SEMICONDUCTORS

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LET US START FROM THE MICROSCOPIC ORIGIN OF RESISTANCE

MANY BODY PHYSICS

COLLECTIVE PHENOMENA

Consider Yourself an Electron

You can run without problem from a point A to Point B without any problem

Consider Yourself an Electron

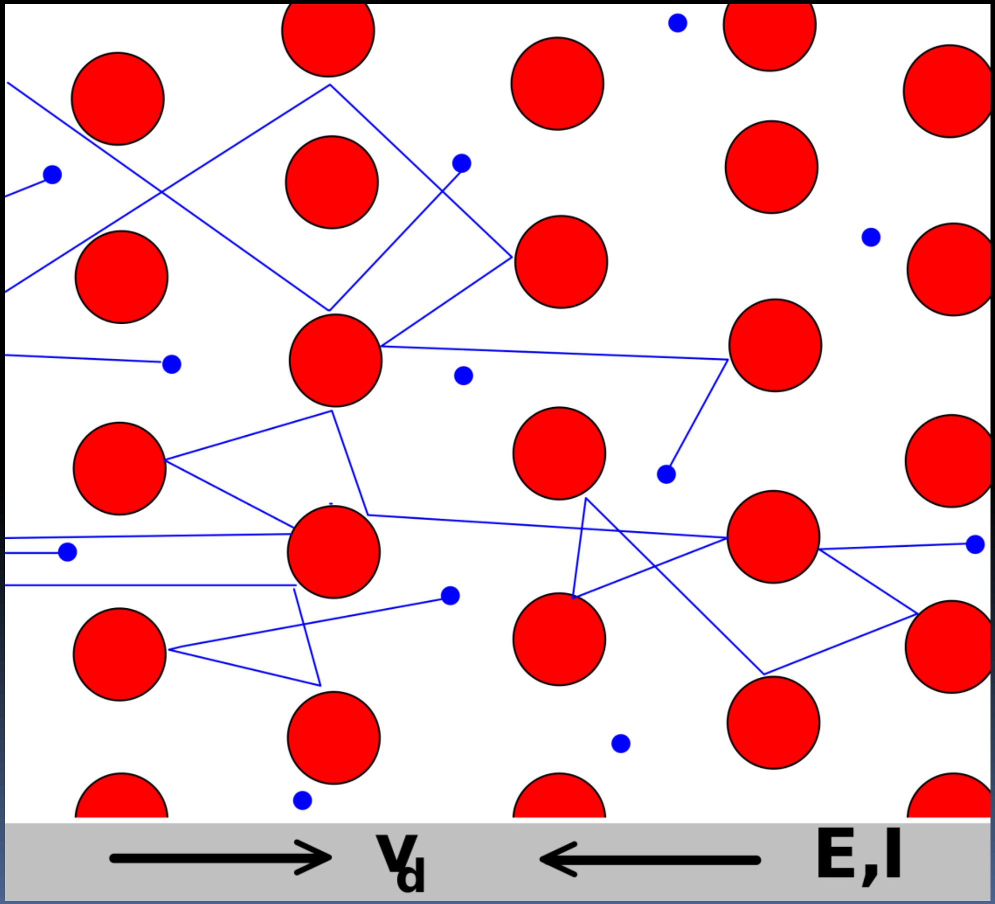
You CAN'T run without problem from a point A to Point B…You have to jostle, **may even collide with others** and find your way to reach

Consider Yourself an Electron

If the Members of the parade stand still then you can run inhibited within the gaps
However, if they start to walk/rotate/move sideways then your movement will be restricted

Origin of Electrical Resistance

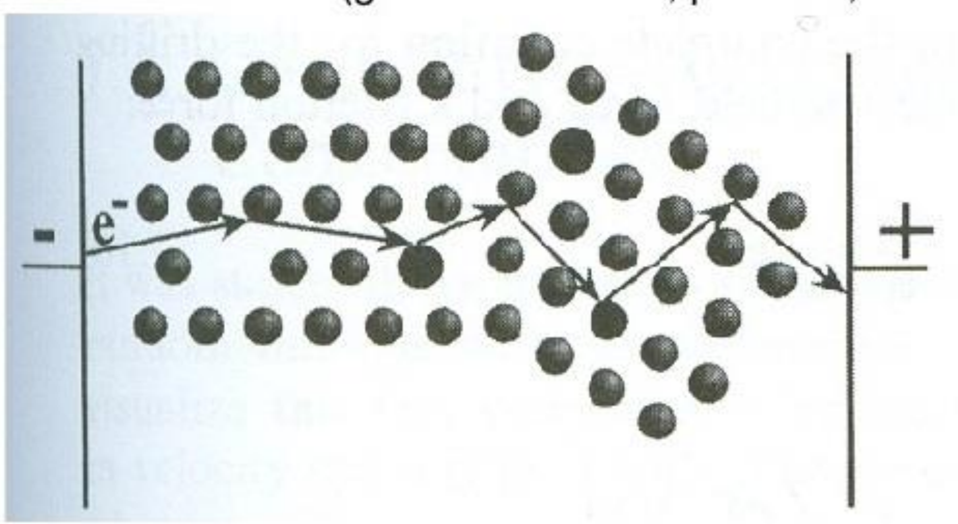
Scattering of Charge Carriers with Lattice Ions and Impurities inside the Solid



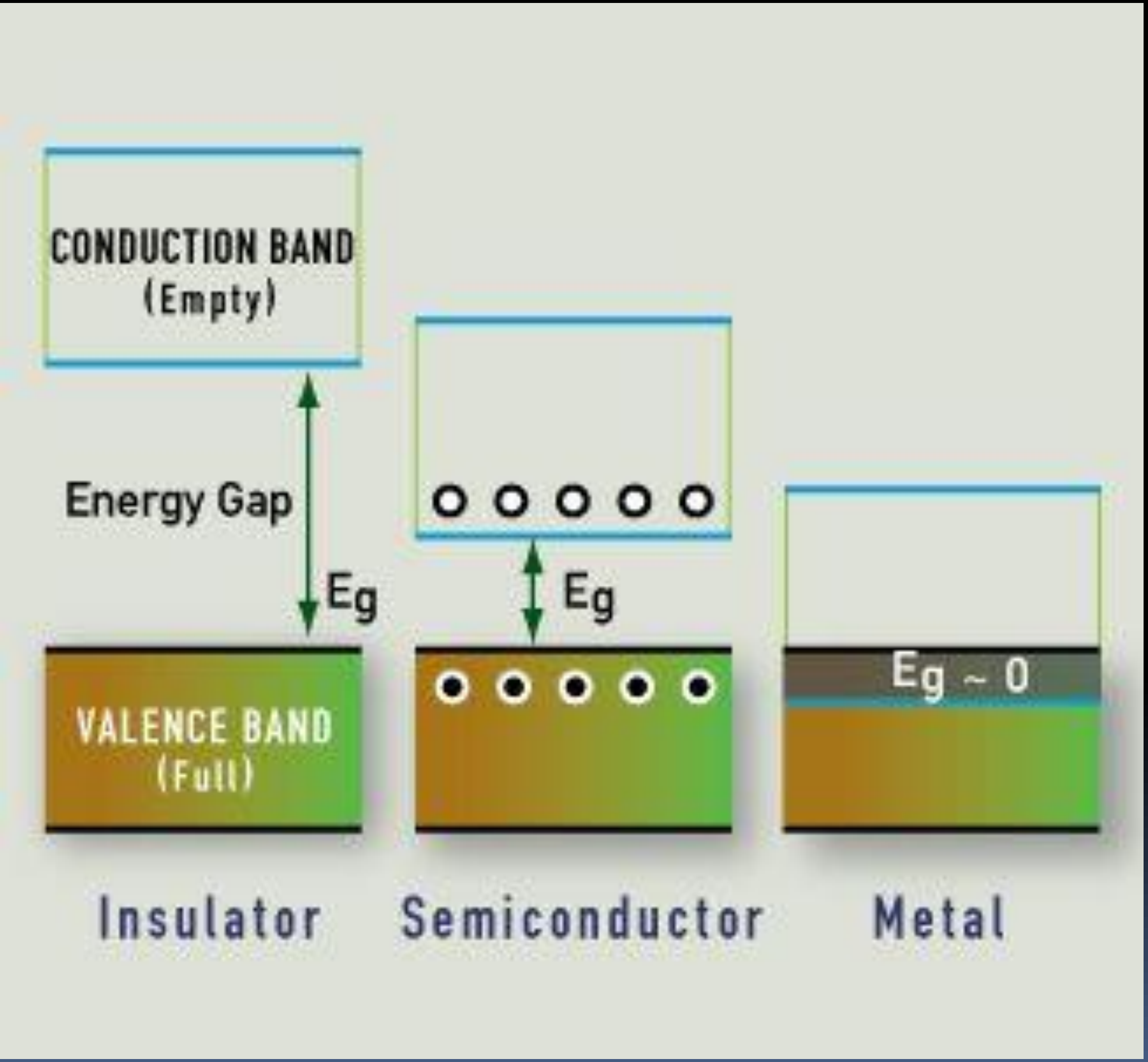
Origin of Electrical Resistance

Scattering: origin of resistivity/conductivity

- Primary Scattering Events
  1. Thermal defects (k_bT at room temperature is about 25 meV).
  2. Atomic Defects (impurities/dopants)
  3. 2d and/or 3d defects (grain boundaries, particles, dislocations)



