

MODULE I



CBCC OFFERED BY DEPARTMENT OF ELECTRONIC SCIENCE

- **MODULE – 1: INTRODUCTION TO SEMICONDUCTOR PHYSICS & DEVICE FABRICATION TECHNOLOGY**
- **MODULE – 2: JUNCTION DIODES**
- **MODULE – 3: BIPOLAR JUNCTION TRANSISTORS**
- **MODULE – 4: FIELD EFFECT TRANSISTORS**
- **MODULE – 5: ANALOG CIRCUITS**
- **MODULE – 6: DIGITAL ELECTRONICS**

MODULE – 1: INTRODUCTION TO SEMICONDUCTOR PHYSICS & DEVICE FABRICATION TECHNOLOGY

- CONCEPT OF ENERGY BANDS
- FERMI LEVEL
- INTRINSIC AND EXTRINSIC SEMICONDUCTORS,
- PTYPE AND N-TYPE SEMICONDUCTORS
- ENERGY BAND DIAGRAM
- EFFECTIVE MASS
- CARRIER TRANSPORT, MOBILITY, DRIFT AND DIFFUSION, CARRIER RECOMBINATION
- INTRODUCTION TO DEVICE FABRICATION TECHNOLOGY.

WHY STUDY ELECTRONICS !

FOR A PROFESSIONAL IN ANY FIELD

SAME REASON –WHY WE STUDIED GEOGRAPHY IN SCHOOL – TO UNDERSTAND THE WORLD AROUND YOU

THE EARLIER QUESTIONS OF WHAT CAUSES DAY AND NIGHT OR AN ECLIPSE OR WHY IS SIMLA/KASHMIR FAMOUS FOR APPLES AND NAGPUR/DARJEELING FOR ORANGES.....

HAVE BEEN REPLACED BY

HOW MUCH RAM DO I NEED FOR MY MOBILE

WHAT SHOULD BE THE KVA OF THE HOME INVERTER I BUY

WHY DO I NEED AN INVERTER AC INSTEAD OF A NON-INVERTER ONE

WHY SHOULD I PAY EXTRA FOR A 6NM TECHNOLOGY PROCESSOR FOR MY MOBILE INSTEAD OF A 14NM ONE

HOW DOES A BLDC FAN REDUCE MY ELECTRIC BILL OR HOW DOES A PENDRIVE STORE MY MEMORIES AND WORK DATA

THE QUESTIONS ARE ENDLESS AND I NEED TO KNOW THEM FOR MAKING INFORMED DECISIONS IN MY EVERYDAY LIFE

SEMICONDUCTORS- THE BUILDING BLOCK OF ELECTRONIC DEVICES



A semiconductor is a physical substance designed to manage and control the flow of current in electronic devices and equipment. It does not allow the free flow of electric current and neither does it repel it completely. Thus, it fits between a conductor and an insulator.

Why does the Device scientist love them ?

- The resistivity of semiconductor materials can be controlled over a wide range, either permanently or dynamically, Making them highly versatile for various applications.
- Semiconductors have a negative temperature coefficient of resistance, which means that their resistance decreases with increasing temperature and vice-versa.
- Although semiconductors in their neutral state behave like a poor conductor, a significant improvement can be made to their current carrying capacity by mixing small amounts of impurities (usually another metallic substance such as arsenic or gallium).
□ Certain semiconductors are used to make LEDs or light-emitting diodes by exploiting their optical properties; herein, the electrons relax by emitting light instead of producing heat.

- **SILICON**

SILICON IS THE SEVENTH MOST ABUNDANT ELEMENT ON EARTH, DERIVED FROM THE REACTIONS BETWEEN SILICON DIOXIDE AND CARBON MATERIALS LIKE COAL, AND MAKES UP FOR AS MUCH AS 25% OF OUR PLANET'S CRUST BY WEIGHT. IT IS FOUND AS OXIDES AND SILICATES IN NATURE AND IS USED AS A CRUCIAL COMPONENT IN MICROELECTRONICS AND COMPUTER CHIPS. SILICON IS THE MOST COMMONLY USED MATERIAL TO FORM SEMICONDUCTORS.

- **GERMANIUM**

SIMILAR IN APPEARANCE TO SILICON BUT NOT AS ABUNDANT IN NATURE, GERMANIUM IS ANOTHER WIDELY USED ELEMENT FOR FABRICATING SEMICONDUCTORS. IT IS PRESENT IN THE EARTH'S CRUST, MINED FROM SPHALERITE ZINC AND COPPER ORES. HOWEVER, IT IS LESS VALUABLE THAN SILICON DUE TO ITS THERMAL SENSITIVITY AND COST. A COMMON USE FOR GERMANIUM DOPED WITH SILICON IS SEEN IN HIGH-SPEED DEVICES AND APPLICATIONS.

WHO DECIDES MY NATURE – CONDUCTOR/SEMICONDUCTOR/INSULATOR ?

- **CONDUCTORS, SEMICONDUCTORS, AND INSULATORS:**

THEIR DESCRIPTION IS PROVIDED IN TERMS OF:

- ENERGY BANDS FOR ELECTRONS IN SOLIDS**
- THE PAULI EXCLUSION PRINCIPLE**

**IN ORDER FOR A MATERIAL TO CONDUCT ELECTRICITY, IT MUST BE POSSIBLE TO GET THE ELECTRONS MOVING
(I.E., GIVE THEM SOME ENERGY).**

SEMI-CLASSICAL PICTURE OF CONDUCTION

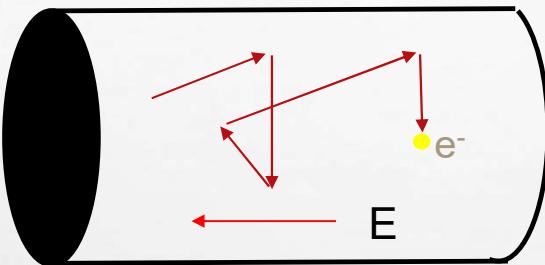
Wire with cross section A

$$J = nev_{\text{drift}}$$

$$v_{\text{drift}} = a\tau = \frac{F}{m}\tau = \frac{eE}{m}\tau$$

$$J = \frac{ne^2\tau}{m}E = \sigma E, \text{ where}$$

$$\sigma \equiv \frac{ne^2\tau}{m} = \text{conductivity}$$



n = # free electrons/volume

τ = time between scattering events

J = current density = I/A

F = force = $-eE$

a = acceleration = F/m

Metal: scattering time gets shorter with increasing T

$$\text{Resistivity} \uparrow$$
$$\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$$

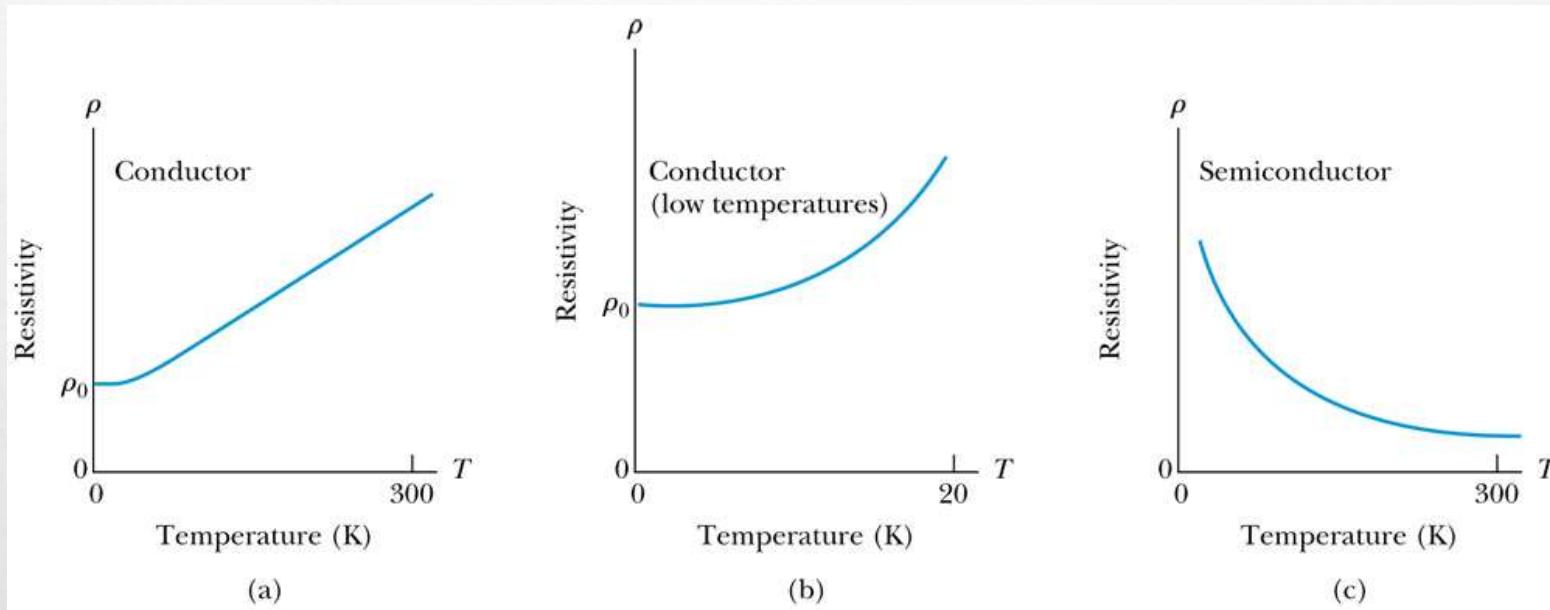
A more accurate description requires that we treat the electron as a quantum mechanical object.

Temperature, T

DOES CONDUCTIVITY DEPEND ON JUST THE NUMBER OF ELECTRONS ?

