Lecture 1: Semiconductor Physics

Why semiconductors?

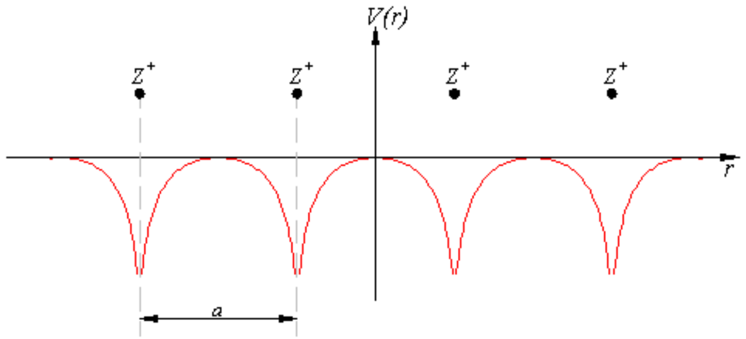
- **SEMICONDUCTORS: They are here, there, and everywhere**

• **Computers, palm pilots, laptops, anything "intelligent"**	Silicon (Si) MOSFETs, ICs, CMOS
• **Cell phones, pagers**	Si ICs, GaAs FETs, BJTs
• **CD players**	AlGaAs and InGaP laser diodes, Si photodiodes
• **TV remotes, mobile terminals**	Light emitting diodes (LEDs)
• **Satellite dishes**	InGaAs MMICs (Monolithic Microwave ICs)
• **Fiber networks**	InGaAsP laser diodes, pin photodiodes
• **Traffic signals, car taillights**	GaN LEDs (**green**, **blue**) InGaAsP LEDs (**red**, **amber**)
• **Air bags**	Si MEMs, Si ICs

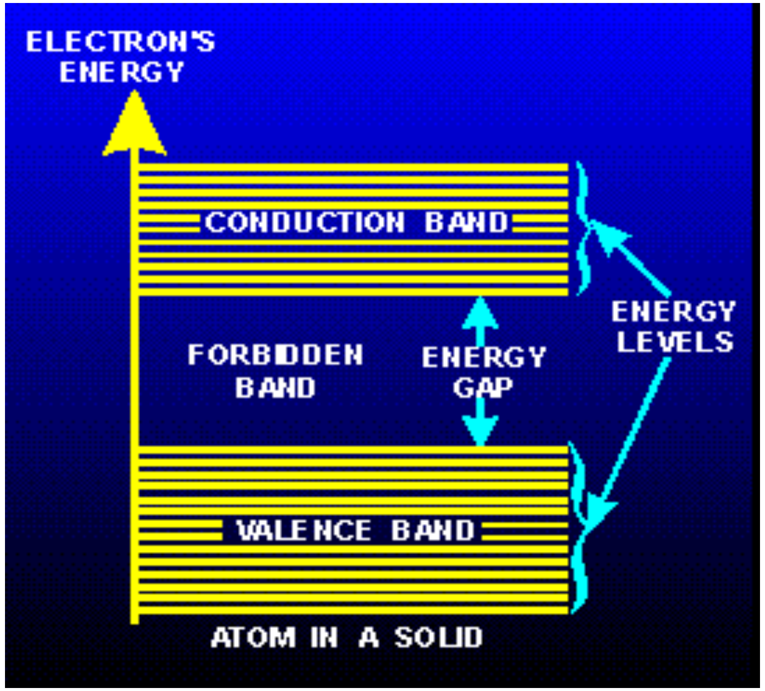
- **and, they are important, especially to Elec. Eng.& Computer Sciences**

BAND THEORY OF SOLIDS

- Potential experienced by an electron in a crystal is periodic.

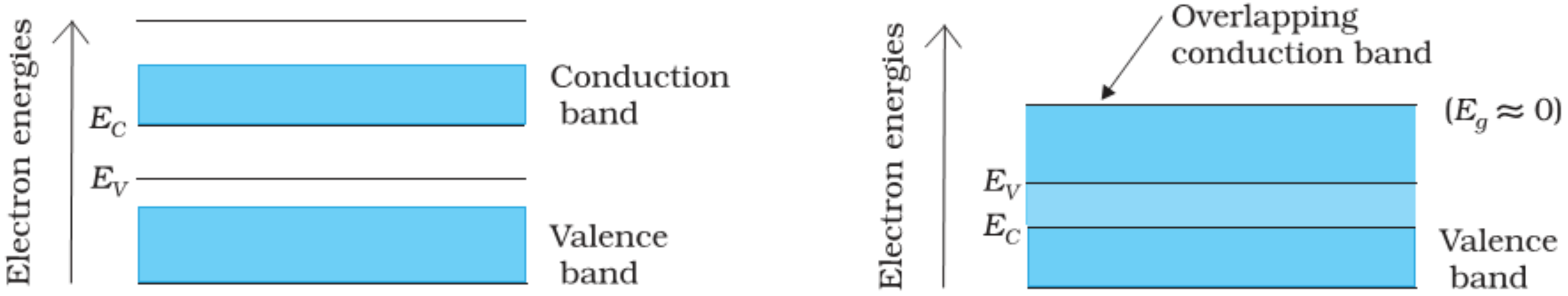


- The energy spectrum of an electron moving in a periodic potential consist of a set of allowed energy regions or bands separated by forbidden energy regions called the band gaps.