Insulators, Semiconductors And Metals

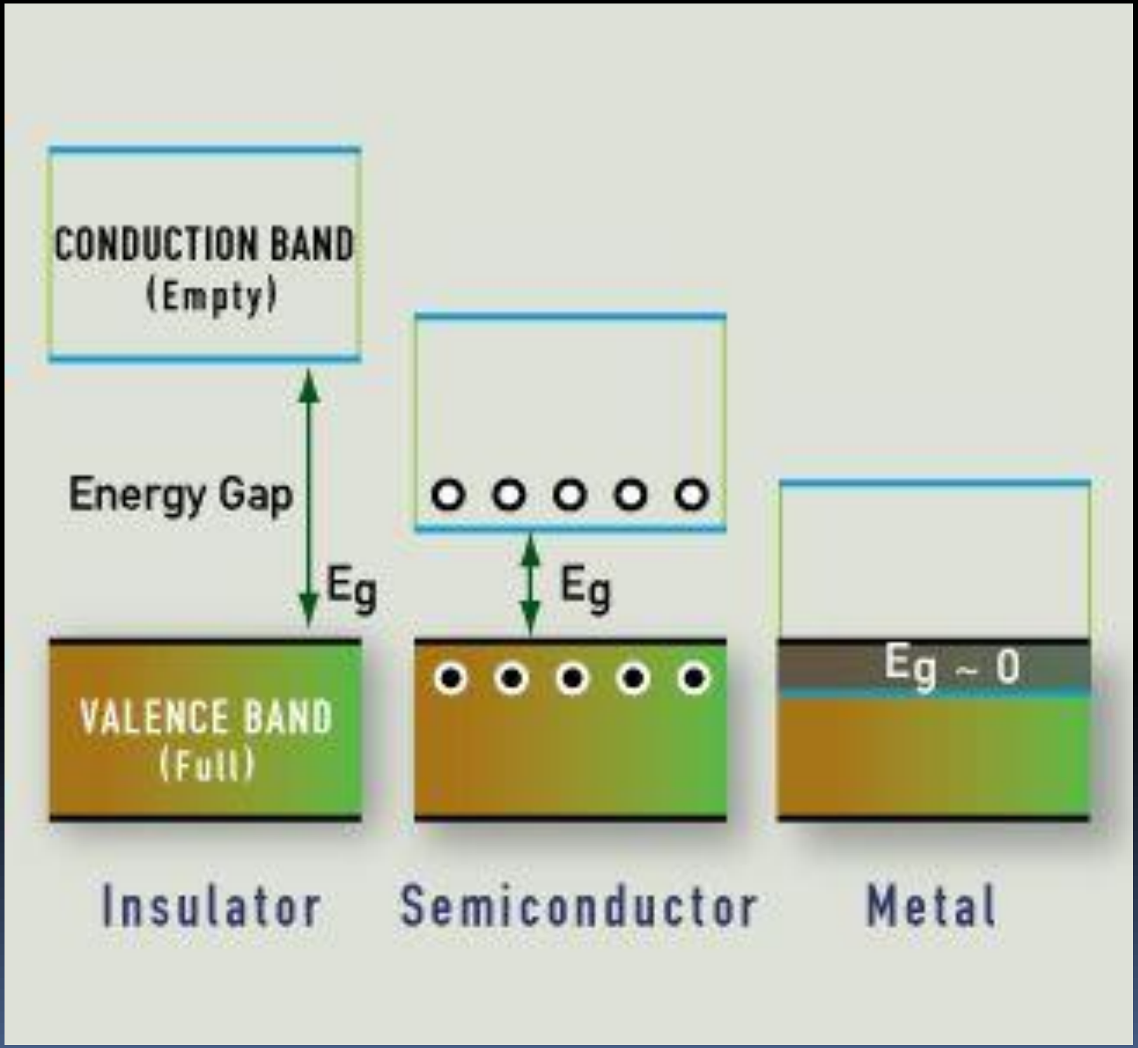


Full and Partially Full Halls

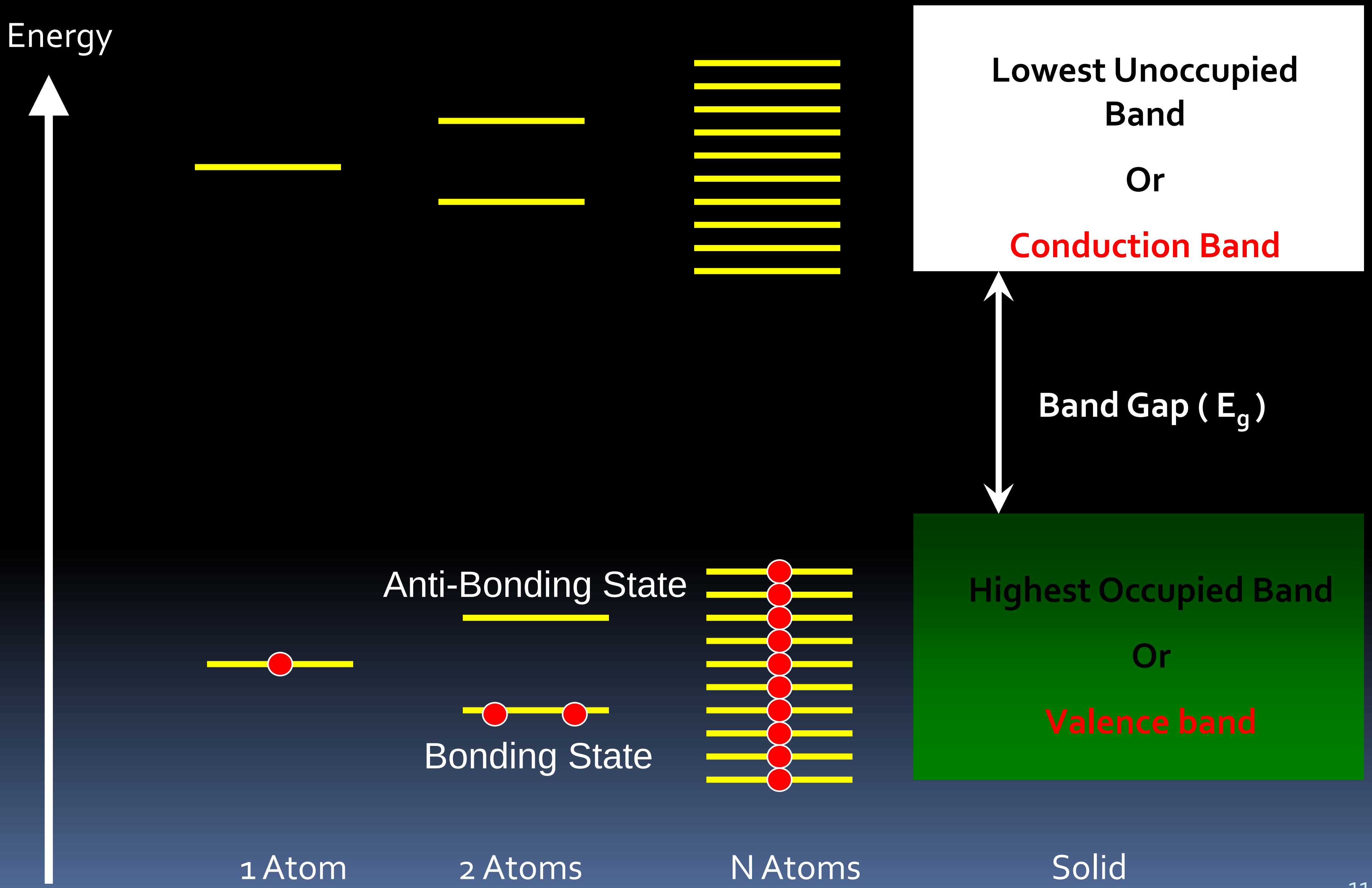
⇐ **All seats are full. People have less mobility to move**

Hall filled hall. People ⇒ have much higher mobility to move from one place to other

Insulators, Semiconductors And Metals



FORMATION OF ENERGY BANDS



E_C , E_V & $E_G=(E_C - E_V)$

Energy

E_C (Lowest Edge of the Conduction Band) $\Rightarrow$

E_V (Highest Edge of the Valence Band) $\Rightarrow$

Lowest Unoccupied Band

Or

Conduction Band

Band Gap (E_G)

Highest Occupied Band

Or

Valence band

Solid

FERMI DIRAC PROBABILITY DISTRIBUTION

f(E) = The probability that an electron will occupy a level with energy E.

1-f(E)= The probability that a level with energy E remains unoccupied.

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

Consequence of Quantum Nature of Electrons : Two Electrons are indistinguishable

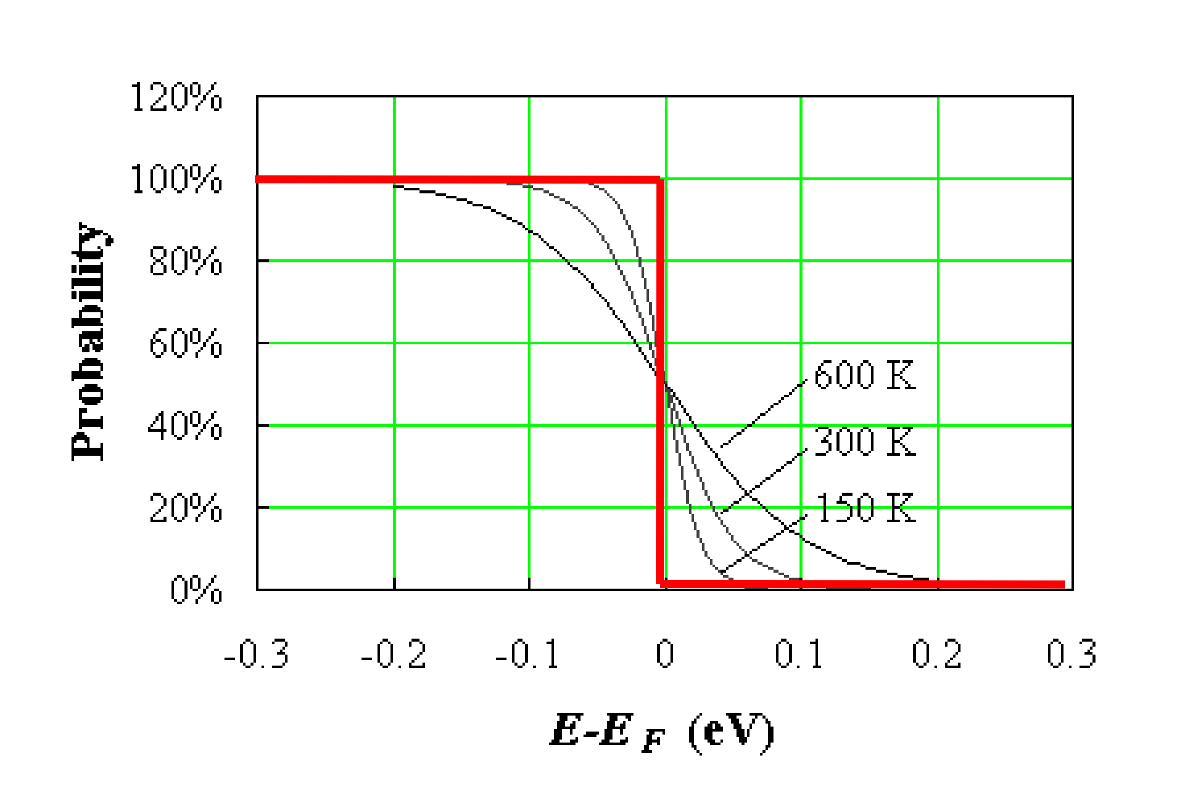
DEFINITION OF FERMI LEVEL

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

Probability that electron will occupy an energy level at $E = E_F$ is ½ at all temperature above $T=0$ K.

Very Definition of the
Fermi Level (or Chemical Potential)

FERMI DIRAC PROBABILITY DISTRIBUTION



@ T = 0 K

Fermi Dirac Distribution

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

FERMI DIRAC PROBABILITY DISTRIBUTION

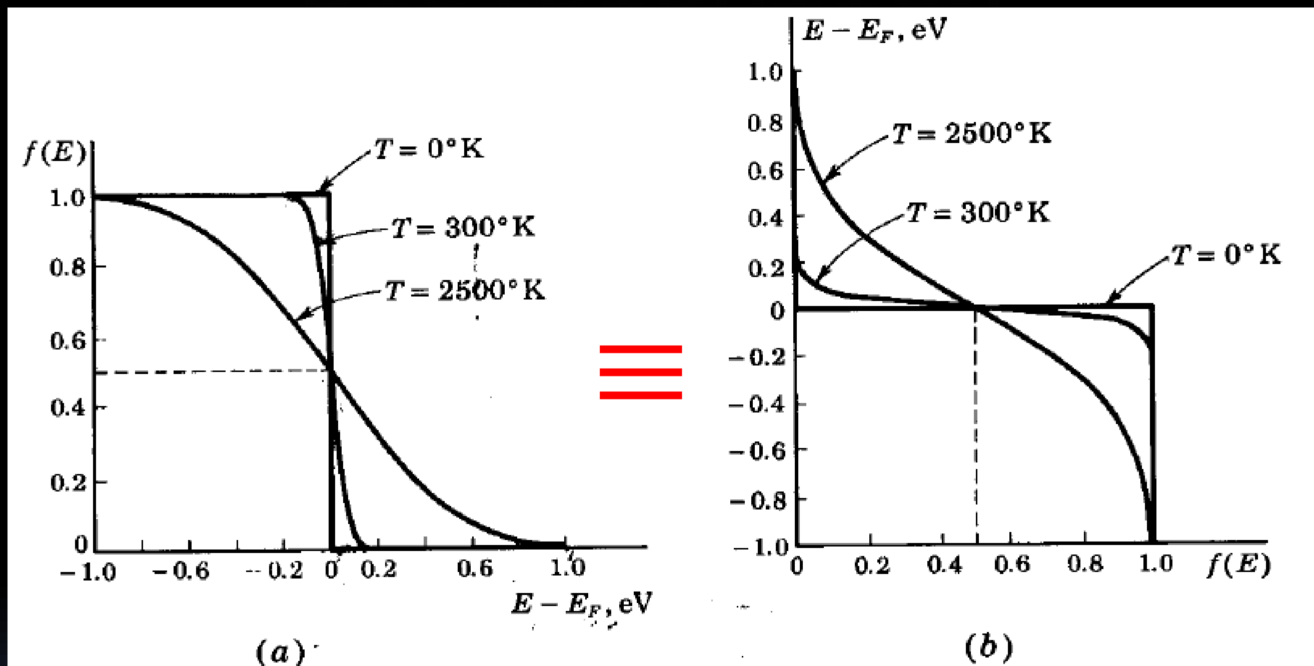
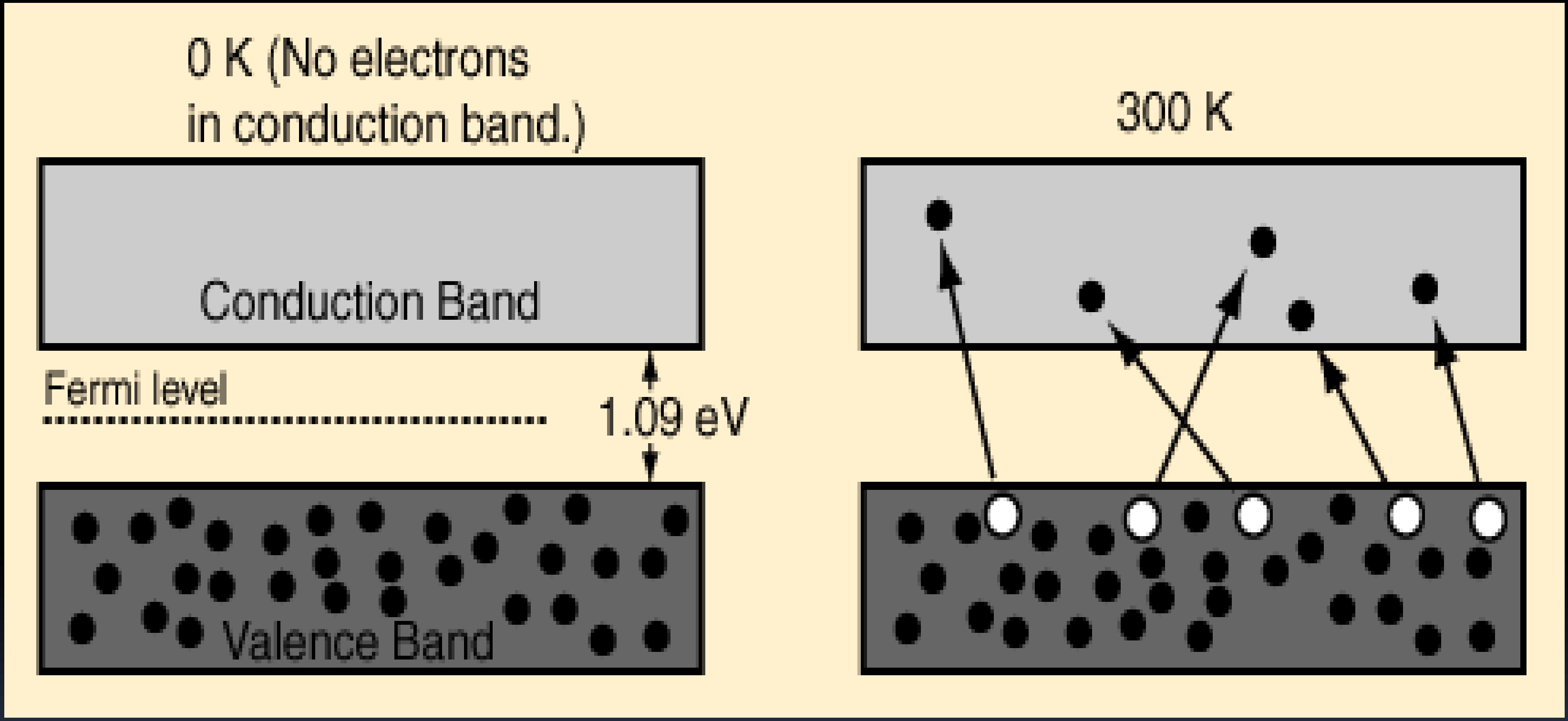


