

EEM 214

Lecture 2

Carrier Modelling

Review of electrostatics

Bohr atomic model

Carrier properties

Energy band diagram

Band gap and material classification

State and carrier distribution

Fermi function & equilibrium distribution

Semiconductor physics

How do we go from this...



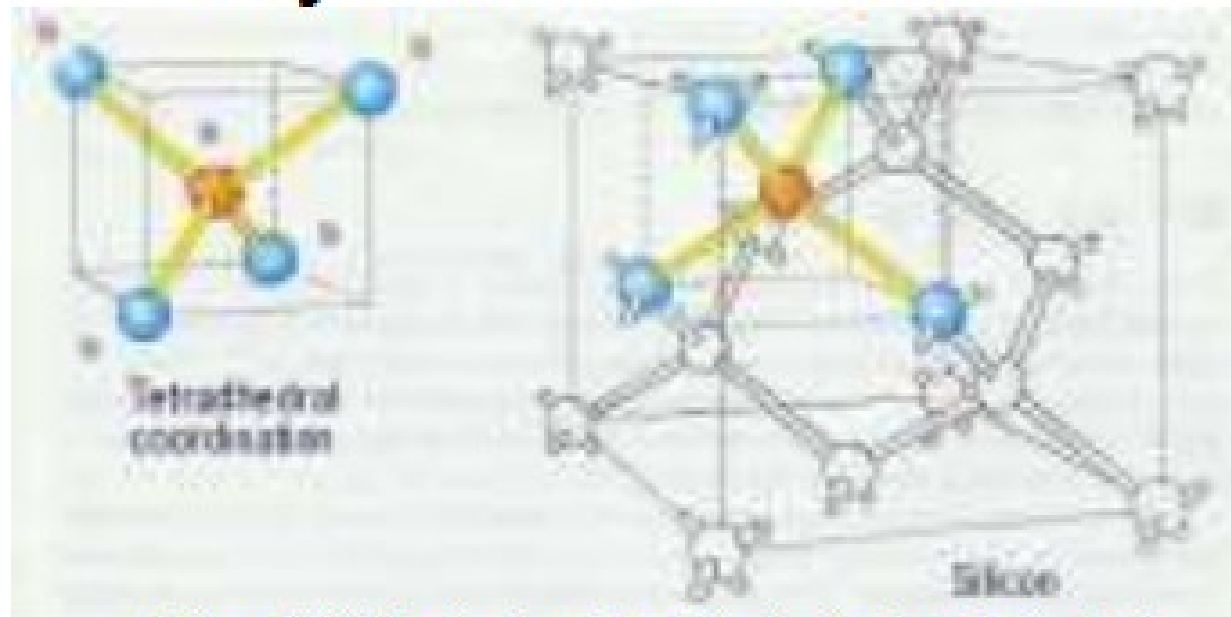
to this?

$$i_D = I_S \left(e^{v_D / \eta V_T} - 1 \right)$$

What determines current?

- # of charge carriers
 - state and carrier distribution
- Speed of charge carriers
 - mobility, drift, diffusion

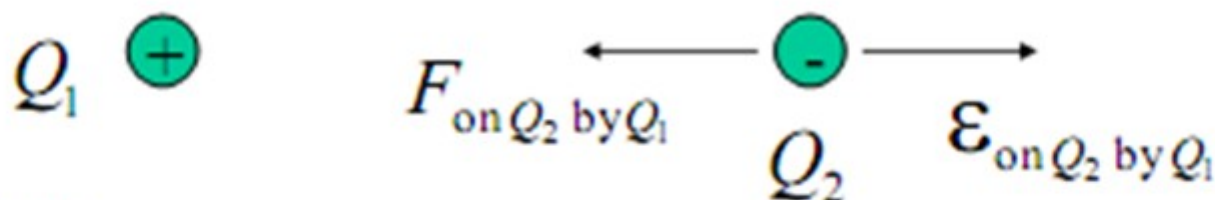
Crystalline silicon



sol.sci.uop.edu/~jfalward/semiconductordevices/semiconductordevices.html

- 3D lattice: each Si atom bonded to 4 neighbors
- Density: 5×10^{22} atoms/cm³
- Distance between atoms: 0.235nm
- Q: If Si transistor gate is 15nm wide, how many atoms wide is the gate?

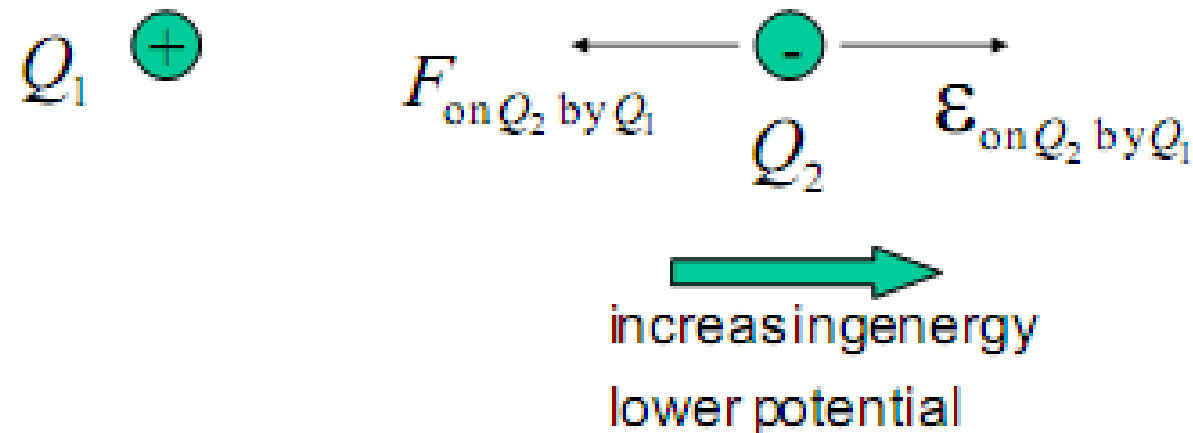
Review of electrostatics



- Charge
 - Basic unit: Coulomb
 - q (charge of an electron) = 1.6×10^{-19} C
- Current
 - $1 \text{ A} = 1 \text{ C} / 1 \text{ sec}$
- Electric field: force per unit charge

