n E_x$$

(cm²/V-s)

- Given average velocity, find *current density*:

$$J_x = q \cdot n \cdot \langle v_x \rangle = qn\mu_n E_x$$

$$J_x: A/cm^2$$

Drift Current (3)

- Therefore *current density* is *proportional to electric field* (*Ohm's Law*):

$$J_x = \underbrace{qn\mu_n} E_x$$

$$\sigma = qn\mu_n$$

$$J_x = \sigma E_x$$

or $V = I.R$
Since, $J = I/A = E/\rho$
And $E = V/L$

- σ is the *conductivity* of the material
($\sigma = 1/\rho$, where ρ = *resistivity*)

Drift Current Example

- Find the approximate electron current for intrinsic silicon
 - Size = 1 cm^3
 - Voltage applied: 1V
- $\mu_n = 600 \text{ cm}^2/\text{V}\cdot\text{s}$
 $q = 1.6 \times 10^{19} \text{ C}$

Diffusion Current

- Diffusion is due to electron or hole concentration gradient
 - Concentration gradient = d_n/d_x or d_p/d_x
- Flux density ϕ_n, ϕ_p is rate of electron or hole flow, per unit area

$$\phi_n = -D_n \frac{dn}{dx} \quad \phi_p = -D_p \frac{dp}{dx}$$

Note: -ve sign captures motion from high conc. toward low conc.

- D_n, D_p is diffusion coefficient

$$J_n = qD_n \frac{dn}{dx} \quad J_p = -qD_p \frac{dp}{dx}$$

Direction of electron current is opposite to the direction of its conc. gradient

Direction of hole current is same as the direction of its conc. gradient

Total Current: Electrons

➤ Drift:

- Electrons drift opposite to the electric field
- Drift current is in the same direction as the electric field

➤ Diffusion:

- Electrons diffuse in the direction of decreasing concentration
- Diffusion current is in opposite direction to decreasing concentration

$$J_n(x) = \underbrace{q\mu_n n(x)E(x)}_{\text{drift}} + \underbrace{qD_n \frac{dn(x)}{dx}}_{\text{diffusion}}$$

Total Current: Holes

➤ *Drift:*

- Holes drift with the electric field
- Drift current is in the same direction as the electric field

➤ *Diffusion:*

- Holes diffuse in the direction of *decreasing concentration*
- Diffusion current is in *same direction as decreasing concentration*

$$J_p(x) = \underbrace{q\mu_p p(x)E(x)}_{\text{drift}} - \underbrace{qD_p \frac{dp(x)}{dx}}_{\text{diffusion}}$$

Equilibrium

- At equilibrium, no current flows
- Any diffusion current must be balanced by an equal drift current, and vice-versa.
- For example (for electrons):

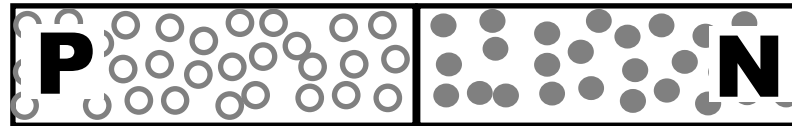
$$q\mu_n n(x)E(x) = -qD_n \frac{dn(x)}{dx}$$

- Equilibrium Fermi level must be flat:

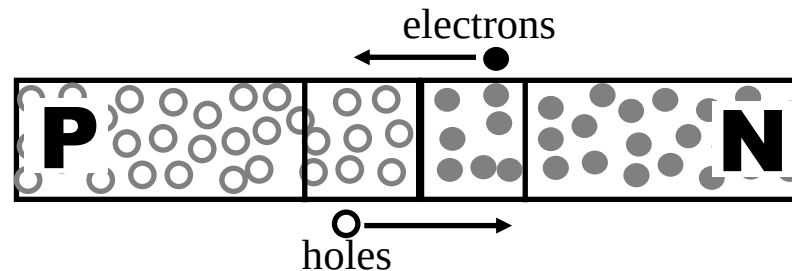
$$\frac{dE_F}{dx} = 0$$

P/N Junctions

- ❑ put two types of semiconductors together

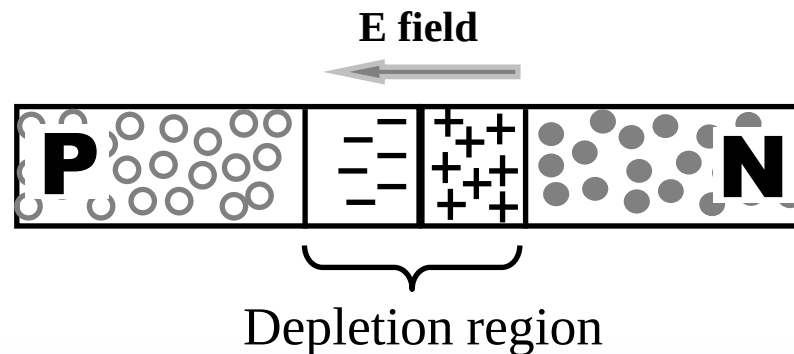


- Large concentration gradient at junction

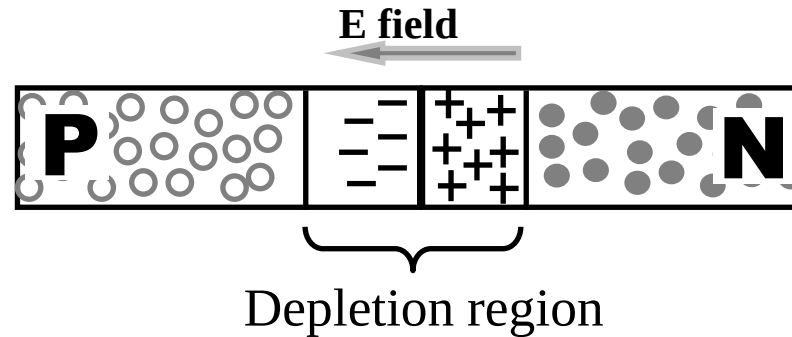


P/N Junctions (2)

- Immobile ions are left behind
 - Electric field forms, from N to P
 - E-field causes drift in opposite direction as diffusion
 - **Equilibrium** No current flows

