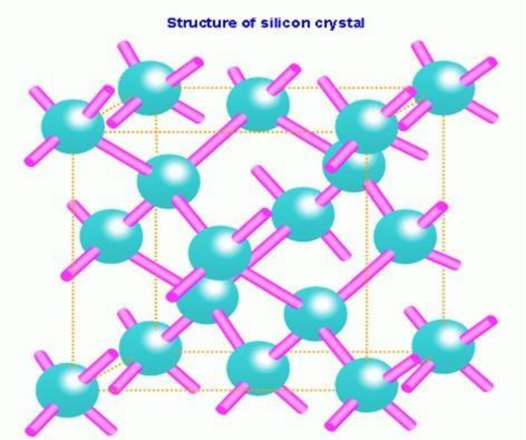
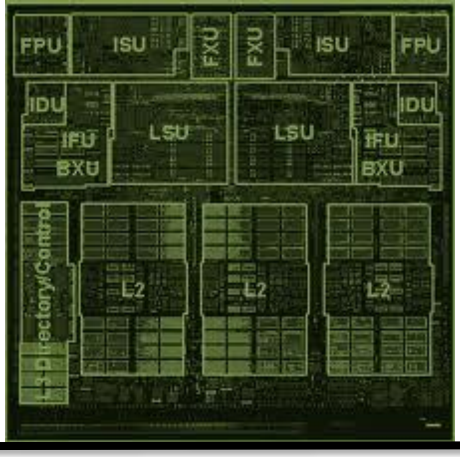
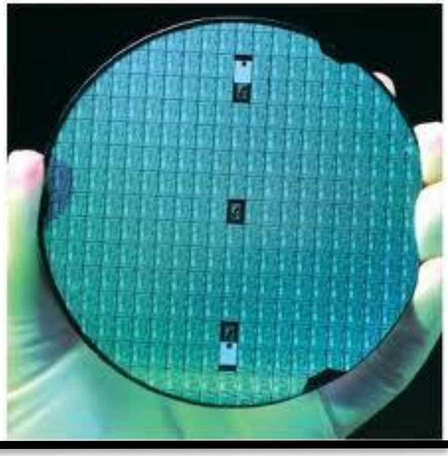






ECE 225

Lecture 2

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

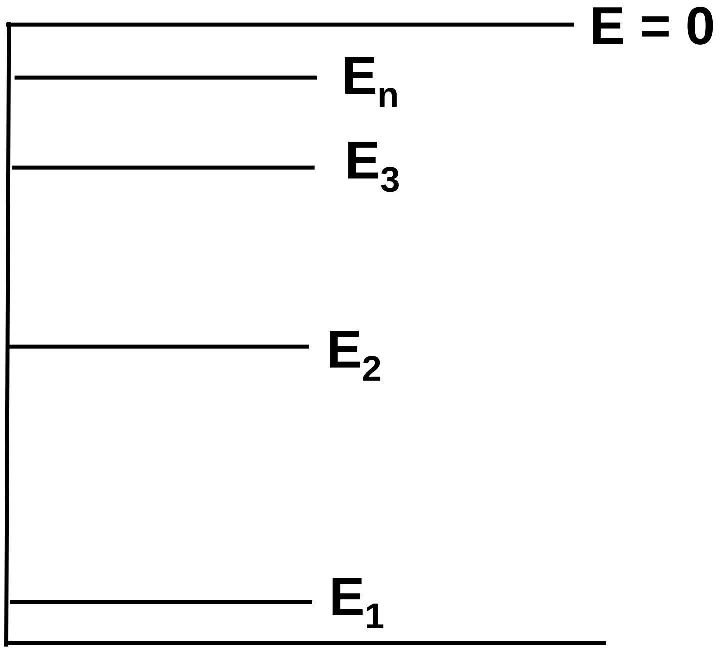
Please Review Lecture 5, ECE 122A, Fall 2015

http://www.ece.ucsb.edu/courses/ECE122/122_F15Banerjee/

Band Model of Solids

- Electron Energy Levels

$$E_n = \frac{-Z^2 m_0 q^4}{8 \varepsilon_0^2 h^2 n^2}$$



Z= # of protons in nucleus

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

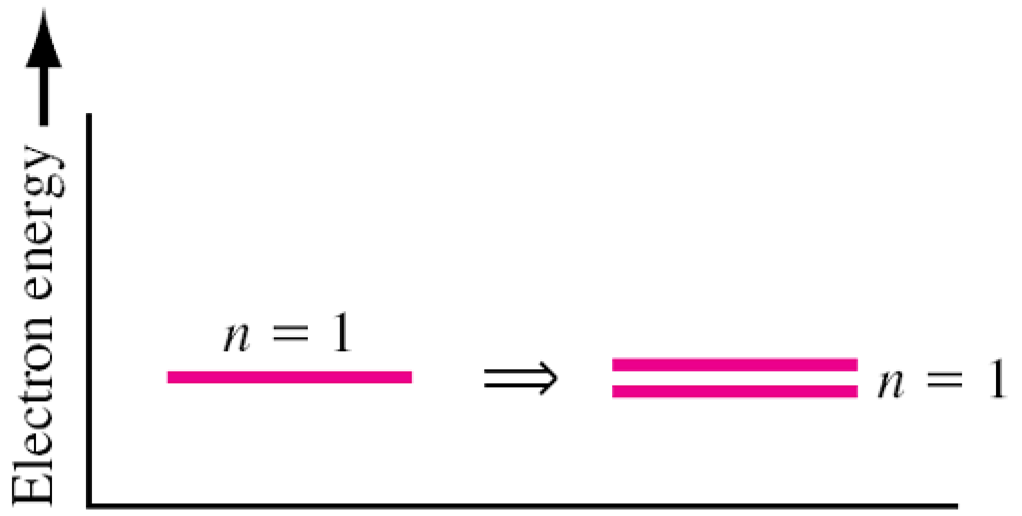
m_0 = free electron mass

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

Band Model of Solids

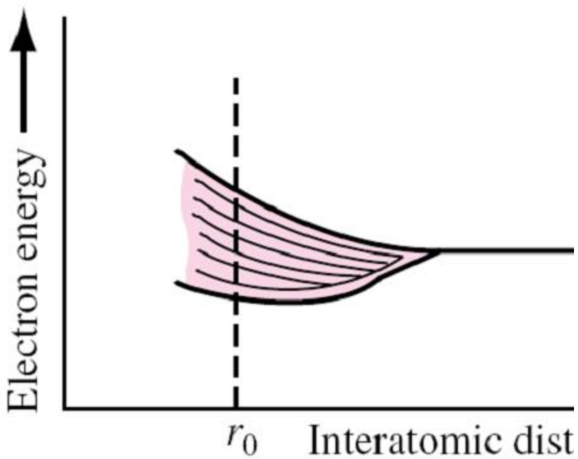
Pauli Exclusion Principle (PEP)

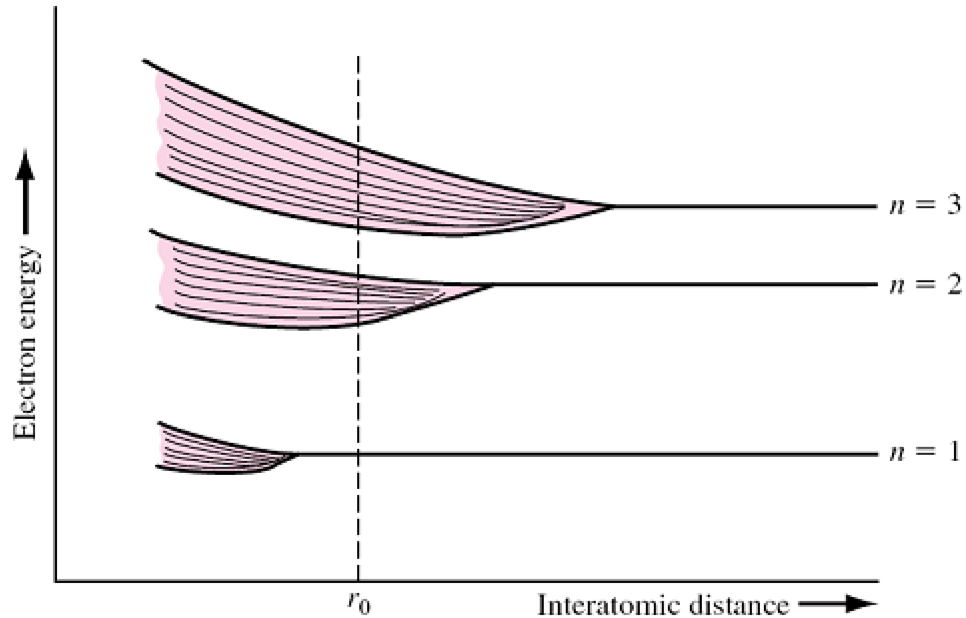
The splitting of the discrete states into two states in consistent with the Pauli exclusion principle.