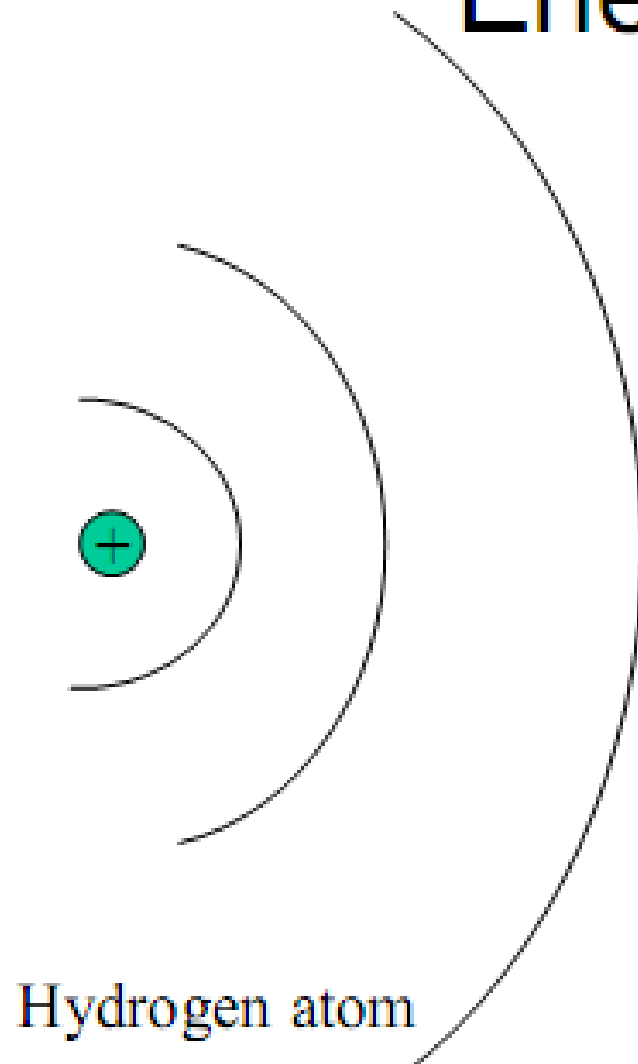
$$|\mathcal{E}_{\text{on } Q_2}| = \frac{Q_1}{4\pi \epsilon_0 r^2}$$

Review of electrostatics ...



- Energy=Work: force x distance
 - Basic unit: Joules
- Potential = Work per unit charge
 - Basic unit: 1 Volt = 1 J / 1 C

Energy levels



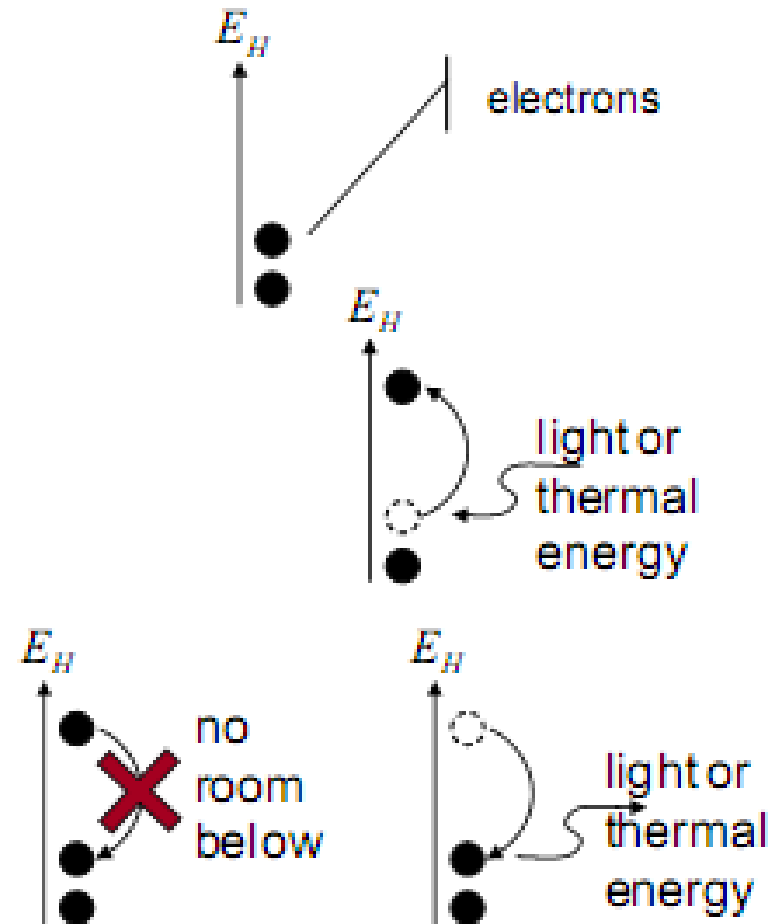
$$E_H = -\frac{13.6}{n^2} \text{ eV}, \quad n = 1, 2, 3, \dots$$

$$\begin{aligned} 1 \text{ eV} &= 1 \text{ electron - volt} \\ &= 1.6 \times 10^{-19} \text{ joules} \end{aligned}$$

There are actually sublevels
w/in these levels.

Rules for electrons

- Tend to settle to lowest levels.
- Need extra energy to move to higher levels.
- Can move to lower or equal energy levels if not filled. Give up energy when moving to lower levels