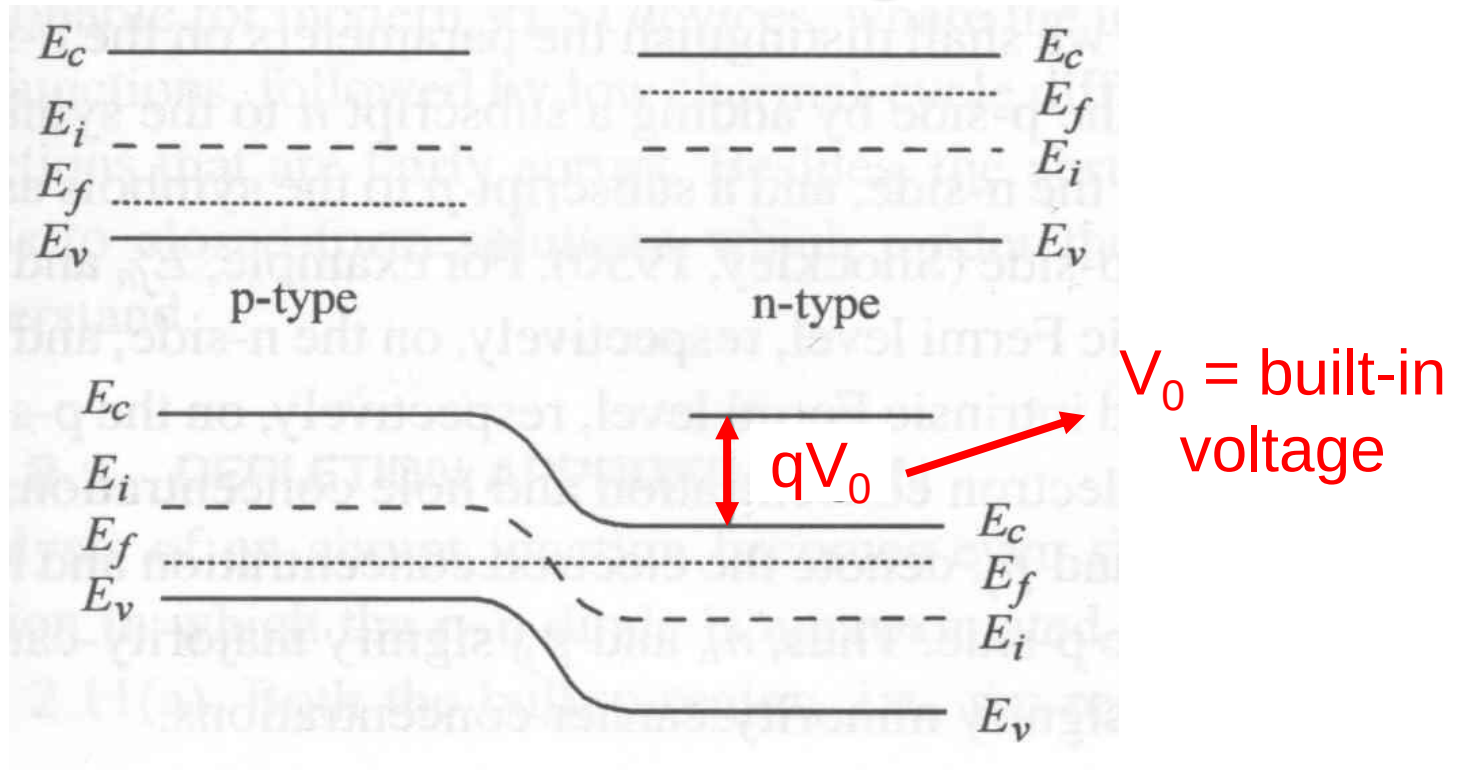


Depletion Region



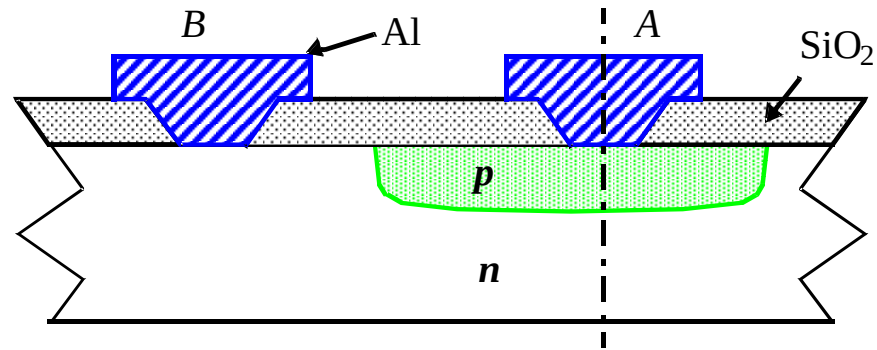
- Depletion region forms around junction
 - “Depleted” of any mobile charges (holes or electrons)
 - Charge in depletion region due to fixed ions
 - Electric field causes a potential difference across junction: known as built-in voltage V_0

P/N Junction Band Diagram

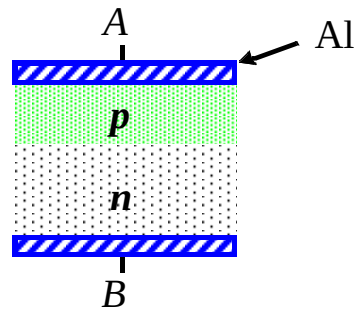


- At thermal equilibrium, no net current flow
 - When drift+diffusion currents=0, $\frac{dE_f}{dx} = 0$
- Bands must bend so that Fermi level is constant

