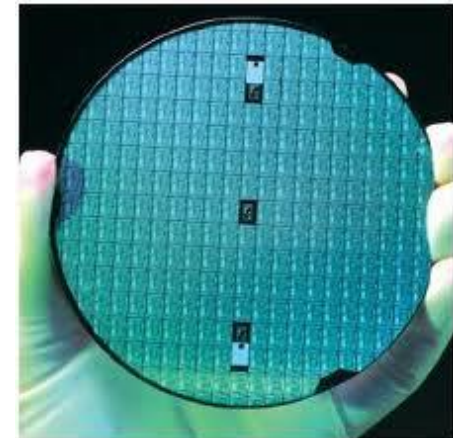
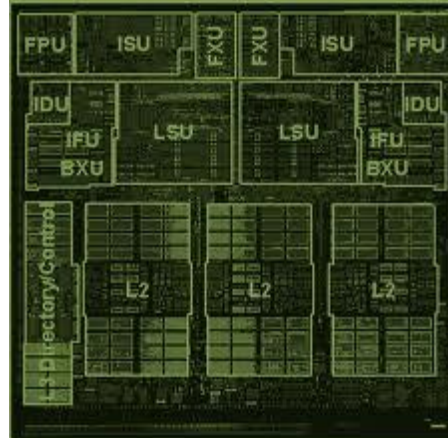
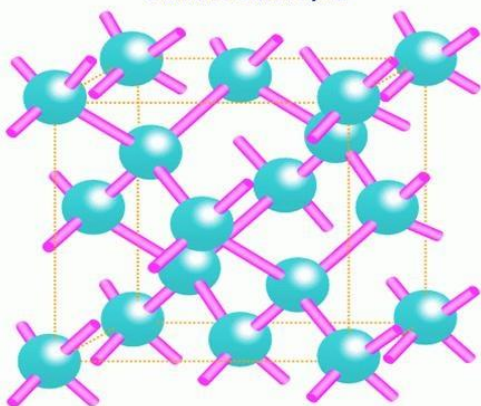


Structure of silicon crystal



ECE 225

Lecture 3

Semiconductor Physics Review

Prof. Kaustav Banerjee
Electrical and Computer Engineering
University of California, Santa Barbara

Outline

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

Band Model of Solids

- Electron Energy Levels

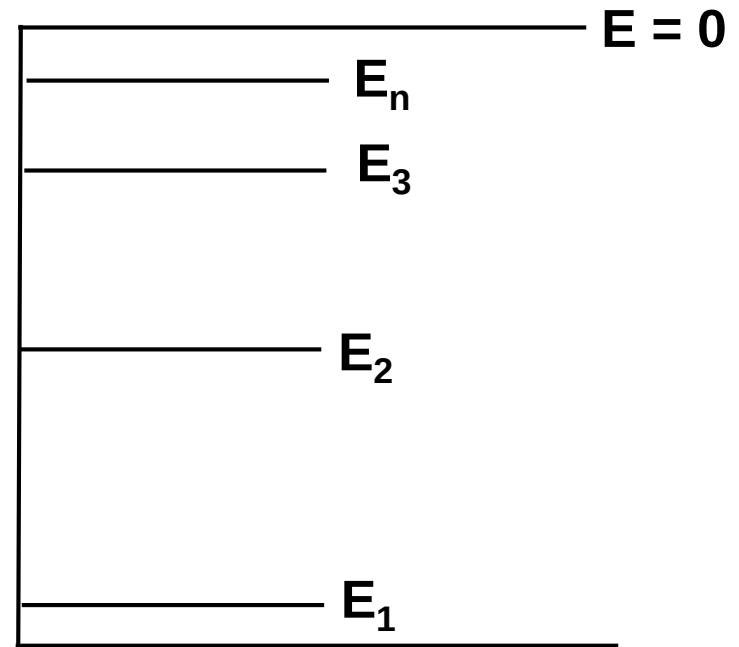
$$E_n = \frac{-Z^2 m_0 q^4}{8 \epsilon_0^2 h^2 n^2}$$

Z = # of protons in nucleus

q = charge of electron (= -1.6×10^{-19} C)

m_0 = free electron mass

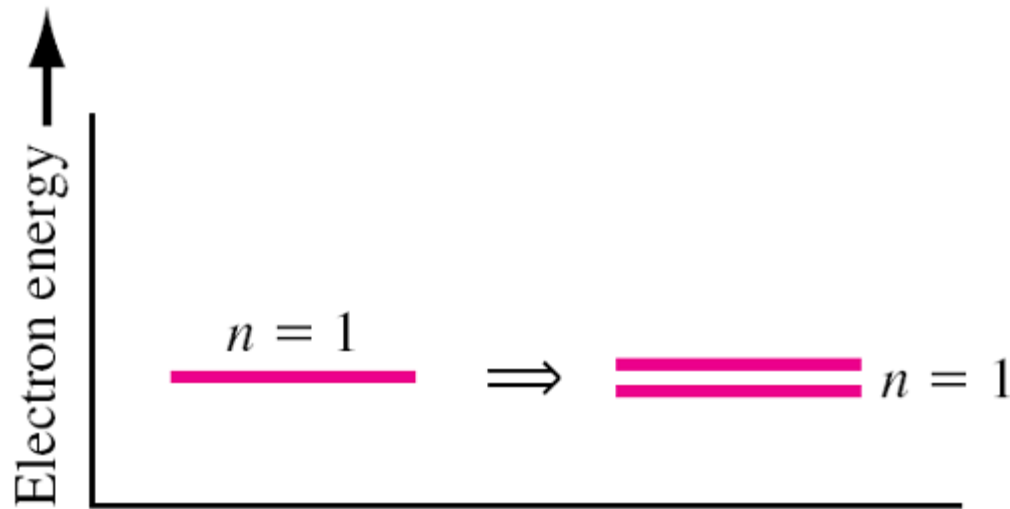
For Hydrogen atom, $Z=1$, $E_n = -13.6/n^2$ eV



Band Model of Solids

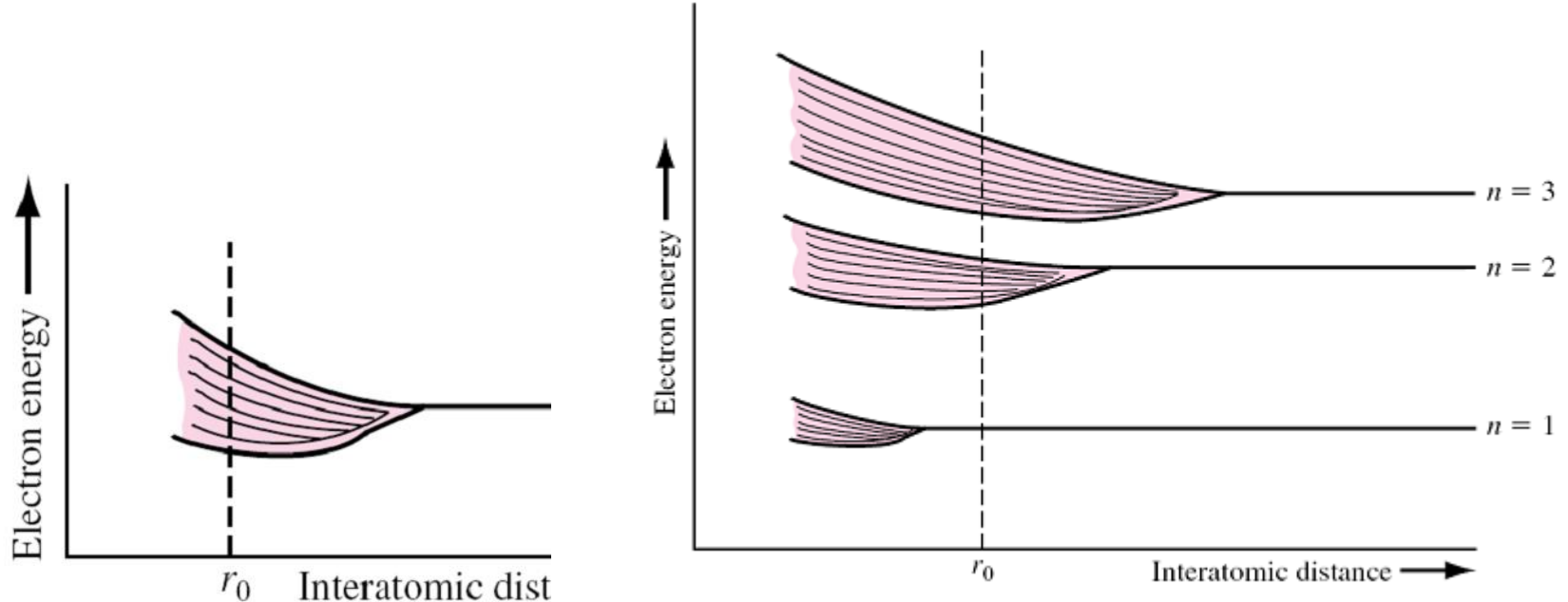
Pauli Exclusion Principle (PEP)