Band Model of Solids

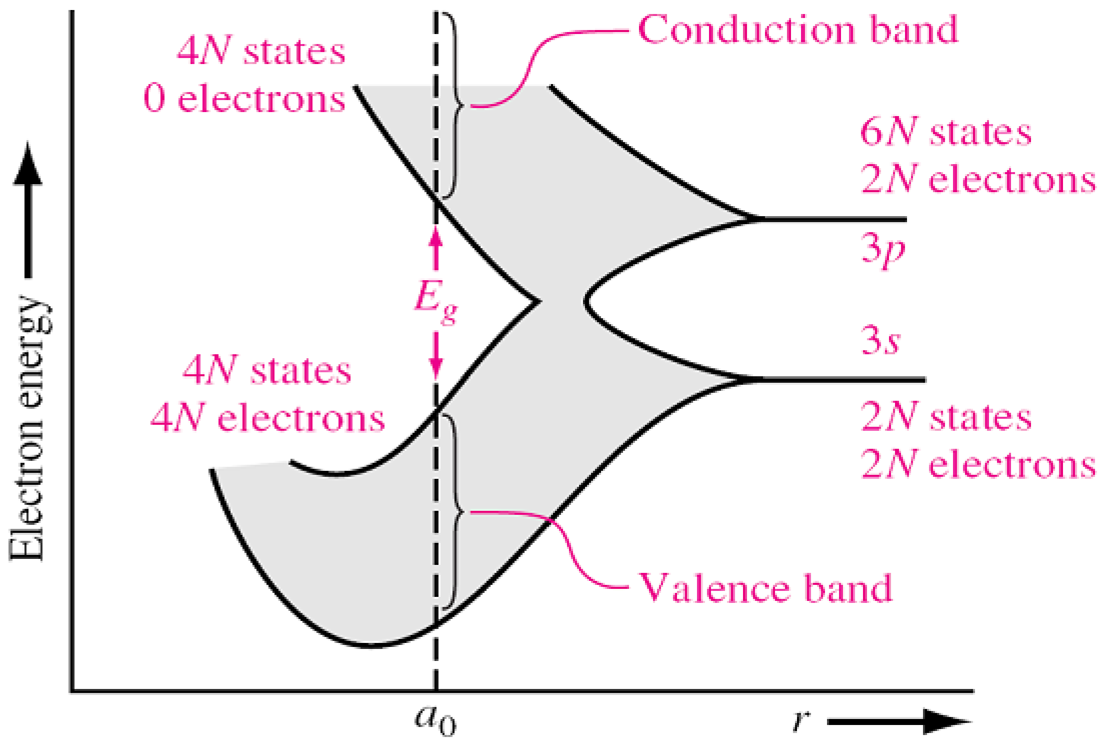
- The allowed/forbidden energy band



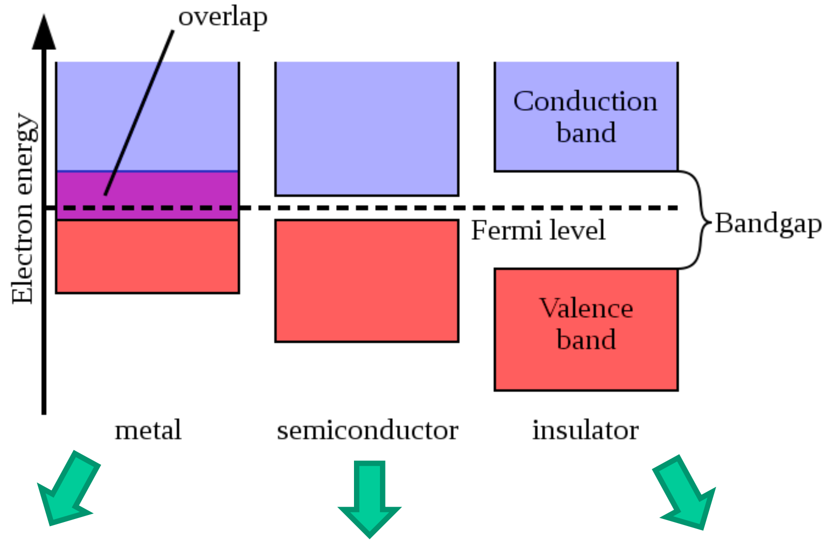


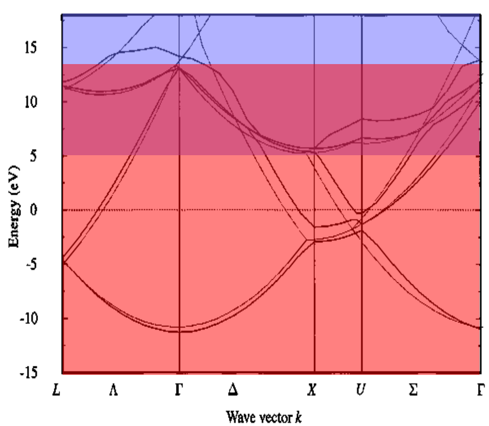
Band Model of Solids

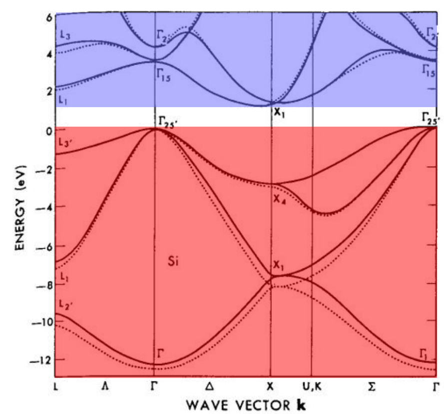
- Silicon: The 14 electrons are placed into the following 3 energy levels and 5 orbitals: $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$
- The splitting of the 3s and 3p states of Si into the allowed and forbidden bands