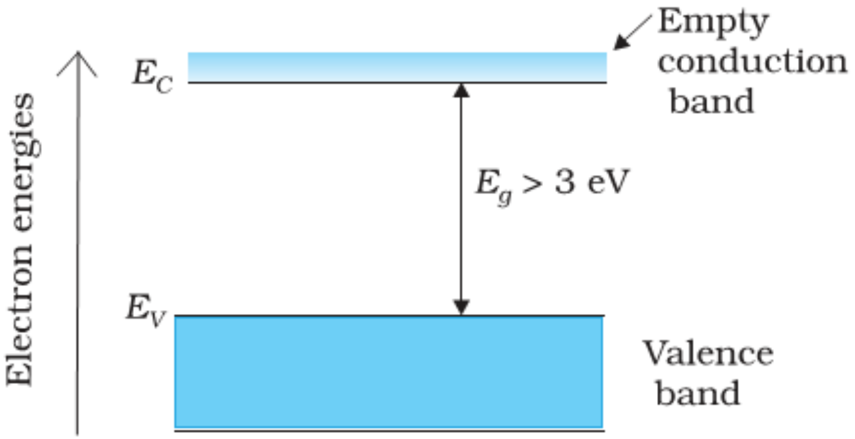


CLASSIFICATION OF SOLIDS

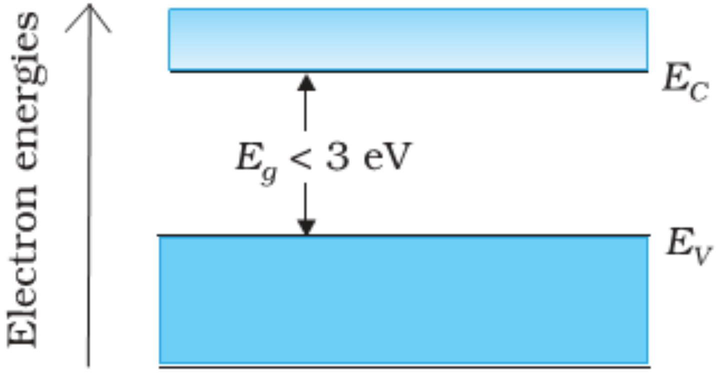
❑ Depending on the size of band gap, the solids are classified in to three categories.