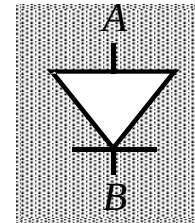
The Diode



Cross-section of pn -junction in an IC process

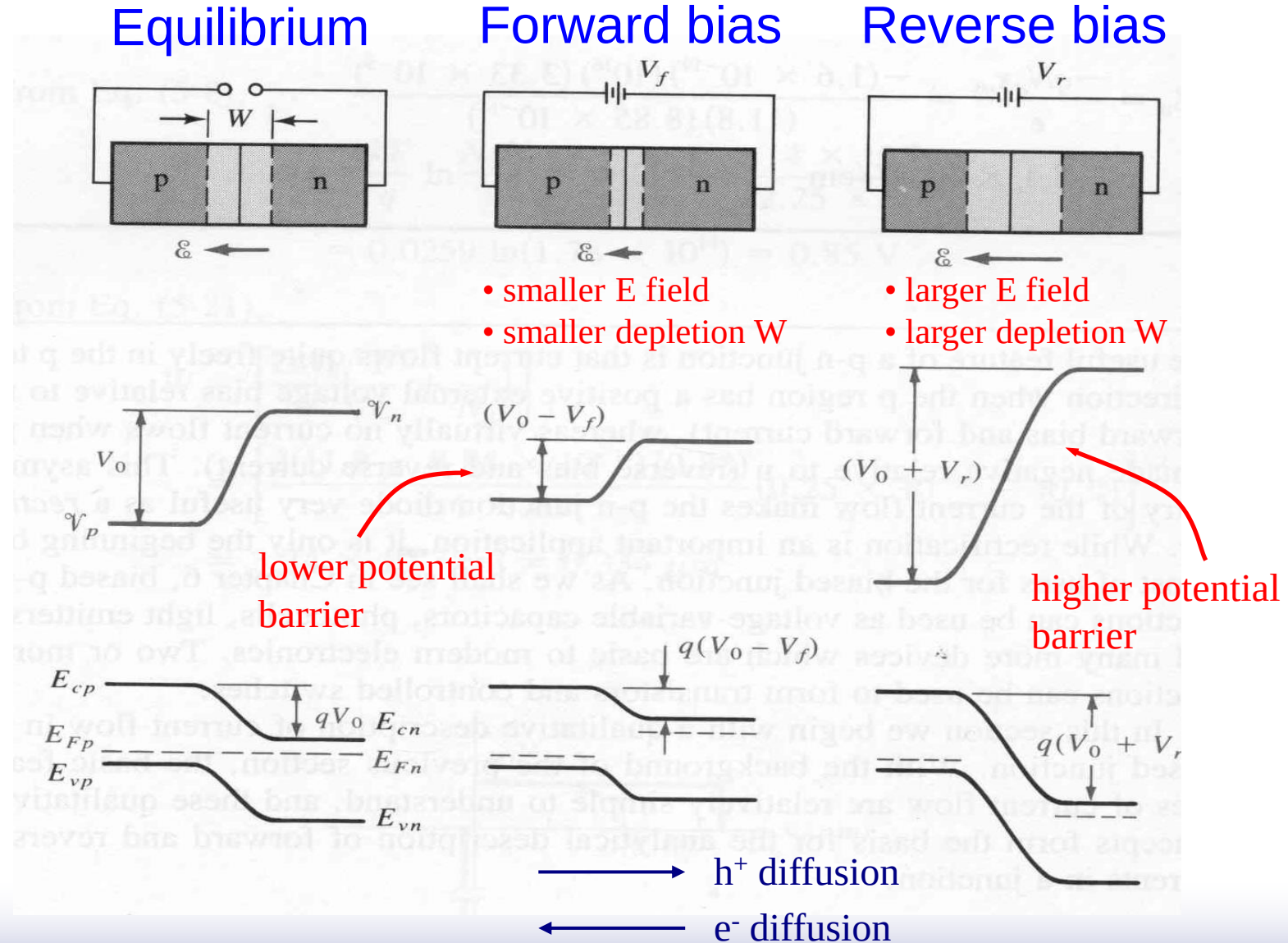


One-dimensional representation



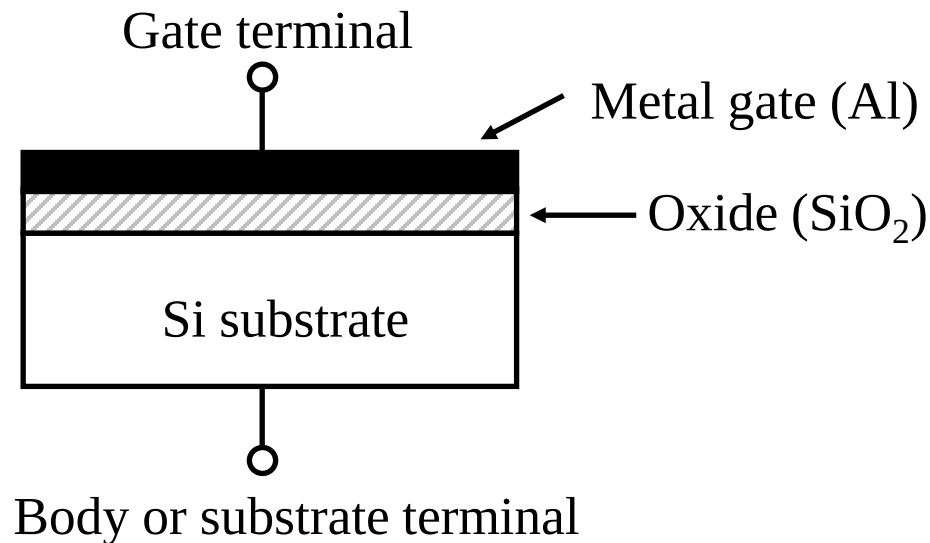
diode symbol

Bias Effects on PN Junction

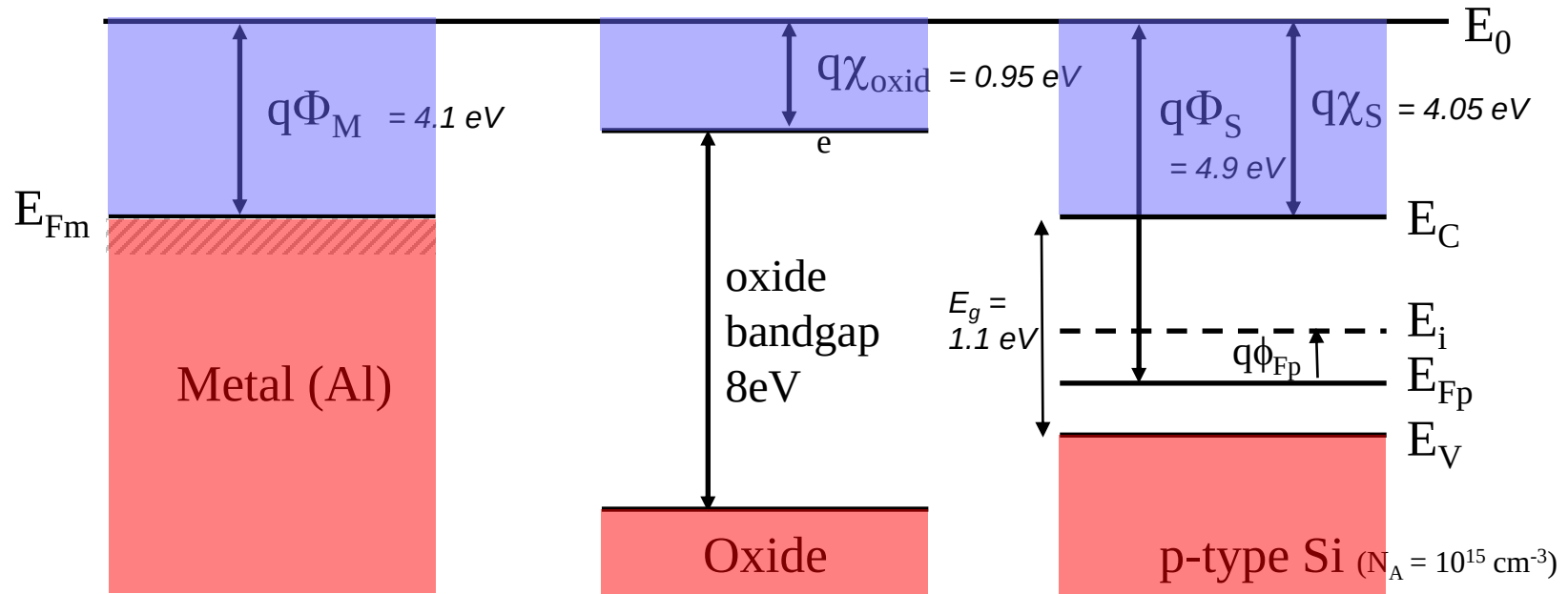


MOS Structure

- MOS: Metal-oxide-semiconductor
 - Gate: metal (or polysilicon)
 - Oxide: silicon dioxide, grown on substrate
- MOS capacitor: two-terminal MOS structure