Element	Atomic Number	Valency	Electrical Conductivity (S/m)
Hydrogen (H)	1	1	Insulator
Helium (He)	2	0	Insulator
Lithium (Li)	3	1	$1.08 \text{ \AA} - 10^7$
Beryllium (Be)	4	2	$2.5 \text{ \AA} - 10^7$
Boron (B)	5	3	Insulator
Carbon (C)	6	4	Graphite: $2.0 \text{ \AA} - 10^4$, Diamond: Insulator
Nitrogen (N)	7	3	Insulator
Oxygen (O)	8	2	Insulator
Fluorine (F)	9	1	Insulator
Neon (Ne)	10	0	Insulator
Sodium (Na)	11	1	$2.1 \text{ \AA} - 10^7$
Magnesium (Mg)	12	2	$2.3 \text{ \AA} - 10^7$
Aluminum (Al)	13	3	$3.5 \text{ \AA} - 10^7$
Silicon (Si)	14	4	Semiconductor (around 1.56 S/m)
Phosphorus (P)	15	3	Insulator
Sulfur (S)	16	2	Insulator
Chlorine (Cl)	17	1	Insulator
Argon (Ar)	18	0	Insulator
Potassium (K)	19	1	$1.4 \text{ \AA} - 10^7$
Calcium (Ca)	20	2	$2.9 \text{ \AA} - 10^7$
Iron (Fe)	26	2	$1.0 \text{ \AA} - 10^7$
Copper (Cu)	29	1	$5.96 \text{ \AA} - 10^7$
Silver (Ag)	47	1	$6.30 \text{ \AA} - 10^7$
Gold (Au)	79	1	$4.10 \text{ \AA} - 10^7$
Lead (Pb)	82	2	$4.8 \text{ \AA} - 10^6$

RESISTIVITY VS. TEMPERATURE



(a) Resistivity versus temperature for a typical conductor. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \rightarrow 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity increases dramatically as $T \rightarrow 0$.

BAND THEORY OF SOLIDS

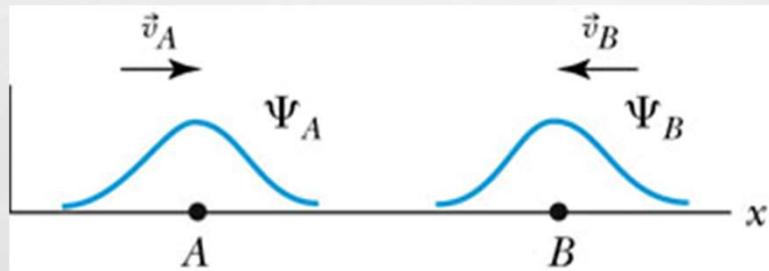
- IN ORDER TO ACCOUNT FOR *DECREASING* RESISTIVITY WITH INCREASING TEMPERATURE AS WELL AS OTHER PROPERTIES OF SEMICONDUCTORS, A NEW THEORY KNOWN AS THE BAND THEORY IS INTRODUCED.
- THE ESSENTIAL FEATURE OF THE BAND THEORY IS THAT THE ALLOWED ENERGY STATES FOR ELECTRONS ARE NEARLY CONTINUOUS OVER CERTAIN RANGES, CALLED ENERGY BANDS, WITH FORBIDDEN ENERGY GAPS BETWEEN THE BANDS.

A more accurate description requires that we treat the electron as a quantum mechanical object.

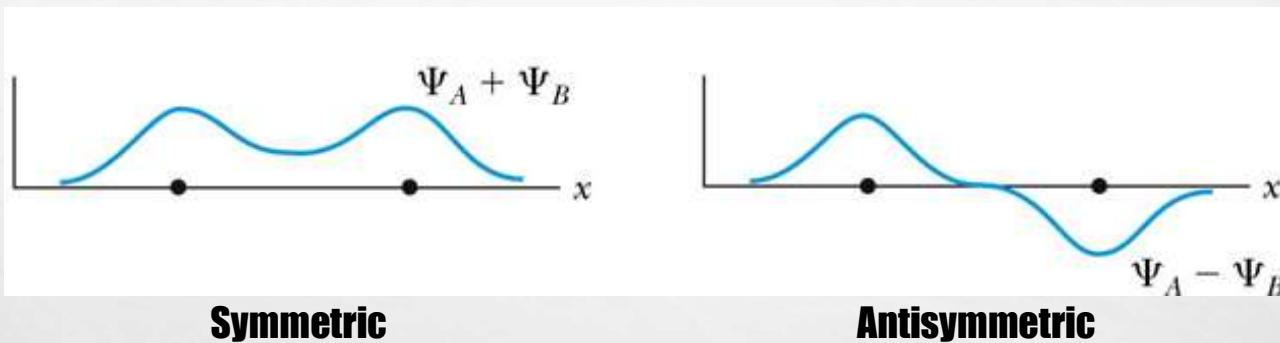
De-Broglie relation -

The **de Broglie relation** expresses the wave-particle duality, proposing that particles such as electrons exhibit both wave-like and particle-like properties. It relates the wavelength λ (lambda) of a particle to its momentum ($p=mv$).
The **de Broglie equation** is given by:

- CONSIDER INITIALLY THE KNOWN WAVE FUNCTIONS OF TWO HYDROGEN ATOMS FAR ENOUGH APART SO THAT THEY DO NOT INTERACT.



- INTERACTION OF THE WAVE FUNCTIONS OCCURS AS THE ATOMS GET CLOSER:



- AN ELECTRON IN THE SYMMETRIC STATE HAS A NONZERO PROBABILITY OF BEING HALFWAY BETWEEN THE TWO ATOMS, WHILE AN ELECTRON IN THE ANTISYMMETRIC STATE HAS A ZERO PROBABILITY OF BEING AT THAT LOCATION.
- IN THE SYMMETRIC CASE THE BINDING ENERGY IS SLIGHTLY STRONGER RESULTING IN A LOWER ENERGY STATE.

- EACH “ALLOWED” WAVEFUNCTION CORRESPONDS TO AN ALLOWED ENERGY STATE
- PAULI EXCLUSION PRINCIPLE STATES THAT NO TWO ELECTRONS CAN SHARE THE SAME STATE
- THUS THERE IS A SPLITTING OF ALL POSSIBLE ENERGY LEVELS (1s, 2s, AND SO ON).

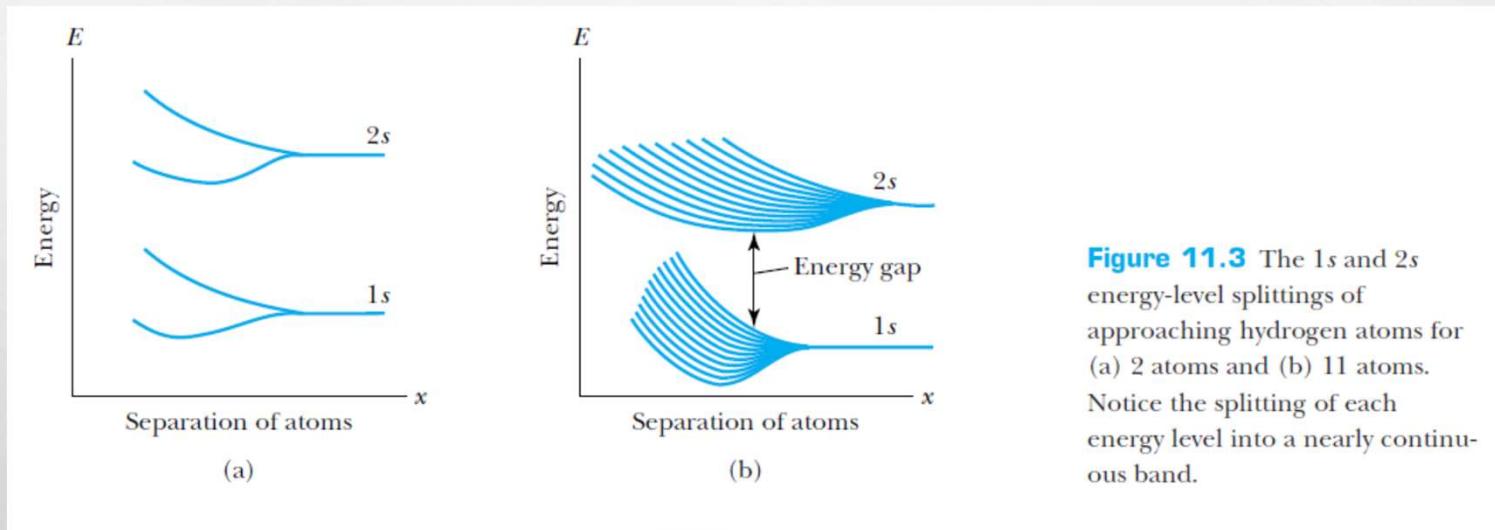
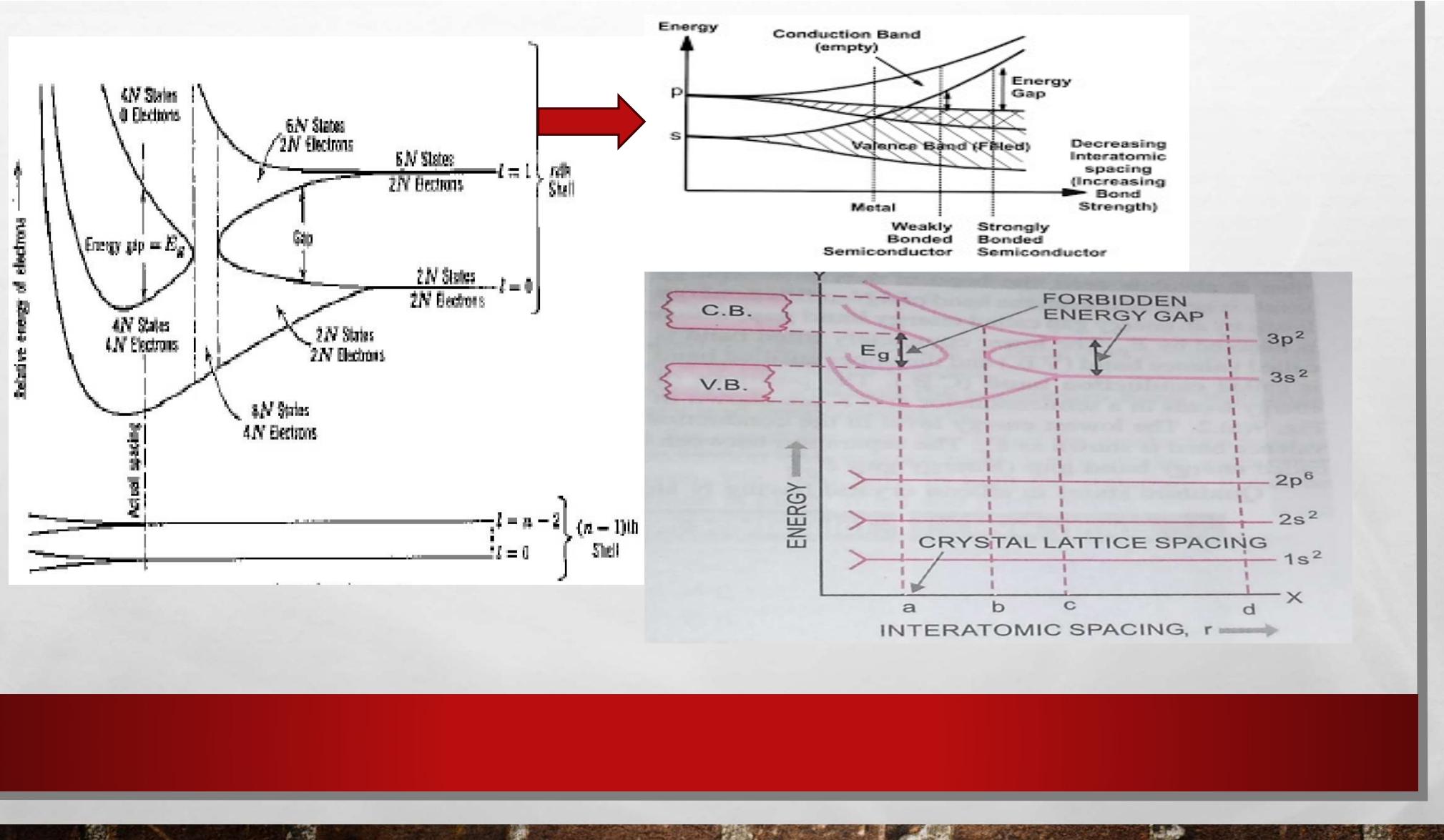