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



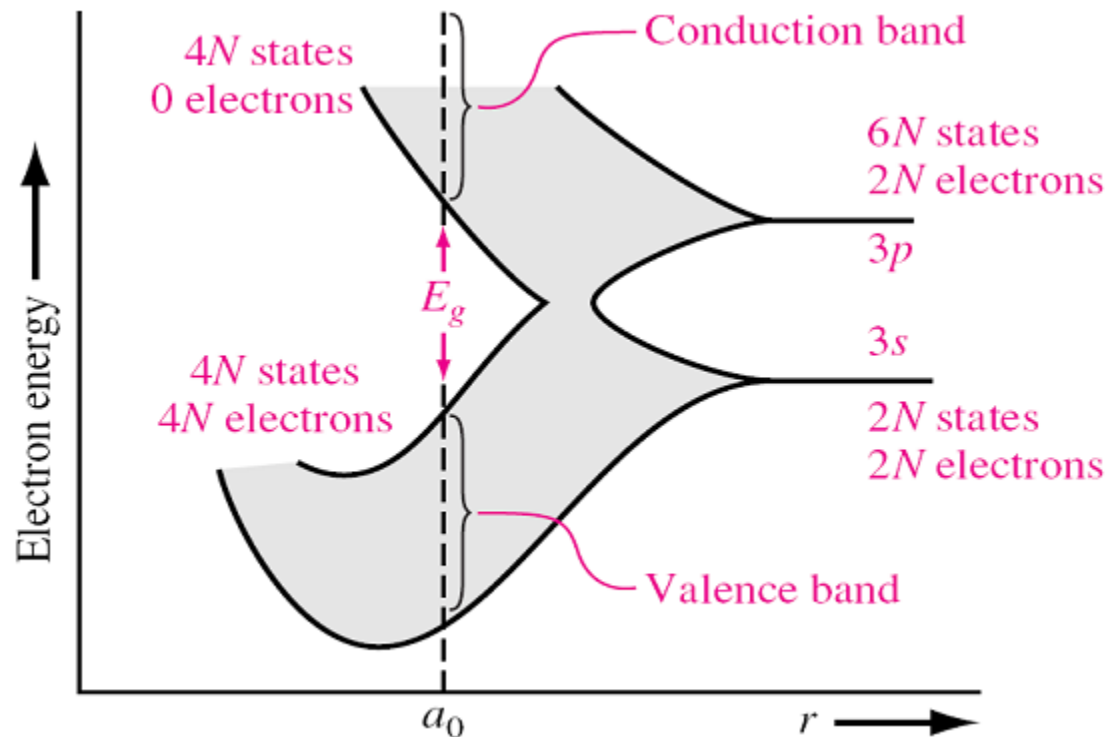
Band Model of Solids

□ The allowed/forbidden energy band

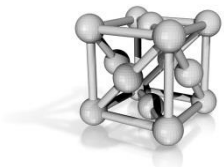
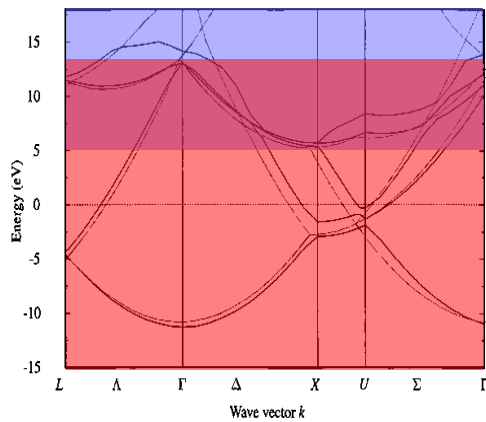
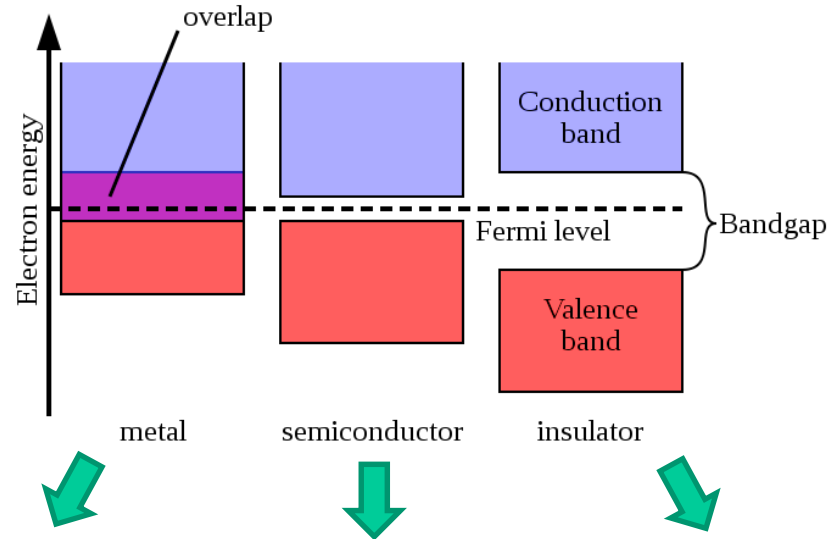


Band Model of Solids

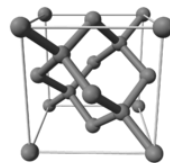
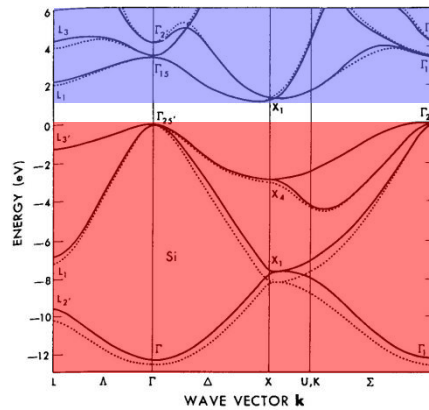
- Silicon: The 14 electrons are placed into the following 3 energy levels and 5 orbitals: $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$
- The splitting of the 3s and 3p states of Si into the allowed and forbidden bands



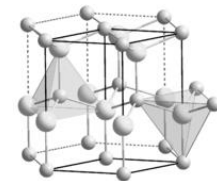
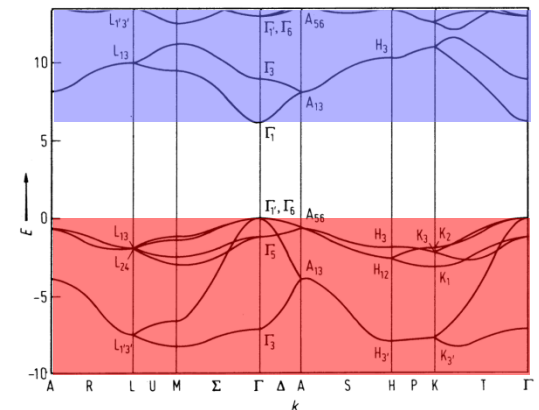
Semiconductors/Metals/Insulators