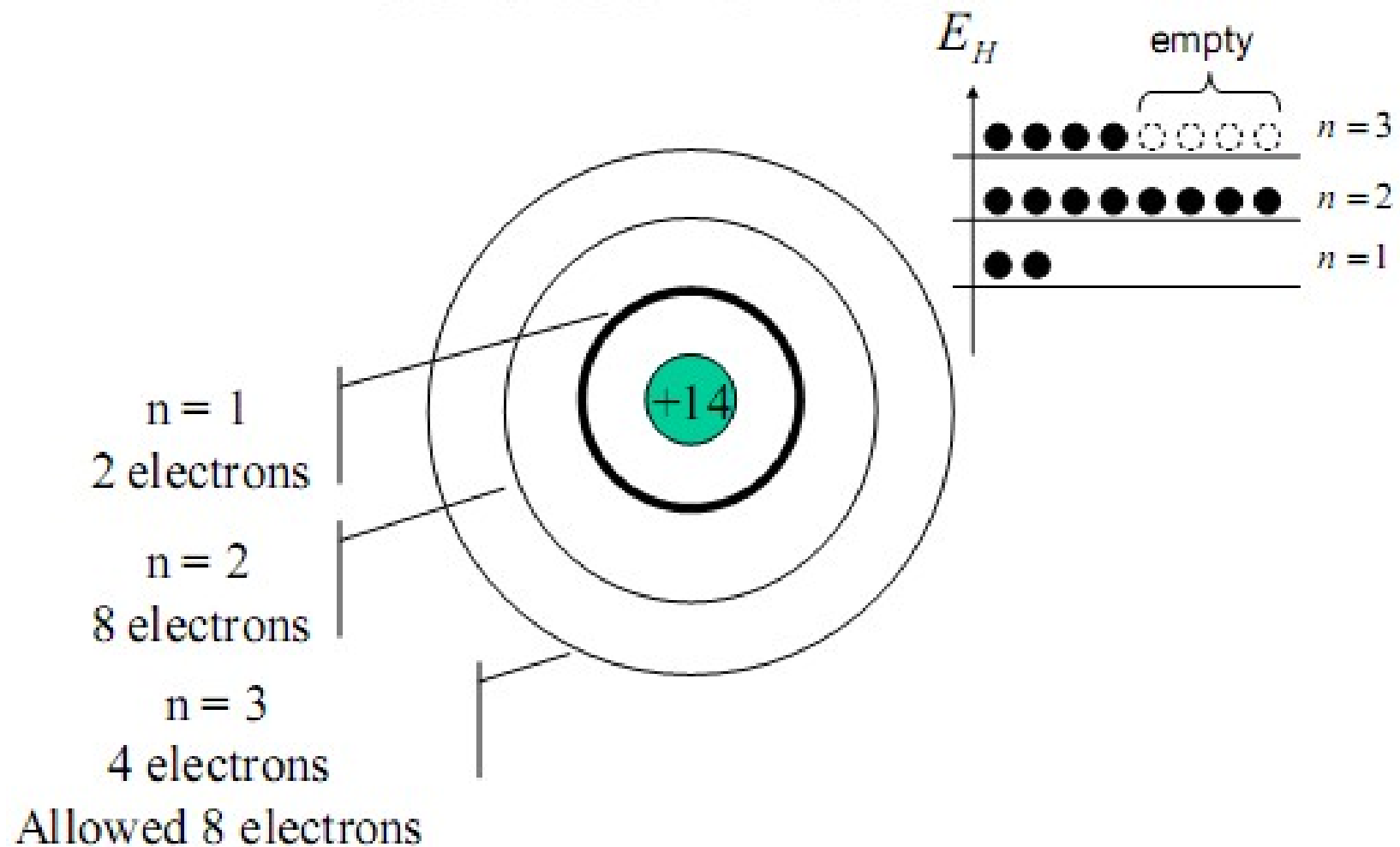


Periodic Table of Elements

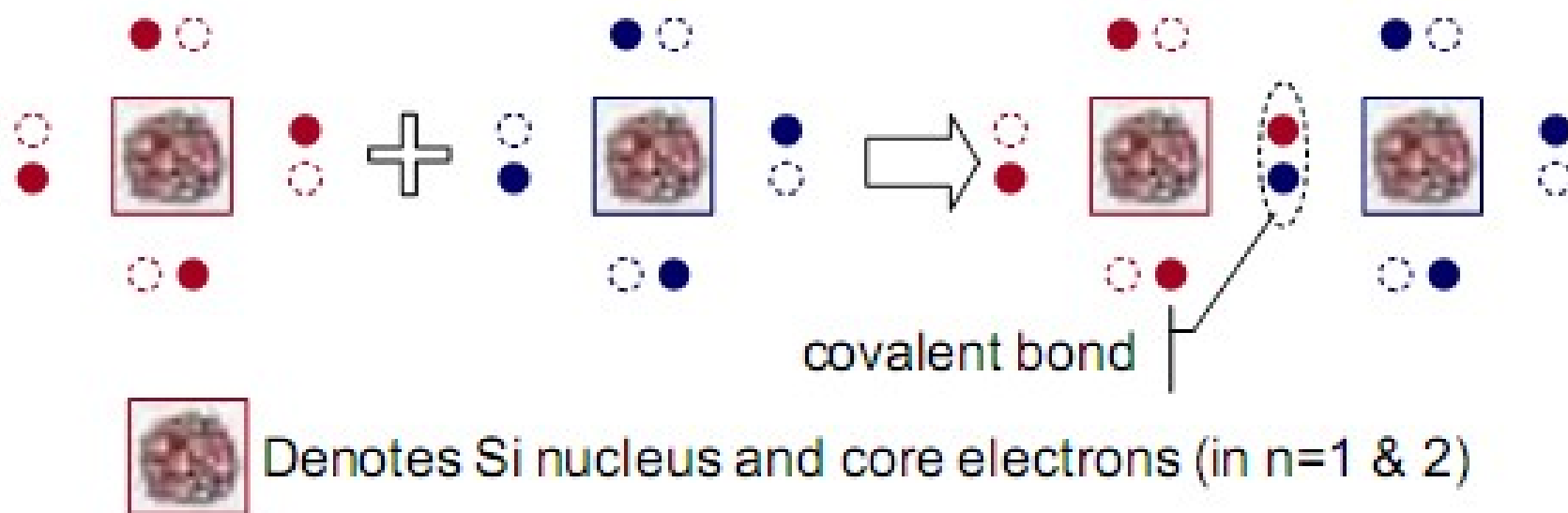
II	III	IV	V	VI
Be ⁴	B ⁵	C ⁶	N ⁷	O ⁸
Mg ¹²	Al ¹³	Si ¹⁴	P ¹⁵	S ¹⁶
Zn ³⁰	Ga ³¹	Ge ³²	As ³³	Se ³⁴
Cd ⁴⁸	In ⁴⁹	Sn ⁵⁰	Sb ⁵¹	Te ⁵²