Figure 11.3 The 1s and 2s energy-level splittings of approaching hydrogen atoms for (a) 2 atoms and (b) 11 atoms. Notice the splitting of each energy level into a nearly continuous band.



WHEN DOES A MATERIAL BECOME AN INSULATOR/SEMICONDUCTOR OR CONDUCTOR ?

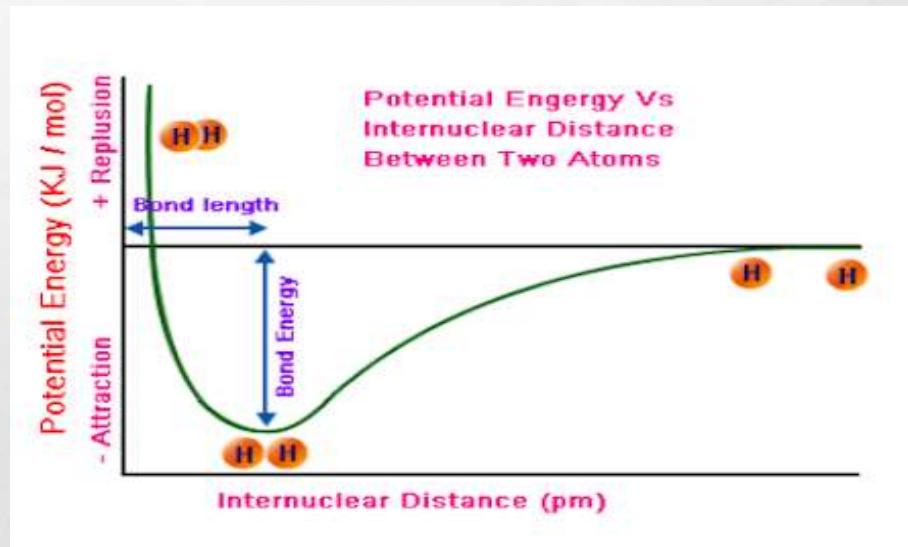
- Attractive force – between proton of one atom and electron of another.
- Repulsive – Electron-electron and nuclear repulsion(due to protons)

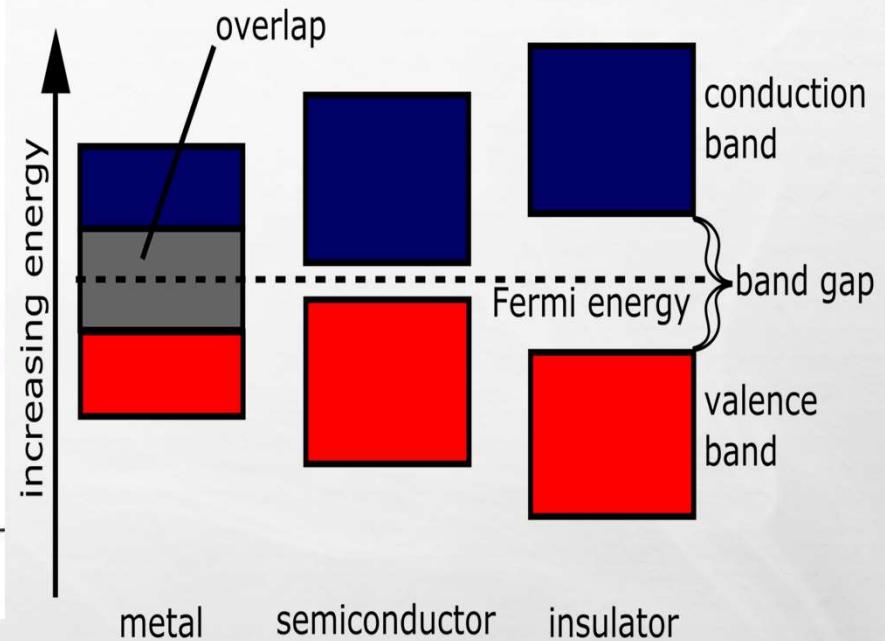
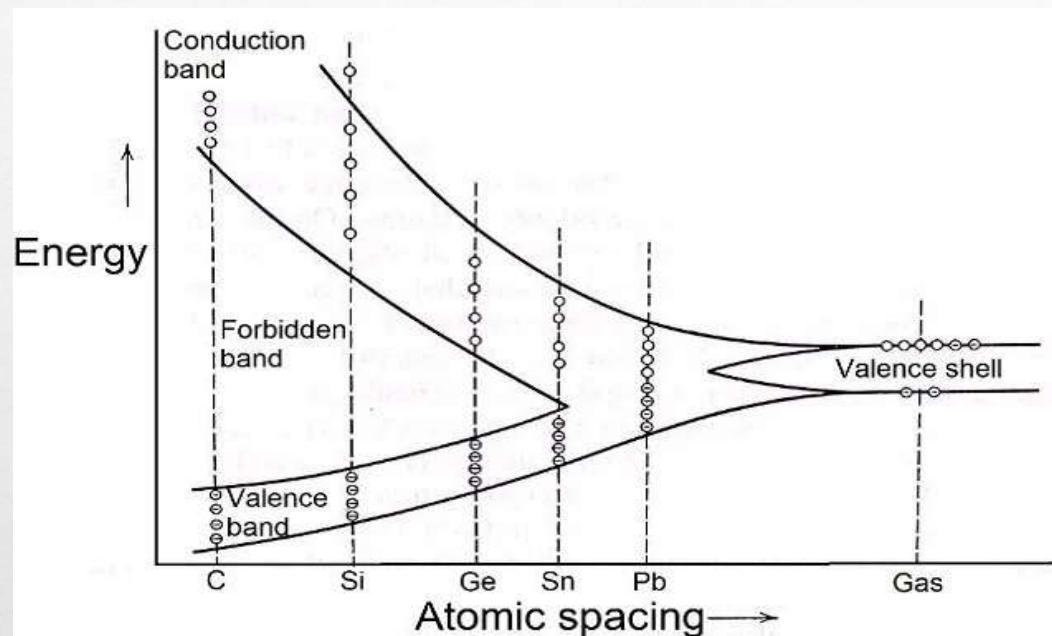
- For like charges (repulsive force), the potential energy increases as the distance decreases.
- For opposite charges (attractive force), the potential energy decreases (becomes more negative) as the particles move closer to each other.