Al



Si

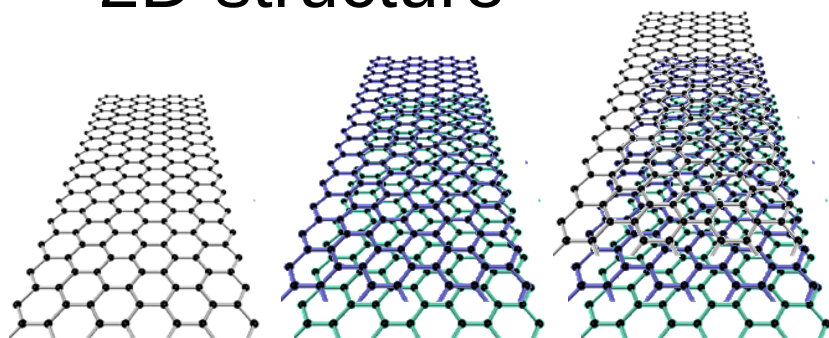


AlN

Semiconductors/Metals/Insulators

- Graphene

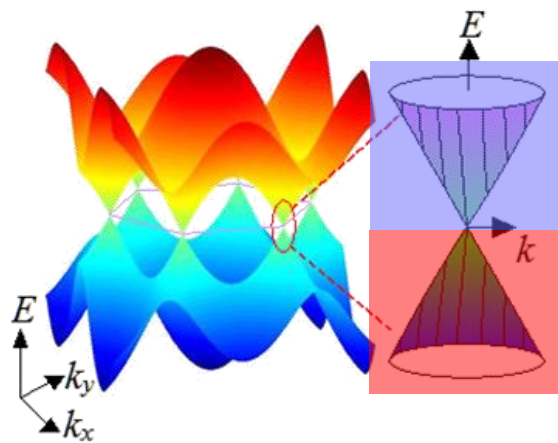
- 2D structure



Monolayer

Bilayer

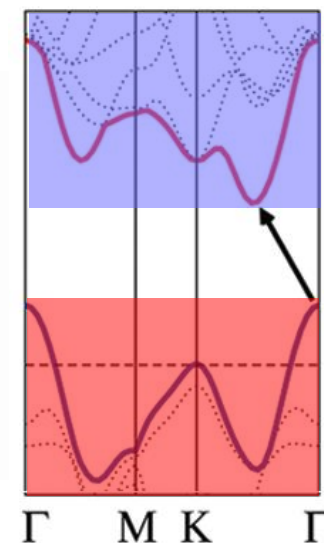
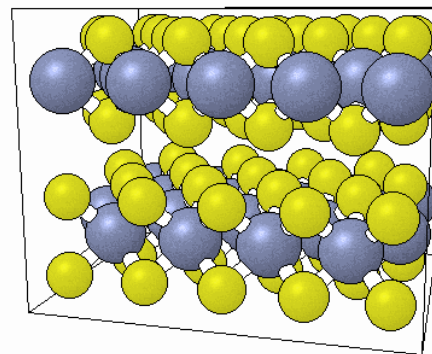
Multi-layer



- MoS₂

- 2D structure like graphene

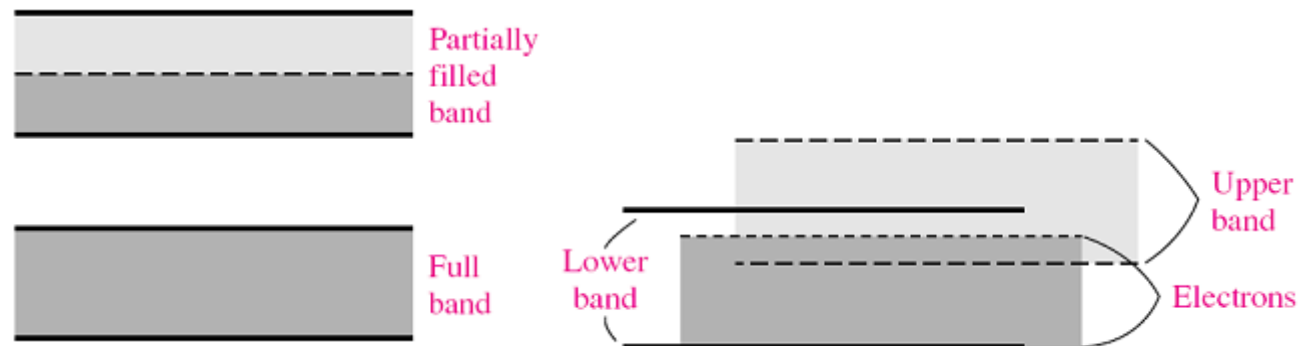
- but it has a band-gap



Metals, Semiconductors and Insulators

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

➤ **metallic**



Metals, Semiconductors and Insulators

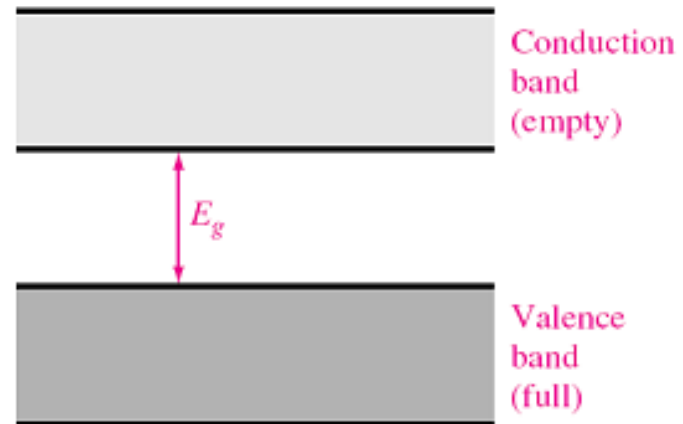
➤ Insulator

➤ Examples:

➤ SiO₂

➤ AlN

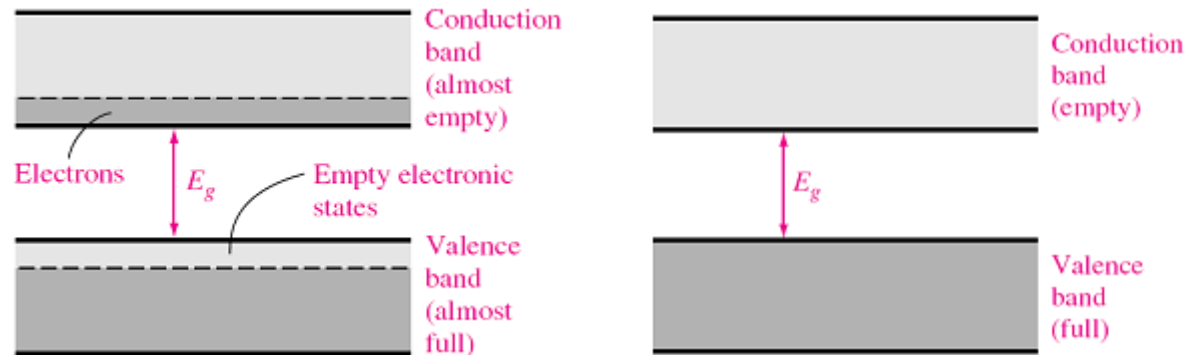
➤ h-BN (graphene family)



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



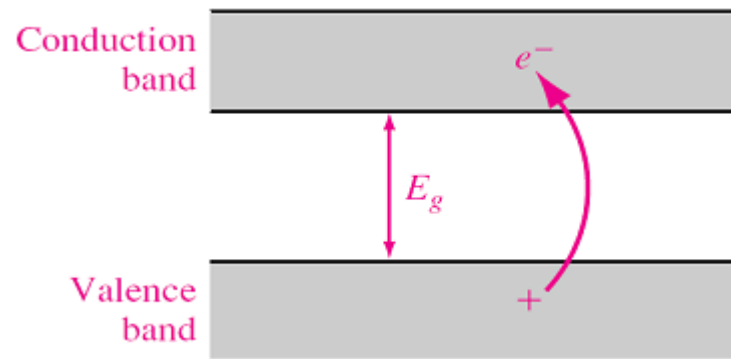
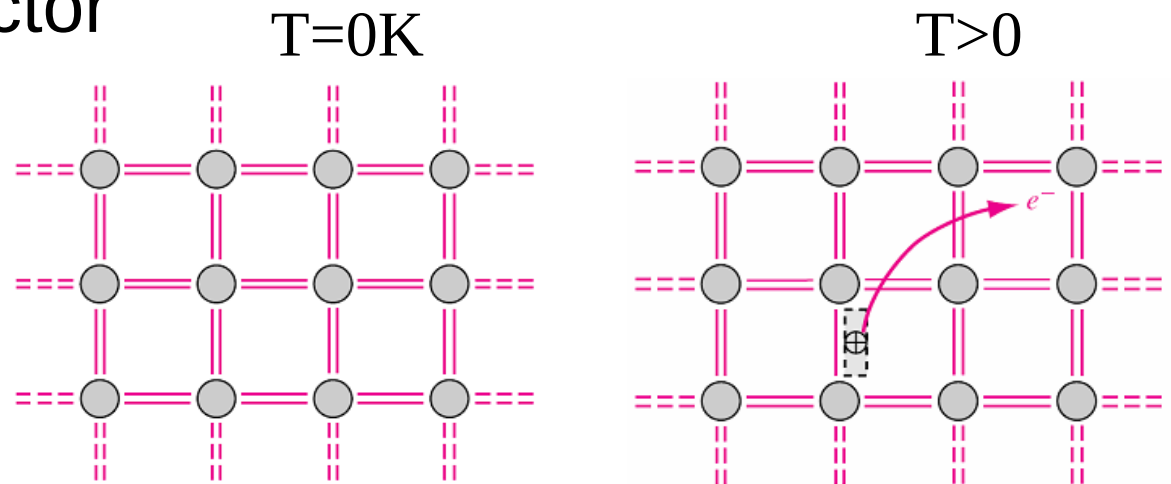
- Impurities in semiconductors are almost fully ionized at room temperatures