Roman numeral at top col indicates # of valence electrons

Isolated Si atom



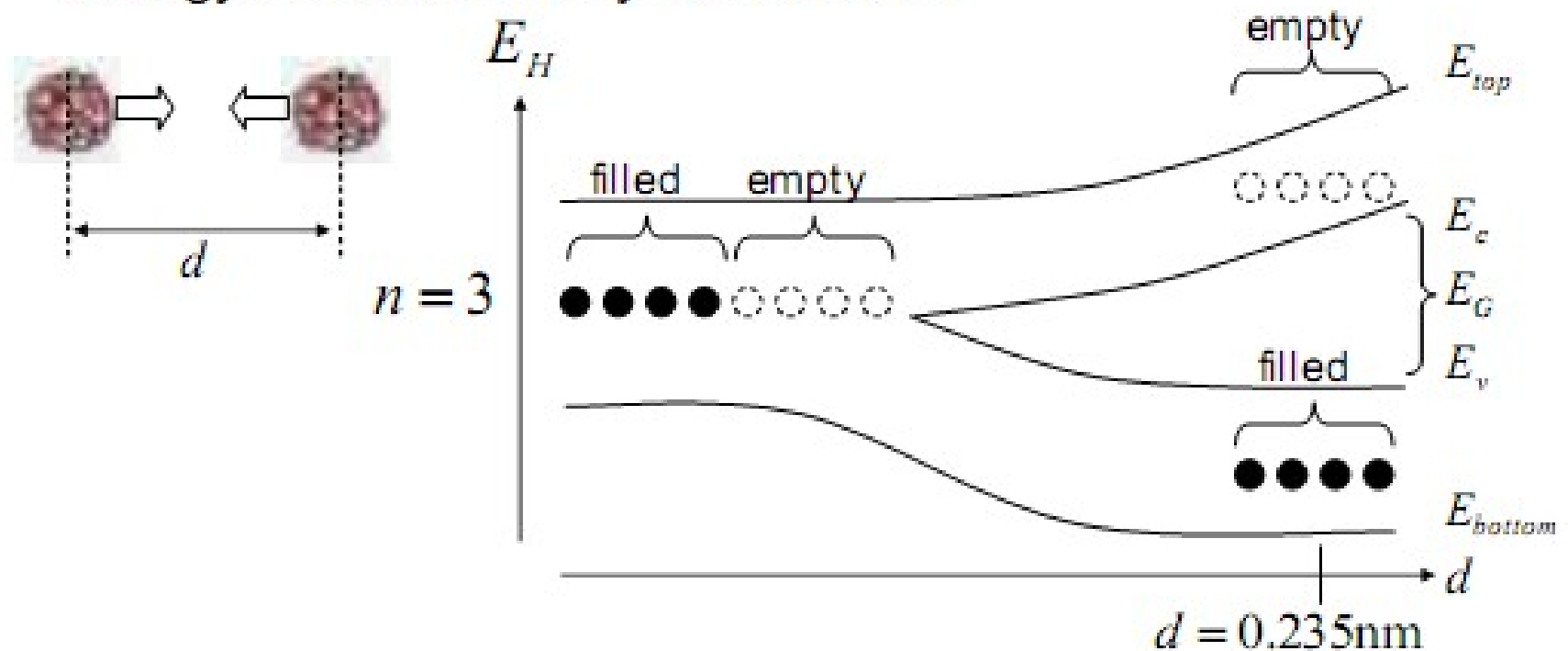
Covalent bonding bet. Si atoms



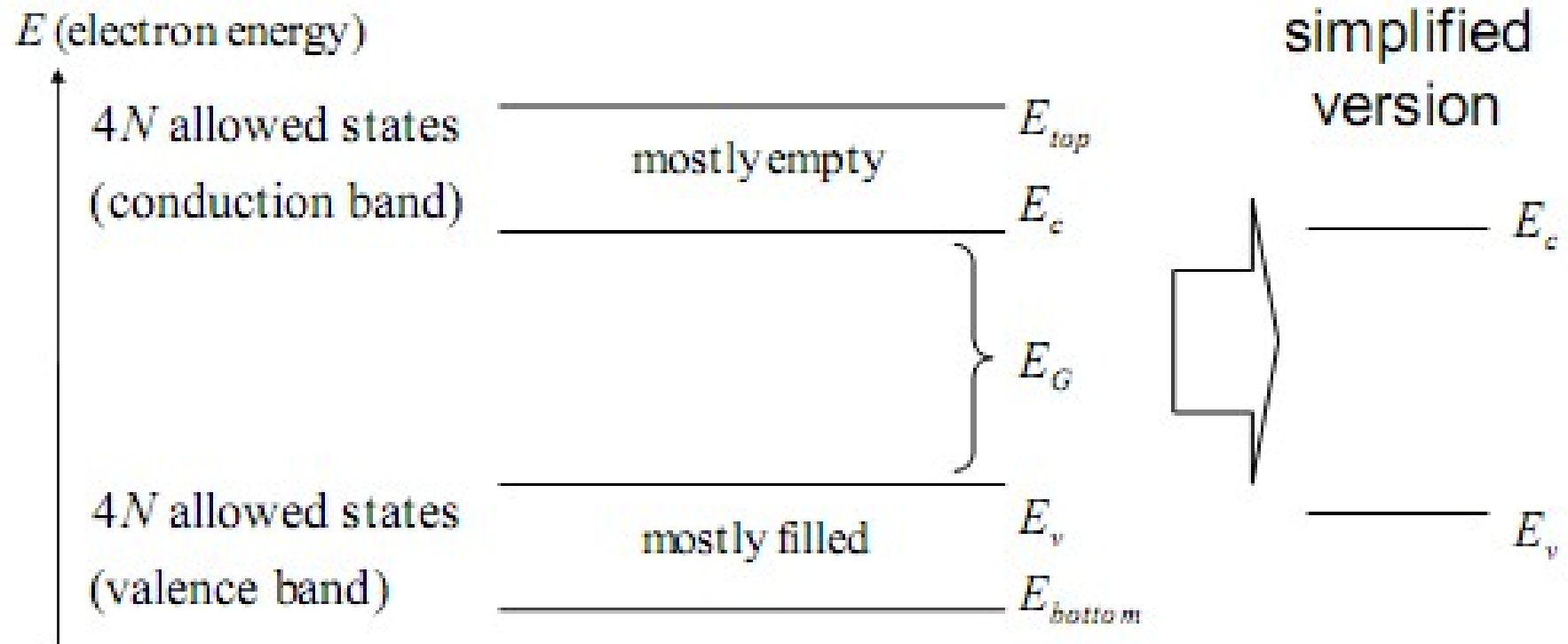
- Each atom shares 4 electrons w/ its 4 neighbors, filling in 4 previously empty $n=3$ levels