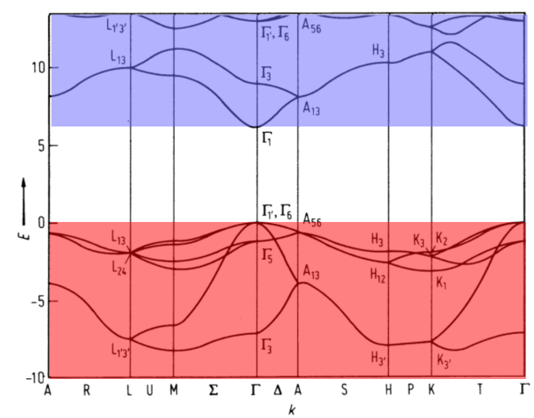


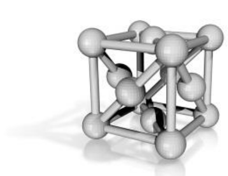
Semiconductors/Metals/Insulators



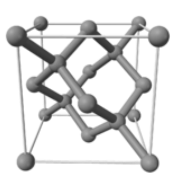




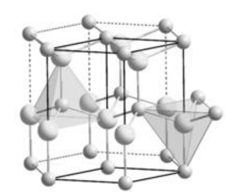




Al



Si

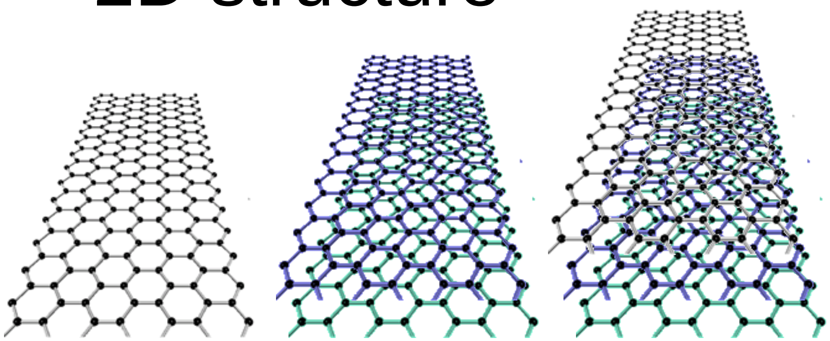


AlN

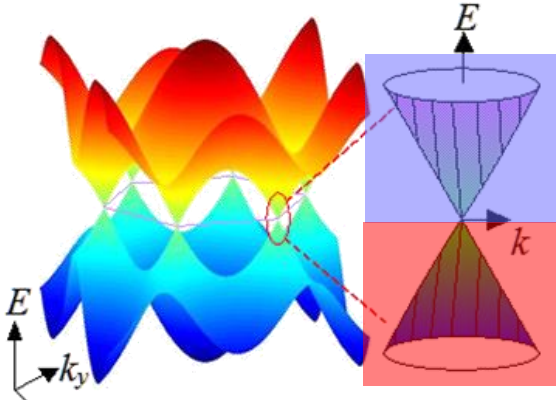
Semiconductors/Metals/Insulators

– Graphene

- 2D structure

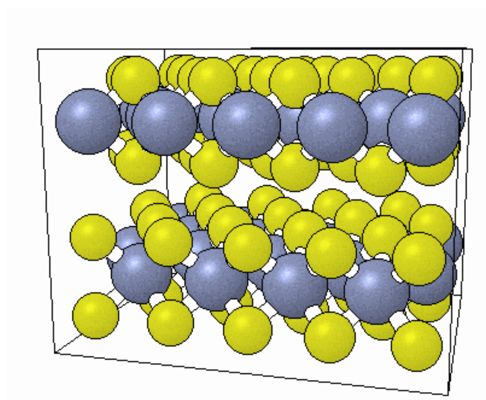


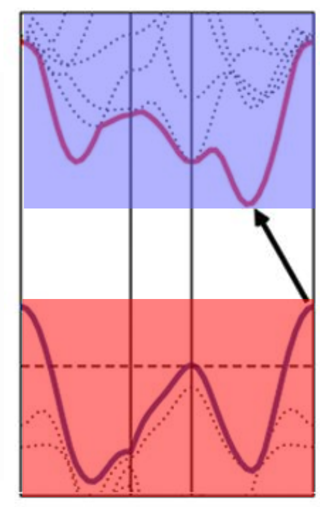
Monolayer Bilayer Multi-layer



– MoS_2

- 2D structure like graphene
- but it has a band-gap



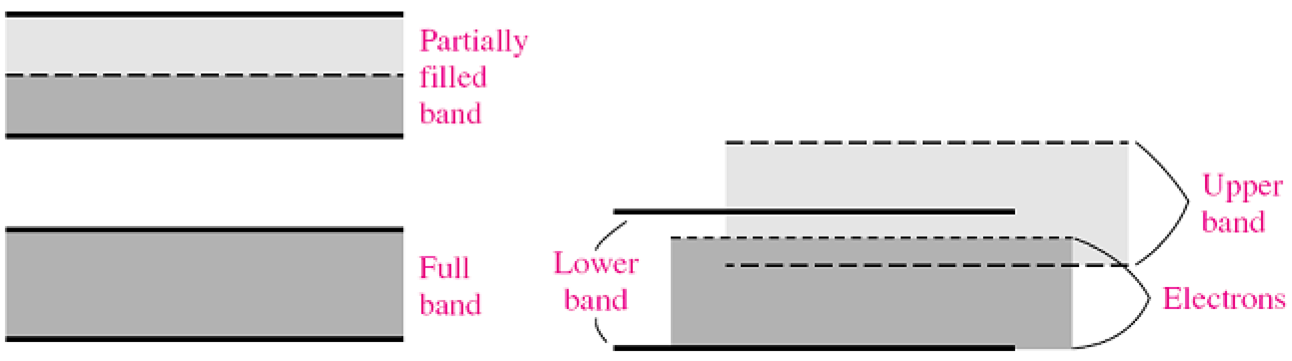


Metals, Semiconductors and Insulators

- 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

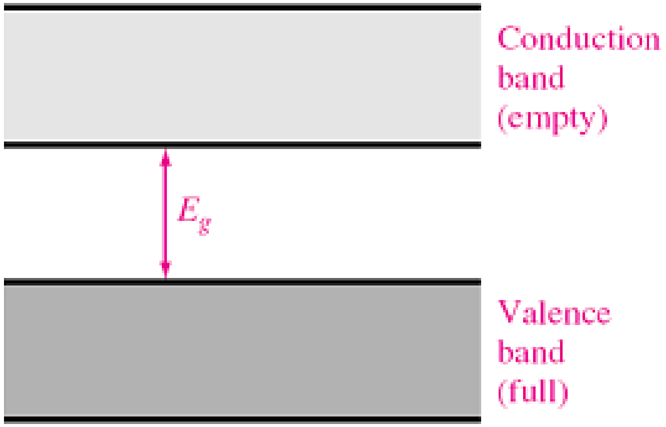
- **metallic**



Metals, Semiconductors and Insulators

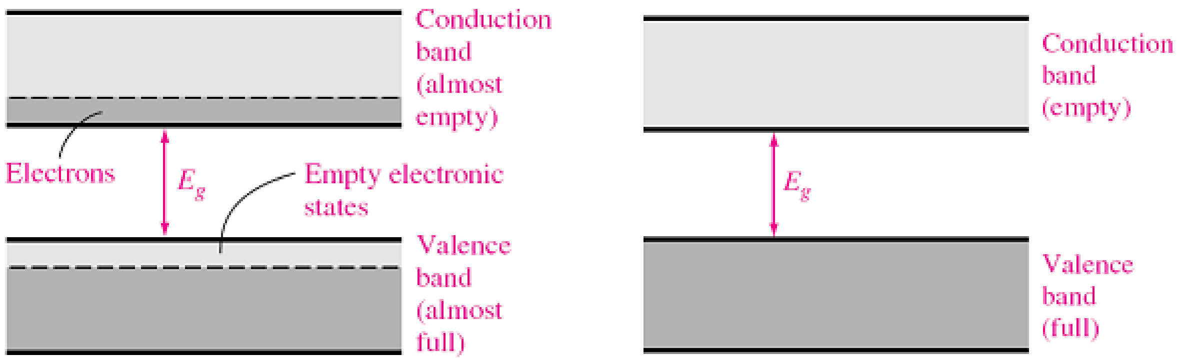
- Insulator

- 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 ~ 5 eV is an insulator

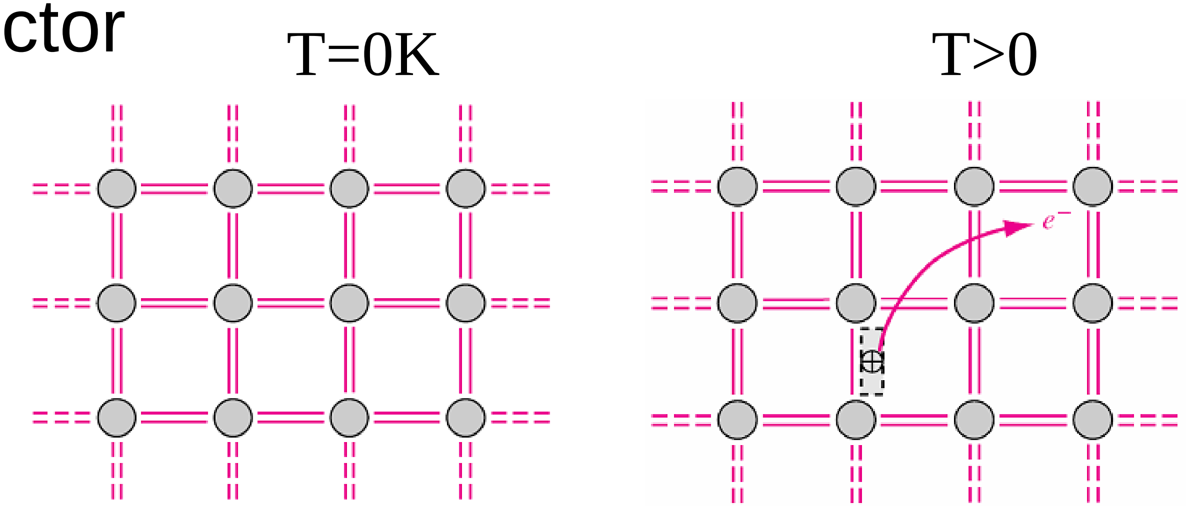


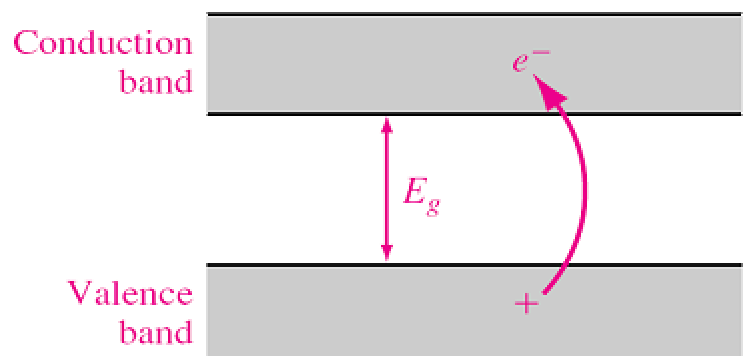
- Impurities in semiconductors are almost fully ionized at room temperatures

  - ***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.