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

Metals, Semiconductors and Insulators

- Two types of charged particles exist in a semiconductor

- Electron
- Hole



Electron Concentration (n) in a Bulk Semiconductor

➤ two concepts

- Density of States (DOS)
- Fermi-Dirac Occupation Function

➤ DOS:

- Definition: $D(E) dE = \#$ of “allowed” energy states between E and $E+dE$ per unit volume
- Expressed in cm^{-3}

Electron Concentration in a Semiconductor

➤ Fermi-Dirac Occupation Function

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

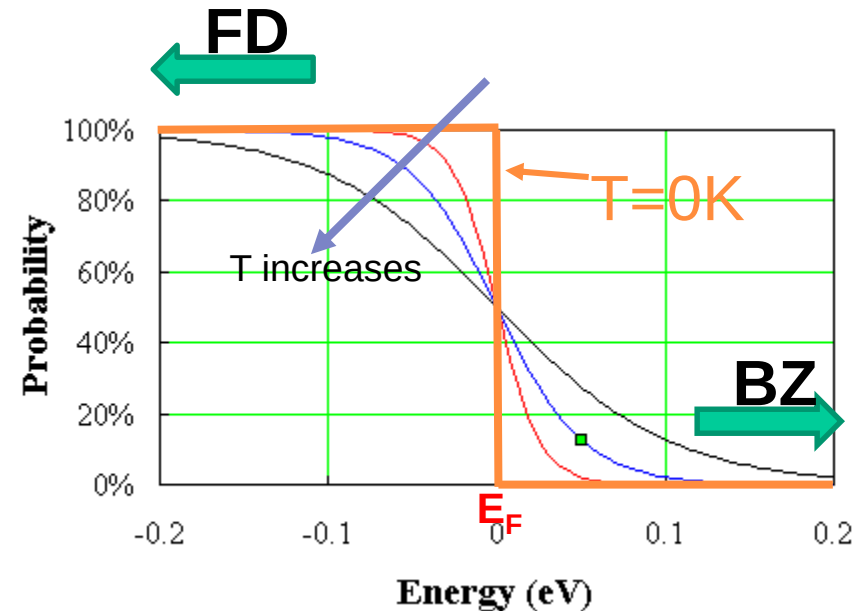
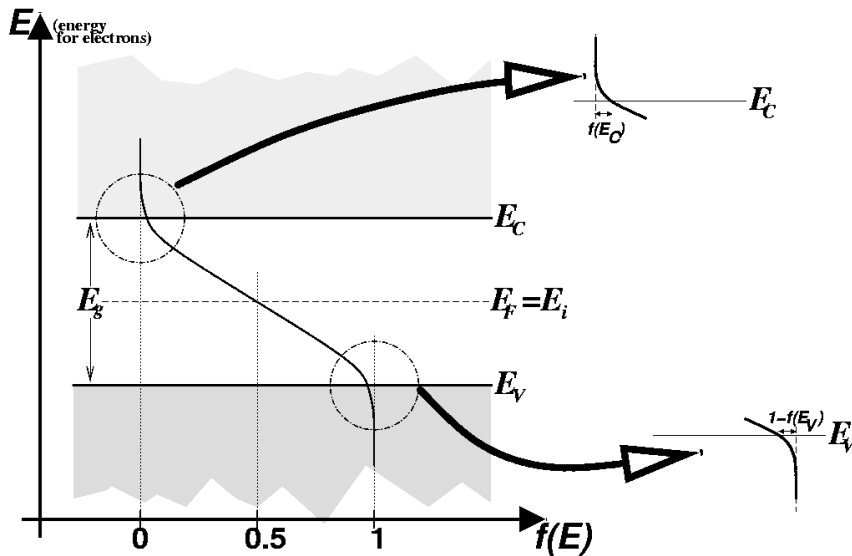
➤ $f_D(E) = 0.5$ at $E = E_F$ (E_F is the **Fermi level**...)

➤ $f_D(E)$ = probability of occupation of a state of energy E , given that such a state exists.

➤ Probability of a **hole** in a state of energy E is
($1 - f_D(E)$)
(**Why?**)

Occupation Function....

□ Fermi-Dirac Function $f(E)$:



- At higher 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

$$n = \int_{E_C}^{\infty} D(E) f(E) dE$$

➤ Integrating:

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

➤ Analogous expression for hole concentration:

➤ (A hole is a vacant state in a band)

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

N_C and N_V are called the “effective density of states”....why?

Electron and Hole Concentrations

- Exercise: calculate n_0 for intrinsic (undoped, pure) Si at 300K
 - $N_c = 3.2 \times 10^{19} \text{ cm}^{-3}$
 - $E_i - E_v = 0.5506 \text{ eV}$
 - $E_g = 1.11 \text{ eV}$
- Result: $n_0 = 1.45 \times 10^{10} \text{ cm}^{-3} = p_0$

Extrinsic Semiconductors

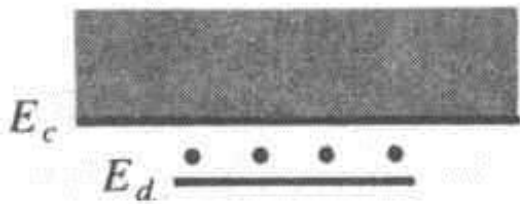
- To increase conductivity, *doping* adds *impurities* to silicon crystal
- Two types of impurities:
 - donors
 - Acceptors
 - *Impurities* are ionized when they donate or accept an electron

N-Type Semiconductors

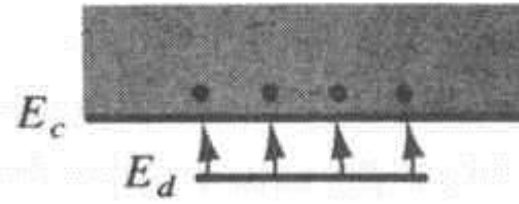
- **N-Type**: Large concentration of electrons in conduction band
- **Created by donor impurities**
 - One extra electron than Silicon
 - Silicon: periodic table column IV
 - Donors: periodic table column V
 - Phosphorus (P)
 - Arsenic (As)
 - Antimony (Sb)
- **Doping concentration**: N_D (atoms/cm³)

N-Type Semiconductors (2)

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



$T = 0\text{ K}$



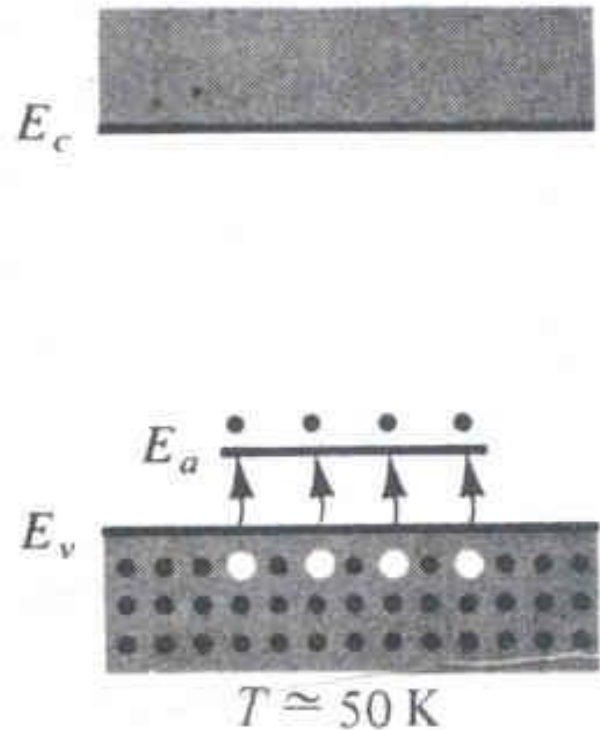
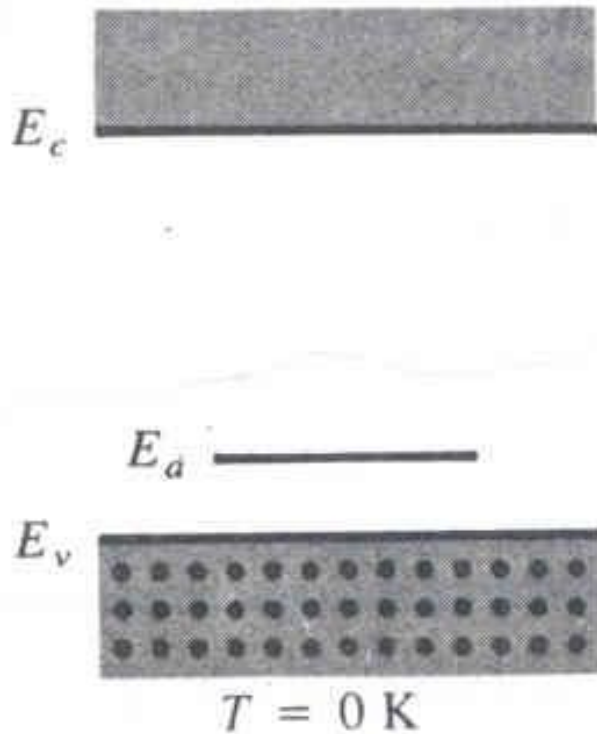
$T \approx 50\text{ K}$