Transition from monatomic to crystalline Si

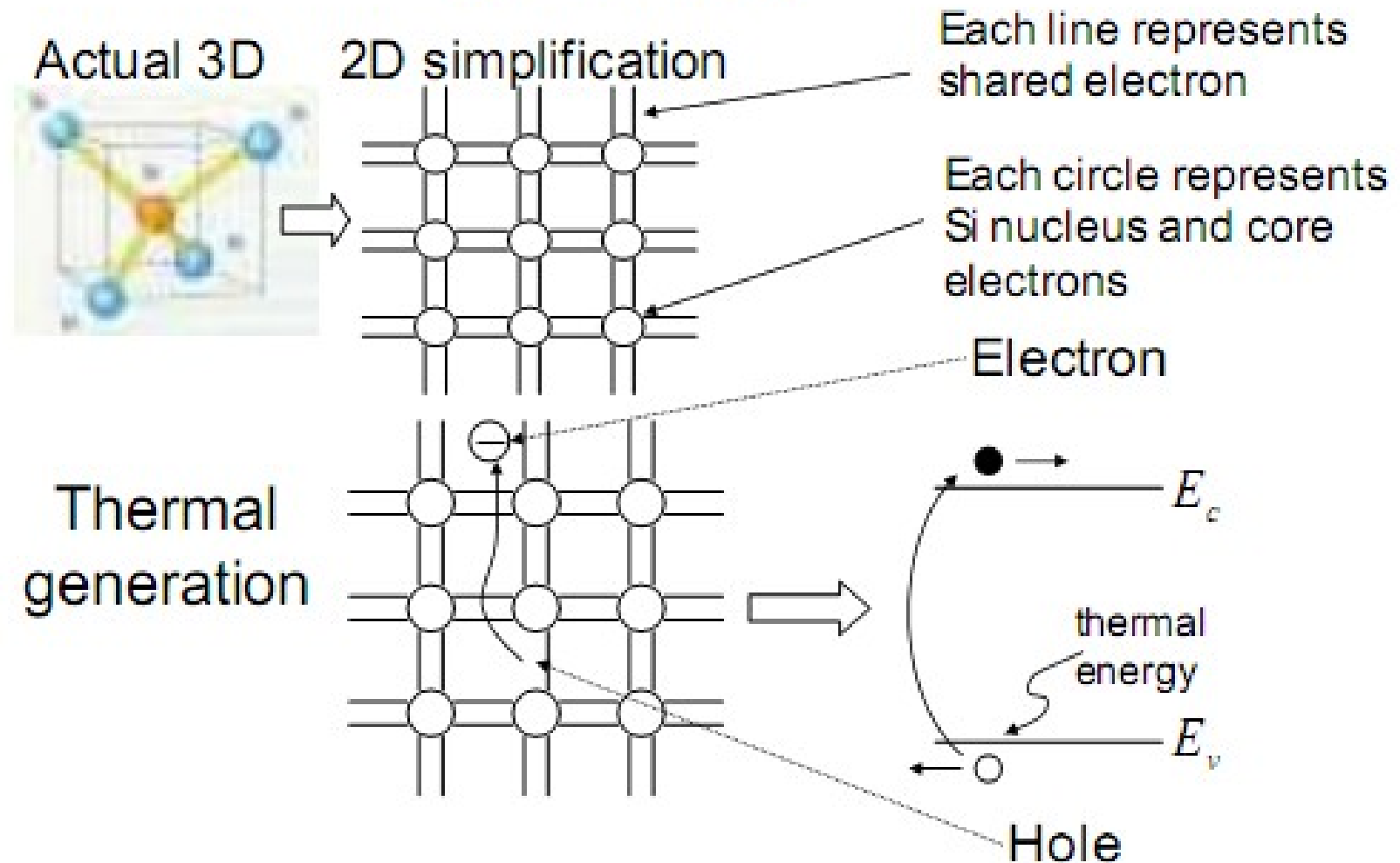
- As many Si atoms are brought closer together, the energy levels for every atom shifts



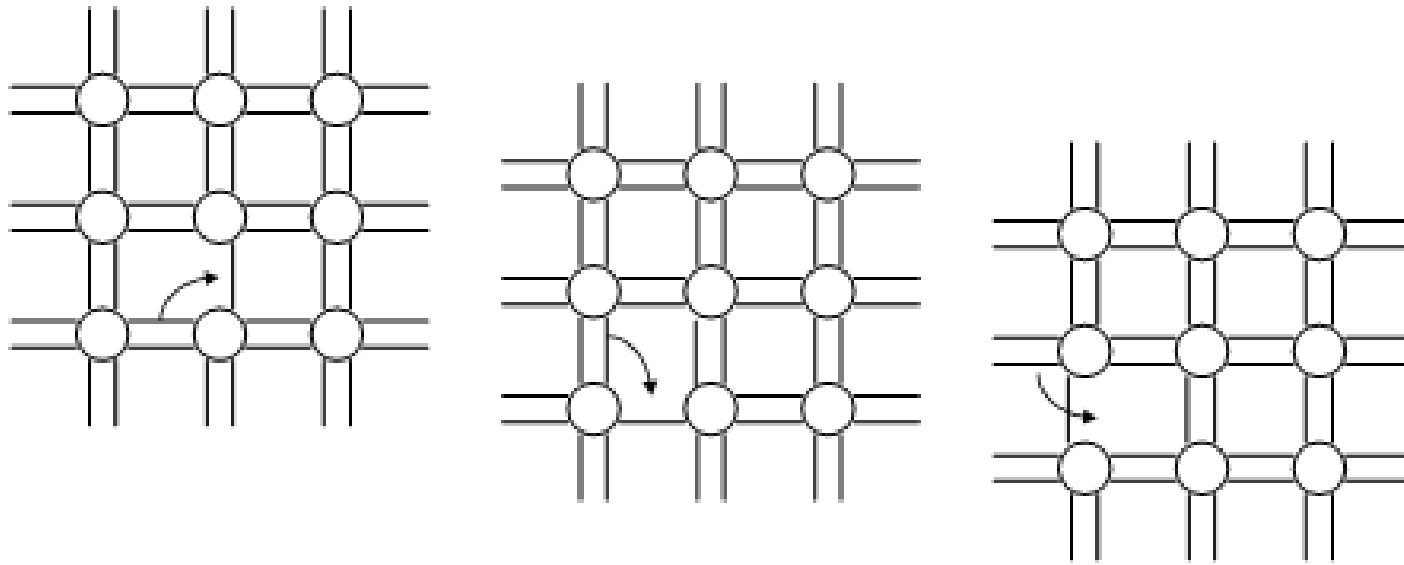
Crystalline Si (N atoms)