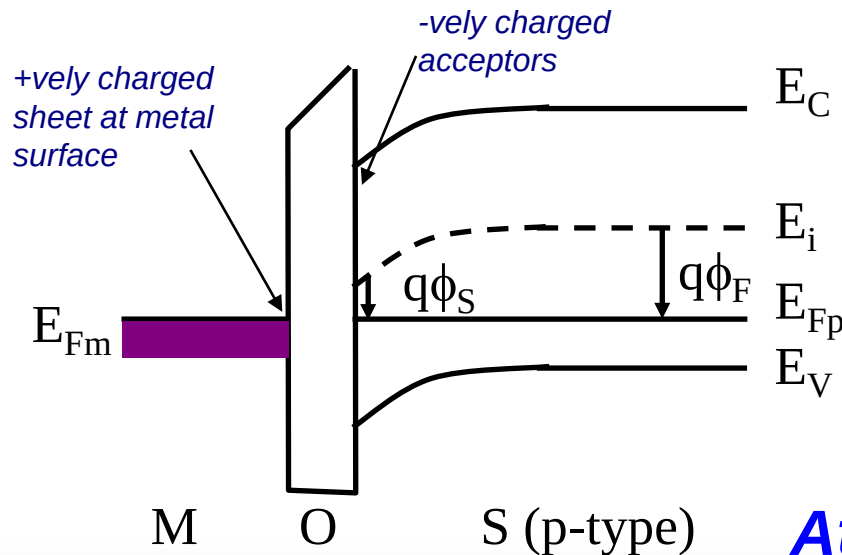
MOS Energy Band Diagram



- **Work function** ($q\Phi_M$, $q\Phi_S$): energy required to take electron from Fermi level to free space
- **Electron affinity** is the energy required to move an electron from conduction band to free space ($E_0 = q\chi_s$)
- **Work function** difference between Al and Si = 0.8 V

MOS Energy Band Diagram

- Bands must bend for Fermi levels to line up
- Amount of bending is equal to work function difference: $q\Phi_M - q\Phi_S$
- Fermi levels equalized by transfer of -ve charge from materials with higher E_F (smaller work functions) across interfaces to materials with lower E_F
- **Part of voltage drop occurs across oxide, rest occurs next to O-S interface**



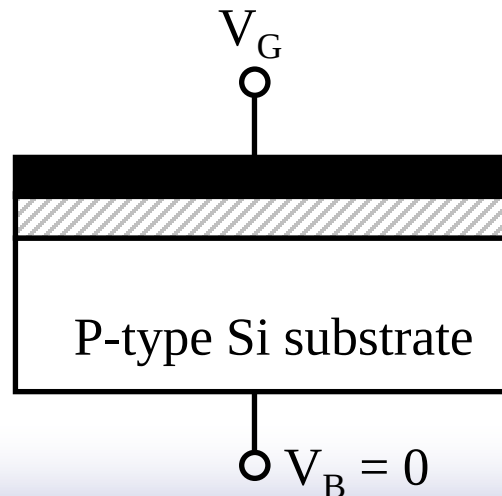
ϕ_F = Fermi potential
(difference between E_F
and E_i in bulk)

ϕ_S = surface potential

At equilibrium, Fermi levels must line up!!