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)

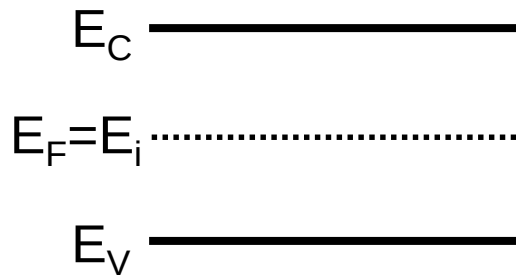
- Acceptor impurities create “acceptor level” in energy band diagram



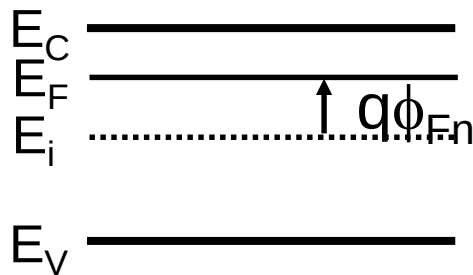
Extrinsic Energy Band Diagram

➤ Effect of doping on Fermi level E_F

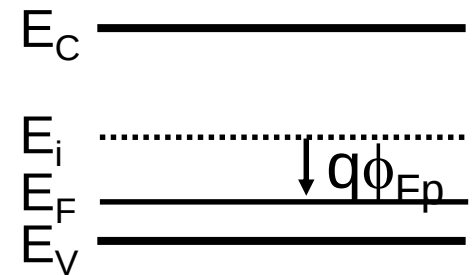
- N-Type: Fermi level moves up
- P-Type: Fermi level moves down
- Degenerate doping can move E_F above E_C or below E_V



Intrinsic



N-type



P-type

$$q\phi_F = E_F - E_i$$

$$\begin{aligned}\phi_F &: \text{V} \\ q\phi_F &: \text{eV}\end{aligned}$$

ϕ_F is called the Fermi potential

Extrinsic Energy Band Diagram (2)

- Recalling these equations:

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

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

- New position of E_F can be found for any doping level
- **Example:** find position of E_F for last example with 10^{16} As atoms/cm³

Extrinsic Energy Band Diagram (3)

For n-type semi

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

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

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

(since $q\phi_F = E_F - E_i$)

For p-type semi

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

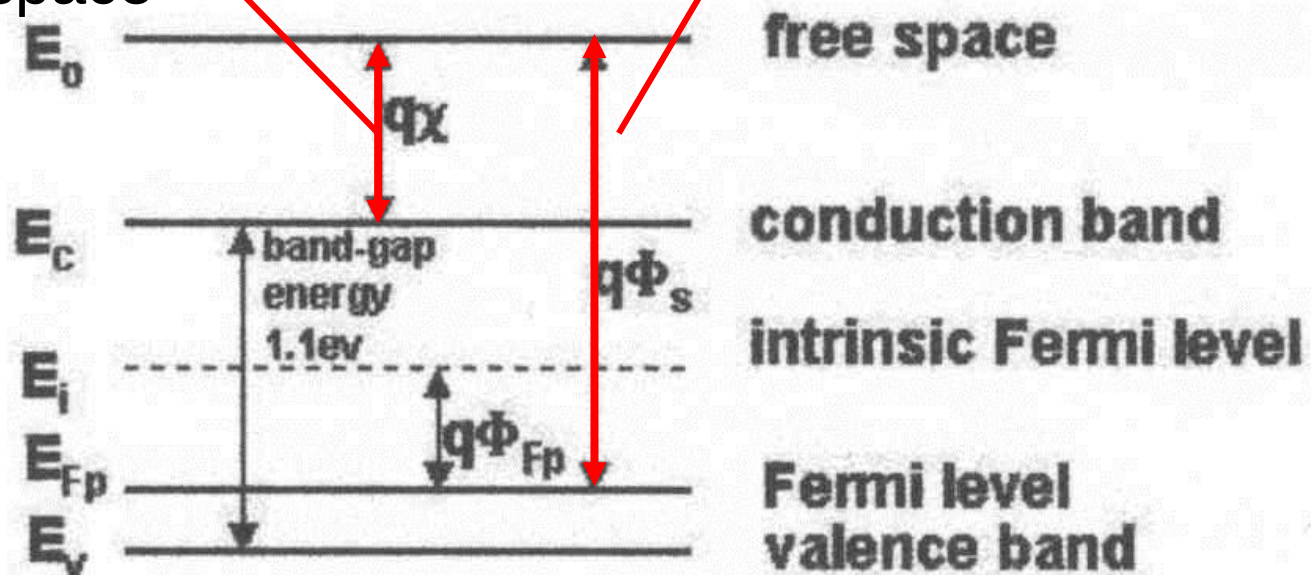
$$E_i - E_F = -kT \ln \frac{n_i}{N_A}$$

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

Extrinsic Semiconductor (Summary)

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
- Semiconductors rely on interaction between these two currents!
- Current density (J) is always used rather than actual current value: A/cm^2
- Actual current $I = J \cdot A$

Drift Current

- With no electric field, there is no net motion of electrons, but each electron moves randomly....why?
- 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)

- Given average velocity, find **current density**:

$$J_x = \frac{nq^2\bar{t}}{m_n^*} E_x$$

Hint: estimate the **charge** crossing an area **A** in time **dt..... = nq<v>Adt**

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

$$\mu_n = \frac{q\bar{t}}{m_n^*}$$

$$J_x = qn\mu_n E_x$$

$$J_x = A/cm^2$$

$$n = \text{electrons/cm}^3$$

$$\mu = cm^2/V-s$$

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

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

- D_n, D_p is **diffusion coefficient**

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

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):

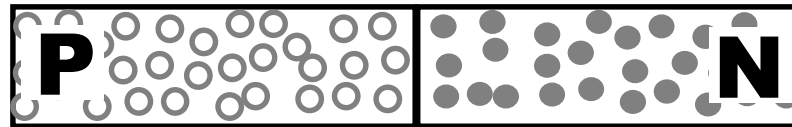
$$q\mu_n n(x)E(x) = -qD_n \frac{dn(x)}{dx}$$

- Equilibrium **Fermi level** must be **flat**:

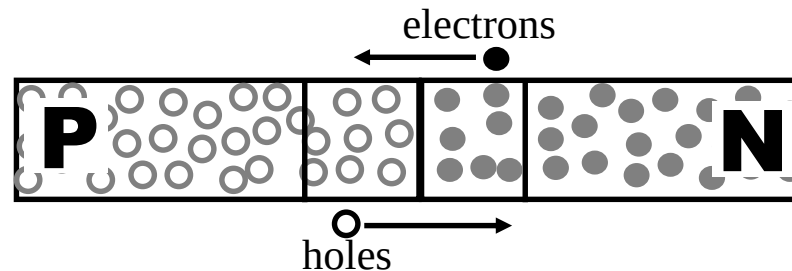
$$\frac{dE_F}{dx} = 0$$

P/N Junctions

- put two types of semiconductors together

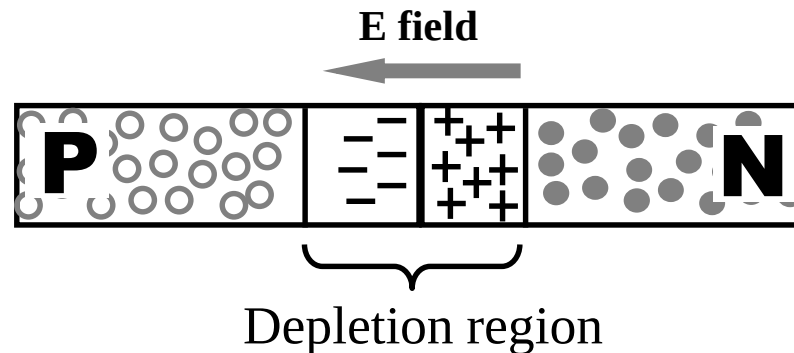


- Large concentration gradient at junction

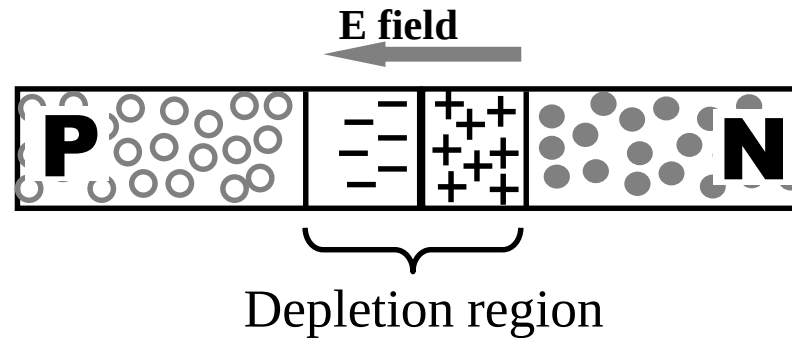


P/N Junctions (2)

- 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

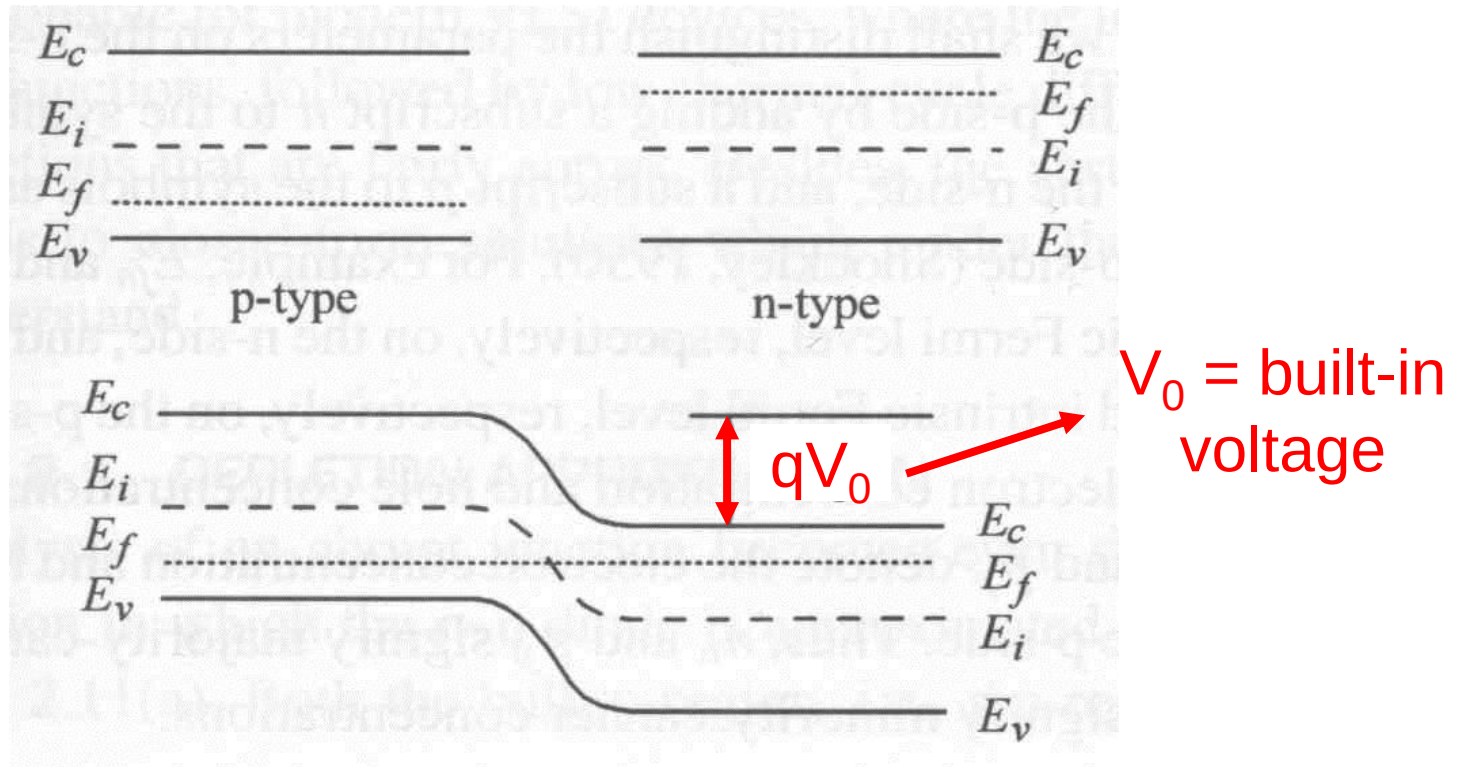


Depletion Region



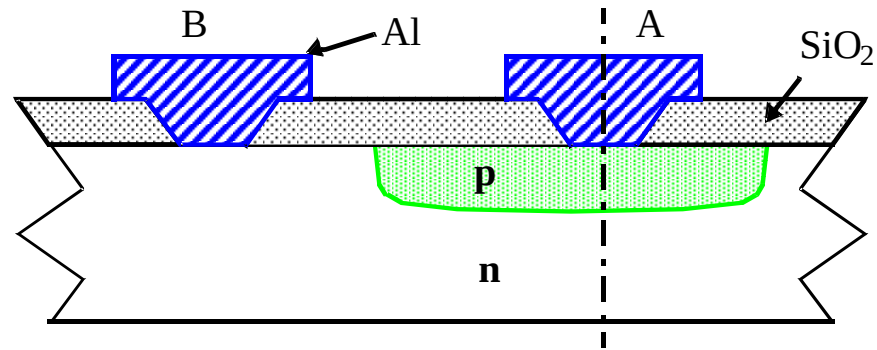
- Depletion region forms around junction
 - “Depleted” of any mobile charges (holes or electrons)
 - Charge in depletion region due to fixed ions
 - Electric field causes a potential difference across junction: known as built-in voltage V_0

P/N Junction Band Diagram

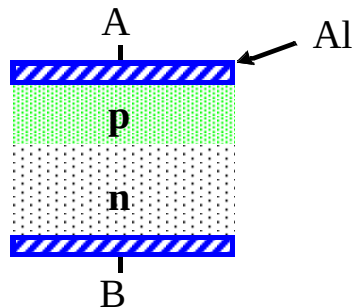


- At thermal equilibrium, no net current flow
 - When drift+diffusion currents=0, $\frac{dE_f}{dx} = 0$
- Bands must bend so that Fermi level is constant

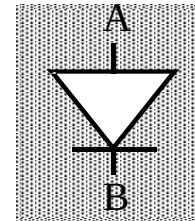
The Diode



Cross-section of pn junction in an IC process



One-dimensional representation

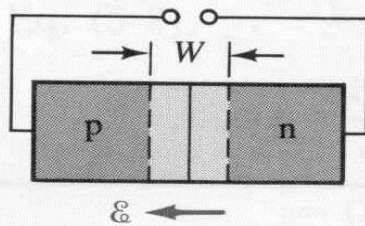


diode symbol

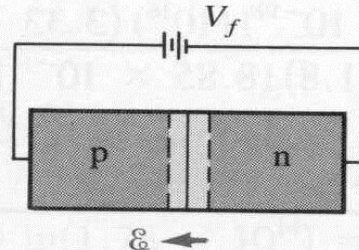
Mostly occurring as parasitic element in Digital ICs