Fig. 19-3 The Fermi-Dirac function $f(E)$ gives the probability that a state of energy E is occupied.

Fermi Dirac Distribution

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

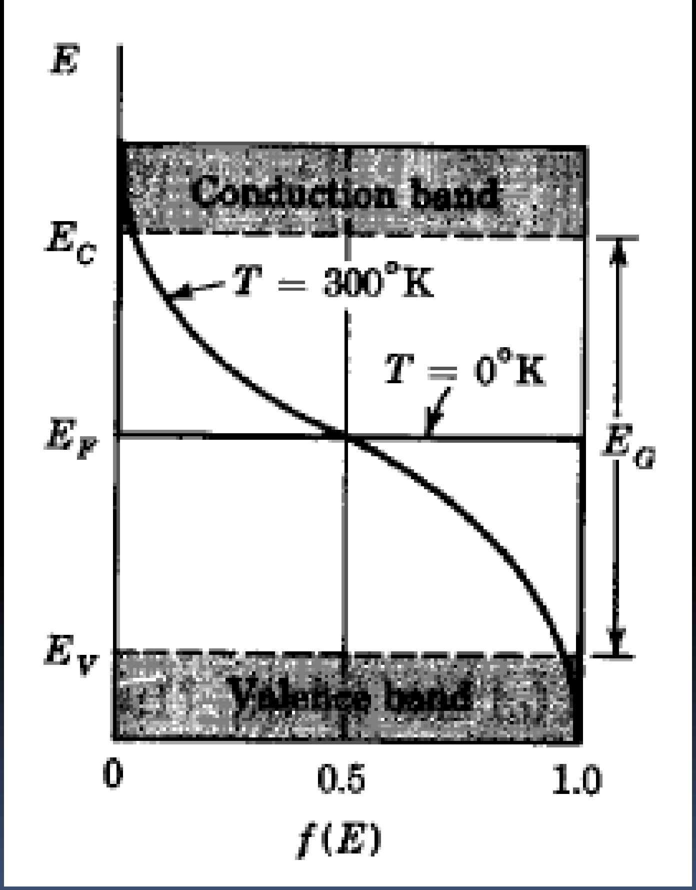
THERMAL GENERATION OF FREE ELECTRONS



Semiconductor is a perfect insulator at zero Kelvin

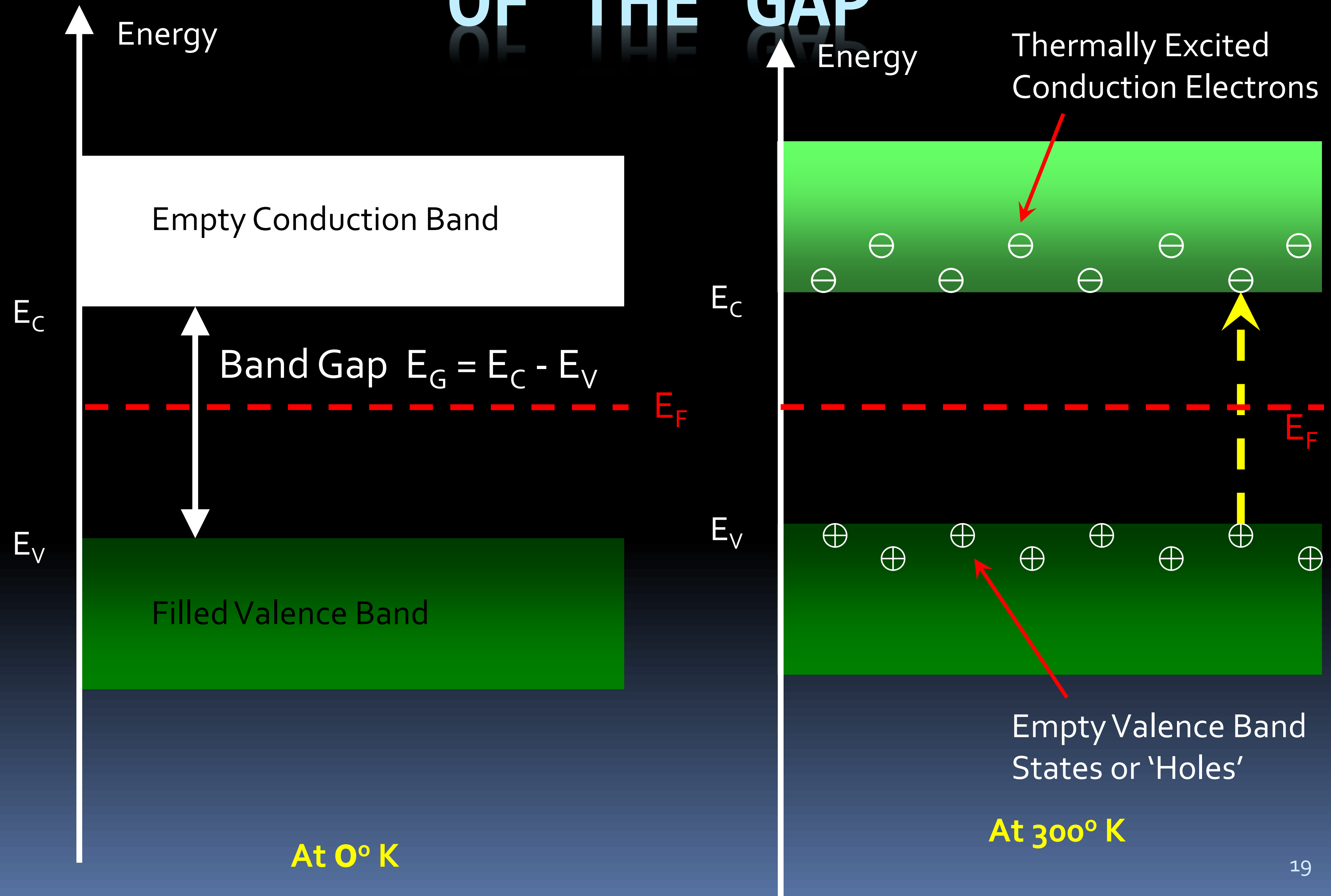
http://hyperphysics.phy-astr.gsu.edu/HBASE/Solids/semcn.html

SPREAD OF FERMI DIRAC DISTRIBUTION WITH TEMPERATURE



From : fig 19.8 Millman & Halkias, Integrated Electronics.

WHY FERMI LEVEL IS AT THE MIDDLE OF THE GAP



DENSITY OF ELECTRONS

$$N(E) = \text{Density of available Energy State}$$

$$f(E) = \text{Probability that an electron will occupy an energy level } E$$

$$\text{Density of Electrons} \quad n(E) \sim N(E)f(E)$$

Probability of Occupation of a State with Energy E X Number of Available Energy States = Actual Electron Population of that State with Energy E

NUMBER OF STUDENTS OCCUPYING THE SEATS AT RAMAN HALL

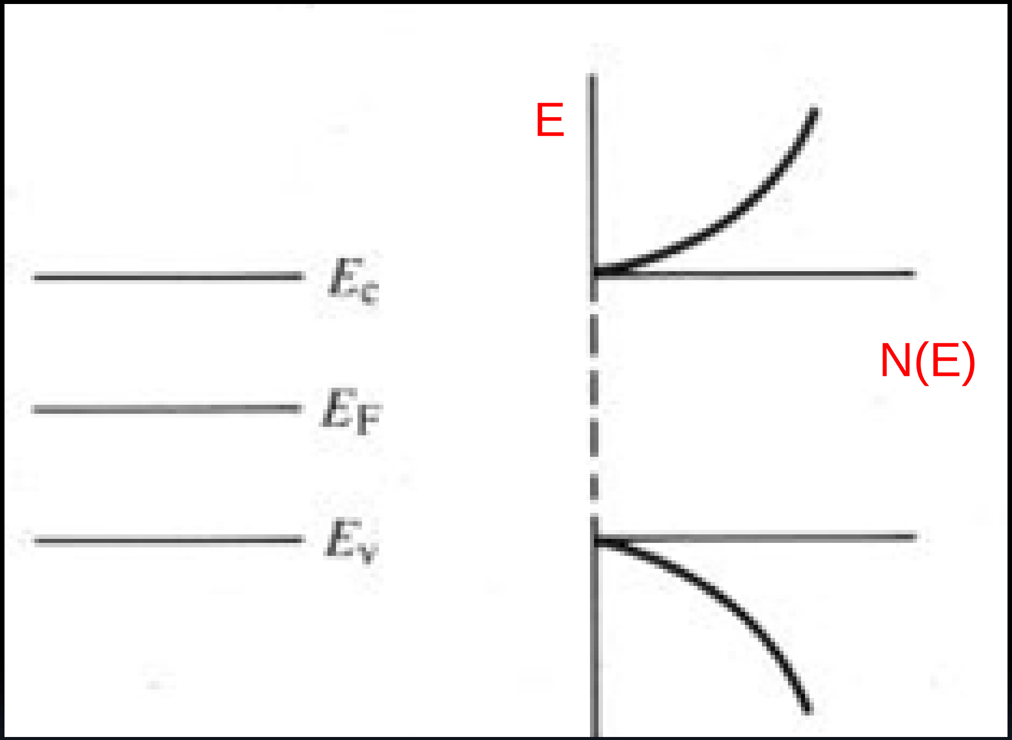
$$N(E) = \text{Available Bench Seats in the first year (Say 50)}$$

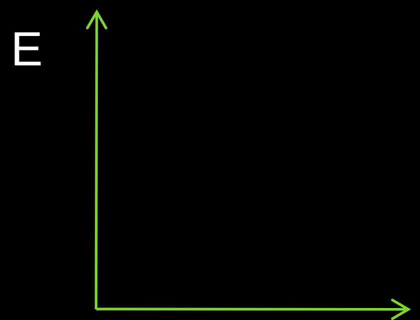
$$f(E) = \text{Probability that a student is practicing for KARVA ! (Say 60\%)}$$

$$\text{Number of Students sitting on the bench} \quad n(E) \sim N(E)f(E)$$

$$n(E) = 50 \times (1 - 0.6) = 20$$

N(E)~DENSITY OF AVAILABLE STATES





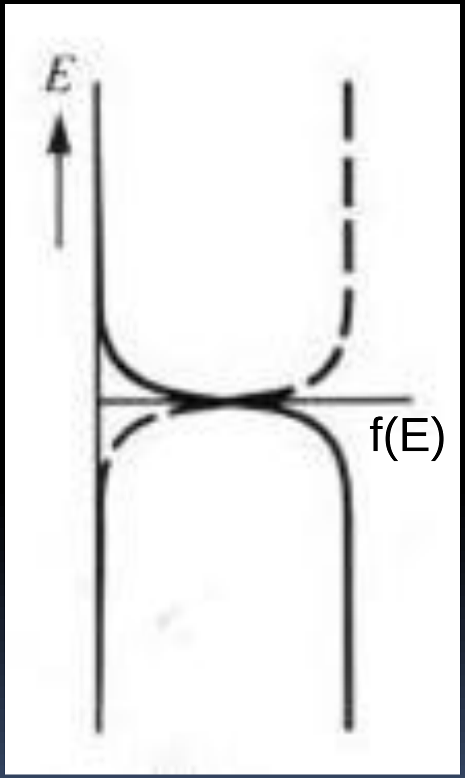
Density of States N(E)