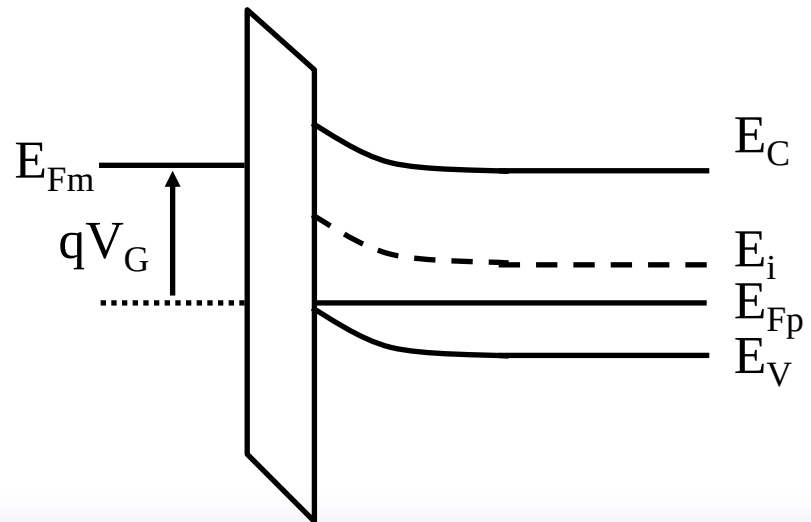
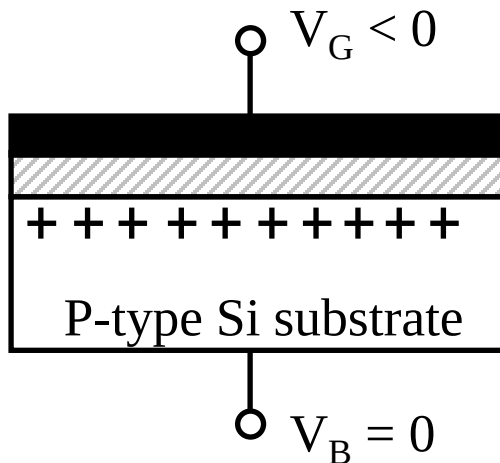
MOS Capacitor Operation

- Assume p-type substrate
- Three regions of operation
 - Accumulation ($V_G < 0$)
 - Depletion ($V_G > 0$ but small)
 - Inversion ($V_G \gg 0$)



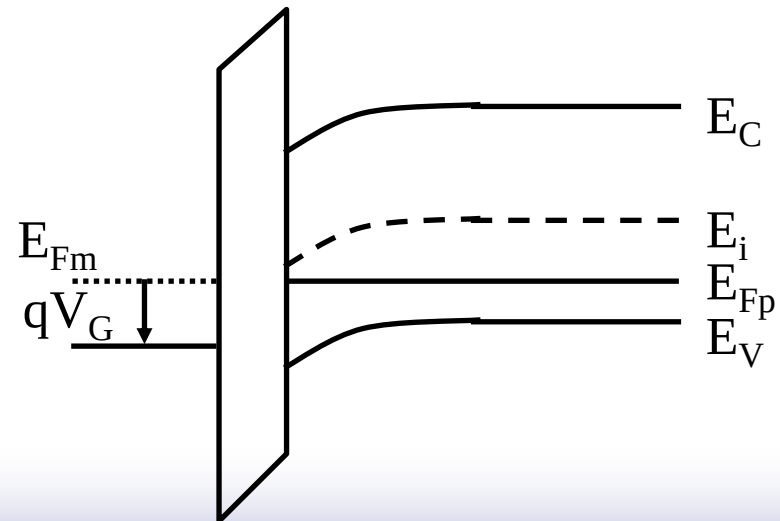
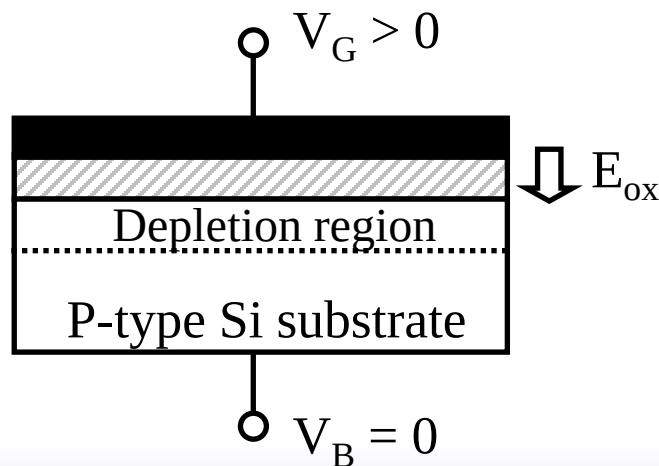
Accumulation