Bias Effects on PN Junction

Equilibrium

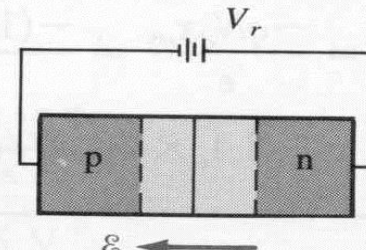


Forward bias

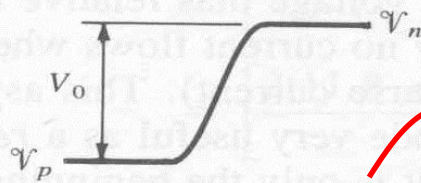


- smaller E field
- smaller depletion W

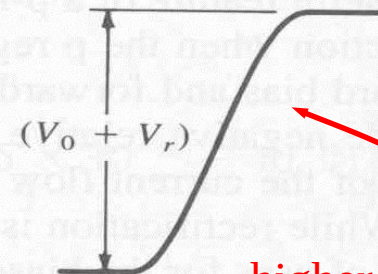
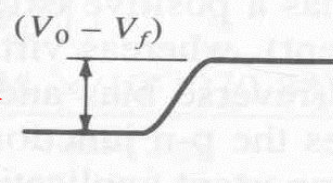
Reverse bias



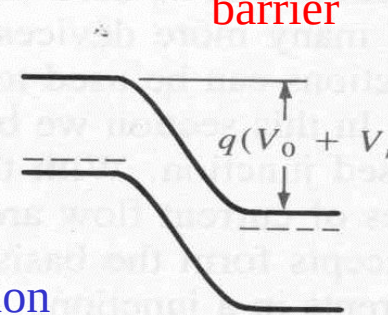
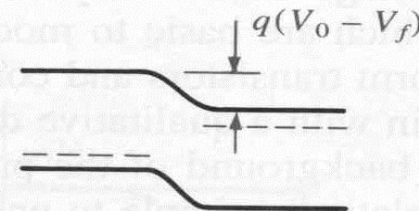
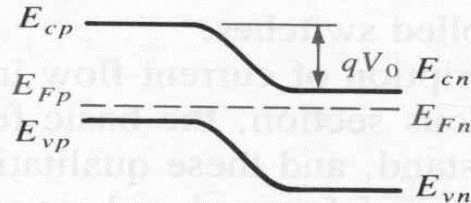
- larger E field
- larger depletion W



lower potential barrier



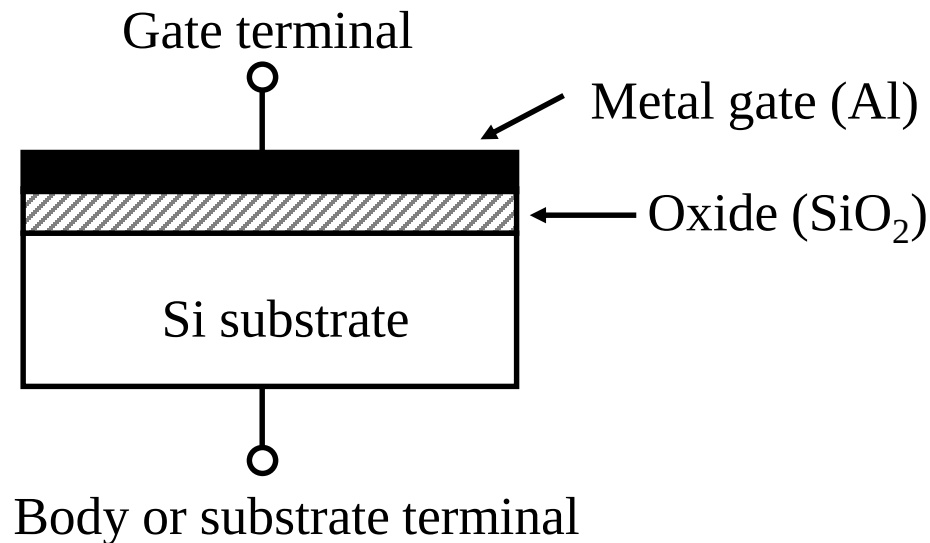
higher potential barrier



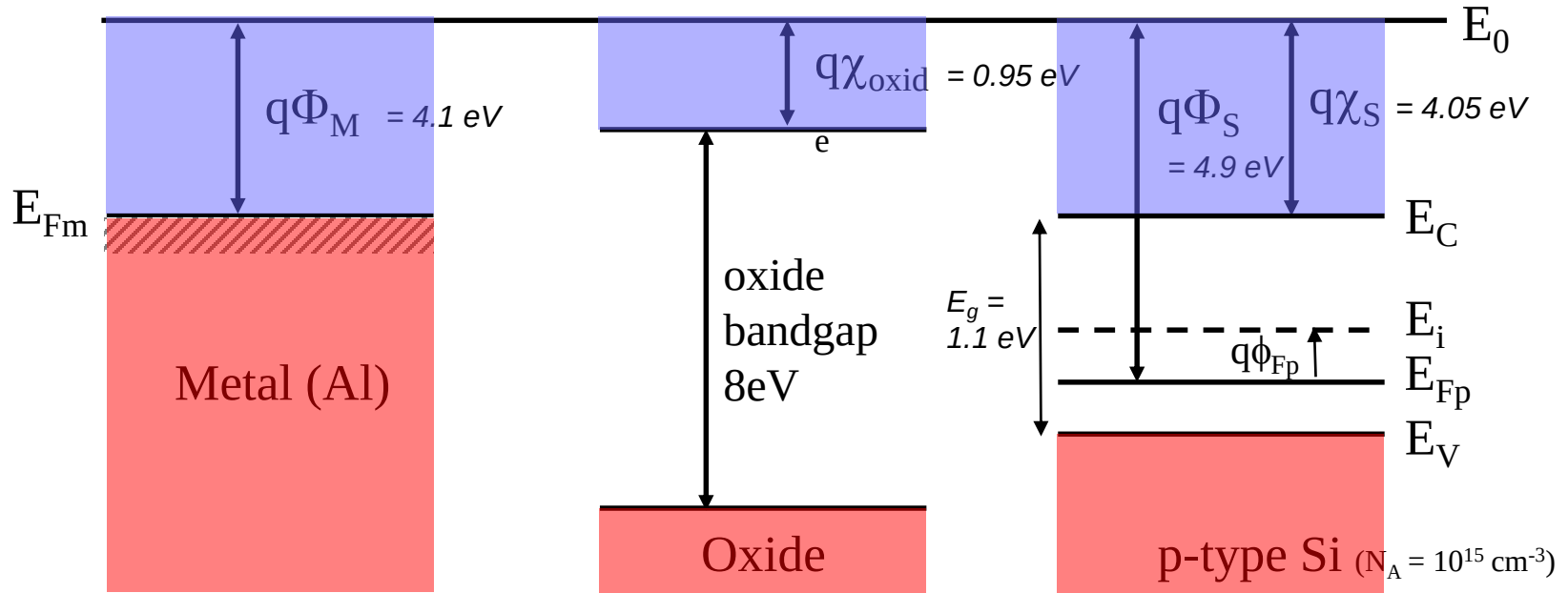
→ h^+ diffusion
← e^- diffusion

MOS Structure

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



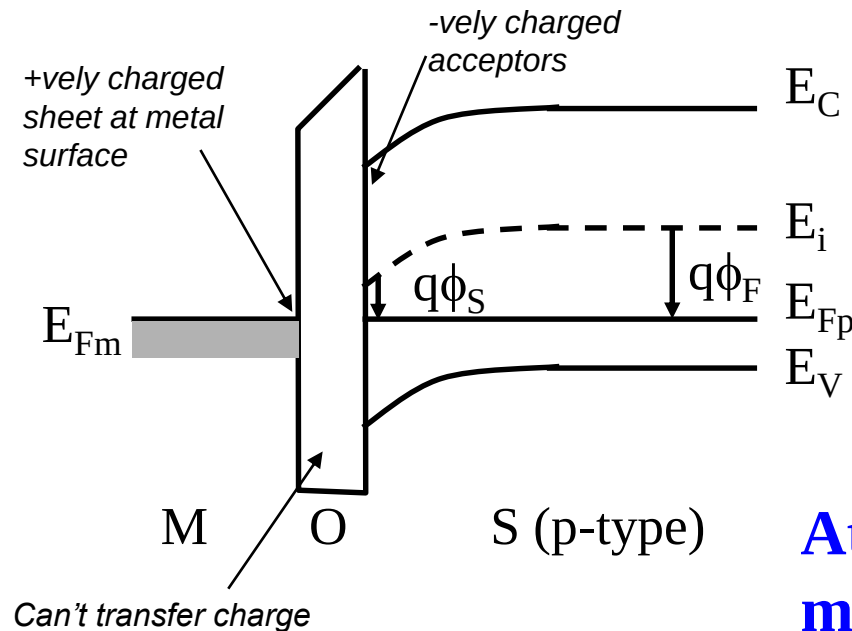
MOS Energy Band Diagram



- **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**



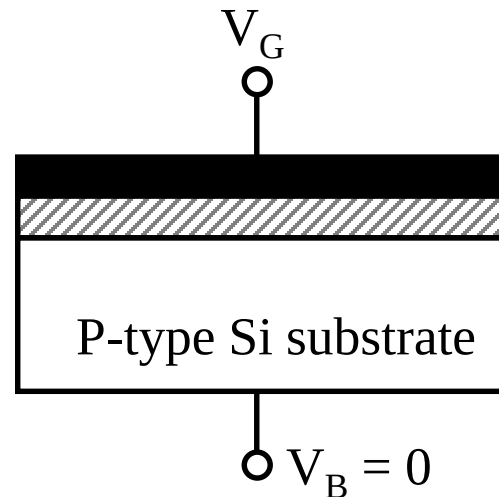
ϕ_F = Fermi potential
(difference between E_F
and E_i in bulk)