For 3D Bulk Semiconductors only

$$N_C(E) = \gamma\left(E - E_C\right)^{1/2}$$

$$N_V(E) = \gamma\left(E_V - E\right)^{1/2}$$

FERMI DIRAC PROBABILITY DISTRIBUTION OF ELECTRONS & HOLES

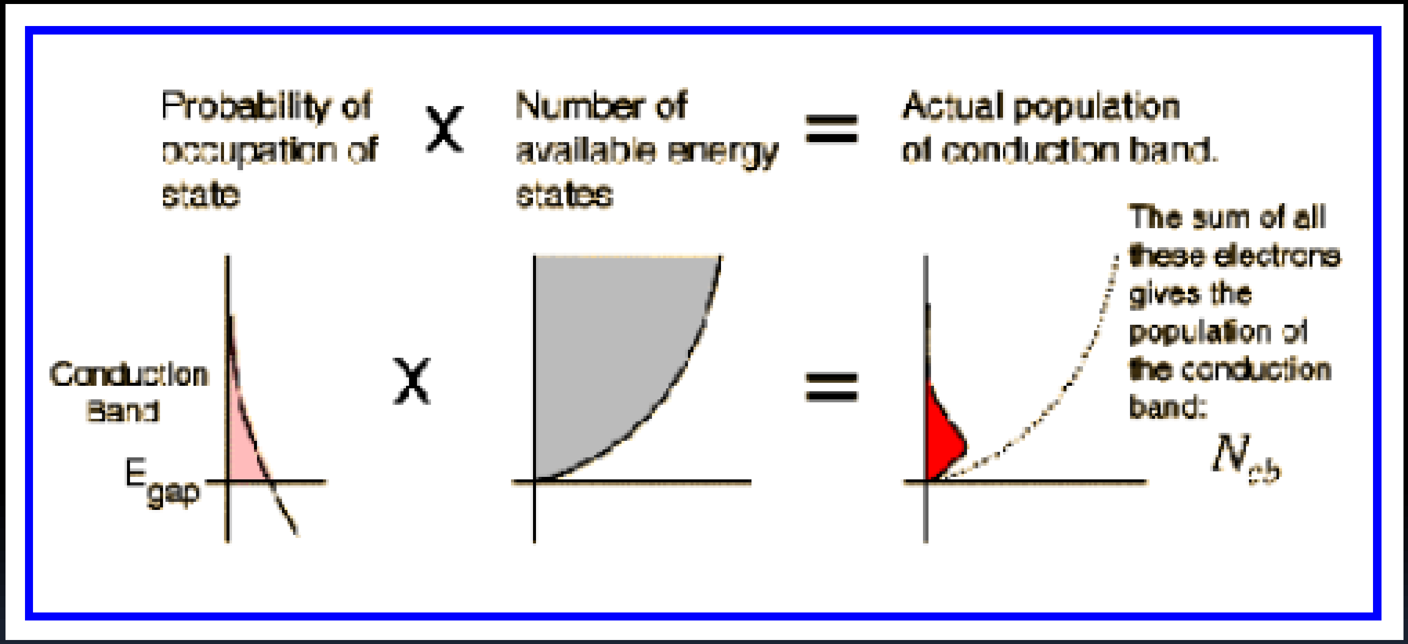


Absence of Electron ≡ Presence of Hole

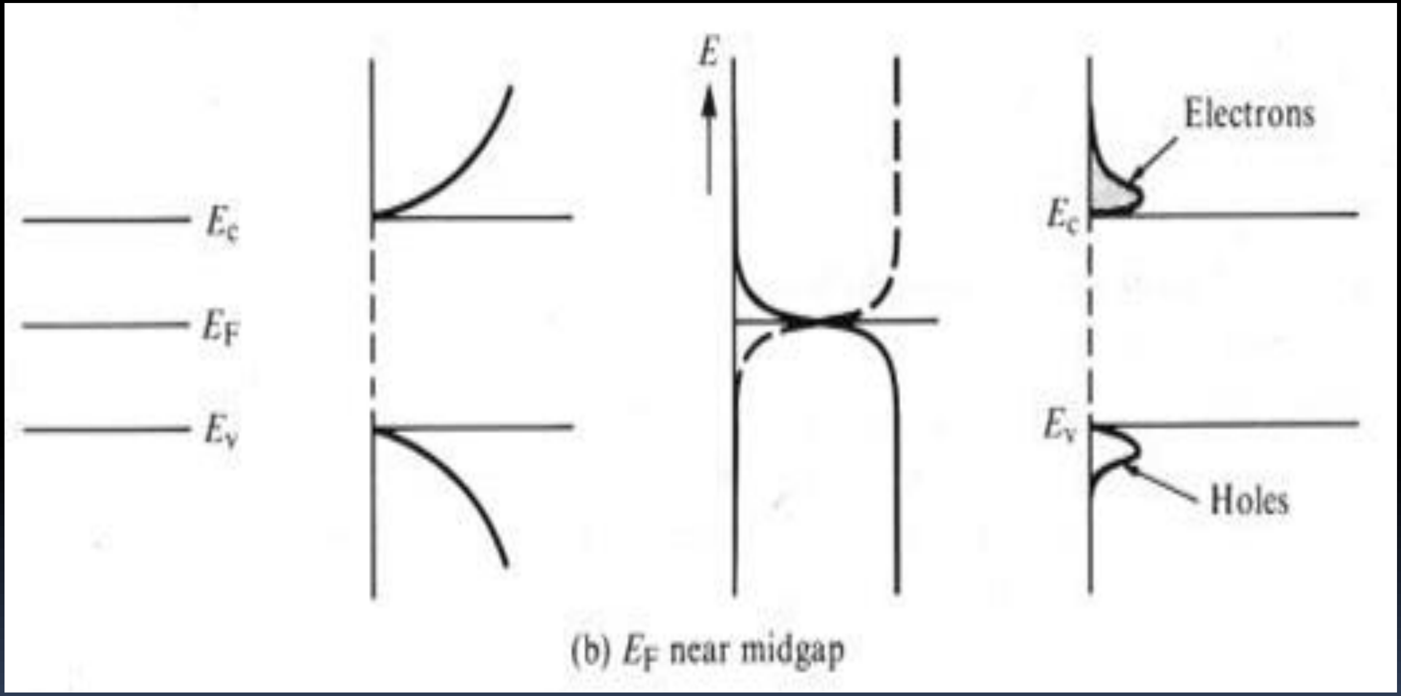
1- f(E) = The probability that a Hole will occupy an energy level with energy E.

Solid Line ~ f(E); Dotted Line ~ 1-f(E)

DENSITY OF ELECTRONS



FERMI DIRAC PROBABILITY DISTRIBUTION AND DENSITY OF ELECTRONS



(b) E_F near midgap

Band Gap Density of State F(E) Concentration of e & h

Intrinsic Semiconductor Only

DENSITY OF ELECTRONS IN THE CONDUCTION BAND

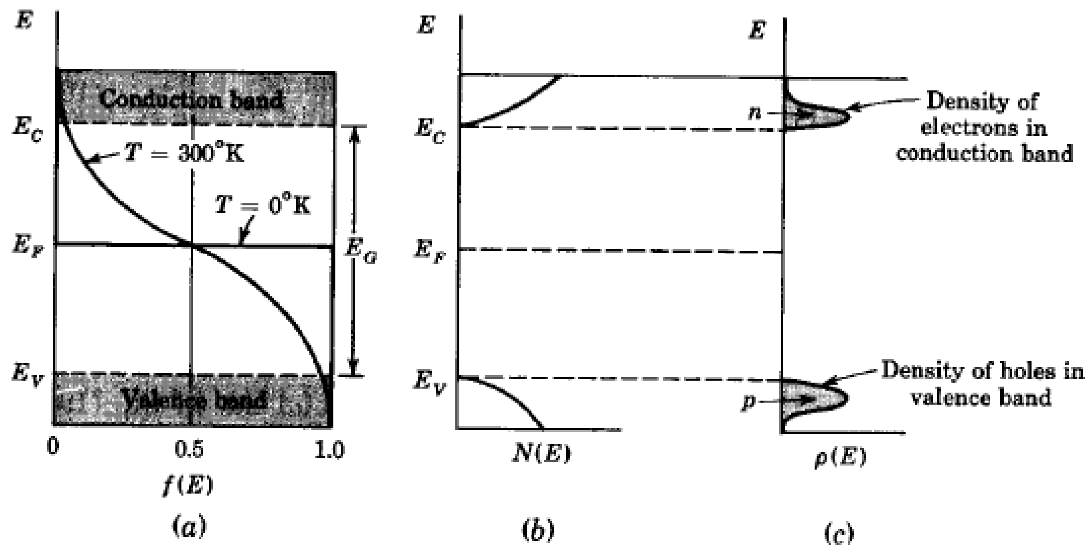


Fig. 19-8 (a) Energy-band diagram for an intrinsic semiconductor. The Fermi-Dirac probability function $f(E)$ is drawn at 0° K and at room temperature. (b) The density of states $N(E)$ in each band. (c) The density of carriers $\rho(E) = N(E)f(E)$ for electrons and $N(E)[1 - f(E)]$ for holes at room temperature. (Not drawn to scale.)

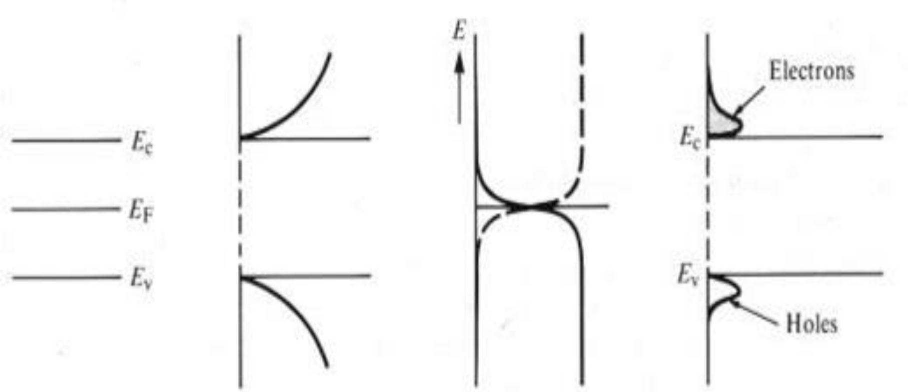
$$n_C = \int_{E_C}^{\infty} N(E)\, f(E)\, dE$$

From : fig 19.8 Millman & Halkias, Integrated Electronics.

DENSITY OF ELECTRONS IN THE CONDUCTION BAND

$$N_C(E) = \gamma\left(E - E_C\right)^{\frac{1}{2}}; \quad \gamma = \frac{4\pi}{\mathrm{h}^3}\left(2m_e^{\;*}\right)^{3/2}\left(1.602\times10^{-19}\right)^{3/2} in\,(\mathrm{m}^{-3})(\mathrm{eV})^{-3/2}$$

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



(b) E_F near midgap

For $E \geq E_C$

$$n_C = \int_{E_C}^{\infty} N(E)\, f(E)\, dE$$

DENSITY OF ELECTRONS IN THE CONDUCTION BAND

$$\text{In case of } \; E \geq E_C \;\&\; \left(\mathrm{E} - \mathrm{E_F}\right) >> kT$$

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

$$n_C = \int_{E_C}^{\infty} N(E)\, f(E)\, dE = N_C \, e^{-\frac{\left(E_C - E_F\right)}{k_B T}}$$

$$N_C = 2\left(\frac{2\pi m_e^{\,*} k_B T}{h^2}\right)^{3/2} \left(1.602 \times 10^{-19}\right)^{3/2}$$

DENSITY OF HOLES IN THE VALENCE BAND

$$E \leq E_V \; \& \left(\mathrm{E} - \mathrm{E}_F\right) >> kT$$

$$f_p = 1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} = \frac{1}{1 + \exp\left(\frac{E_F - E}{k_B T}\right)}$$

$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

PHYSICAL CONSTANTS

$$\text{Boltzman Constant}\,(k_B) = 8.617\,3\underline{43}(15) \times 10^{-5}\ \text{eV/Kelvin}$$

$$\text{Plank Constant}\,(h) = 6.626\,068\,\underline{96}\,(33)\ \text{x}\,10^{-34}\ \text{Joule-second}$$

$$m_h^{*} = \text{Effective Mass of Hole in Si} = 0.16_L \times m_e$$

$$m_e = 9.109\,382\,\underline{15}\,(45)\ \text{x}\,10^{-31}\ \text{kg}$$

Fundamental Physical Constants

http://physics.nist.gov/cuu/Constants/index.html

THINK!