- Negative voltage on gate: attracts holes in substrate towards oxide
- Holes “accumulate” on Si surface (surface is more strongly p-type)
- Electrons pushed deeper into substrate



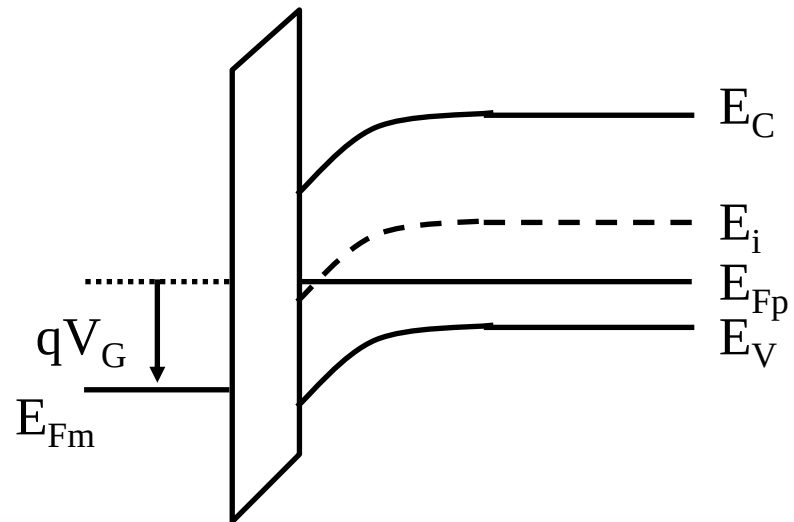
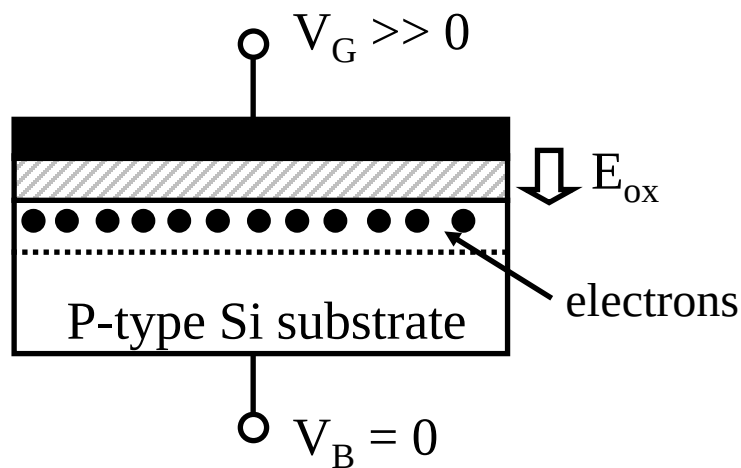
Depletion

- ❑ Positive voltage on gate: repels holes in substrate
 - Holes leave behind negatively charged acceptor ions
- ❑ Depletion region forms: devoid of carriers
 - Electric field directed from gate to substrate
- ❑ Bands bend downwards near surface
 - Surface becomes less strongly p-type (E_F close to E_i)



Inversion

- Increase voltage on gate, bands bend more
- Additional minority carriers (electrons) attracted from substrate to surface
 - Forms “inversion layer” of electrons
- Surface becomes n-type



Inversion

- Definition of inversion
 - Point at which density of electrons on surface = density of holes in bulk
 - Surface potential is same as ϕ_F , but different sign

Remember:

$$q\phi_F = E_F - E_i$$