The electrostatic potential is given by:

$$V=kQ_1Q/r$$

The graph of electrostatic potential (V) versus interatomic distance (r) typically represents the interaction between two charged particles. The general shape of this graph depends on whether the interaction is attractive or repulsive:





For a solid to conduct it needs –

- Carrier
- Space to move

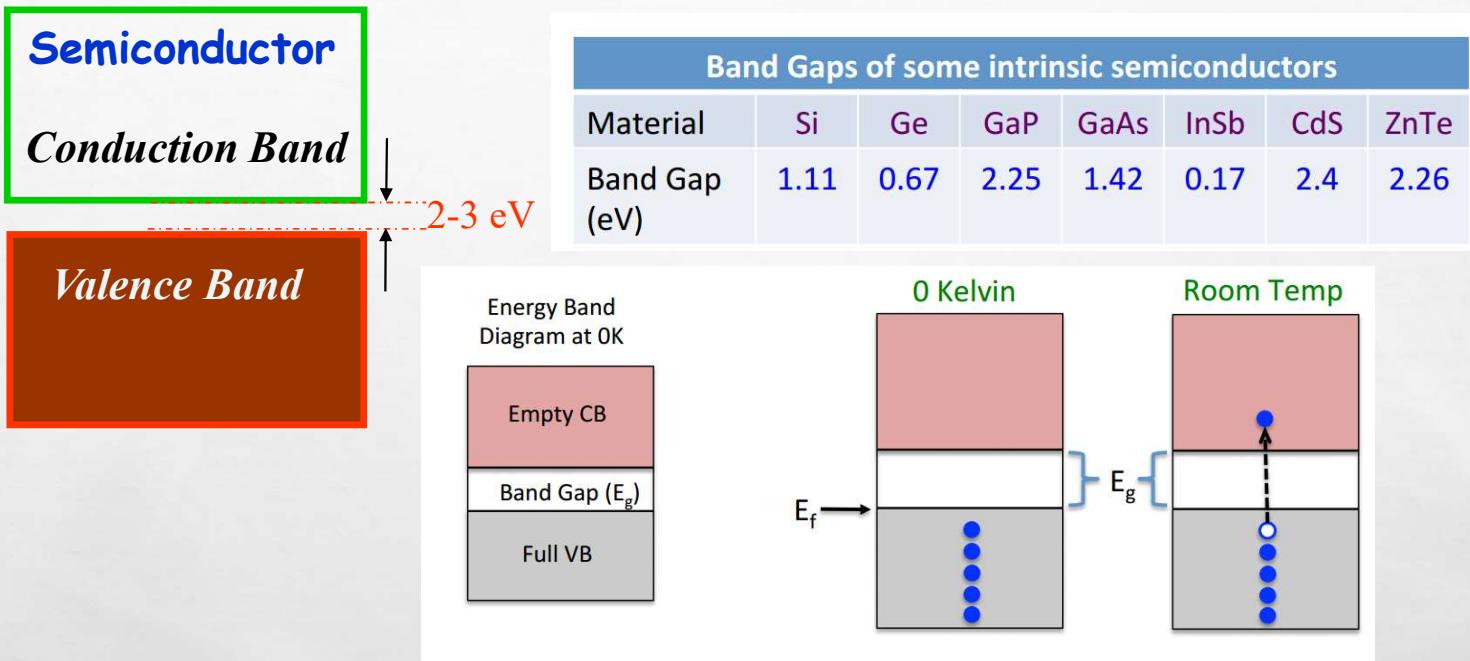
So a completely filled band with many electrons is as useless as an empty band

Energy band diagram: METALS



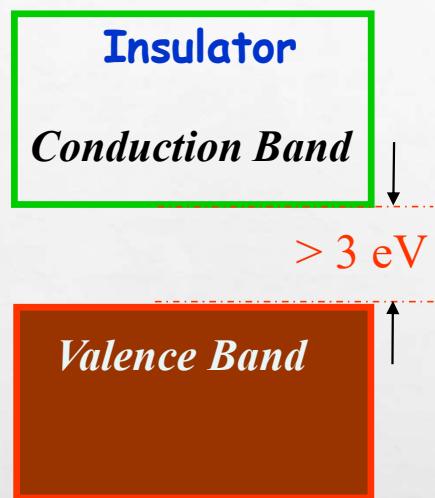
- ❑ Monovalent metals: Ag, Cu, Au → 1 e⁻ in the outermost orbital
⇒ outermost energy band is only half filled
- ❑ Divalent metals: Mg, Be → overlapping conduction and valence bands
⇒ they conduct even if the valence band is full
- ❑ Trivalent metals: Al → similar to monovalent metals!!!
⇒ outermost energy band is only half filled !!!

Energy band diagram: SEMICONDUCTORS

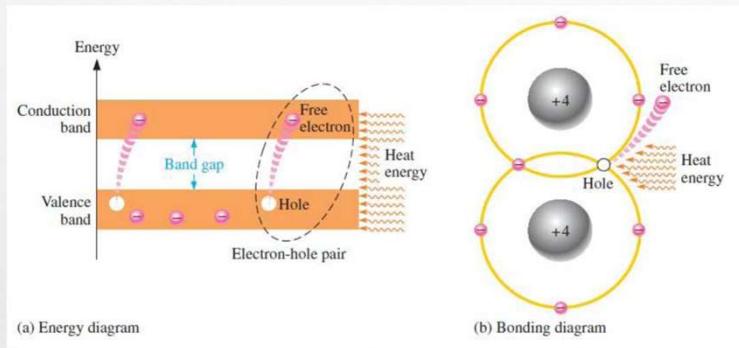


- ❑ Elements of the 4th column (C, Si, Ge, Sn, Pb) → valence band full but no overlap of valence and conduction bands
- ❑ Diamond → PE as strong function of the position in the crystal
⇒ Band gap is 5.4 eV
- ❑ Down the 4th column the outermost orbital is farther away from the nucleus and less bound
⇒ the electron is less strong a function of the position in the crystal ► reducing band gap down the column

Energy band diagram: INSULATORS



Charge Carriers in Semiconductors – Electrons and holes -



When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a hole.

For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an electron-hole pair.

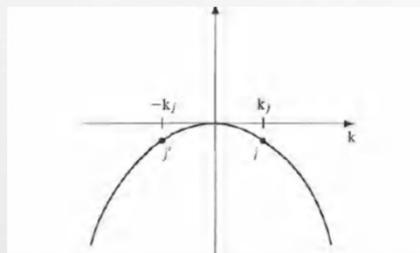
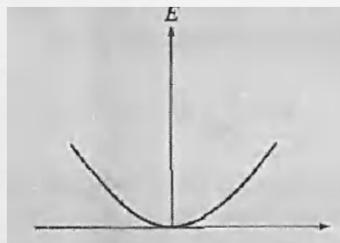
Recombination occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

What are 'holes' ?

$$\mathbf{p} = m\mathbf{v} = \hbar\mathbf{k}$$

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{\mathbf{p}^2}{m} = \frac{\hbar^2}{2m}\mathbf{k}^2$$

$$\frac{d^2E}{d\mathbf{k}^2} = \frac{\hbar^2}{m}$$



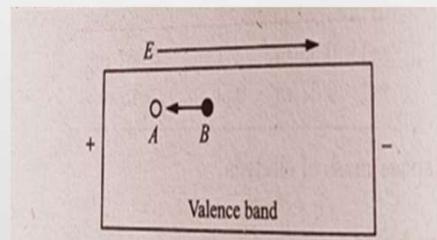
We know $J=nqv$

$$J = (-q) \sum_i^N v_i = 0 \quad (\text{filled band})$$

$$J = (-q) \sum_i^N v_i - (-q)v_j \quad (\text{jth electron missing})$$

$$= \frac{+q}{V} v_j$$

If the jth electron is removed



As the electron(B) moves from B to A . The hole position (A) shifts just like a positive charge in the direction of the field !

Effective mass of charge carriers

Total Force on a charged particle in a solid

$$F_{\text{Total}} = F_{\text{Ext}} + F_{\text{int}}$$

where $F_{\text{Ext}} = eE$ due to the externally applied electric field

F_{int} = due to the internal field created by the ions in the crystal solid.

We need to correlate the motion of the charge carrier with the external electric field which we know.

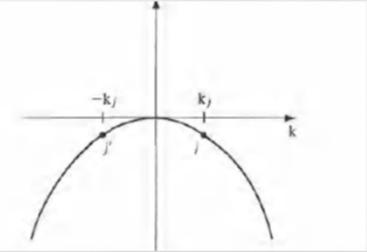
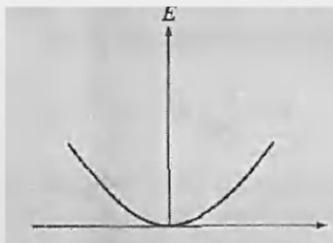
So we assume an “effective mass” just like effective current or r.m.s. value in electric circuits

Which includes the effect of the internal field

$$F_{\text{Ext}} = eE = F_{\text{Total}} - F_{\text{int}} = m^* a$$

$$\frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

$$m^* = \frac{\hbar^2}{d^2 E / dk^2}$$



E-K / (Band) Diagram

For 'holes' the same Force , i.e. Electric field produces a motion in the opposite direction

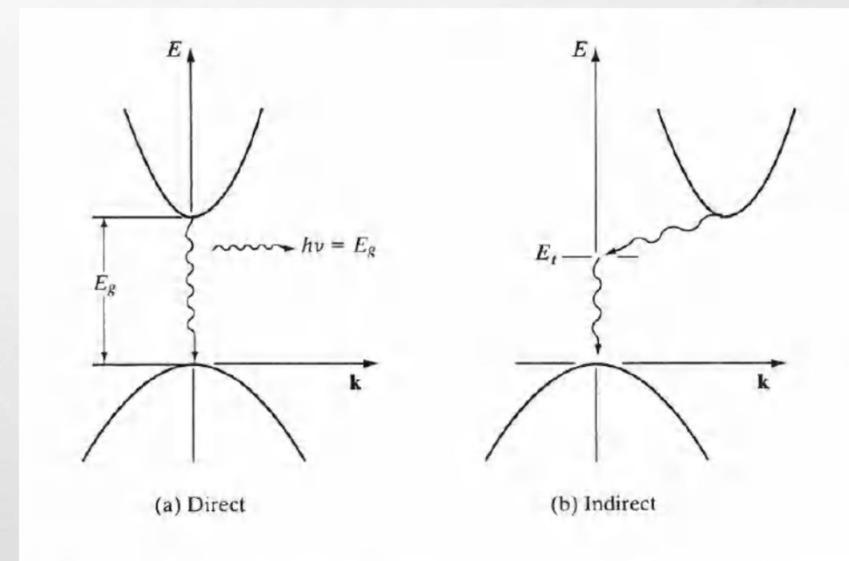
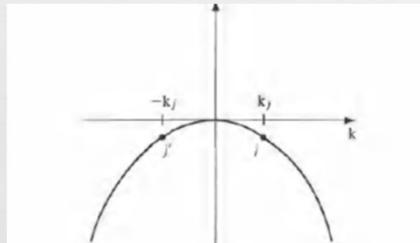
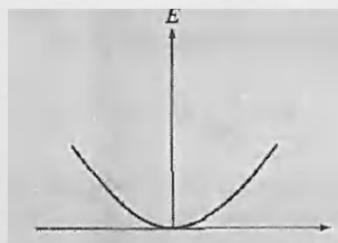
So we can justify that by

$$F_{\text{Ext}} = m^* a = (-m^*)x(-a)$$

i.e. a NEGATIVE EFFECTIVE MASS !