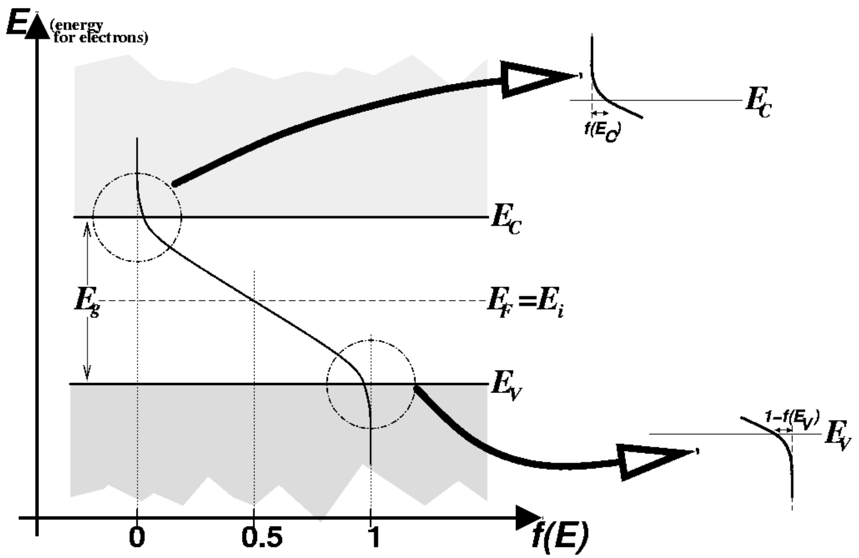
  - Probability of a hole in a state of energy E is

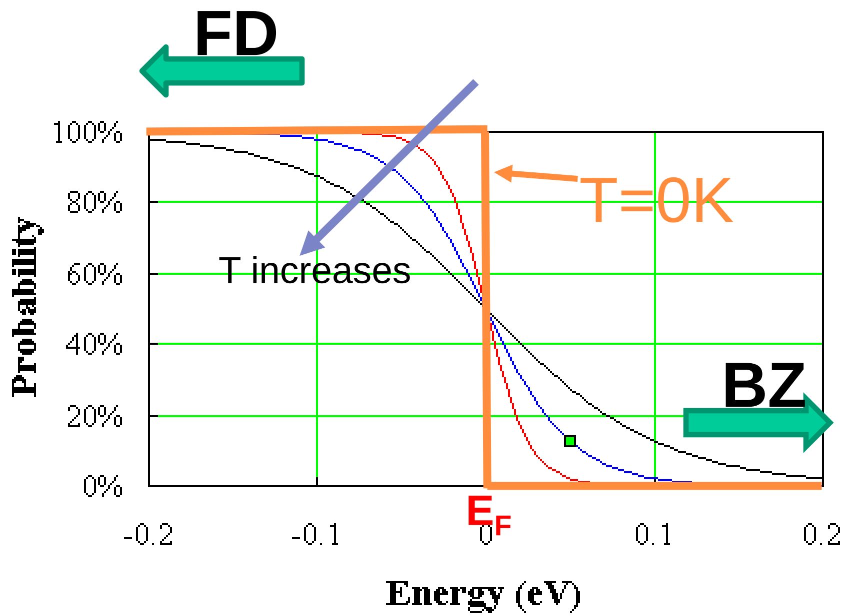
$(1 – f_D(E))$

(Why?)

Occupation Function….

- **Fermi-Dirac Function f(E):**





- At higher temperatures, **$(E-E_F) >> kT$**
- **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
  - $N_c = 3.2 \times 10^{19}$ cm^{-3}
  - $E_i - E_V = 0.5506$ eV
  - $E_g = 1.11$ eV
- Result: $n_0 = 1.45 \times 10^{10}$ cm^{-3} $= p_o$

Extrinsic Semiconductors

- To increase conductivity, *doping* adds impurities to silicon crystal

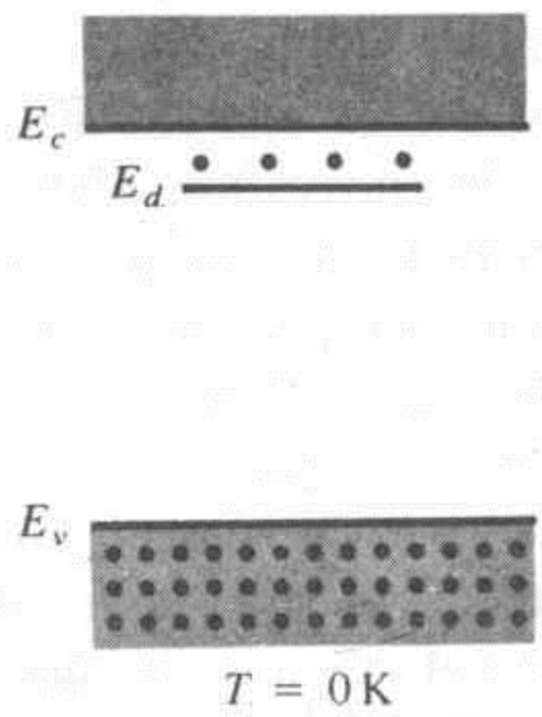
- Two types of impurities:
  - **donors**
  - **Acceptors**
  - Impurities are ionized when they donate or accept an electron

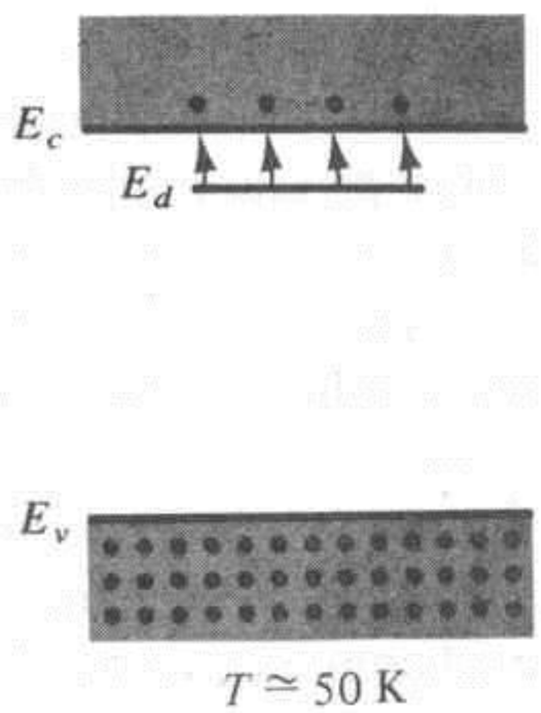
N-Type Semiconductors

- 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
    - Phosporus (P)
    - Arsenic (As)
    - Antimony (Sb)
- Doping concentration: N_D (atoms/cm^3)

N-Type Semiconductors (2)