ϕ_S = surface potential

**At equilibrium, Fermi levels
must line up!!**

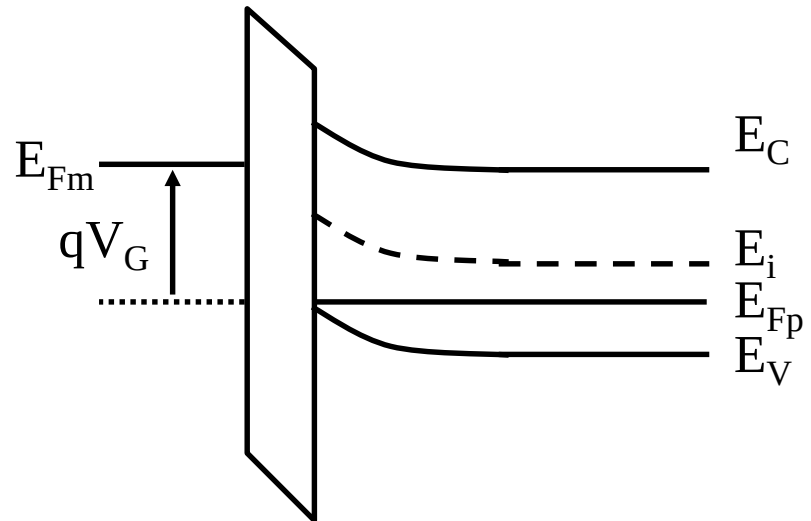
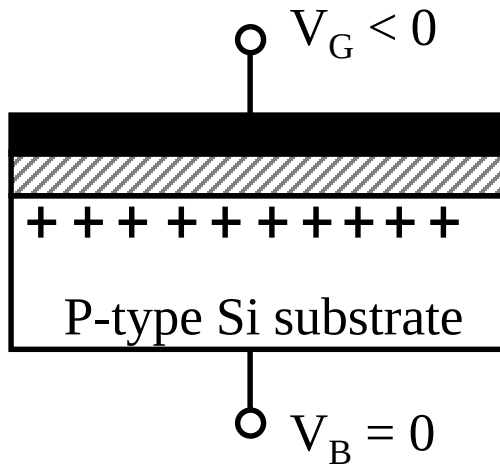
MOS Capacitor Operation

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



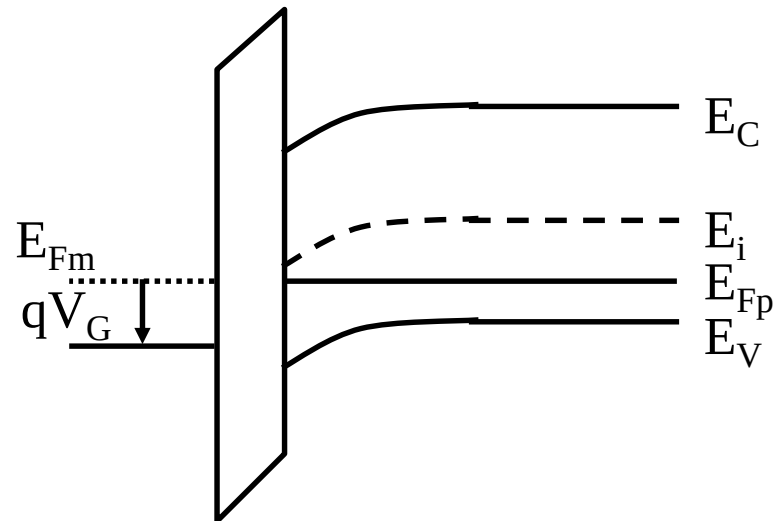
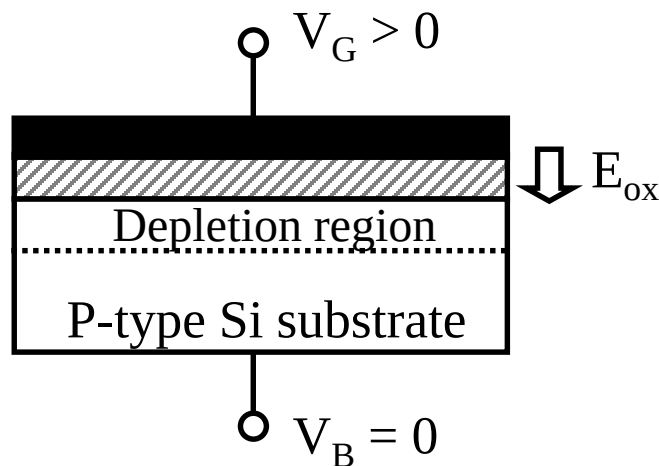
Accumulation

- 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



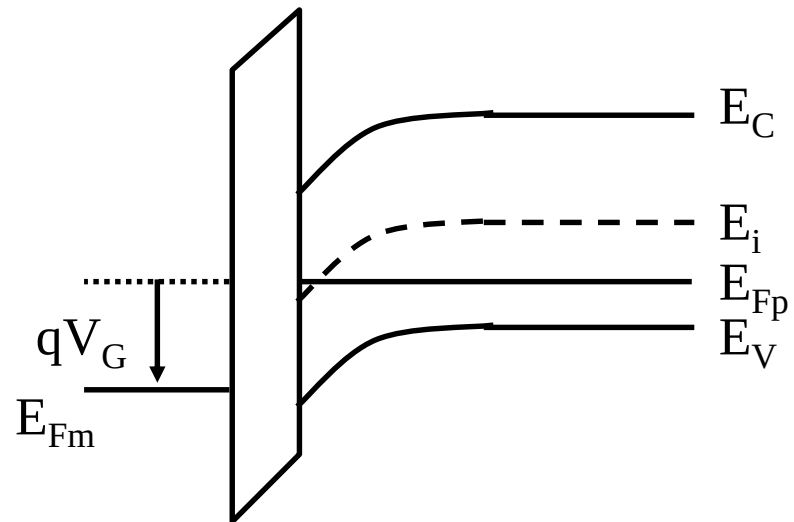
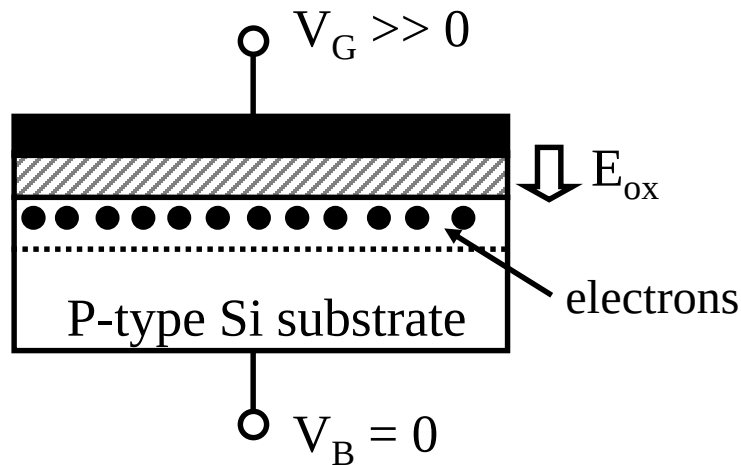
Depletion

- 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:

$$q\phi_F = E_F - E_i$$