so for the same the same E-K relation , it implies an opposite curvature

since (d^2E/dk^2) represents the curvature of the E-K diagram



Detailed calculation of effective mass

$$v = V_g = \frac{dv}{d\left(\frac{1}{\lambda}\right)} = \frac{d\omega}{dk} = \frac{1}{\hbar} \frac{dE}{dk} \quad \dots(1.50)$$

where, $E = \hbar\omega$, $k = \frac{2\pi}{\lambda}$ and $\omega = 2\pi\nu$.

In case of free electrons, the $E-k$ relationship is given by

$$E = \frac{\hbar^2 k^2}{2m}$$

or,

$$\frac{dE}{dk} = \frac{\hbar^2}{m} k$$

$$v = V_g = \frac{1}{\hbar} \frac{dE}{dk} = \frac{1}{\hbar} \frac{\hbar^2 k}{m} = \frac{\hbar k}{m} = \frac{p}{m} \quad \dots(1.51)$$

$$dE = -e\epsilon V_g dt = -\frac{e\epsilon}{\hbar} \frac{dE}{dk} dt$$

where V_g is the group velocity of electron wave packet.

Again,

$$dE = \frac{dE}{dk} dk$$

$$\therefore \frac{dE}{dk} dk = -\frac{e\epsilon}{\hbar} \frac{dE}{dk} dt$$

$$\therefore dk = -\frac{e\epsilon}{\hbar} dt$$

or,

$$\hbar \frac{dk}{dt} = -e\epsilon = F$$

or,

$$\frac{d}{dt}(\hbar k) = F$$

$$\frac{dp}{dt} = F$$

$\dots(1.52)$

where F is the force exerted by the applied field on the electron. The above relation is an analogue of Newton's second law of motion for the electron moving in periodic crystal potential. Equation (1.52) states that the time rate of change of crystal momentum is equal to the external force on the electron.

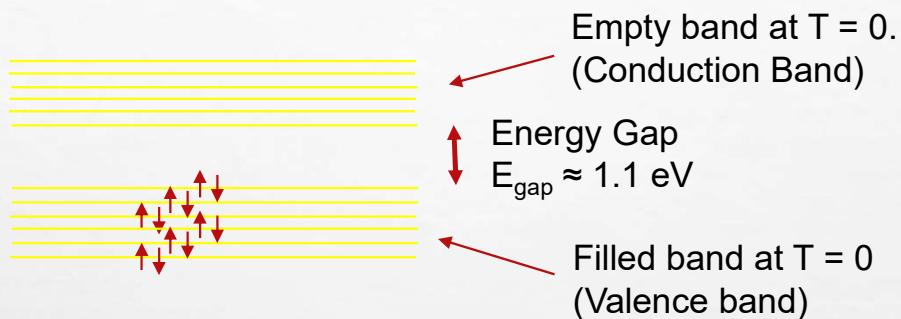
The acceleration of the electron wave packet is given by

$$\frac{dV_g}{dt} = \frac{1}{\hbar} \frac{d}{dt} \left(\frac{dE}{dk} \right) = \frac{1}{\hbar} \frac{d^2 E}{dk^2} \frac{dk}{dt} = -\frac{e\epsilon}{\hbar^2} \frac{d^2 E}{dk^2} = \frac{F}{m^*}$$

where m^* is the effective mass of electron given by

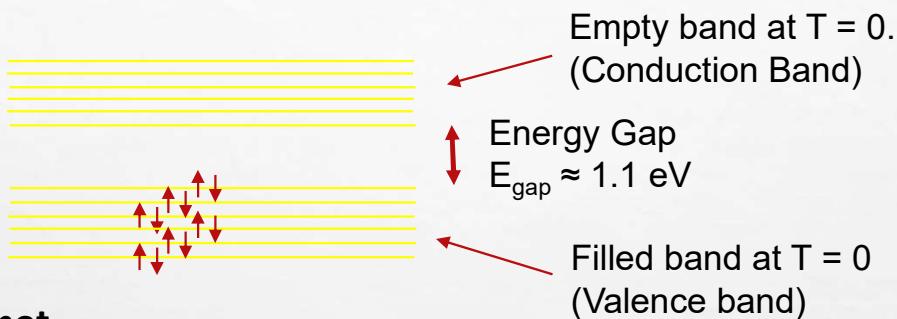
$$m^* = \frac{\hbar^2}{d^2 E / dk^2} \quad \dots(1.53)$$

GENERATION OF CARRIERS



The electrons in a filled band cannot contribute to conduction, because with reasonable E fields they cannot be promoted to a higher kinetic energy. Therefore, at T = 0, pure semiconductors are actually insulators.

SEMICONDUCTORS

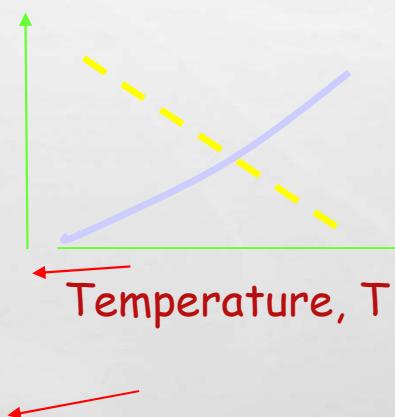


The electrons in a filled band cannot contribute to conduction, because with reasonable E fields they cannot be promoted to a higher kinetic energy. Therefore, at T = 0, pure semiconductors are actually insulators.

At higher temperatures, however, some electrons can be thermally promoted into the conduction band.

$$\rho \equiv \frac{1}{\sigma}$$

Resistivity



Metal: scattering time τ gets shorter with increasing T

Semiconductor: number n of free electrons increases rapidly with T (much faster than τ decreases)

This graph only shows trends. A semiconductor has much higher resistance than a metal.

SO HOW TO INCREASE CARRIERS ?

CONSIDER ELECTRONS IN A SEMICONDUCTOR, E.G., SILICON. IN A PERFECT CRYSTAL AT $T = 0$ THE VALENCE BANDS ARE FILLED AND THE CONDUCTION BANDS ARE EMPTY \rightarrow NO CONDUCTION. WHICH OF THE FOLLOWING COULD BE DONE TO MAKE THE MATERIAL CONDUCTIVE?

- A. HEAT THE MATERIAL
- B. SHINE LIGHT ON IT
- C. ADD FOREIGN ATOMS THAT CHANGE THE NUMBER OF ELECTRONS

SOLUTION

CONSIDER ELECTRONS IN A SEMICONDUCTOR, E.G., SILICON. IN A PERFECT CRYSTAL AT T=0 THE VALENCE BANDS ARE FILLED AND THE CONDUCTION BANDS ARE EMPTY ☐ NO CONDUCTION. WHICH OF THE FOLLOWING COULD BE DONE TO MAKE THE MATERIAL CONDUCTIVE?

A. HEAT THE MATERIAL

B. SHINE LIGHT ON IT

C. ADD FOREIGN ATOMS THAT CHANGE THE NUMBER OF ELECTRONS

a and b: Both of these add energy to the material, exciting some of the electrons into the conduction band.

c: Adding foreign atoms (called “doping”) will either cause the material to have too many electrons to fit into the valence band (some will go into the conduction band), or cause the valence band to have unfilled states. In either case, some electrons will have nearby (in energy) states to which they can be excited.

IMPURITY SEMICONDUCTOR

- IT IS POSSIBLE TO FINE-TUNE A SEMICONDUCTOR'S PROPERTIES BY ADDING A SMALL AMOUNT OF ANOTHER MATERIAL, CALLED A *DOPANT*, TO THE SEMICONDUCTOR CREATING WHAT IS CALLED AN IMPURITY SEMICONDUCTOR.
- AS AN EXAMPLE, SILICON HAS FOUR ELECTRONS IN ITS OUTERMOST SHELL (THIS CORRESPONDS TO THE VALENCE BAND) AND ARSENIC HAS FIVE.

THUS WHILE FOUR OF ARSENIC'S OUTER-SHELL ELECTRONS PARTICIPATE IN COVALENT BONDING WITH ITS NEAREST NEIGHBORS (JUST AS ANOTHER SILICON ATOM WOULD), THE FIFTH ELECTRON IS VERY WEAKLY BOUND.

IT TAKES ONLY ABOUT 0.05 EV TO MOVE THIS EXTRA ELECTRON INTO THE CONDUCTION BAND.

- THE EFFECT IS THAT ADDING ONLY A SMALL AMOUNT OF ARSENIC TO SILICON GREATLY INCREASES THE ELECTRICAL CONDUCTIVITY.