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



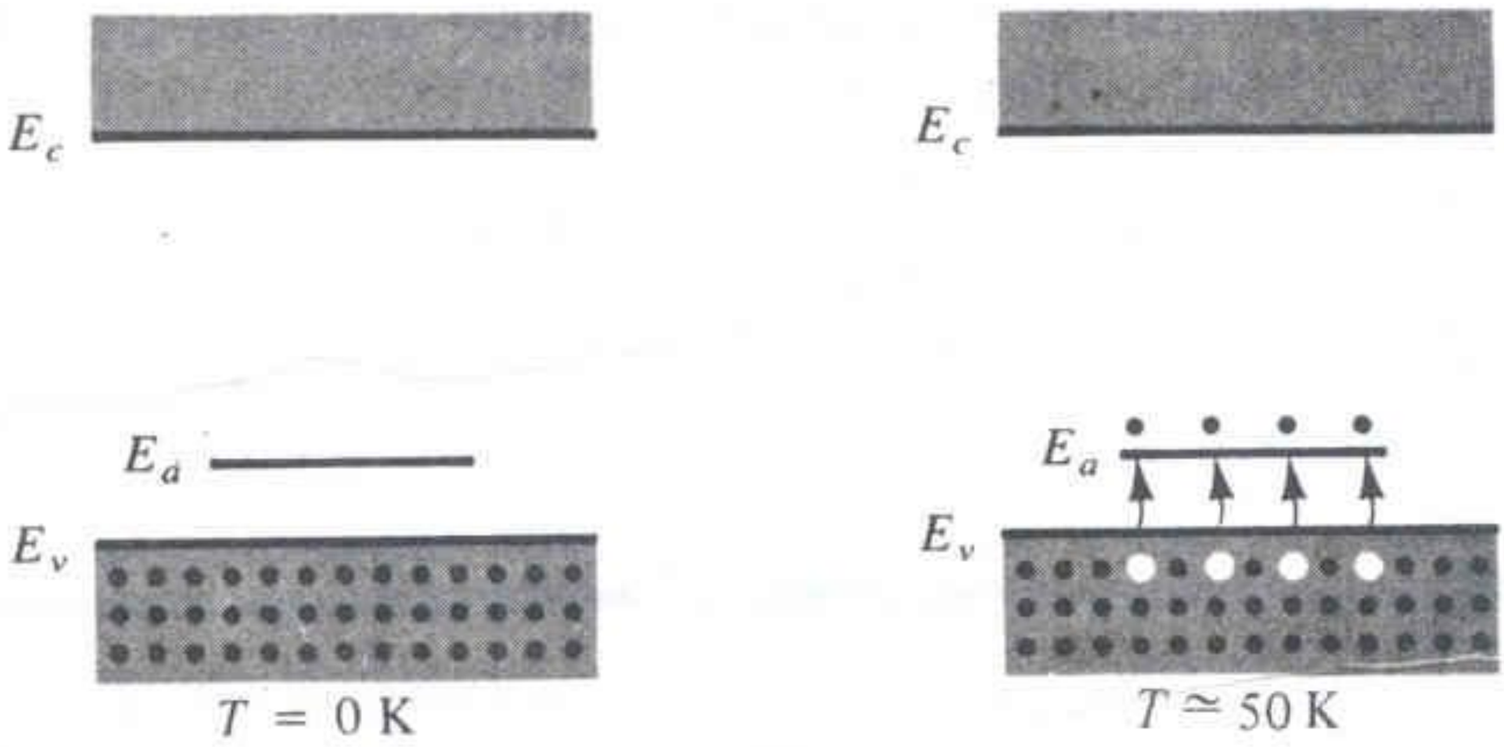


P-Type Semiconductors

- 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

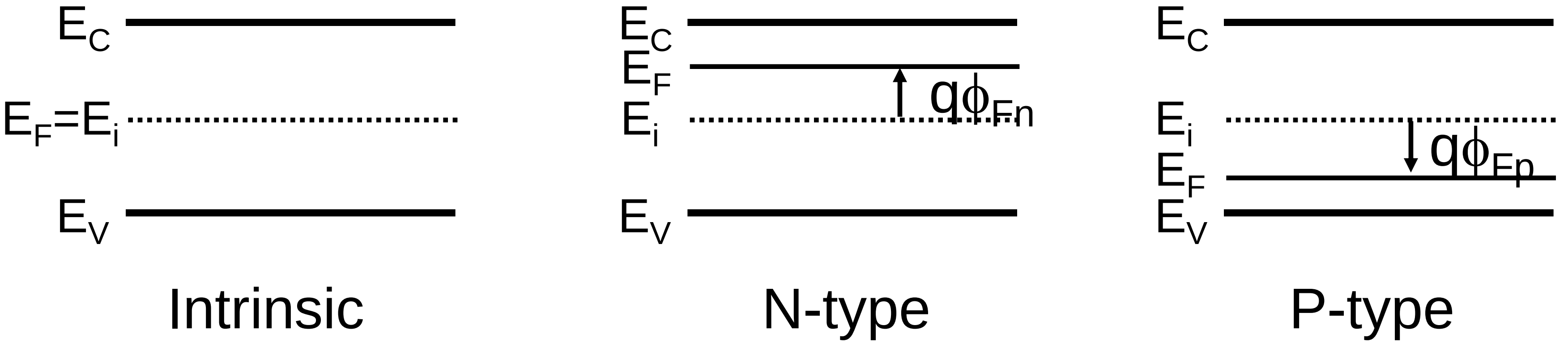
P-Type Semiconductors (2)

- 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



$$q\phi_F = E_F - E_i$$

ϕ_F: V
$q\ \phi_F$: eV

ϕ_F is called the Fermi potential

Extrinsic Energy Band Diagram (2)

- Recalling these equations:

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

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

- 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/cm^3

Extrinsic Energy Band Diagram (3)

For n-type semi

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

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

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

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

For p-type semi

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

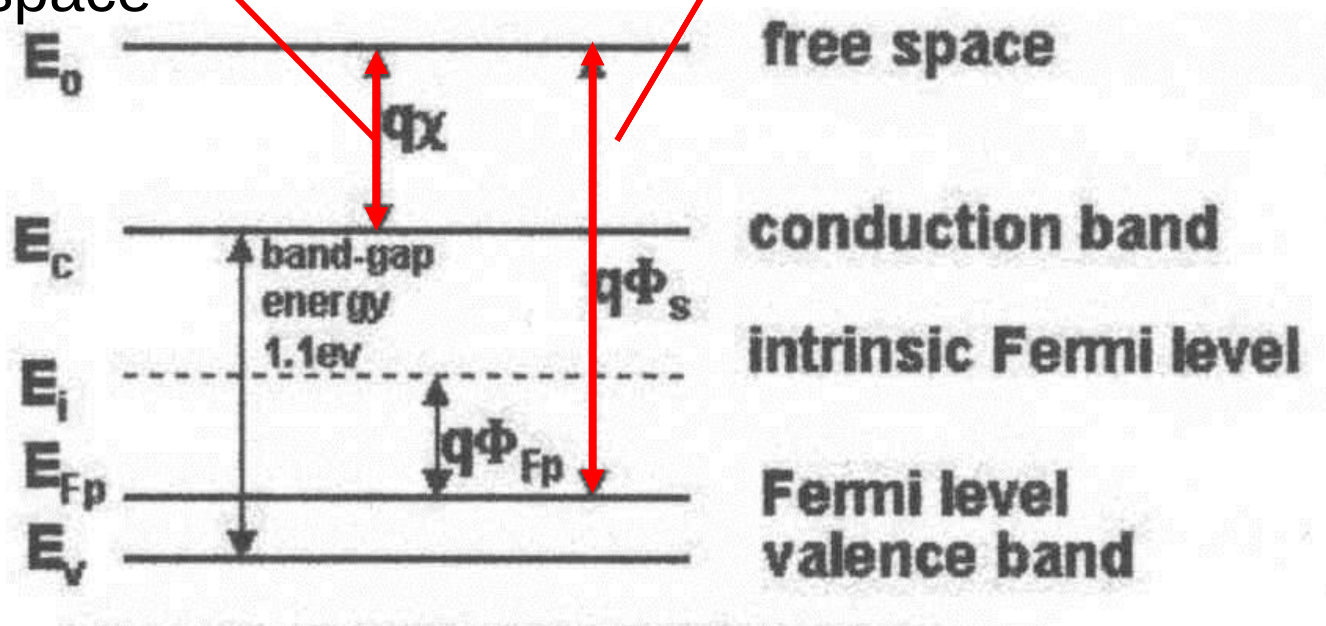
$$E_i - E_F = -kT \ln \frac{n_i}{N_A}$$

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

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: $$F_x = -q\mathrm{E}_x$$

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

Drift Current (2)

- Given average velocity, find current density:

$$J_x = \frac{nq^2\bar{t}}{m_n^*}\mathrm{E}_x$$

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

$$\boxed{\begin{gathered}\mu_n = \frac{q\bar{t}}{m_n^*} \\ J_x = qn\mu_n\mathrm{E}_x\end{gathered}}$$

J_x = A/cm^2

n = electrons/cm^3

μ = cm^2/V-s

Drift Current (3)

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

$$J_x = \underbrace{qn\mu_n}\mathrm{E}_x$$

$$\sigma = qn\mu_n$$

$$\mathrm{J}_x = \sigma E_x$$

or V = I.R
Since, J = I/A = E/ρ
And E = V/L

- σ is the conductivity of the material (σ=1/ρ, where ρ=resistivity)

Drift Current Example

- Find the approximate electron current for intrinsic silicon
  - Size = 1 cm^3
  - Voltage applied: 1V

  - μ_n = 600 $cm^2/V \bullet s$
    q = 1.6 x 10^{19} 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 hole current is same as the direction of its conc. gradient

Direction of electron current is opposite to 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):

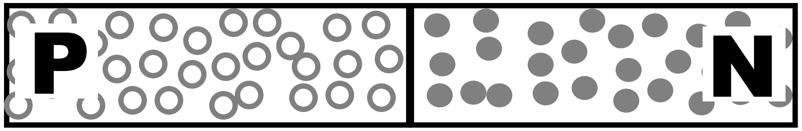
$$q\mu_n n(x)E(x) = -qD_n \frac{dn(x)}{dx}$$

- Equilibrium Fermi level must be flat:

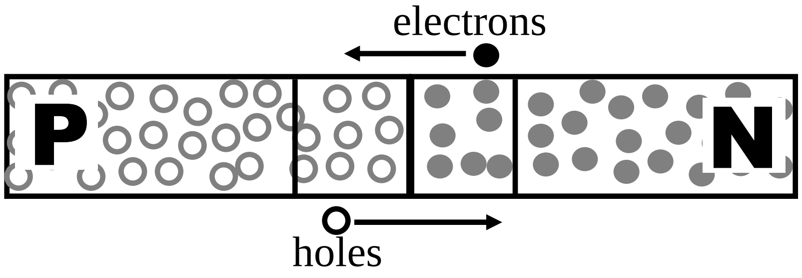
$$\boxed{\frac{dE_F}{dx} = 0}$$

P/N Junctions

- put two types of semiconductors together

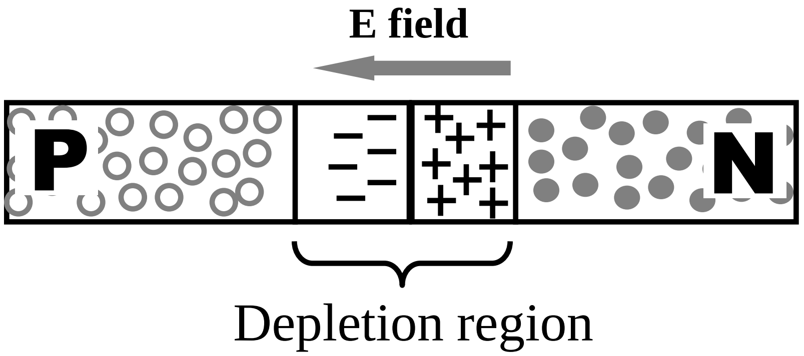


➢ Large concentration gradient at junction

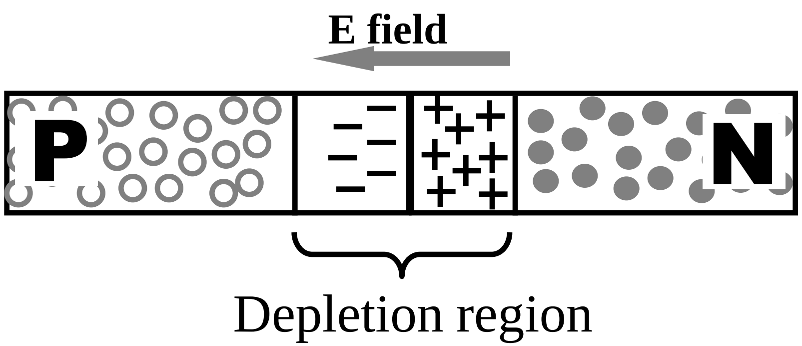


P/N Junctions (2)

- 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

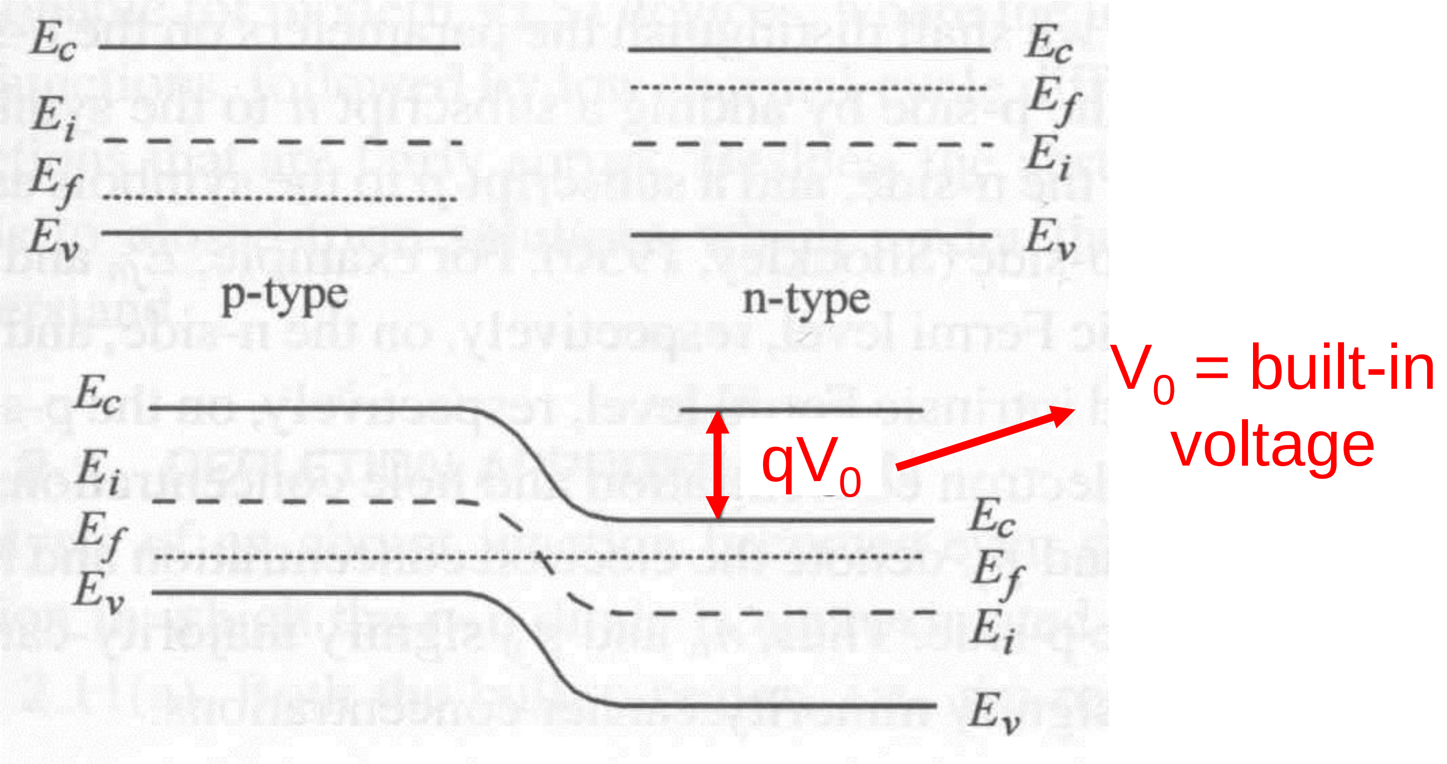


Depletion Region



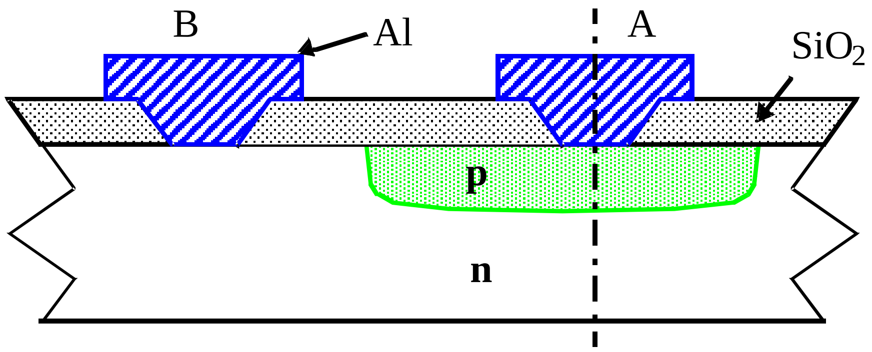
- Depletion region forms around junction
  - “Depleted” of any mobile charges (holes or electrons)
  - Charge in depletion region due to fixed ions
  - Electric field causes a potential difference across junction: known as built-in voltage V_0

P/N Junction Band Diagram

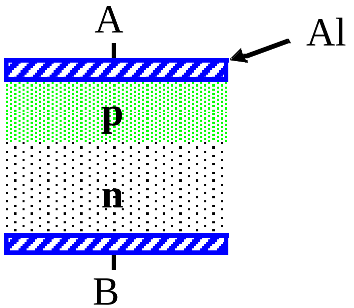


- At thermal equilibrium, no net current flow
  - When drift+diffusion currents=0, $\frac{dE_f}{dx} = 0$
- Bands must bend so that Fermi level is constant