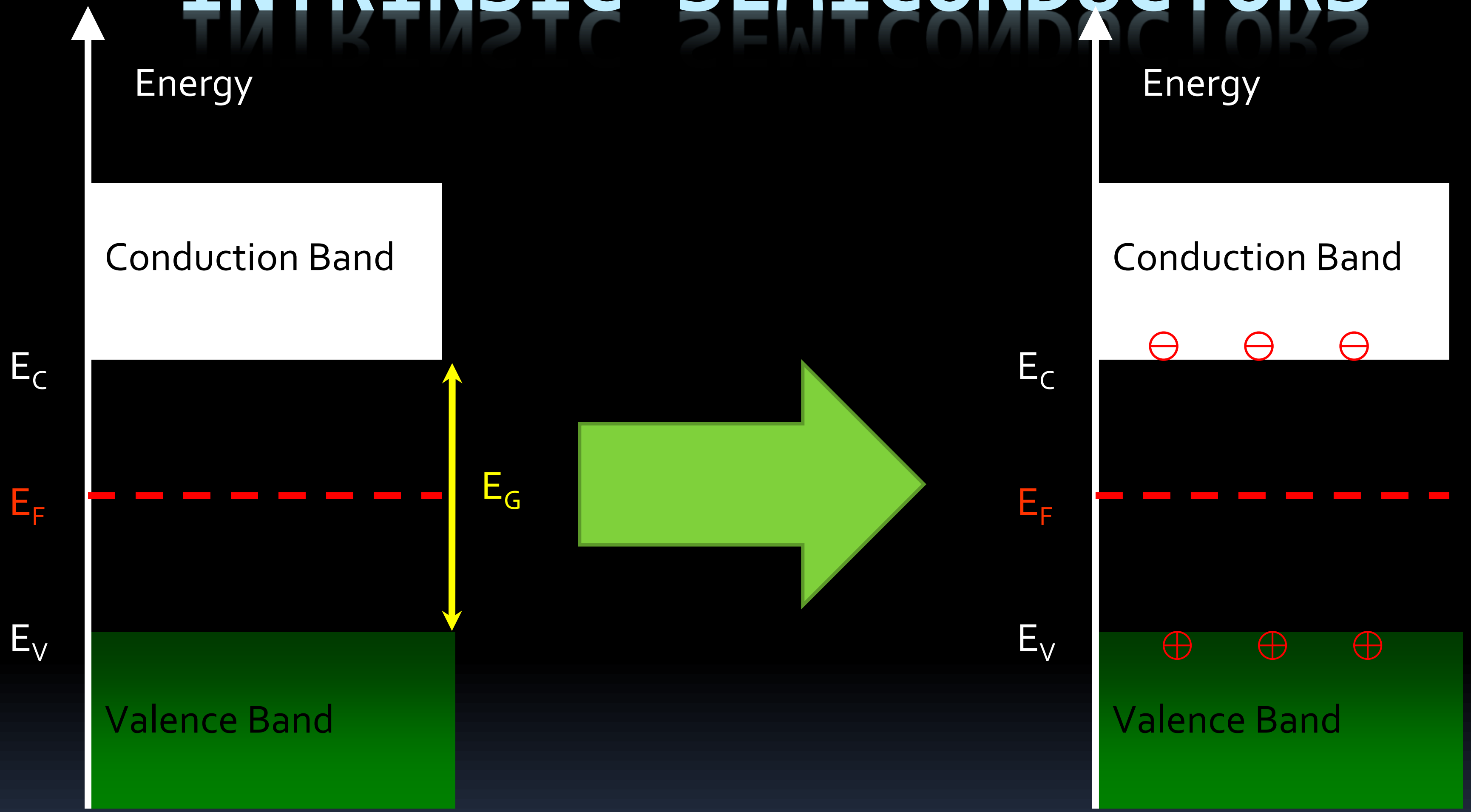
In case of intrinsic semiconductor $n_i = p_i$ then,

$$\text{Does } n_C = p_V \text{ imply that } E_F = \frac{E_C + E_V}{2} \text{ ?}$$

n_C is the number of electrons in the conduction band

p_V is the number of holes in the valence band

INTRINSIC SEMICONDUCTORS



At 0 K

At High (?) Temperature (K)

Intrinsic Semiconductors ⇒ Current carrying carriers are generated only by thermal excitation across the band gap.

THINK !

Do we need $(k_B T) \geq E_G$ for Thermal Excitation ?

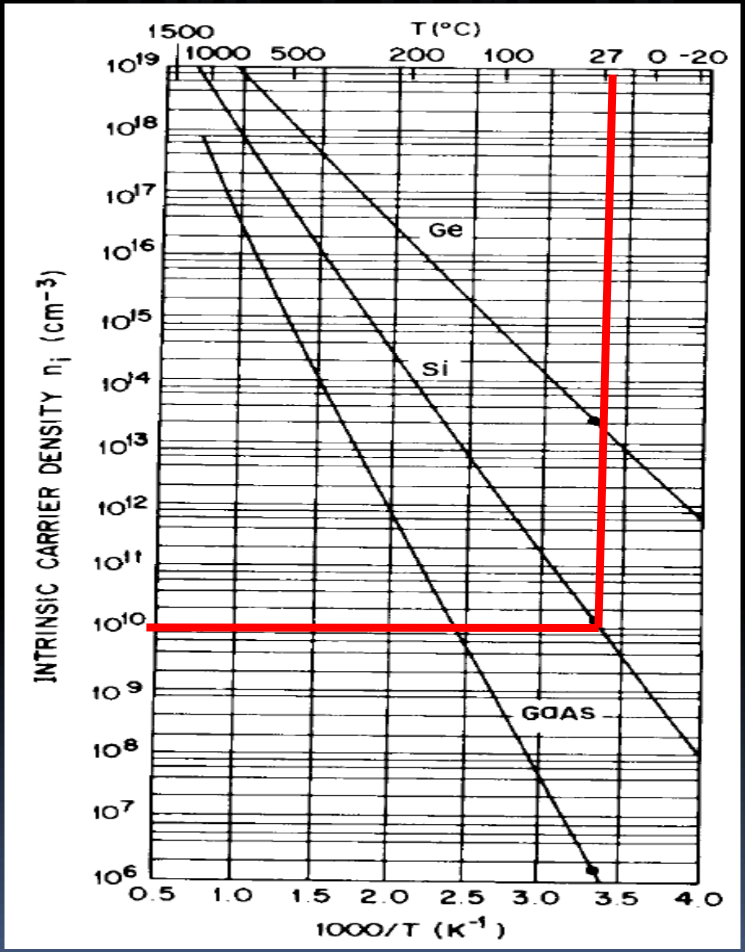
E_G of Silicon at 300 K is 1.12 eV

$$k_B T = 0.025\,\text{eV at } 300\,\text{K}$$

$$\Downarrow$$

How some electrons are excited across the band gap at Room Temperature ?

INTRINSIC ELECTRON DENSITY AS A FUNCTION OF TEMPERATURE



Intrinsic (n_i) electron density around room temperature is ~ 10^{10} cm^{-3} in Silicon

Small

Also $n_i = p_i$

Ch 1, S. M. Sze, Physics of Semiconductor Devices.

GROUP IV IN THE PERIODIC TABLE

Periodic Table of the Elements

- Solids
- Liquids
- Gases
- Artificially Prepared

Atomic Number — 26
Symbol — Fe
Name — Hydrogen
1.0079 — Atomic Weight

PERIOD	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 H Hydrogen 1.00794																	2 He Helium 4.00260
2	3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.99840	10 Ne Neon 20.1797
3	11 Na Sodium 22.98977	12 Mg Magnesium 24.3050											13 Al Aluminum 26.98154	14 Si Silicon 28.0855	15 P Phosphorus 30.97376	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.93805	26 Fe Iron 55.845	27 Co Cobalt 58.93320	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
6	55 Cs Cesium 132.90545	56 Ba Barium 137.327		72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium (226)		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (268)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium						

57 La Lanthanum 138.9055	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

COVALENT & IONIC COMPOUNDS

Covalent and Ionic Crystals

Covalent (Group IV)	III-V Compounds	II-VI Compounds	I-VII Compounds (Ionic)
C (diamond)	BN	BeO	LiF
	BP	BeS	LiCl
	AlN	MgO	NaF
Si	AlP	MgS	NaCl
	GaP	CaO	KF
	AlAs	CaS	KCl
		ZnS	LiBr
Ge	GaAs	CaSe	KBr
	InP	ZnSe	NaI
	AlSb	CdS	RbCl
	GaSb	CdSe	RbBr
	InAs	ZnTe	KF
α-Sn	InSb	CdTe	RbI
			CsBr

Table 1.2 J. P. McKelvey, Solid State and Semiconductor Physics

INTRINSIC GERMANIUM

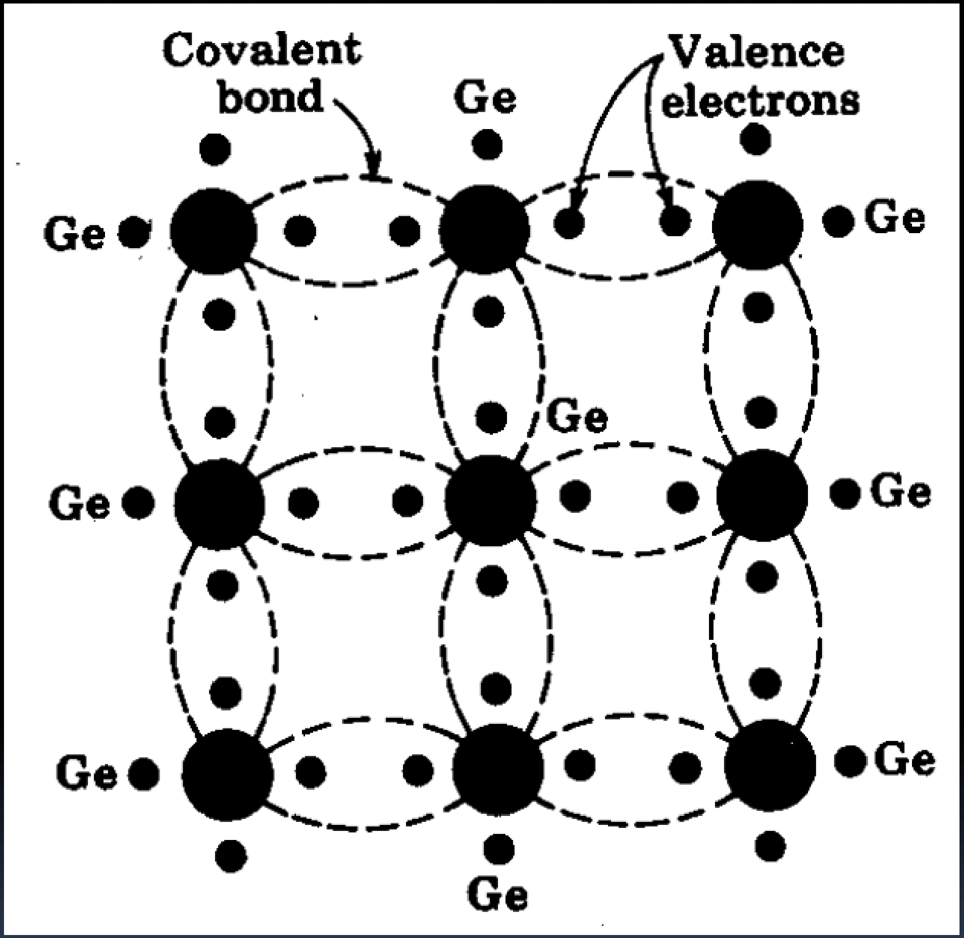


Fig 2.3 Millman & Halkias, Intergrated Electronics

4 fold coordinated Ge atoms.

Each atom share 8 valence electrons.