Si in 2D

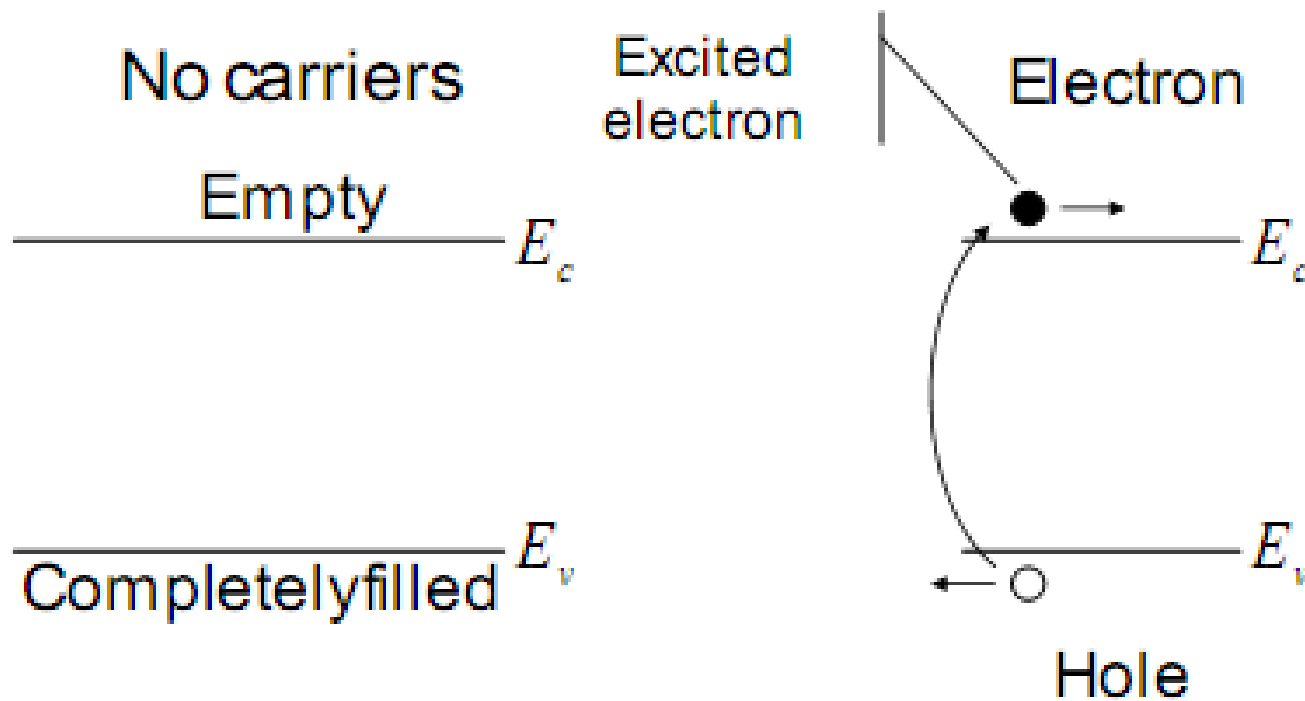


How holes move



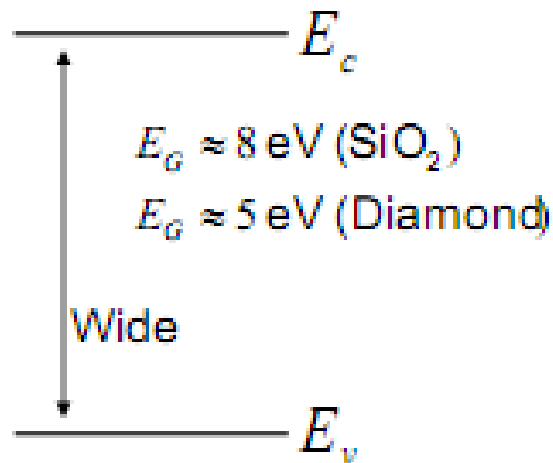
- Holes “move” when shared electron moves to fill it in
- Electrons move faster than holes

Energy band diagram & carriers

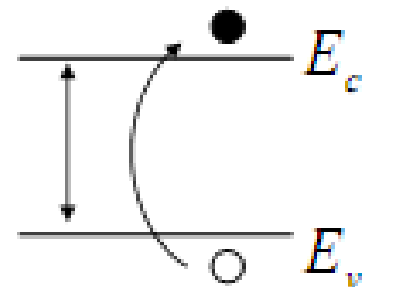


Energy bands for different materials

Insulator

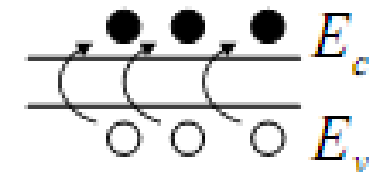


Semiconductor



$E_G = 1.42 \text{ eV}$ (GaAs)
 $E_G = 1.12 \text{ eV}$ (Si)
 $E_G = 0.66 \text{ eV}$ (Ge)
 (Room temp)

Metal



or



Carriers & electrical properties

- More carriers = higher conductivity
- Can also increase # of carriers by doping (introducing impurities)
 - Purity of Si used in chips: 99.9999999%!
(less than 1 non-Si atom in 10^9 Si atoms)
 - Pure Si: **intrinsic** semiconductor
 - Doped Si: **extrinsic** semiconductor

Intrinsic carrier concentration

- Thermal excitation creates electron-hole pairs

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

$$p = \text{number of free holes} / \text{cm}^3$$

- Intrinsic carrier concentration (room temp)