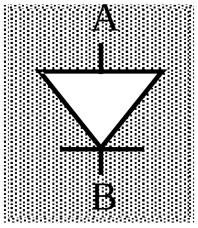
The Diode



Cross-section of pn-junction in an IC process



One-dimensional representation

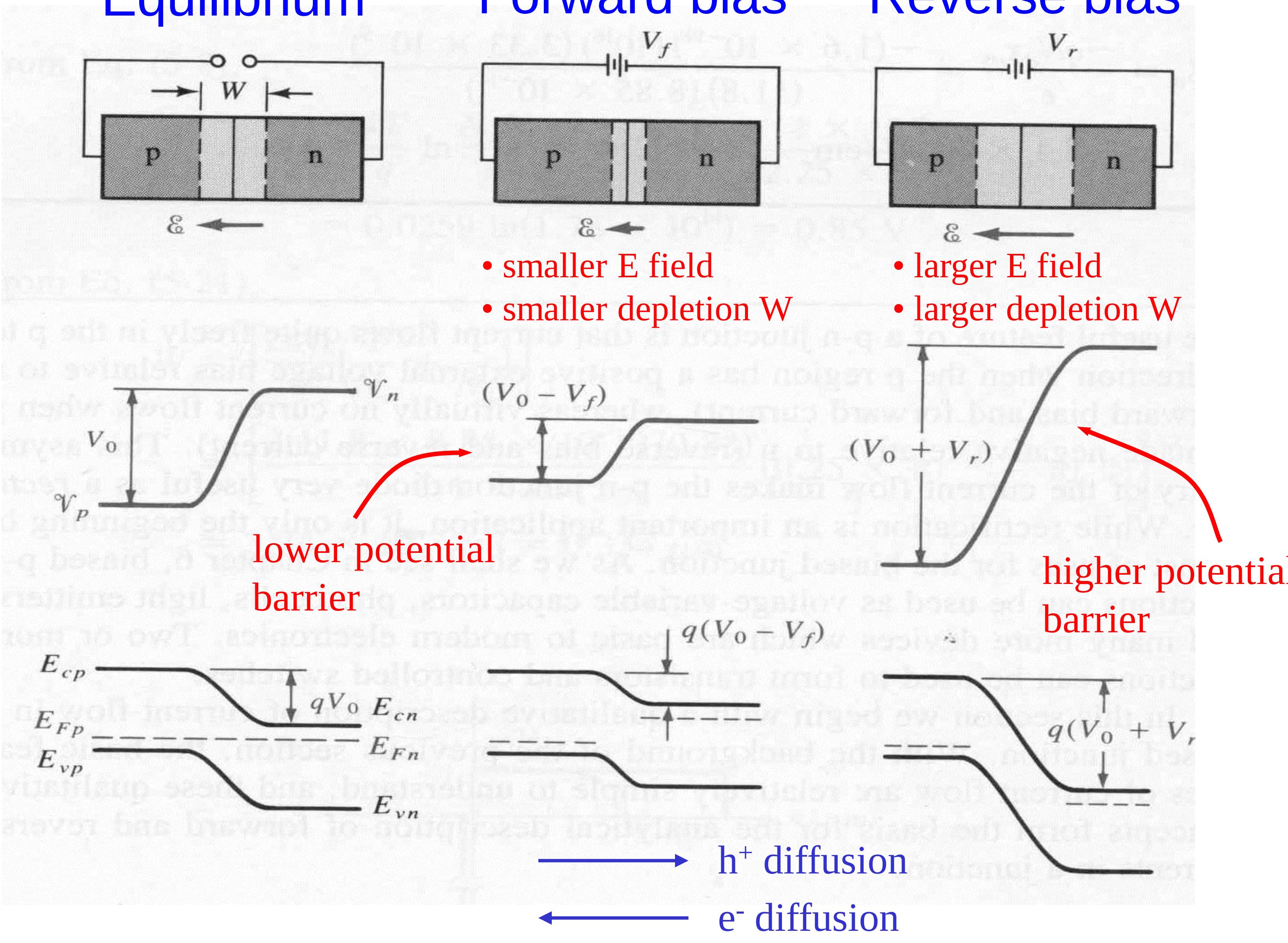


diode symbol

Mostly occurring as parasitic element in Digital ICs

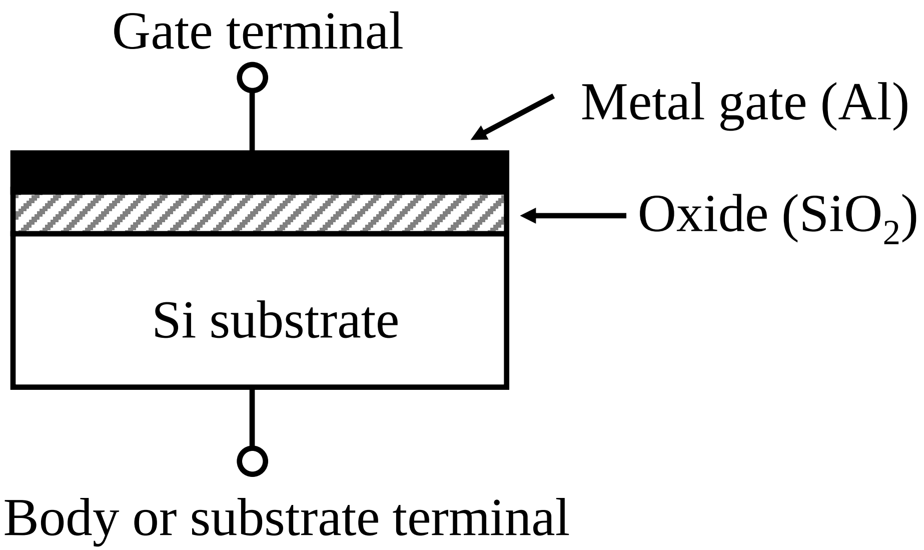
Bias Effects on PN Junction

Equilibrium | Forward bias | Reverse bias

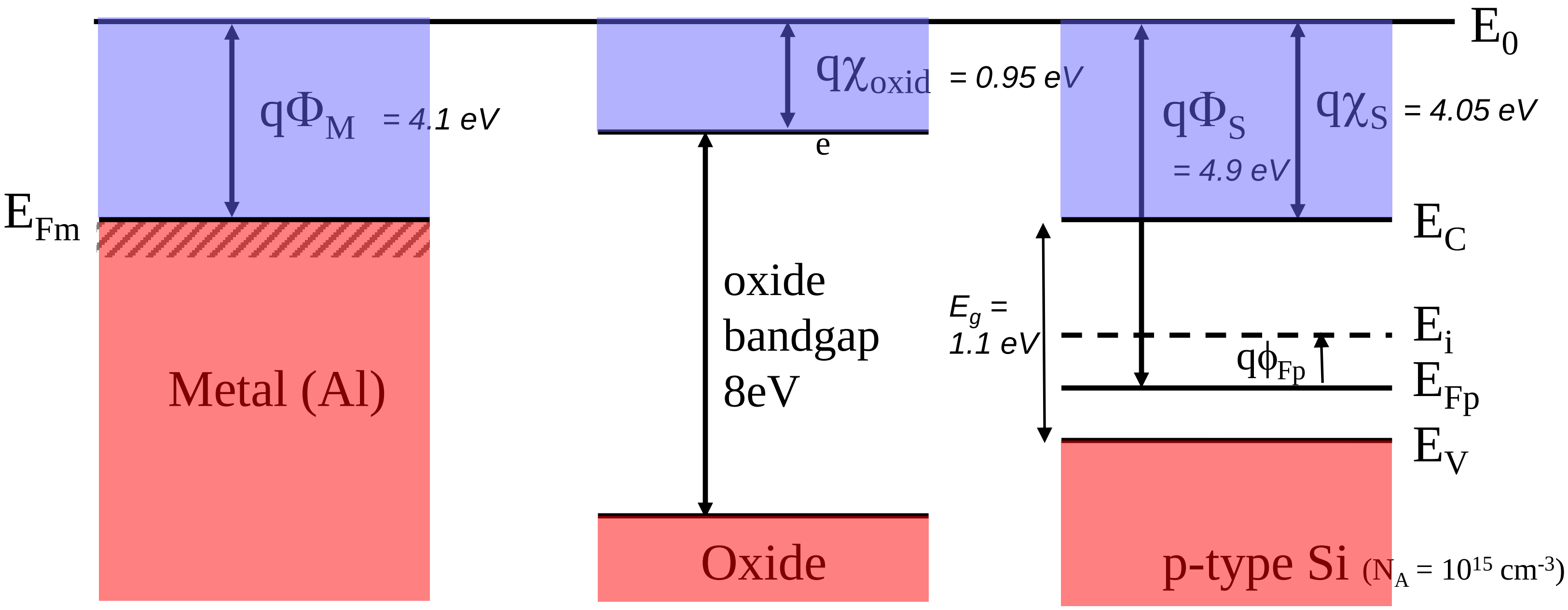


MOS Structure

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



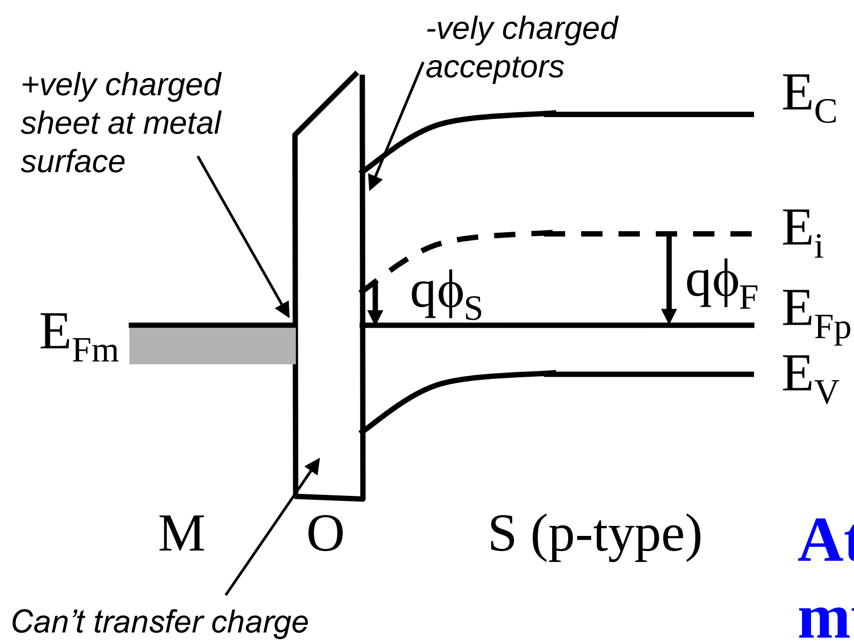
MOS Energy Band Diagram



- 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) = qX_s
- Work function difference between Al and Si = 0.8V

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**



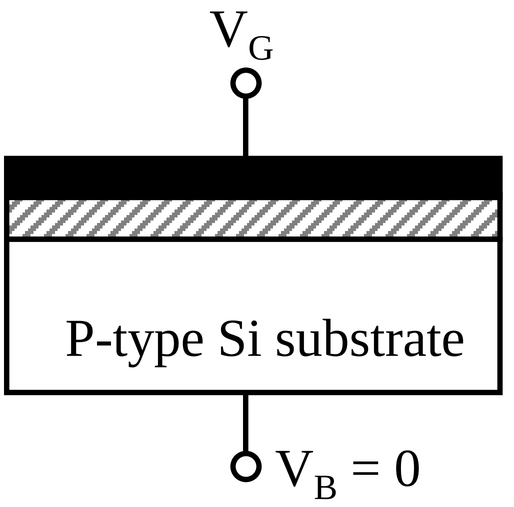
ϕ_F = Fermi potential (difference between E_F and E_i in bulk)

ϕ_S = surface potential

At equilibrium, Fermi levels must line up!!