Metal



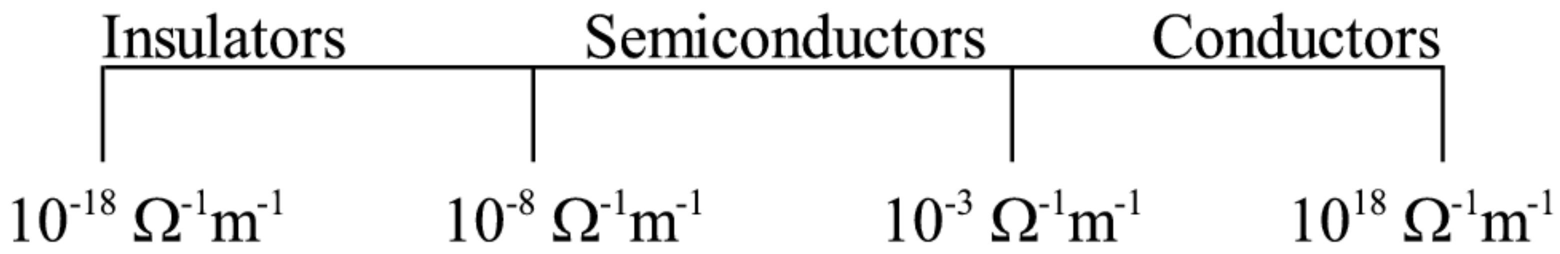
Insulator



Semiconductor

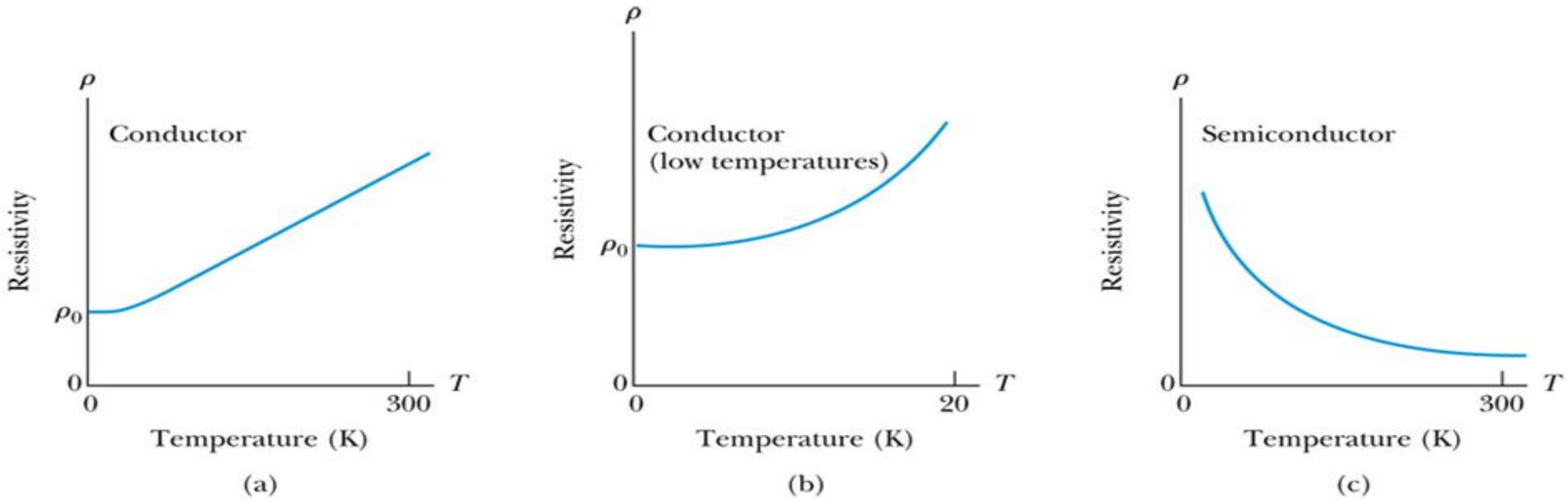
PROPERTIES OF SEMICONDUCTORS

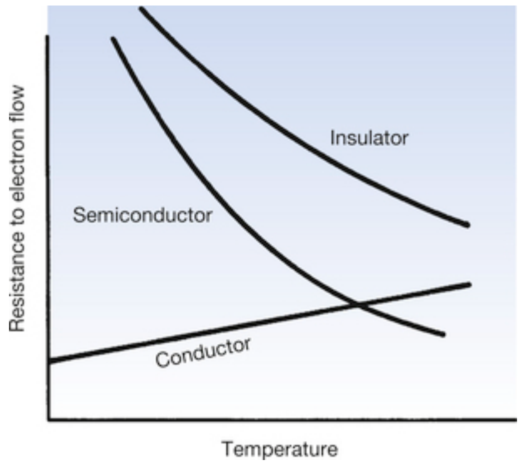
- Semiconductors are materials whose electrical properties lie between Conductors and Insulators.



PROPERTIES OF SEMICONDUCTORS

- Semi conductors have negative temperature coefficient of resistance.





Semiconductor Materials

- **Elemental semiconductors** – Si and Ge (column IV of periodic table) – compose of single species of atoms
- **Compound semiconductors** – combinations of atoms of column III and column V and some atoms from column II and VI. (combination of two atoms results in binary compounds)
- There are also three-element (ternary) compounds Gallium Arsenide Phosphide (GaAsP) and four-elements (quaternary) compounds such as InGaAsP.

(a)	II	III	IV	V	VI
		B	C		
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b) Elemental	IV compounds	Binary III-V compounds	Binary II-VI compounds
Si	SiC	AlP	ZnS
Ge	SiGe	AlAs	ZnSe
		AlSb	ZnTe
		GaP	CdS
		GaAs	CdSe
		GaSb	CdTe
		InP	
		InAS	
		InSb	

LED of GaAs, band gap = 1.9 eV
Wavelength = 6533 A (Visible region)

LED of GaAsP, band gap = 1.45 eV
Wavelength = 8560 A (Infra red)

Semiconductor Materials

- The wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and opto-electronic functions.

- **Ge** was widely used in the early days of semiconductor development for transistors and diods.

- **Si** is now used for the majority of rectifiers, transistors and integrated circuits.

- **Compounds** are widely used in high-speed devices and devices requiring the emission or absorption of light.

- The electronic and optical properties of semiconductors are strongly affected by impurities, which may be added in precisely controlled amounts (e.g. an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current). This process called doping.

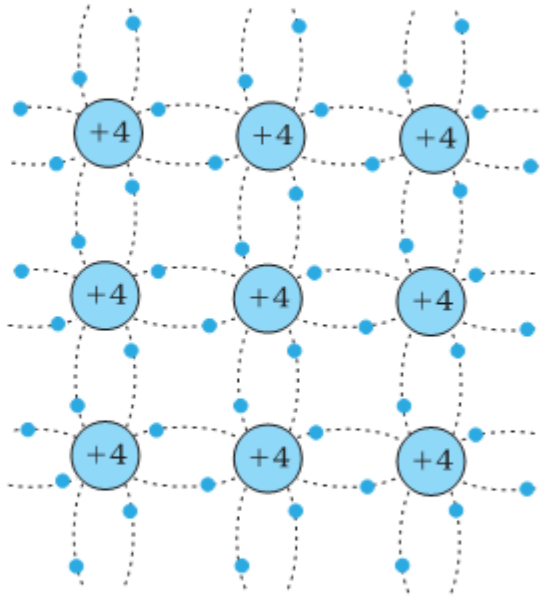
CLASSIFICATION OF SEMICONDUCTORS

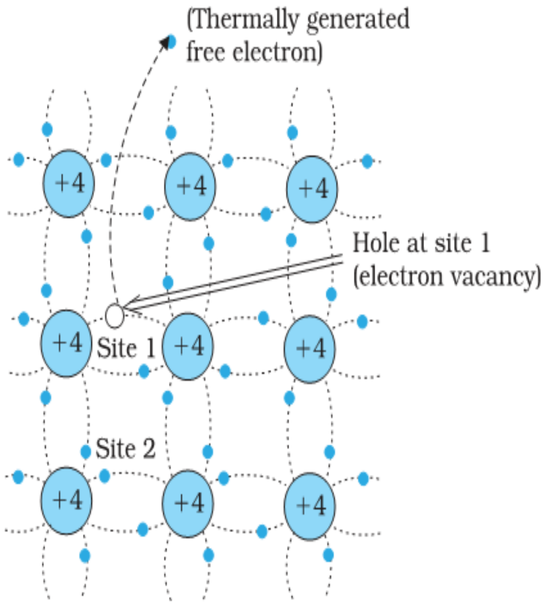
- Semiconductors are classified in two categories.