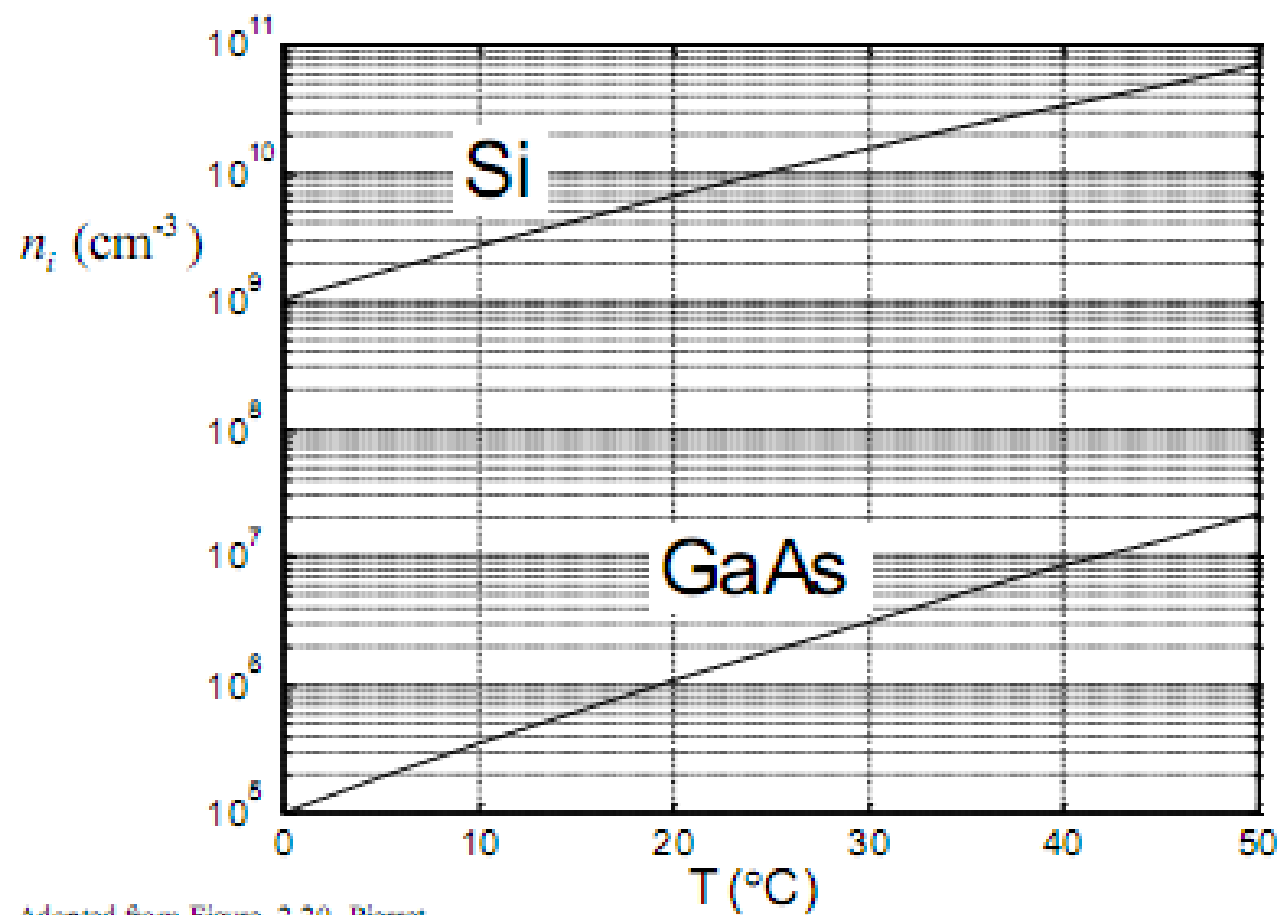
$$n_i \approx 2 \times 10^6 / \text{cm}^3 \quad \text{in GaAs}$$

$$n_i \approx 1 \times 10^{10} / \text{cm}^3 \quad \text{in Si}$$

$$n_i \approx 2 \times 10^{13} / \text{cm}^3 \quad \text{in Ge}$$

- For Si at room temp, < 1 bond in 10^{13} broken!
(assuming 5×10^{22} atoms/cm³)

n_i dependence on T



Adapted from Figure 2.20, Pierret,
Semiconductor Device Fundamentals.

Doping

II	III	IV	V	VI
Be ⁴	B ⁵	C ⁶	N ⁷	O ⁸
Mg ¹²	Al ¹³	Si ¹⁴	P ¹⁵	S ¹⁶
Zn ³⁰	Ga ³¹	Ge ³²	As ³³	Se ³⁴
Cd ⁴⁸	In ⁴⁹	Sn ⁵⁰	Sb ⁵¹	Te ⁵²

Acceptor dopants Donor dopants

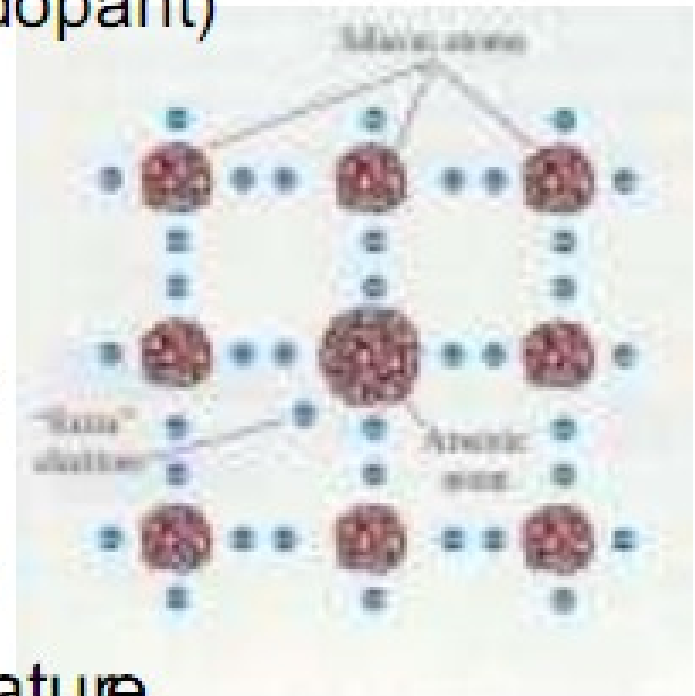
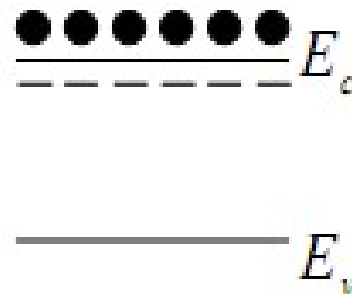
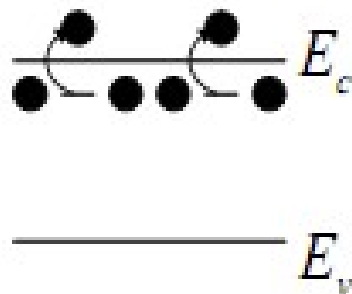
- 1 in 10^3 to 1 in 10^8 dopants are typically introduced to alter Si's electrical properties