N-TYPE SEMICONDUCTOR

- THE ADDITION OF ARSENIC TO SILICON CREATES WHAT IS KNOWN AS AN *N*-TYPE SEMICONDUCTOR (*N* FOR NEGATIVE), BECAUSE IT IS THE ELECTRONS CLOSE TO THE CONDUCTION BAND THAT WILL EVENTUALLY CARRY ELECTRICAL CURRENT.

THE NEW ARSENIC ENERGY LEVELS JUST BELOW THE CONDUCTION BAND ARE CALLED DONOR LEVELS BECAUSE AN ELECTRON THERE IS EASILY DONATED TO THE CONDUCTION BAND.

ACCEPTOR LEVELS

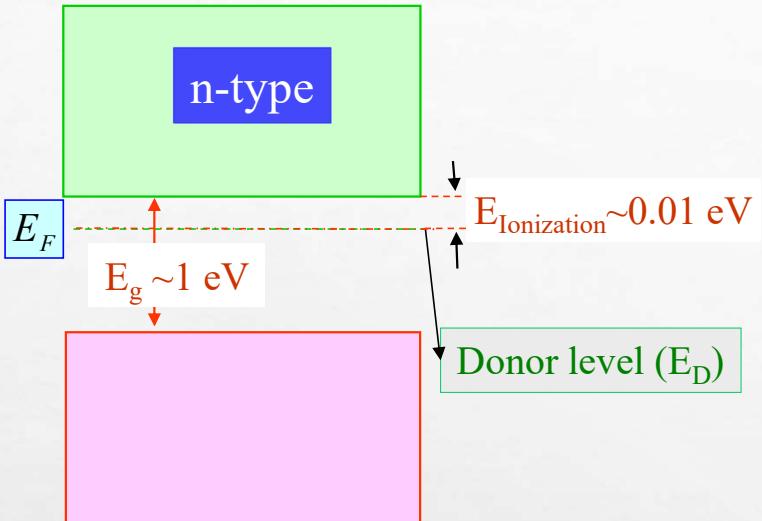
- CONSIDER WHAT HAPPENS WHEN INDIUM IS ADDED TO SILICON.
 - INDIUM HAS ONE LESS ELECTRON IN ITS OUTER SHELL THAN SILICON. THE RESULT IS ONE EXTRA HOLE PER INDIUM ATOM. THE EXISTENCE OF THESE HOLES CREATES EXTRA ENERGY LEVELS JUST ABOVE THE VALENCE BAND, BECAUSE IT TAKES RELATIVELY LITTLE ENERGY TO MOVE ANOTHER ELECTRON INTO A HOLE
 - THOSE NEW INDIUM LEVELS ARE CALLED ACCEPTOR LEVELS BECAUSE THEY CAN EASILY ACCEPT AN ELECTRON FROM THE VALENCE BAND. AGAIN, THE RESULT IS AN INCREASED FLOW OF CURRENT (OR, EQUIVALENTLY, LOWER ELECTRICAL RESISTANCE) AS THE ELECTRONS MOVE TO FILL HOLES UNDER AN APPLIED ELECTRIC FIELD
- IT IS ALWAYS EASIER TO THINK IN TERMS OF THE FLOW OF POSITIVE CHARGES (HOLES) IN THE DIRECTION OF THE APPLIED FIELD, SO WE CALL THIS A *P*-TYPE SEMICONDUCTOR (*P* FOR POSITIVE).
 - ACCEPTOR LEVELS *P*-TYPE SEMICONDUCTORS
- IN ADDITION TO INTRINSIC AND IMPURITY SEMICONDUCTORS, THERE ARE MANY COMPOUND SEMICONDUCTORS, WHICH CONSIST OF EQUAL NUMBERS OF TWO KINDS OF ATOMS.

Extrinsic semiconductors

- ❑ The addition of doping elements significantly increases the conductivity of a semiconductor.
In fact impurity is accidentally present in semiconductors (even in low concentrations like 1 atom in 10^{12} atoms), which make it extrinsic.

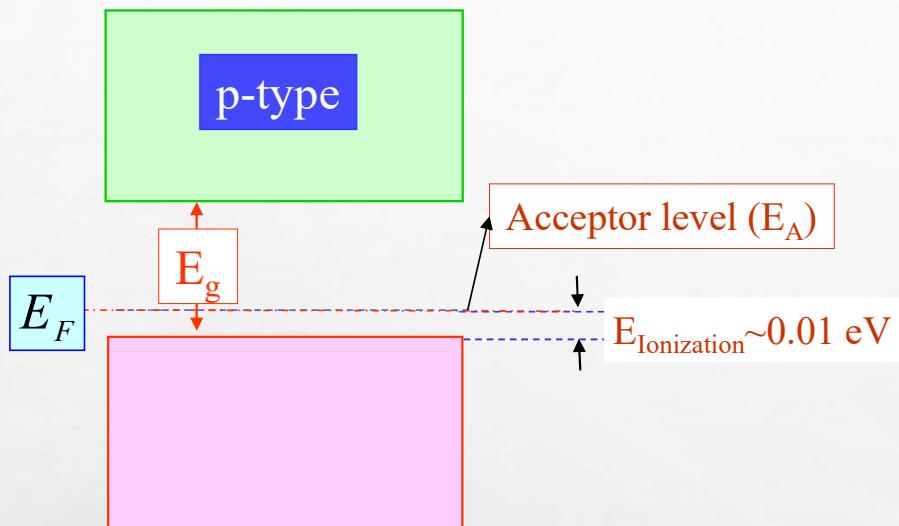
■ Doping of Si

- **V column element** (*P, As, Sb*) → the extra unbonded electron is practically free (*with a radius of motion of $\sim 80 \text{ \AA}$*)
 - ⇒ Energy level near the conduction band
 - ⇒ **n- type** semiconductor
- **III column element** (*Al, Ga, In*) → the extra electron for bonding supplied by a neighbouring Si atom → leaves a hole in Si.
 - ⇒ Energy level near the valence band
 - ⇒ **p- type** semiconductor



- Ionization Energy → Energy required to promote an electron from the Donor level to conduction band.
- $E_{\text{Ionization}} < E_g$
 \Rightarrow even at RT large fraction of the donor electrons are excited into the conduction band.

- ❑ Electrons in the conduction band are the majority charge carriers
- ❑ The fraction of the donor level electrons excited into the conduction band is much larger than the number of electrons excited from the valence band
- ❑ *Law of mass action:* $(n_e)^{\text{conduction band}} \times (n_h)^{\text{valence band}} = \text{Constant}$
- ❑ The number of holes is very small in an n-type semiconductor
- ❑ \Rightarrow Number of electrons \neq Number of holes



- At zero K the holes are bound to the dopant atom
- As $T \uparrow$ the holes gain thermal energy and break away from the dopant atom
 ⇒ available for conduction
- The level of the bound holes are called the acceptor level (which can accept and electron) and acceptor level is close to the valance band
- Holes are the majority charge carriers
- Intrinsically excited electrons are small in number
- ⇒ Number of electrons ≠ Number of holes

Fermi-Dirac distribution and the Fermi-level

Density of states tells us **how many states exist at a given energy E** . The **Fermi function $f(E)$** specifies how many of the existing states at the energy E will be filled with electrons. The function $f(E)$ specifies, **under equilibrium conditions**, the **probability** that an available state at an energy E will be occupied by an electron. It is a **probability distribution function**.

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

(2.7)

E_F = Fermi energy or Fermi level

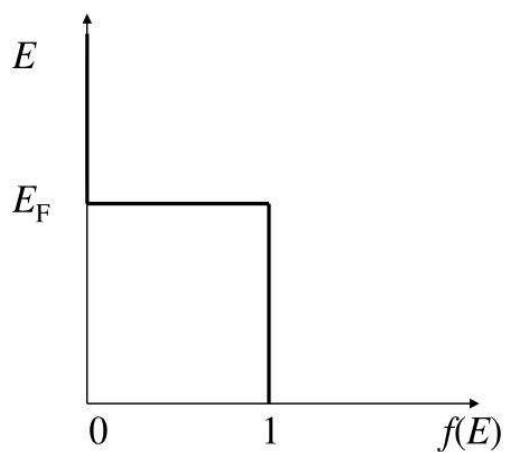
k = Boltzmann constant = 1.38×10^{-23} J/K
= 8.6×10^{-5} eV/K

T = absolute temperature in K

Fermi-Dirac distribution: Consider $T \rightarrow 0$ K

For $E > E_F$:
$$f(E > E_F) = \frac{1}{1 + \exp(+\infty)} = 0$$

For $E < E_F$:
$$f(E < E_F) = \frac{1}{1 + \exp(-\infty)} = 1$$



Fermi-Dirac distribution: Consider $T > 0$ K

If $E = E_F$ then $f(E_F) = \frac{1}{2}$

If $E \geq E_F + 3kT$ then $\exp\left(\frac{E - E_F}{kT}\right) \gg 1$

Thus the following approximation is valid: $f(E) = \exp\left(\frac{-(E - E_F)}{kT}\right)$

i.e., most states at energies $3kT$ above E_F are empty.