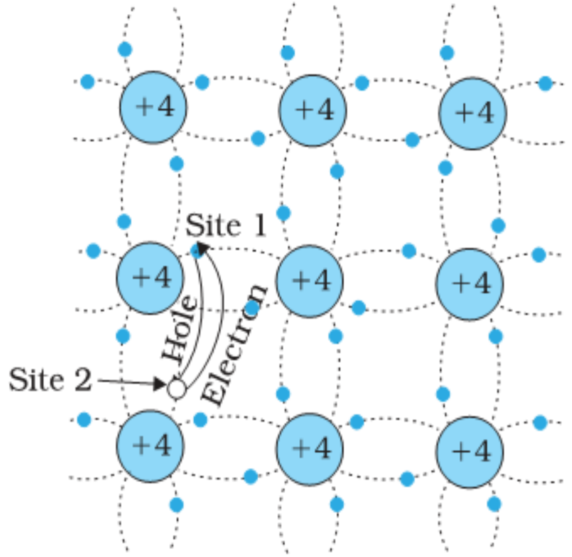
(I) Intrinsic semiconductor

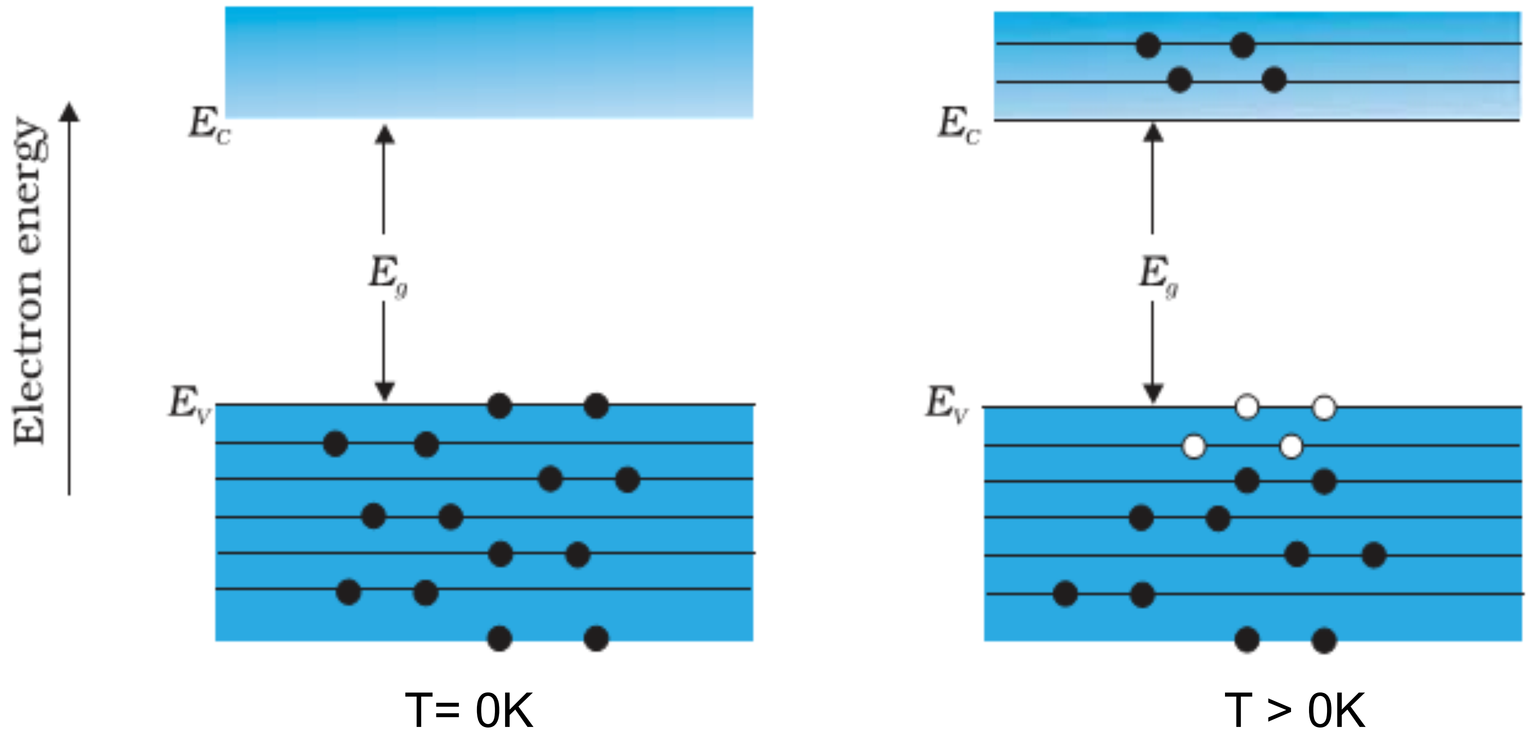
(II) Extrinsic semiconductor

(I) INTRINSIC OR PURE SEMICONDUCTORS (Si, Ge)









- The conductivity of an intrinsic semiconductor depends on its temperature.