Doping: donor action

Donor (electron-increasing dopant)

$$\text{As} \quad |E_B| = 0.054 \text{ eV}$$

N_D = donor dopant density



Increasing T Room temperature

$$n \approx N_D \text{ for typical dopings at room temp}$$

Doping: acceptor action

Acceptor (hole-increasing dopant)

$$B \quad |E_B| = 0.045 \text{ eV}$$

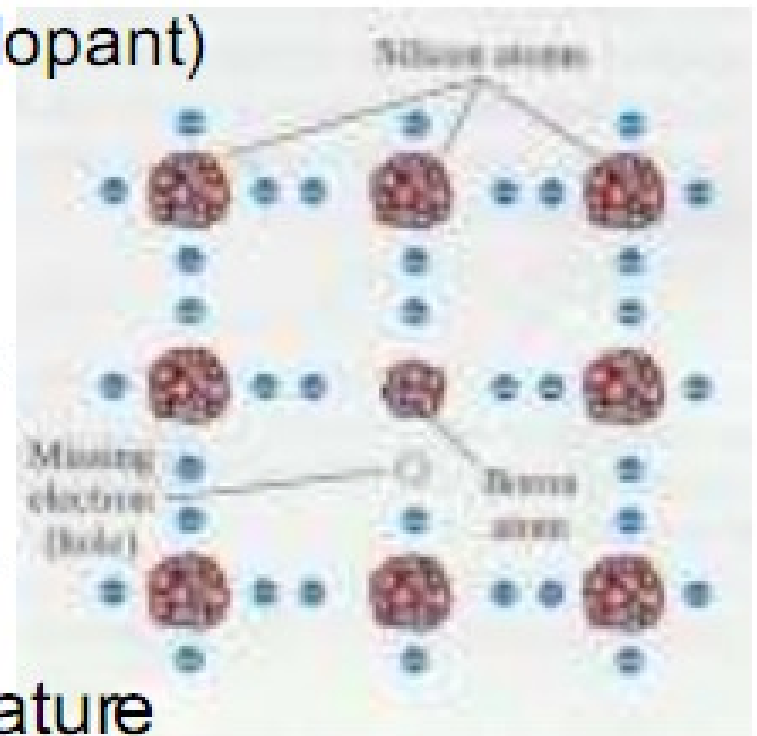
N_A = acceptor dopant density

————— E_c

—●—●—
○ ○ E_v

————— E_c

●●●●●●
○ ○ ○ ○ ○ ○ E_v

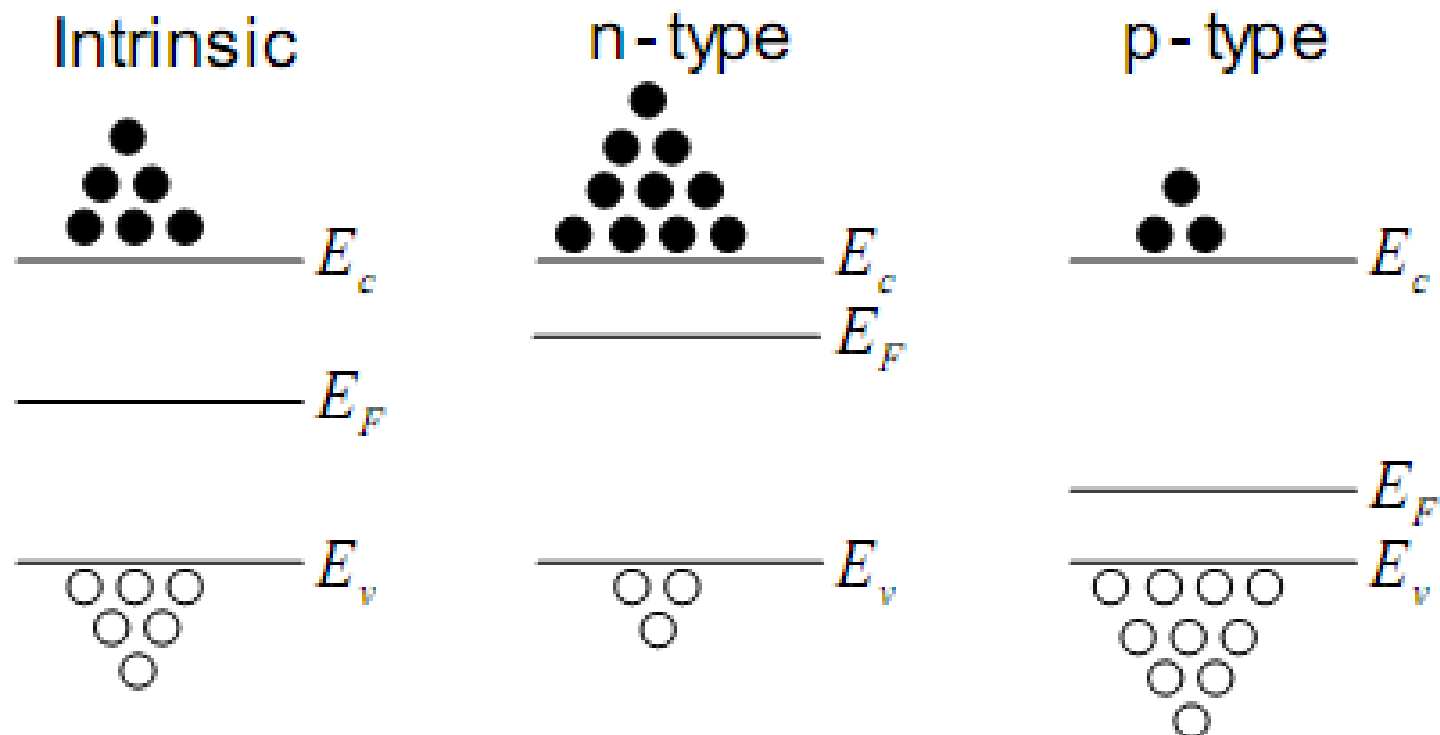


Increasing T Room temperature

$p \approx N_A$ for typical dopings at room temp

Carrier distribution

- Schematic representation



Fermi level

- Carrier density and E_F are related
 - need one to solve the other

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

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

E_F = Fermi energy/level

k = Boltzmann constant
= 8.617×10^{-5} eV/K

T = temp in Kelvin

$$E_i \approx \frac{E_c + E_v}{2}$$

Q: Show $np = n_i^2$

- Assumes **non-degenerate** semicon
 - E_F not too close to E_C or E_V ($>3kT$ away)

Computing carrier density in extrinsic semiconductors

- Previous eqns apply to both intrinsic and extrinsic semicons
- Charge neutrality relationship
 - assuming total ionization

$$p - n + N_D - N_A = 0$$

N_D = # donors/cm³

N_A = # acceptors/cm³

- Carrier concentrations
 - assuming non-degenerate and N_D or $N_A \gg n_i$

For n-type

$$\begin{array}{l} n \approx N_D \\ p \approx n_i^2 / N_D \end{array}$$

For p-type

$$\begin{array}{l} p \approx N_A \\ n \approx n_i^2 / N_A \end{array}$$