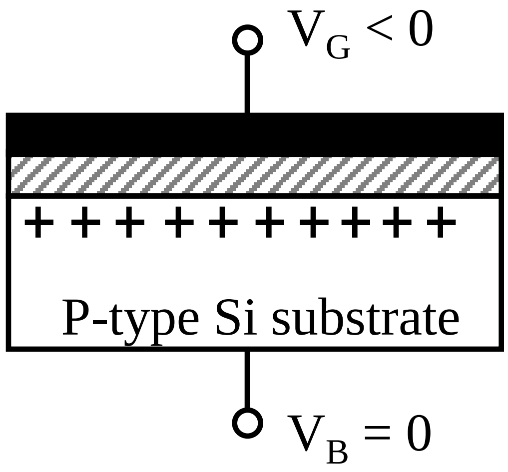
MOS Capacitor Operation

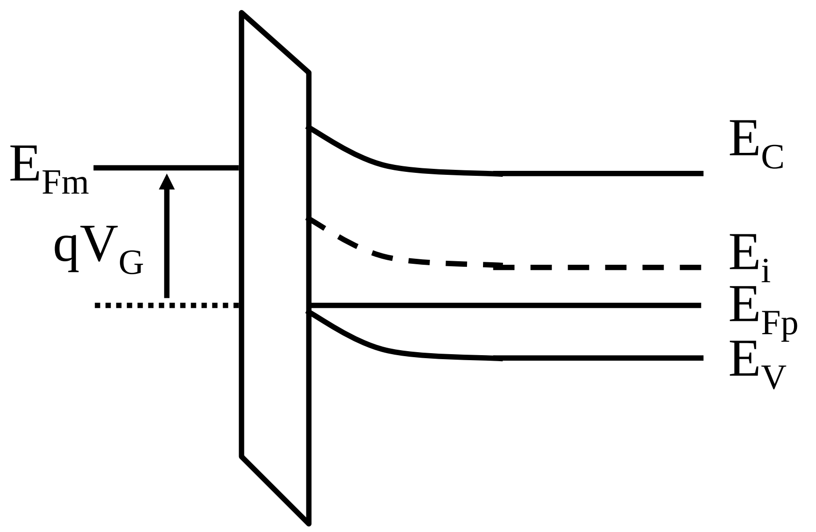
- Assume p-type substrate
- Three regions of operation
  - Accumulation ($V_G < 0$)
  - Depletion ($V_G > 0$ but small)
  - Inversion ($V_G >> 0$)



Accumulation

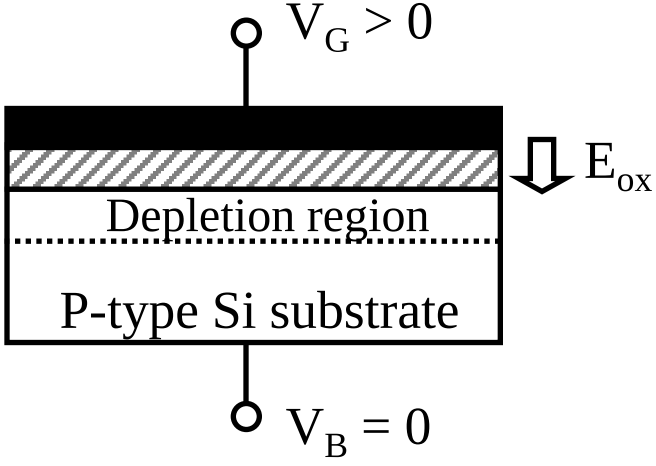
- Negative voltage on gate: attracts holes in substrate towards oxide
- Holes "accumulate" on Si surface (surface is <u>more</u> strongly p-type)
- Electrons pushed deeper into substrate

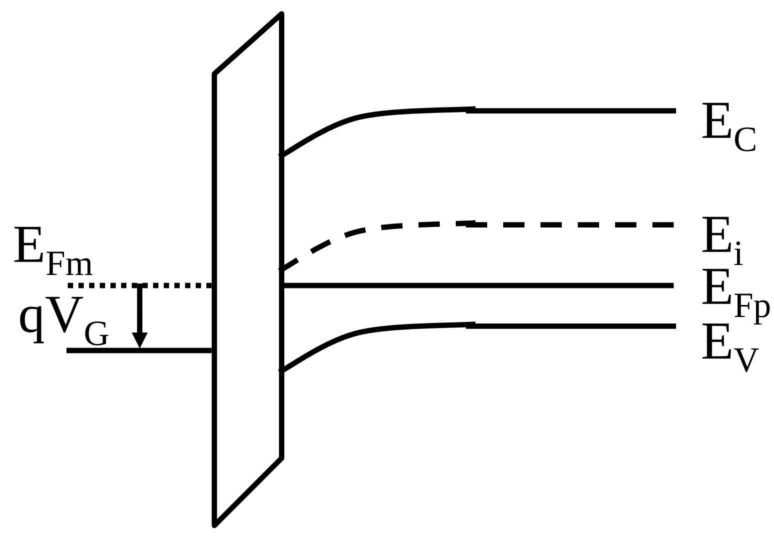




Depletion

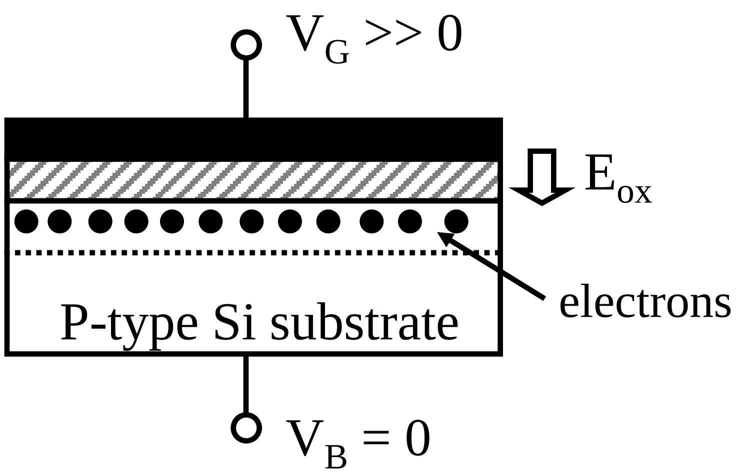
- Positive voltage on gate: repels holes in substrate
  – Holes leave behind negatively charged acceptor ions
- Depletion region forms: devoid of carriers
  – Electric field directed from gate to substrate
- Bands bend downwards near surface
  – Surface becomes <u>less</u> strongly p-type (E_F close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

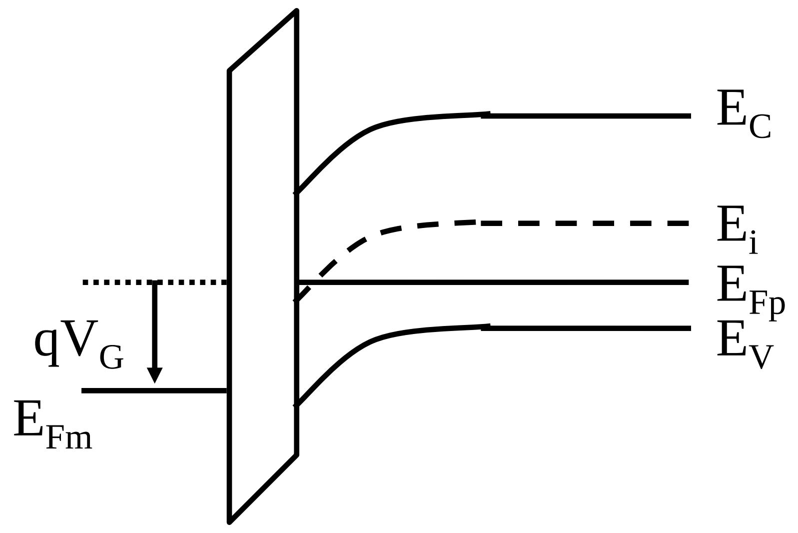




Inversion

- 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:

$q\phi_F = E_F - E_i$