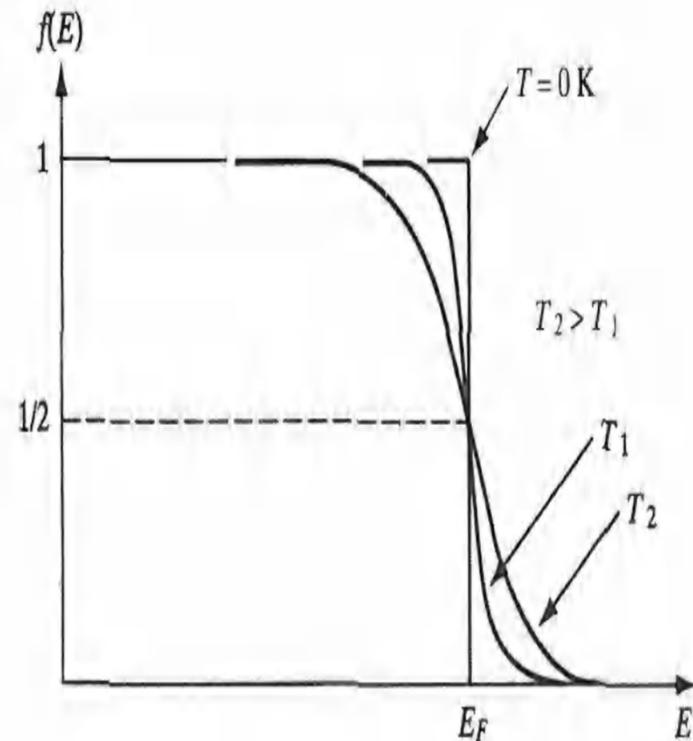
If $E \leq E_F - 3kT$ then $\exp\left(\frac{E - E_F}{kT}\right) \ll 1$

Thus the following approximation is valid: $f(E) = 1 - \exp\left(\frac{E - E_F}{kT}\right)$

So, $1 - f(E)$ = Probability that a state is empty, decays to zero.

So, most states will be filled.

kT (at 300 K) = 0.025 eV, $E_g(\text{Si})$ = 1.1 eV, so $3kT$ is very small in comparison.



EQUILIBRIUM DISTRIBUTION OF CARRIERS

n

$$\int_{E_c}^{\alpha} N(E) f(E) dE$$

p

$$\int_{-\alpha}^{E_F} N(E) (1 - f(E)) dE$$

where $f(E)$ is the Fermi Function and $N(E)$ is the density of States .To avoid

- to avoid the integration we can use the 'effective density of states'- N_c / N_v
- i.e. as if all the states are condensed to the edge of the band

$$n_0 = N_c f(E_c)$$

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

$$[n_0 = N_c e^{-(E_c - E_F)/kT}]$$

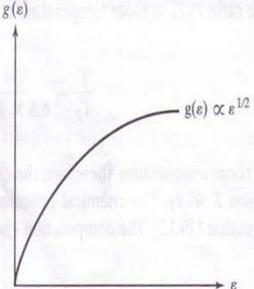
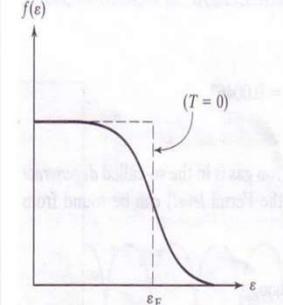
$$N_c = 2 \left(\frac{2\pi m_n^* k T}{h^2} \right)^{3/2}$$

$$p_0 = N_v [1 - f(E_v)]$$

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

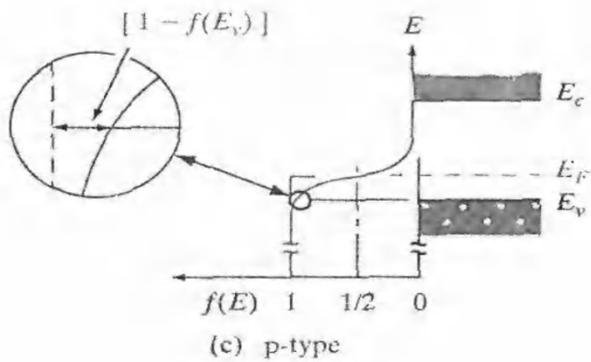
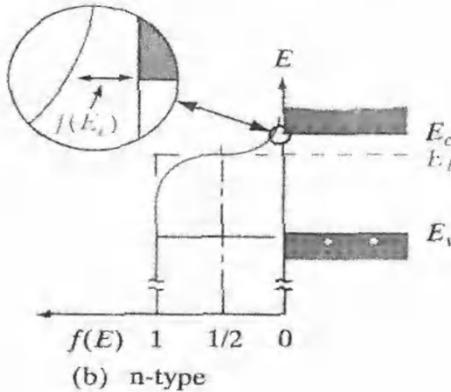
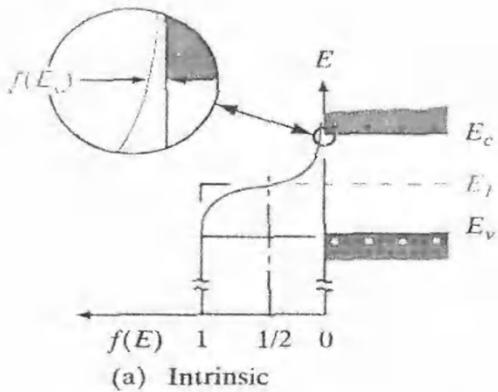
$$[p_0 = N_v e^{-(E_F - E_v)/kT}]$$

(a) Properties of a Fermion gas



$$N_v = 2 \left(\frac{2\pi m_p^* k T}{h^2} \right)^{3/2}$$

POSITION OF FERMI LEVEL AND CARRIER CONCENTRATION



$$n_i = N_c e^{-(E_c - E_i)/kT}, \quad p_i = N_v e^{-(E_i - E_v)/kT}$$

$$\begin{aligned} n_0 p_0 &= (N_c e^{-(E_c - E_f)/kT})(N_v e^{-(E_f - E_v)/kT}) = N_c N_v e^{-(E_c - E_v)/kT} \\ &= N_c N_v e^{-E_v/kT} \\ n_i p_i &= (N_c e^{-(E_c - E_i)/kT})(N_v e^{-(E_i - E_v)/kT}) = N_c N_v e^{-E_v/kT} \end{aligned}$$

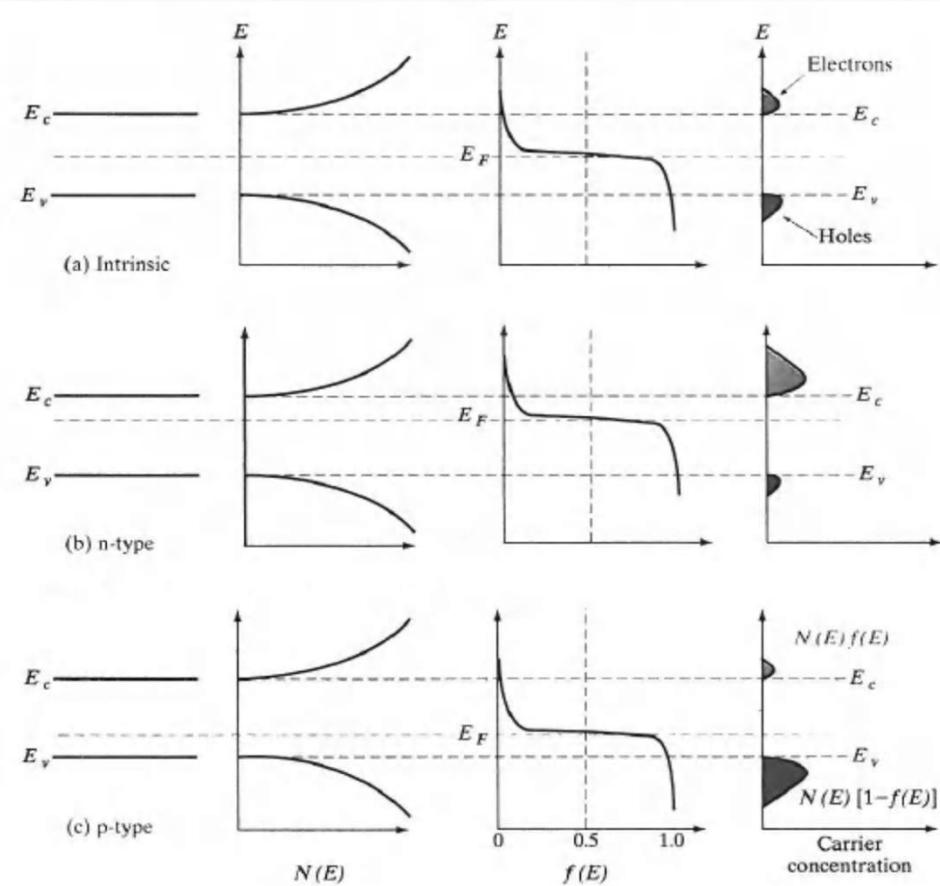
$$n_0 p_0 = n_i^2$$

Law of mass Action

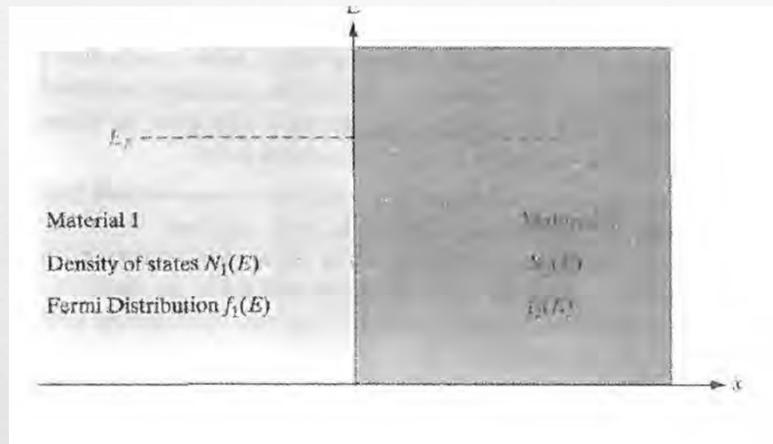
Space-Charge neutrality condition

$$p_0 + N_d^+ = n_0 + N_a^-$$

$$\begin{cases} n_0 = n_i e^{(E_f - E_i)/kT} \\ p_0 = n_i e^{(E_i - E_f)/kT} \end{cases}$$



INVARIANCE OF FERMI LEVEL



$$\text{rate from 1 to 2} \propto N_1(E)f_1(E) \cdot N_2(E)[1 - f_2(E)]$$

$$\text{rate from 2 to 1} \propto N_2(E)f_2(E) \cdot N_1(E)[1 - f_1(E)]$$

$$N_1(E)f_1(E) \cdot N_2(E)[1 - f_2(E)] = N_2(E)f_2(E) \cdot N_1(E)[1 - f_1(E)]$$

$$N_1f_1N_2 - N_1f_1N_2f_2 = N_2f_2N_1 - N_2f_2N_1f_1$$

$$f_1(E) = f_2(E), \quad \text{that is, } [1 + e^{(E - E_{F1})/kT}]^{-1} = [1 + e^{(E - E_{F2})/kT}]^{-1}$$

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

EXAMPLE 3-5 A Si sample is doped with 10^{17} As atoms/cm³. What is the equilibrium hole concentration p_0 at 300 K? Where is E_F relative to E_i ?