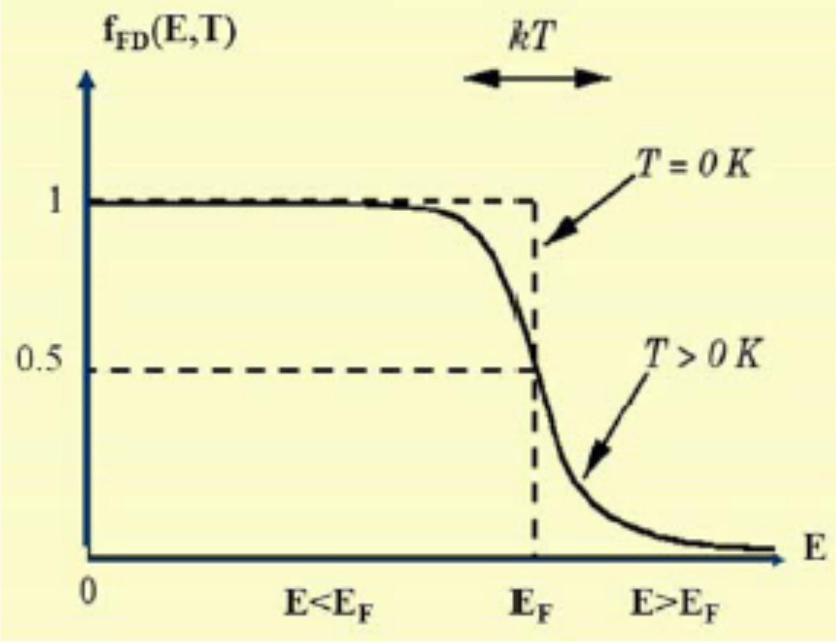
- Due to low conductivity, no important electronic devices can be developed using these semiconductors.

Probability of Occupation of Allowed States

Probability of occupation of an allowed energy state of an energy E

$$f(E) = \frac{1}{1 + e^{\frac{(E - E_F)}{kT}}}$$

Since at room temperature $kT \approx 25.8$ MeV.



Density of Allowed States

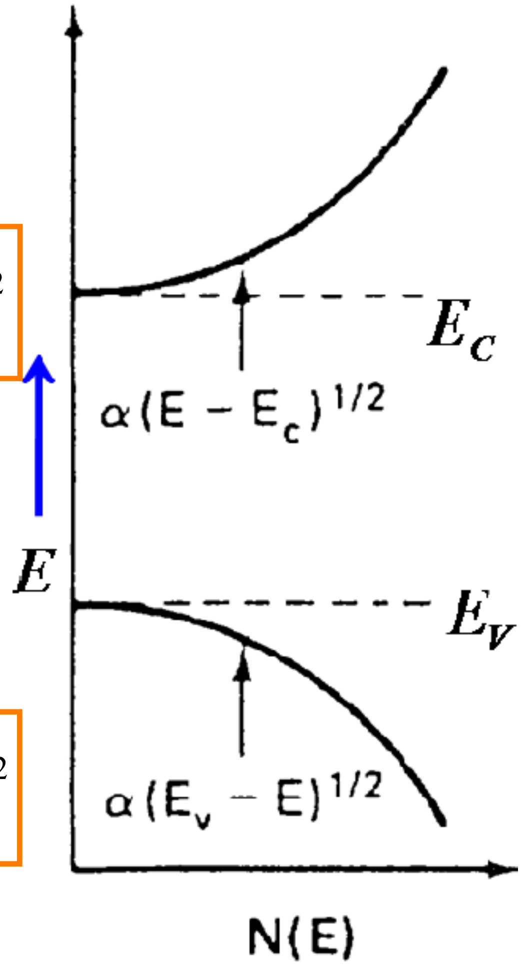
Number of allowed states, g(E), **per unit volume and energy at** an energy E.

Near the conduction band edge, in isotropic crystal,

$$g(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_C)^{1/2}$$

Near the valence band edge, in isotropic crystal,

$$g(E) = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(E_V - E)^{1/2}$$



Remember in metals density of sates per unit volume

$$g(E) = \frac{4\pi}{h^3}(2m)^{3/2}E^{1/2}$$

to consider the effect of periodic lattice potential ***m*** $\rightarrow$ ***m****