DONOR IMPURITIES IN GERMANIUM

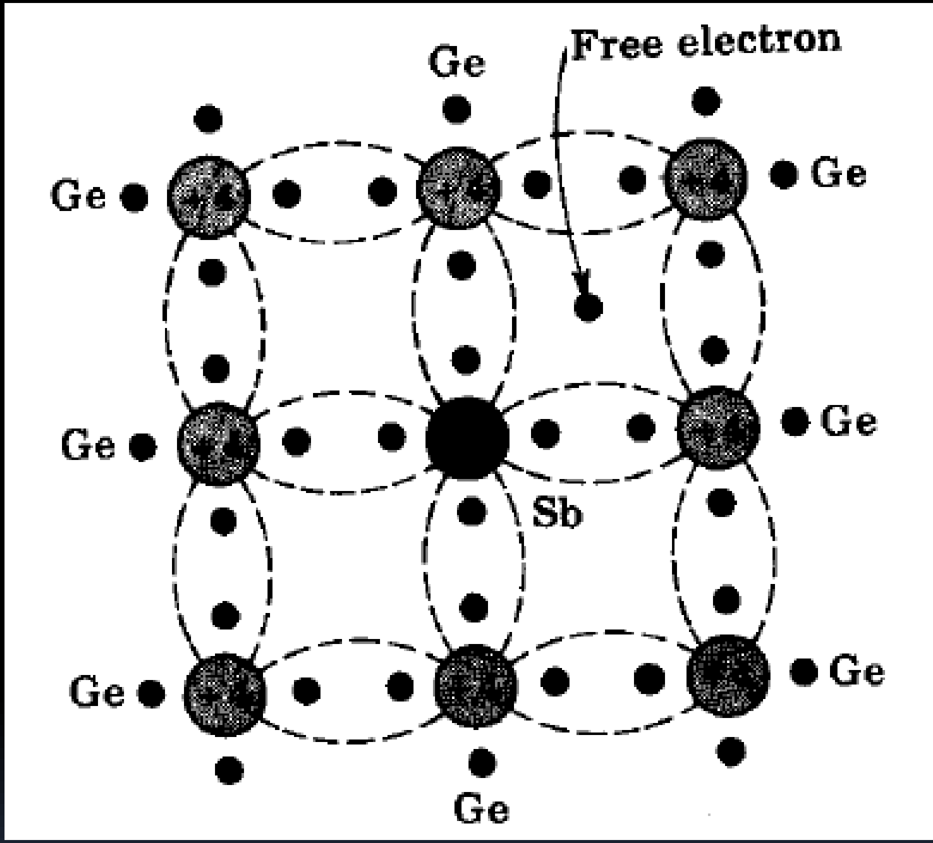


Fig 2.4 Millman & Halkias, Intergrated Electronics

Donor : An impurity atom which becomes positively charged after donating an electron to the material (e.g pentavalent Sb, As in Si); Donors contribute free electrons.

ACCEPTOR IMPURITIES IN GERMANIUM

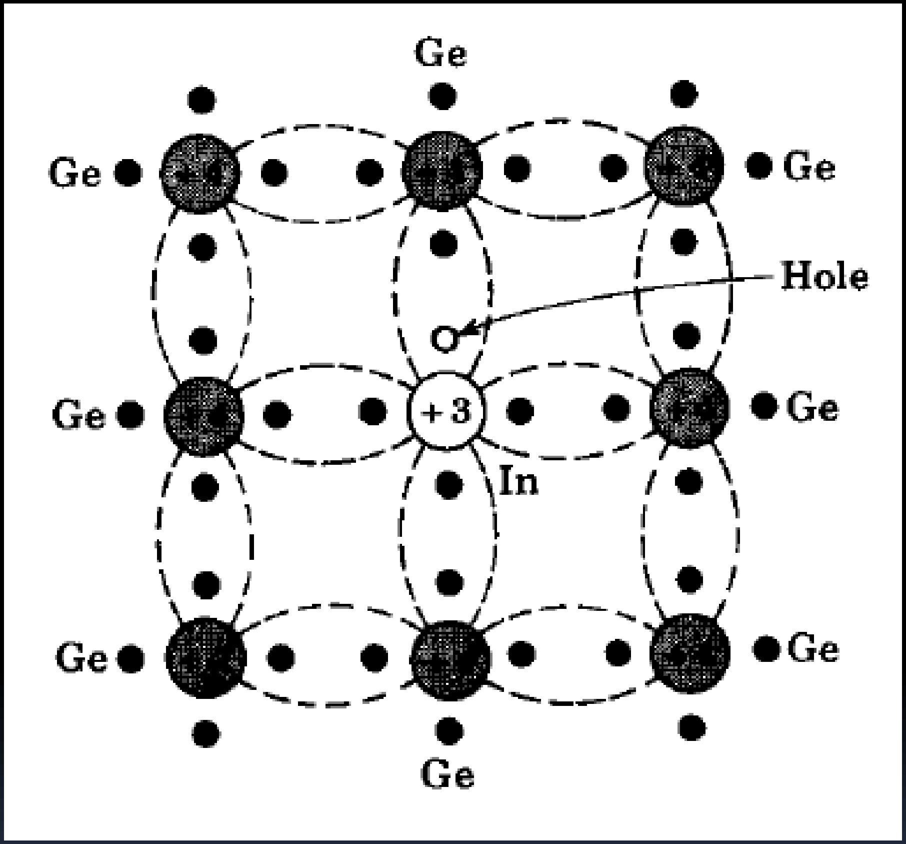
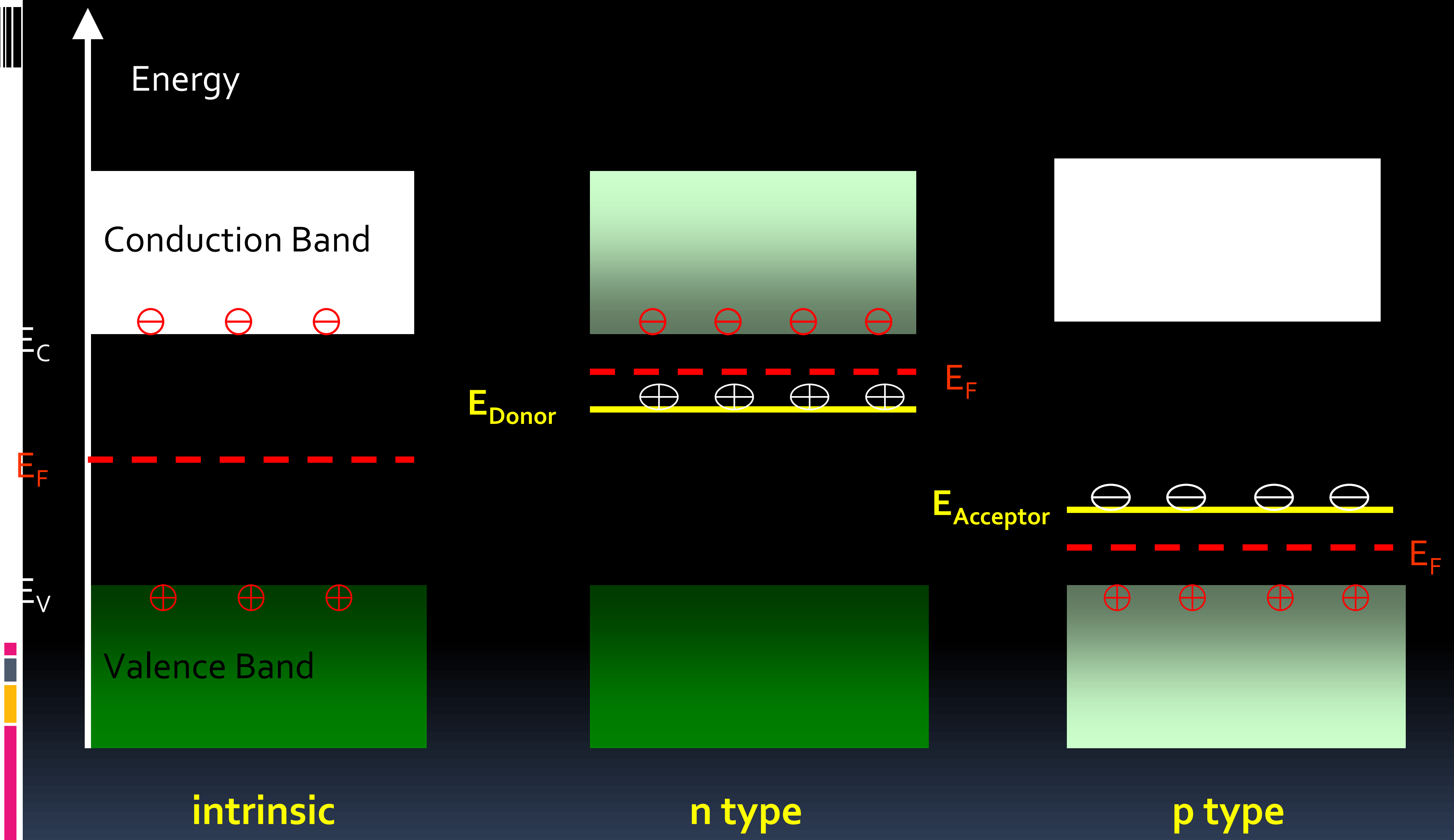


Fig 2.6 Millman & Halkias, Intergrated Electronics

Acceptor : An impurity atom which becomes negatively charged after accepting an electron from the material (e.g trivalent Al in Si); Acceptor contribute free holes.

n and p type semiconductors



Fermi level E_F Determines the Occupation of any State

n and p type semiconductors

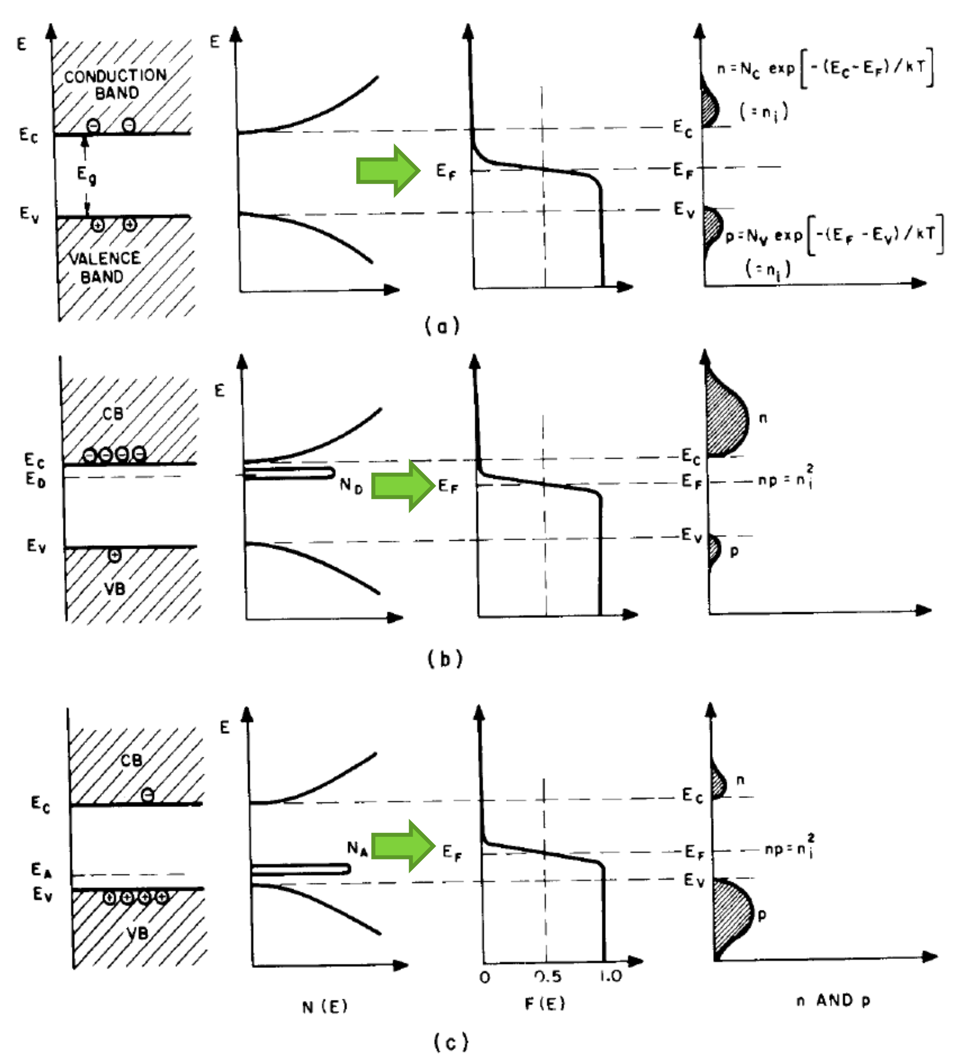
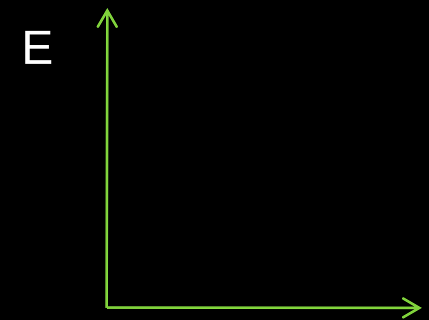
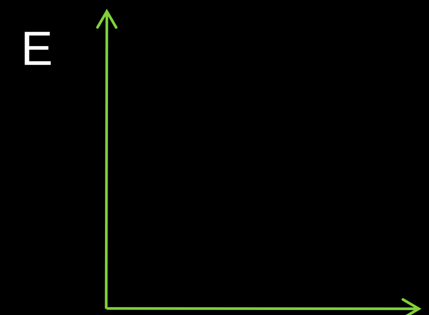


Fig. 14 Schematic band diagram, density of states, Fermi–Dirac distribution, and the carrier concentrations for (*a*) intrinsic, (*b*) *n*-type, and (*c*) *p*-type semiconductors at thermal equilibrium. Note that $pn = n_i^2$ for all three cases.