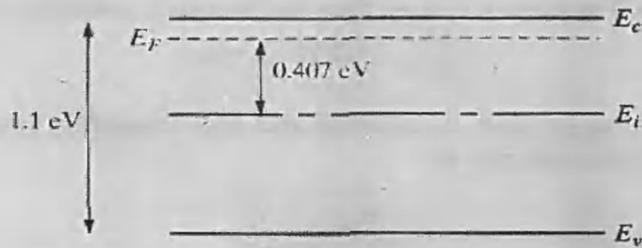
SOLUTION Since $N_d \gg n_i$, we can approximate $n_0 = N_d$ and

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}$$

From Eq. (3-25a), we have

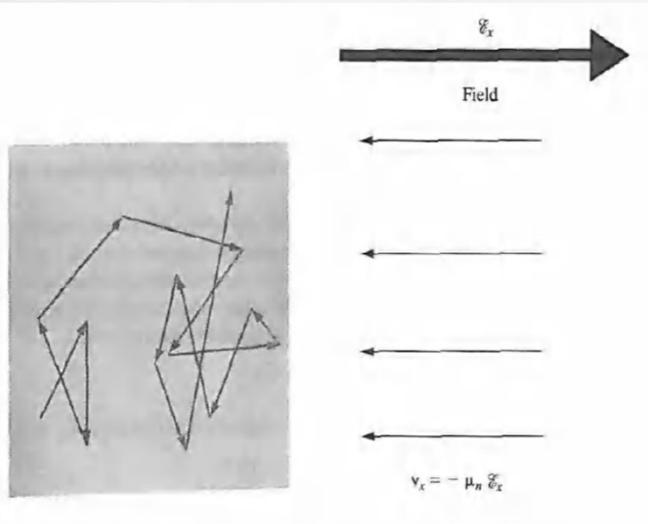
$$E_F - E_i = kT \ln \frac{n_0}{n_i} = 0.0259 \ln \frac{10^{17}}{1.5 \times 10^{10}} = 0.407 \text{ eV}$$

The resulting band diagram is:



MECHANISM OF FLOW – DRIFT AND DIFFUSION

- **DRIFT** = In Absence Of An Electric Field The Electrons Move Randomly Giving A Net Zero Current. On application of an electric field they experience acceleration between two collisions with lattice ions, the average of such acceleration being called the 'relaxation time'. The average velocity produced by such a 'zig-zag' motion through the solid under the influence of an Electric field is called drift velocity.



$$v(t) = v(0) + at$$

$$v(t) = v(0) + (e\epsilon/m^*)t$$

$$\langle v(t) \rangle = \langle v(0) \rangle + (e\epsilon/m^*)\langle t \rangle$$

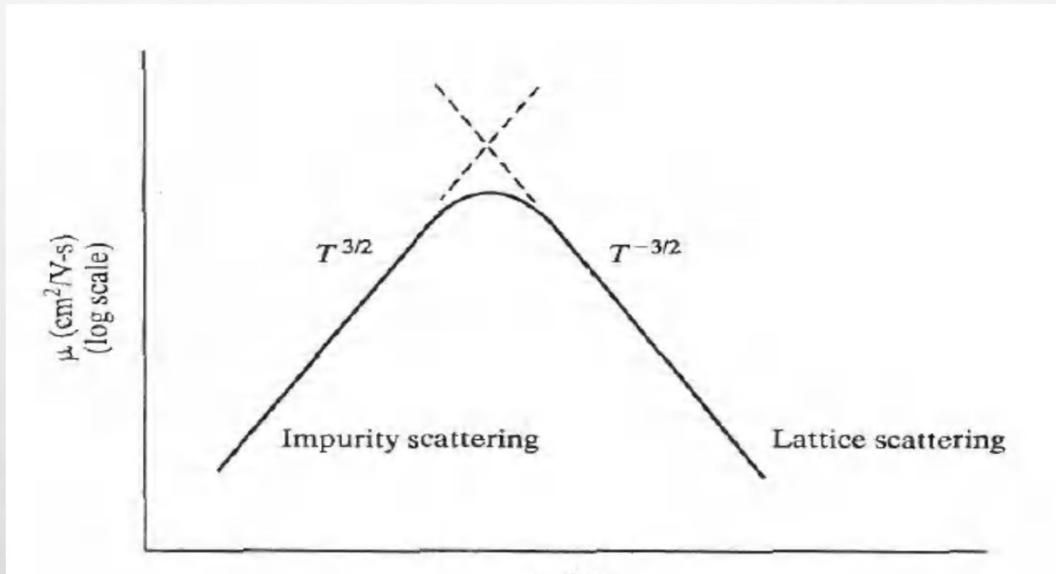
$$V_d = (e\epsilon/m^*)\tau$$

$$V_d = \mu\epsilon \text{ where } \mu = (e\epsilon/m^*)$$

$$I = ne V_d = ne \mu\epsilon = \sigma \epsilon$$

$$I = JA = \sigma \epsilon A = \sigma VA/d = V/(pd/A) = V/R \text{ if we assume } \rho = 1/\sigma$$

MOBILITY VARIATION WITH TEMP



EXAMPLE 3-7 A Si bar 0.1 cm long and $100 \mu\text{m}^2$ in cross-sectional area is doped with 10^{17} cm^{-3} phosphorus. Find the current at 300 K with 10 V applied.

SOLUTION For this applied voltage, we see that the electric field is low enough that we are in the ohmic regime. From Fig. 3-23, for this doping, the $\mu_n = 700 \text{ cm}^2/\text{V}\cdot\text{s}$.

$$\sigma = q\mu_n n_0 = 1.6 \times 10^{-19} \times 700 \times 10^{17} = 11.2(\Omega \cdot \text{cm})^{-1} = \rho^{-1}$$

$$\rho = 0.0893 \Omega \cdot \text{cm}$$

$$R = \rho L/A = 0.0893 \times 0.1/10^{-6} = 8.93 \times 10^3 \Omega$$

$$I = V/R = 10/(8.93 \times 10^3) = \mathbf{1.12 \text{ mA}}$$

DIFFUSION

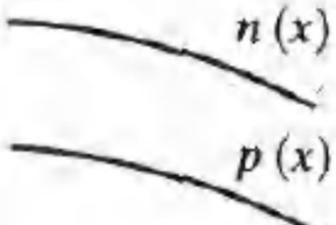
$$\phi_n(x) = -D_n \frac{dn(x)}{dx}$$

$$\phi_p(x) = -D_p \frac{dp(x)}{dx}$$

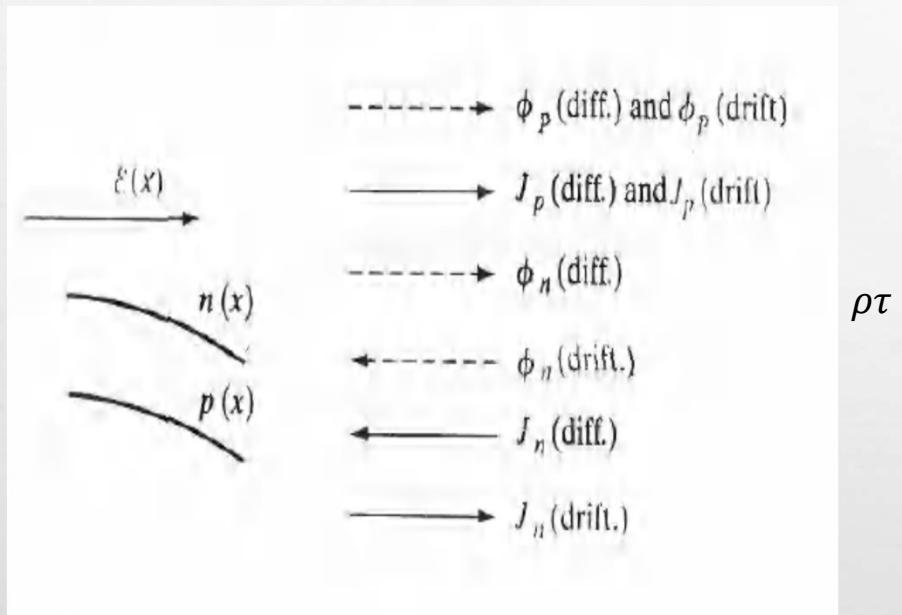
$$J_n(\text{diff.}) = -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx}$$

$$J_p(\text{diff.}) = -(+q)D_p \frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx}$$

$\vec{v}(x)$



MECHANISM OF FLOW – DRIFT AND DIFFUSION



$$\left. \begin{array}{l} J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx} \\ \qquad \qquad \qquad \text{drift} \qquad \qquad \text{diffusion} \\ J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx} \end{array} \right\}$$

$$\begin{aligned} J_n(\text{diff.}) &= -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx} \\ J_p(\text{diff.}) &= -(+q)D_p \frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx} \end{aligned}$$