Charge carriers in semiconductors

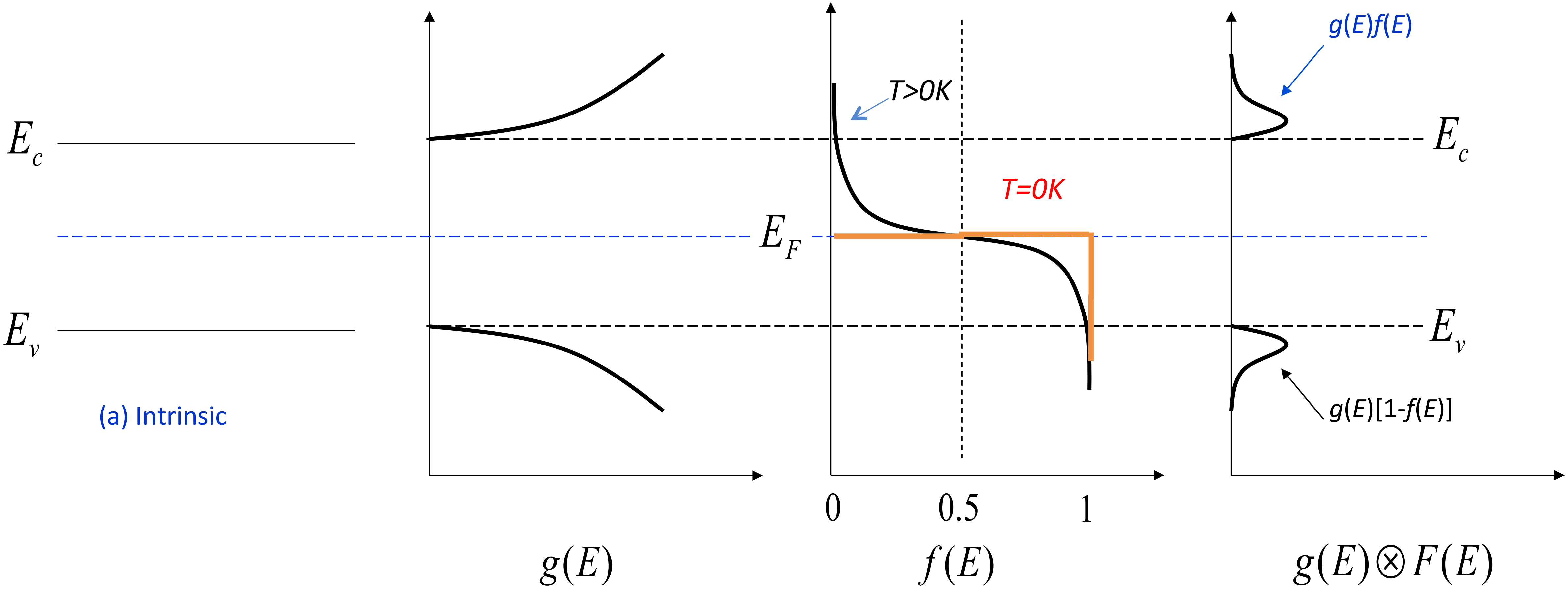
- Current is the rate at which charge flow
- Two types of carriers can contribute the current flow
  - Electrons in conduction band
  - Holes in valence band
- The density of electrons and holes is related to the density of state function and Fermi-Dirac distribution function

$$\boxed{n(E)dE = g_c(E)f_F(E)dE}$$

$n(E)dE$: density of electrons in CB at energy levels between E and $E+dE$

$$\boxed{p(E)dE = g_\upsilon(E)[1 - f_F(E)]dE}$$

$p(E)dE$: density of holes in VB at energy levels between E and $E+dE$



$g(E)$: Density of state

$f(E)$: Probability of occupation (Fermi-Dirac distribution function)

n_0 equation

The thermal equilibrium concentration of electrons in CB

$$\boxed{n_o = \int_{Ec}^{top} n(E)dE = \int_{Ec}^{top} g_c(E) f_F(E) dE}$$

$$\because f_F(E) = \frac{1}{1+\exp\frac{(E-E_f)}{kT}} \qquad g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E-E_c}$$

For electrons in CB,

$$E > E_C \Rightarrow (E-E_f) >> kT$$

$$\Rightarrow \because f_F(E) = \frac{1}{1+\exp\frac{(E-E_f)}{kT}} \approx \exp\frac{-(E-E_f)}{kT} \quad \text{(Boltzmann aproximation)}$$

$$n_o = \int_{Ec}^{top} \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E-E_c}\cdot\exp\frac{-(E-E_f)}{kT}dE = 4\pi\left(\frac{2m_n^*}{h^2}\right)^{3/2} e^{(E_f-E_c)/kT}\int_0^\infty E^{1/2}e^{-E/kT}dE$$

$$n_o = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}\exp\frac{-(E_C-E_f)}{kT}$$

$$(where \quad \int_0^\infty x^{1/2}e^{-ax}dx = \frac{\sqrt{\pi}}{2a\sqrt{a}})$$

We define effective density of states in CB,

$$\boxed{N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}}$$

The thermal-equilibrium electron concentration in CB

$$\boxed{n_o = N_C \exp\frac{-(E_C-E_f)}{kT}}$$

Example ➡ electron concentration

$N_c(300K) = 2.8\times10^{19}\ \mathrm{cm}^{-3}$

E_f is 0.25 eV below E_c

$\Rightarrow$ Find the electron concentration in CB at 300K

Solution

$$n_o \approx N_c \exp\frac{-(E_c - E_f)}{kT}$$

$$= (2.8\times10^{19})\exp\left(\frac{-0.25}{0.0259}\right) = 1.8\times10^{15}\ \mathrm{cm}^{-3}$$

p_o equation

The thermal equilibrium concentration of holes in VB

$$\boxed{p_o = \int_{-\infty}^{E_v} p(E)dE = \int_{-\infty}^{E_v} g_\upsilon(E)(1 - f_F(E))dE}$$

$$\because 1 - f_F(E) = 1 - \frac{1}{1 + \exp\dfrac{(E - E_f)}{kT}} = \frac{1}{1 + \exp\dfrac{(E_f - E)}{kT}}$$

$$g_\upsilon(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_\upsilon - E}$$