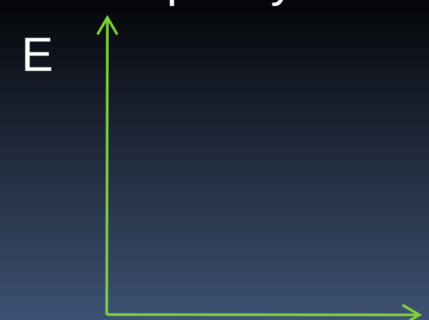
Ch.1 , S. M Sze, Physics of Semiconductor Devices



Density of States N(E)



Occupancy Factor f(E)



Carrier Concentration n(E)

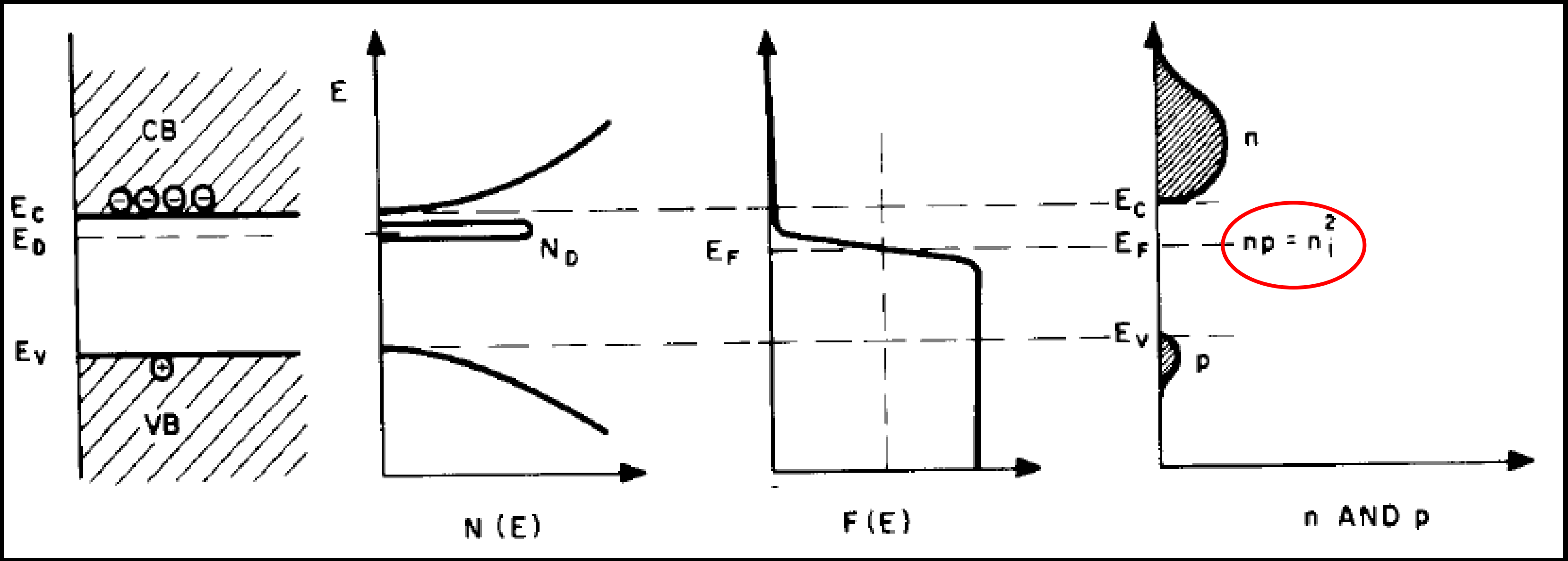
TOTAL ELECTRON DENSITY = INTRINSIC ELECTRON DENSITY + DOPED ELECTRON DENSITY

Intrinsic electron density $\Rightarrow$ Thermally excited electrons across the band gap

Doped electron density $\Rightarrow$ contributed by donor impurities.

MAJORITY & MINORITY CARRIERS

n type Semiconductors



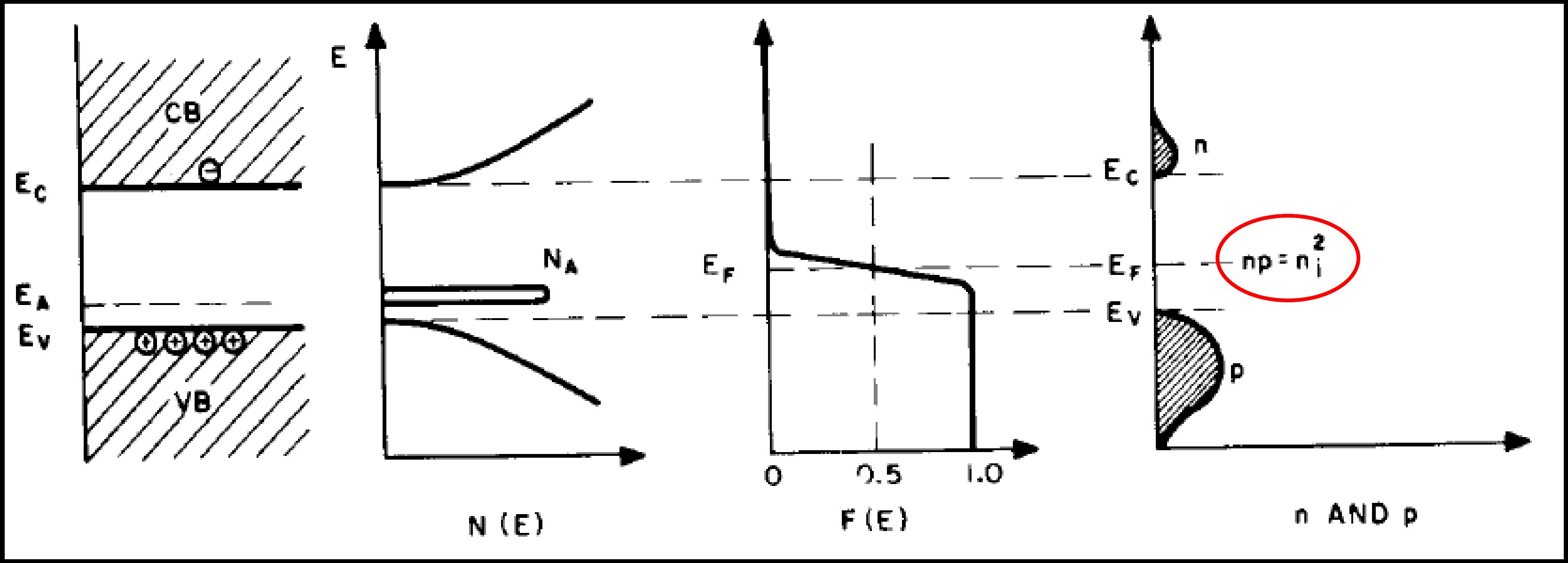
More number of free Electrons (n) $\Rightarrow$ Electrons are Majority carriers.

Less number of free Holes (p) $\Rightarrow$ Holes are Minority carriers

Ch 1, S. M Sze, Physics of Semiconductor Devices

MAJORITY & MINORITY CARRIERS

p type Semiconductors



More number of free Holes (p) ⇒ Holes are Majority carriers.

Less number of free Electrons (n) ⇒ Electrons are Minority carriers

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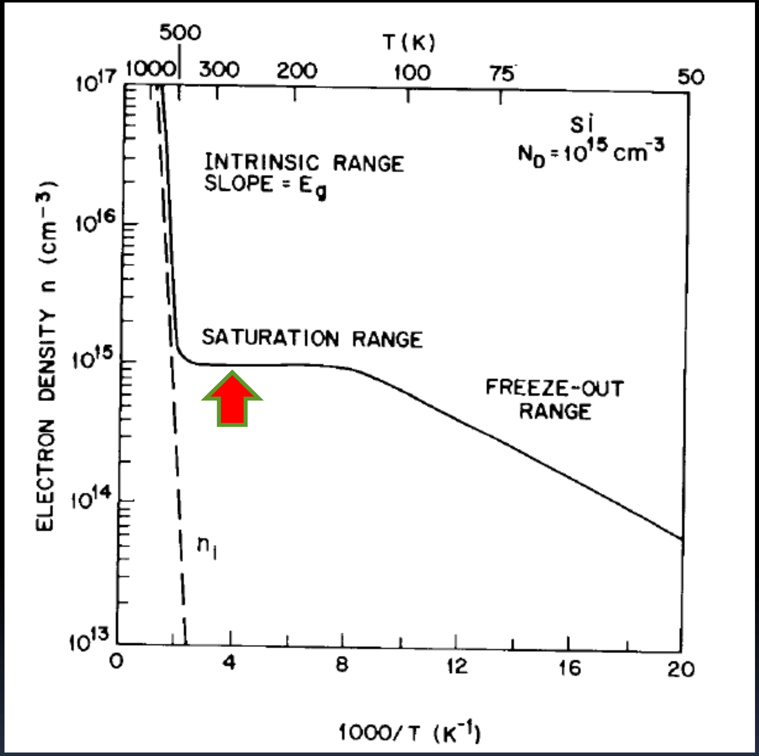
Law of Mass Action

In CHEMISTRY, Law of Mass Action determines the Relative Concentration of ions in weakly ionized electrolytes

$$n.p = 4\left(\frac{2\pi\left(m_e^{*} m_h^{*}\right)^{1/2} k_B T}{h^2}\right) e^{-\frac{E_G}{k_B T}} = n_i^{\,2}$$

Semiconductors can be thought of as weakly ionized electrolytes where a chemical bond having dissociation energy $E_G = (E_C - E_V)$ dissociates to produce an electron in the conduction band and a hole in the valence band.

ELECTRON CONCENTRATION IN DONOR IMPURITY DOPED SILICON



Impurity concentration $\sim 10^{15}$ /cm^3

Room Temperature ~ 300 K

Total Electron Density = INTRINSIC CARRIER DENSITY + DOPANT IMPURITY generated Electron Density.

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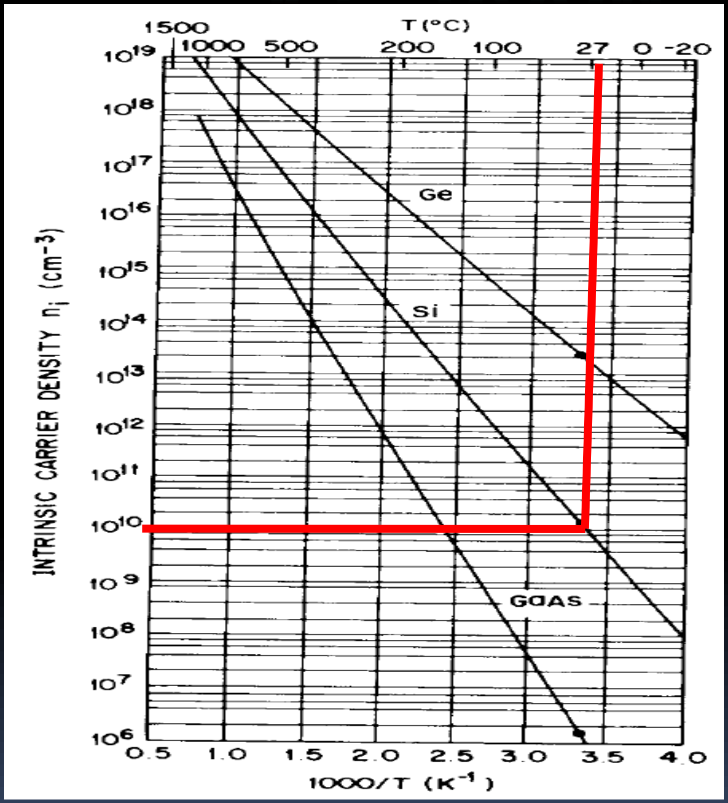
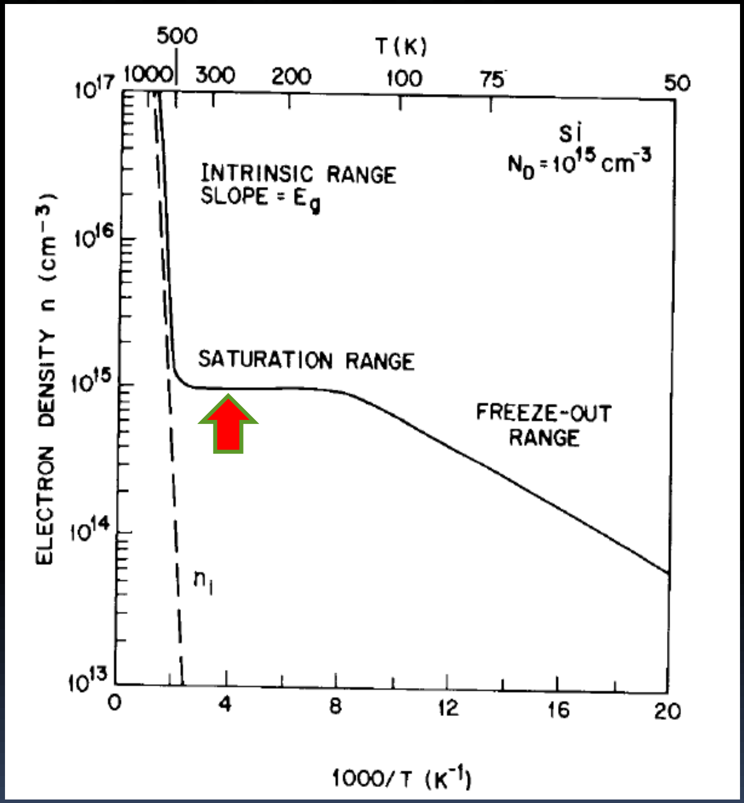
INCREASE IN ELECTRON CONCENTRATION IN DOPED SILICON AT ROOM TEMPERATURE





From ~10^{10} to ~10^{15} per cm^3 !