For holes in VB,

$$E < E_\upsilon \Rightarrow (E_f - E) >> kT$$

$$\Rightarrow 1 - f_F(E) = \frac{1}{1 + \exp\dfrac{(E_f - E)}{kT}} \approx \exp\frac{-(E_f - E)}{kT} \quad \text{(Boltzmann aproximation)}$$

$$p_o = \int_{-\infty}^{E_\upsilon} \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_\upsilon - E} \cdot \exp \frac{-(E_f - E)}{kT} dE$$

$$p_o = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp \frac{-(E_f - E_\upsilon)}{kT} \qquad (where \quad \int_0^\infty x^{1/2} e^{-ax} dx = \frac{\sqrt{\pi}}{2a\sqrt{a}})$$

We define effective density of states in CB,

$$\boxed{N_\upsilon = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}}$$

The thermal-equilibrium electron concentration in CB

$$\boxed{p_o = N_\upsilon \exp \frac{-(E_f - E_\upsilon)}{kT}}$$

Example ⇨ hole concentration

$N_\upsilon(300K) = 1.04 \times 10^{19}\,\text{cm}^{-3}$

E_f is 0.27 eV above E_υ

$\Rightarrow$ Find the hole concentration in VB at 400K

Solution:

$$\frac{N_\upsilon(400K)}{N_\upsilon(300K)} = \left(\frac{400}{300}\right)^{3/2} \Rightarrow N_\upsilon(400K) = (1.04 \times 10^{19})\left(\frac{400}{300}\right)^{3/2} = 1.60 \times 10^{19}\,\text{cm}^{-3}$$

$$p_o = N_\upsilon \exp\frac{-(E_f - E_\upsilon)}{kT}$$

$$= (1.60 \times 10^{19})\exp\left(\frac{-0.27}{0.03453}\right) = 6.43 \times 10^{15}\,\text{cm}^{-3}$$

- For **intrinsic semiconductor**
  - The concentration of electrons in CB is equal to the concentration of holes in VB

$$\boxed{n_o = n_i = N_C \exp\frac{-(E_C - E_{f_i})}{kT}} \quad \boxed{p_o = p_i = N_\upsilon \exp\frac{-(E_{f_i} - E_\upsilon)}{kT}}$$

$$\boxed{n_i = p_i \quad \text{for intrinsic semiconductor}}$$

$$n_i^2 = N_C \exp\frac{-(E_C - E_{f_i})}{kT} \cdot N_\upsilon \exp\frac{-(E_{f_i} - E_\upsilon)}{kT}$$

$$= N_C N_\upsilon \exp\frac{-(E_C - E_\upsilon)}{kT}$$

$$\boxed{n_i^2 = N_C N_\upsilon \exp\frac{-E_g}{kT}}$$

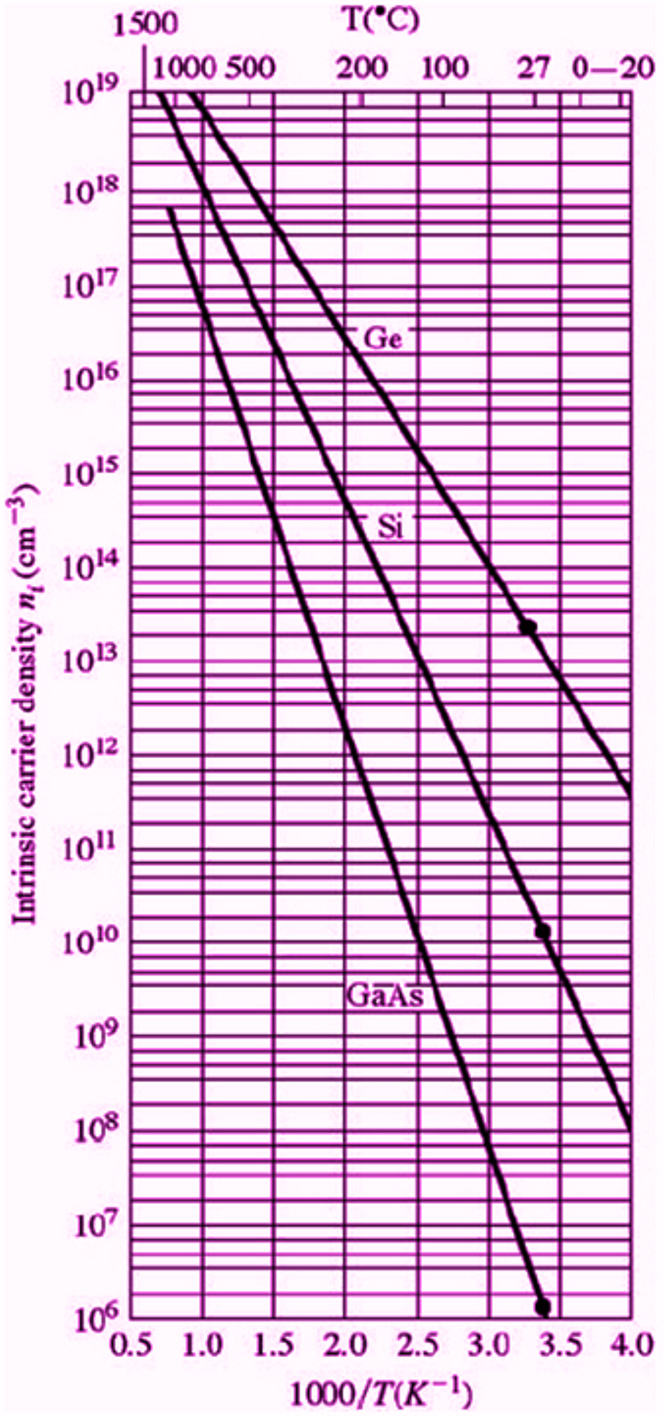
Now, band gap $E_g = E_C - E_V$

- The **intrinsic carrier concentration** is a function of bandgap, independent of Fermi level

At T = 300 K

	$N_c(\text{cm}^{-3})$	$N_v(\text{cm}^{-3})$	m_n^*/m_0	m_p^*/m_0
Silicon	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

Silicon	$n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$
Gallium arsenide	$n_i = 1.8 \times 10^{6}\ \text{cm}^{-3}$
Germanium	$n_i = 2.4 \times 10^{13}\ \text{cm}^{-3}$



The intrinsic carrier concentration is strongly depend on temperature and the intrinsic carrier concentration is nearly increase exponentially with temperature.

The intrinsic carrier concentration of Ge, Si, and GaAs as a function of temperature.

Example → intrinsic carrier concentration

For GaAs, $N_c(300K) = 4.7\times10^{17}\,\mathrm{cm}^{-3}$

$N_\upsilon(300K) = 7.0\times10^{18}\,\mathrm{cm}^{-3}$

$E_g = 1.42\,\mathrm{eV}$

$\Rightarrow$ Find the intrinsic carrier concentration at 300K and 400K

Solution:

$$\boxed{n_i^2 = N_C N_\upsilon \exp\frac{-E_g}{kT}}$$

$$n_i^2(300K) = N_c(300K)N_\upsilon(300K)\exp\left(\frac{-1.42}{0.0259}\right) = 5.09\times10^{12}$$

$$n_i(300K) = 2.26\times10^{6}\,\mathrm{cm}^{-3}$$

$$n_i^2(400K) = N_c(400K)N_\upsilon(400K)\exp\left(\frac{-1.42}{0.03885}\right) = 1.48\times10^{21}$$

$$n_i(400K) = 3.85\times10^{10}\,\mathrm{cm}^{-3}$$

Example → thermal equilibrium concentrations

For Si, bandgap is 1.12 eV

Fermi energy is 0.25 eV below conduction band

$N_C = 2.8\times10^{19}\,\text{cm}^{-3}$ $N_\upsilon = 1.04\times10^{19}\,\text{cm}^{-3}$

Find the thermal equlibrium electron & hole concentrations

Solution:

$$n_o = N_C \exp\frac{-(E_C - E_f)}{kT} \qquad p_o = N_\upsilon \exp\frac{-(E_f - E_\upsilon)}{kT}$$

$$n_o = (2.8\times10^{19})\exp\frac{-0.25}{0.0259} = 1.8\times10^{15}\,\text{cm}^{-3}$$

$$p_o = (1.04\times10^{19})\exp\frac{-0.87}{0.0259} = 2.7\times10^{4}\,\text{cm}^{-3}$$

The electron and hole concentrations change by order of magnitude as the Fermi energy changes by a few tenths of an electron-volt

The intrinsic Fermi-level position

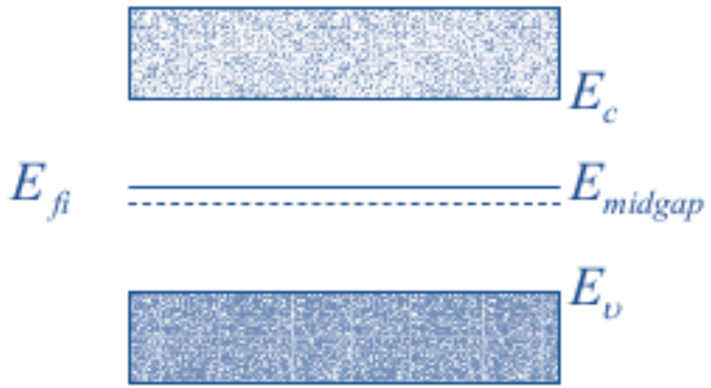
$$\boxed{n_i = p_i \quad \text{for intrinsic semiconductor}}$$

$$N_C \exp\frac{-(E_C - E_{f_i})}{kT} = N_\upsilon \exp\frac{-(E_{f_i} - E_\upsilon)}{kT}$$

$$E_{f_i} = \frac{1}{2}(E_c + E_\upsilon) + \frac{1}{2}kT\ln\left(\frac{N_\upsilon}{N_c}\right)$$

$$E_{f_i} = \frac{1}{2}(E_c + E_\upsilon) + \frac{1}{2}kT\ln\left(\frac{m_p^*}{m_n^*}\right)^{3/2}$$

$$\boxed{E_{f_i} = E_{midgap} + \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)}$$



At 0*K*, $E_{midgap} = \frac{1}{2}(E_c + E_\upsilon)$

i.e., the Fermi level lies in the middle of the conduction band and valence band. This is also true at all other temperatures provided ***m**$_n$*** = m**$_p$******. However, in general, *m$_n$* <m$_p$** and the Fermi level is raised slightly as temperature exceeds 0*K*.

Example → Intrinsic Fermi level

$$m_n^* = 1.08 m_o$$

$$m_p^* = 0.56 m_o$$

$\Rightarrow$ Find the intrinsic Fermi level

Solution:

$$E_{f_i} = E_{midgap} + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$E_{f_i} - E_{midgap} = \frac{3}{4}(0.0259)\ln\left(\frac{0.56}{1.08}\right)^{3/2} = -0.0128\text{eV} = -12.8\text{meV}$$