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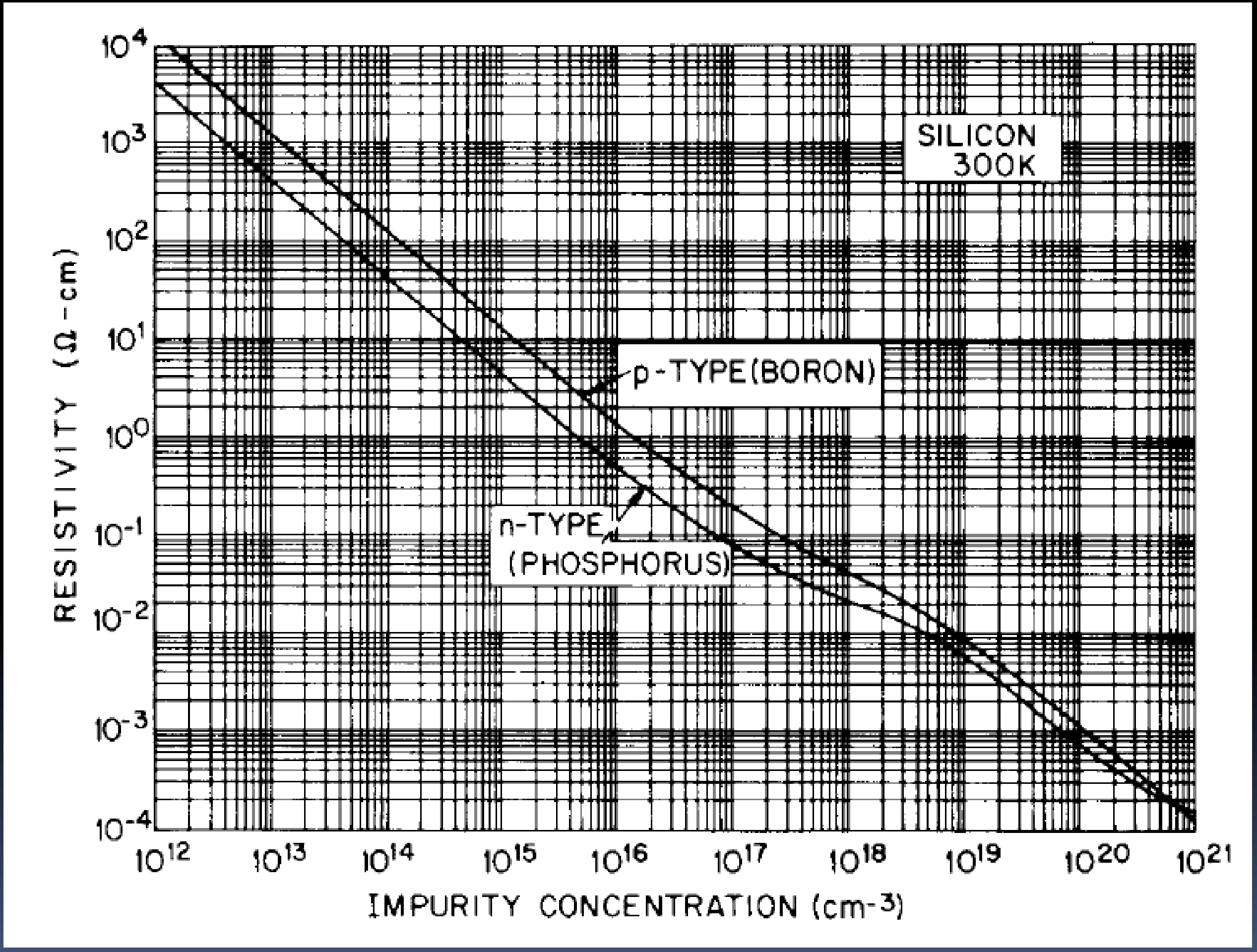
RESISTIVITY DECREASES WITH INCREASED DOPING



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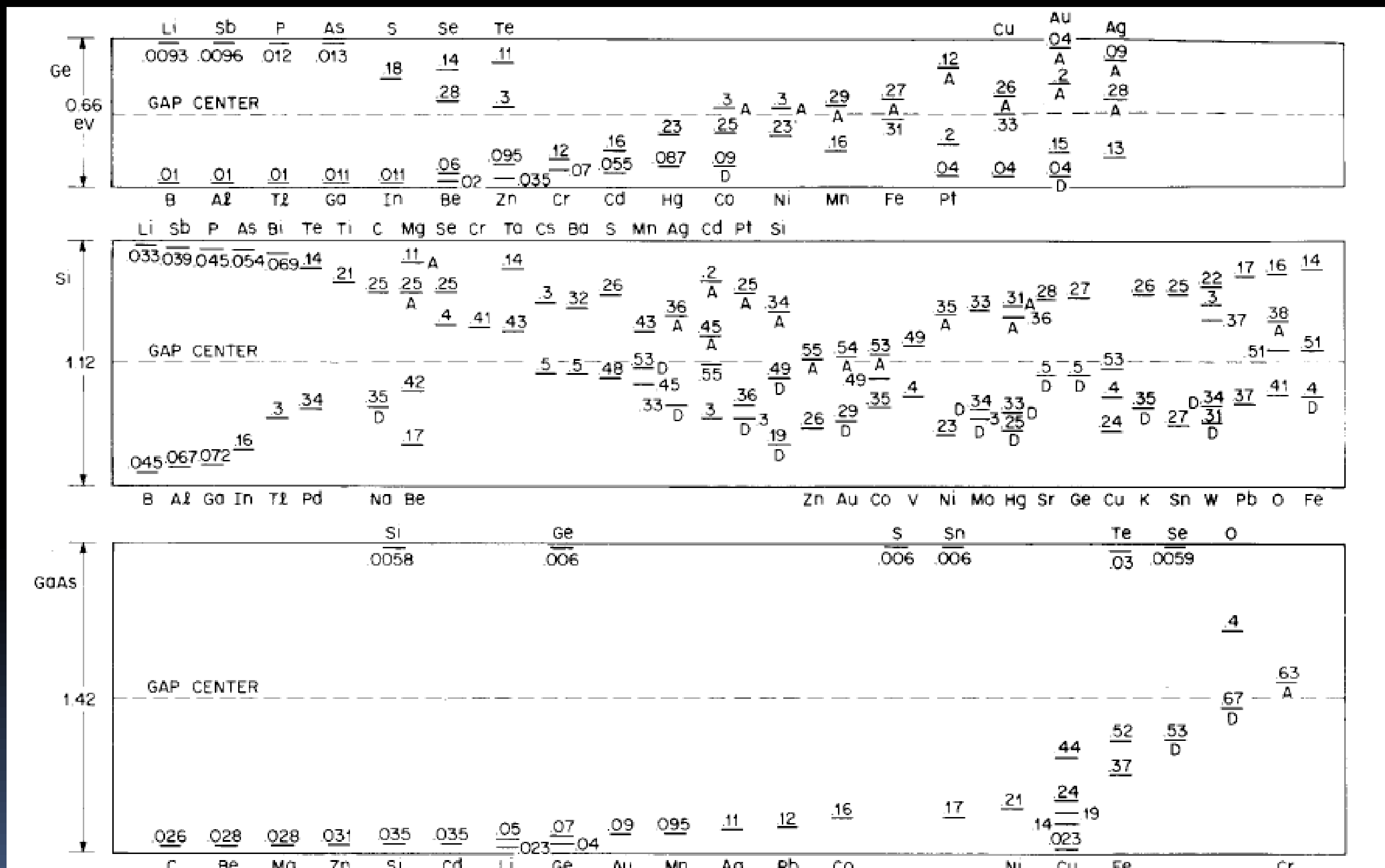
DIFFERENT KIND OF IMPURITY DOPANTS



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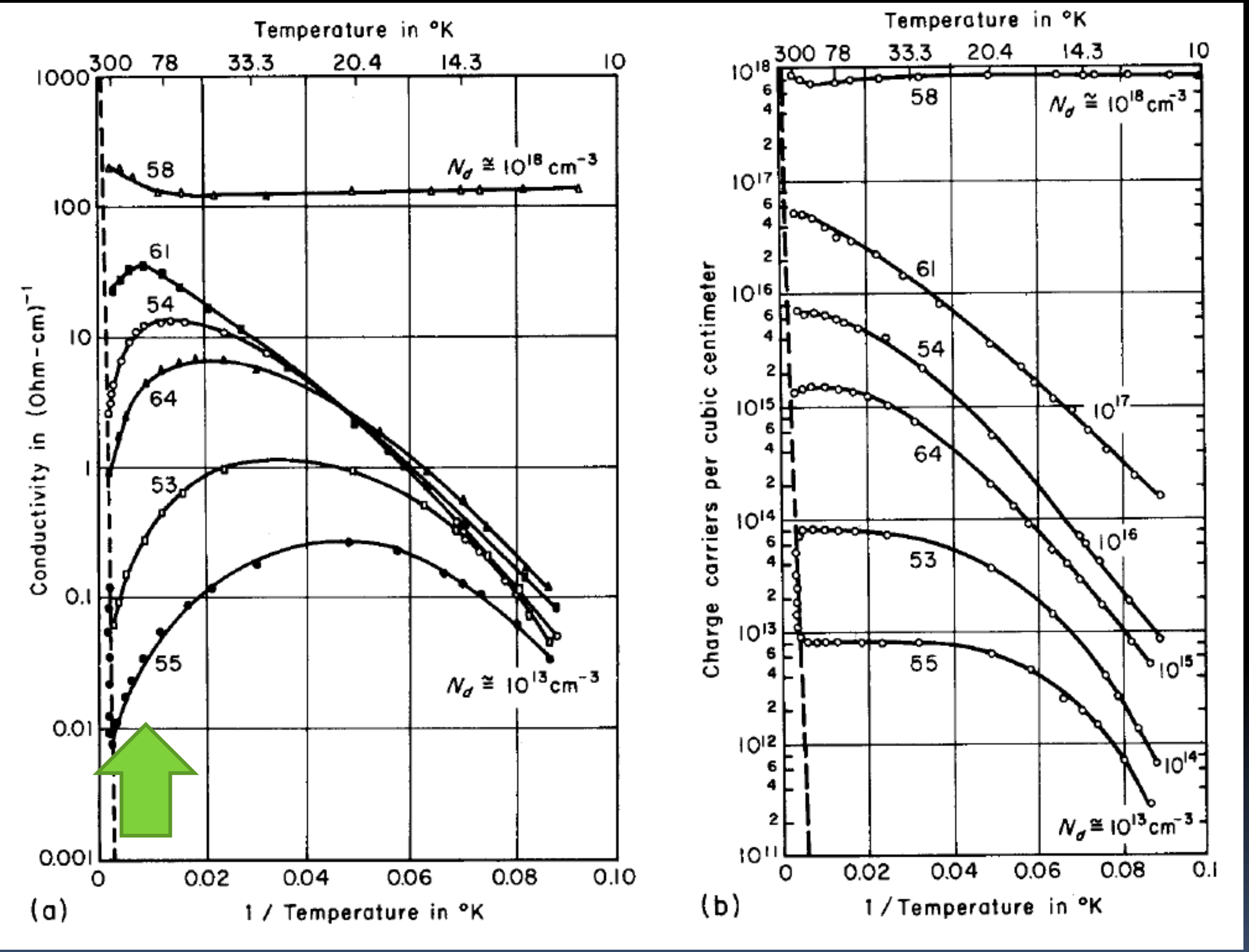
WHAT IS WRONG IN ASKING……

“WHAT IS THE DIFFERENCE BETWEEN A METAL AND A SEMICONDUCTOR IN TERMS OF THEIR TEMPERATURE DEPENDENCE OF THE RESISTANCE ?”

CONDUCTIVITY OF GERMANIUM ALSO DECREASE WITH INCREASING TEMPERATURE



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Conductivity again increases as soon as the intrinsic generation of carriers dominates the impurity doped carriers.

TEMPERATURE DEPENDENCE OF RESISTIVITY

Around room temperature and below room temperature the resistivity of Si can increase with increasing temperature like metals !!!!

Only when at very high temperature (say) > 500^o C the Silicon becomes Intrinsic and resistivity then decreases with increasing temperature.