Sub:	Electronic Devices					Code:	18EC33
Date:	17/12/2021	Duration:	90 mins	Max Marks:	50	Sem: III	Branch: ECE-A,B,C,D

Answer Any FIVE FULL Questions

1. With a neat diagram describe the formation of different energy levels in silicon atom as a function of inter atomic spacing. What are direct and indirect semiconductors? [5+5]

2. Write notes on: (i) intrinsic semiconductor (ii) extrinsic semiconductor
   (iii) impurity scattering   (iv) lattice scattering.   [10]

3. Discuss Zener and Avalanche breakdown mechanisms in details at a p-n junction with suitable diagrams. [10]

4a). Derive the expression of current density in a semiconductor in terms of charge, carrier concentration, mobility and applied electric field.[5]

b) For a Si bar having a length of 4 μm, doped n-type at $10^{17}/cm^3$, calculate the current for an applied voltage of 2 V with area of $0.01 cm^2$. If the voltage is now raised at $100\ V$, what will be the change in current? Electron mobility is $1350\ cm^2/V-sec$, for higher field saturation, the velocity for electron is $V_C = 10^7\ cm/sec$.[5]

5a). What is Hall Effect?   [5]

b) Semiconductor bar with $w = 0.1\ mm$, $t = 10\ \mu m$, and $L = 5\ mm$ with the length along x [5] axis for $B = 10\ kG$ in z direction ($1\ kG = 10^{-5}\ Wb/cm^2$) and a current of $1\ mA$ along x-direction. Given that $V_{AB} = -2\ mV$, $V_{CD} = 100\ mV$. Find the type, concentration, and mobility of the majority carriers. Consider the thickness to be along z-direction.

6. Draw and explain the energy band diagram of a PN junction i) at equilibrium, ii) under [10] forward bias and iii) under reverse bias. Explain qualitatively the effect of biasing on current using current equation and I-V characteristic graph

7. Explain the various bonding forces in solid. Also differentiate between metals, semiconductors [10] and insulators.

Solution

Q1   As the spacing between the two atoms becomes smaller, electron wavefunctions begin to overlap.

- There is a splitting of the discrete energy levels of the isolated atoms into new levels belonging to the pair rather than to individual atoms.
- In a solid, many atoms are brought together, so that the split energy levels form essentially continuous *bands* of energies.
- Consider the imaginary formation of a silicon crystal from isolated silicon atoms(N).
- If we consider *N* Si atoms, there will be 2*N*, 2*N*, 6*N*, 2*N*, and 6*N* states of type 1*s*, 2*s*, 2*p*, 3*s*, and 3*p*, respectively.
- As the interatomic spacing decreases, these energy levels split into bands.
- The "3*s*" and "3*p*" bands grow and merge into a single band composed of a mixture of energy levels.
- At equilibrium this band splits in to valance band and conduction band separated by wide energy gap (forbidden gap)
- Initially 4N(2N+2N) electrons and 8N states are available. As distance $\downarrow$ energy levels split into CB and VB. 4N electrons occupy 4N states in VB and 4N states in CB are empty.
- At 0 K, *every* state in the valence band will be filled, while the conduction band will be completely empty of electrons.
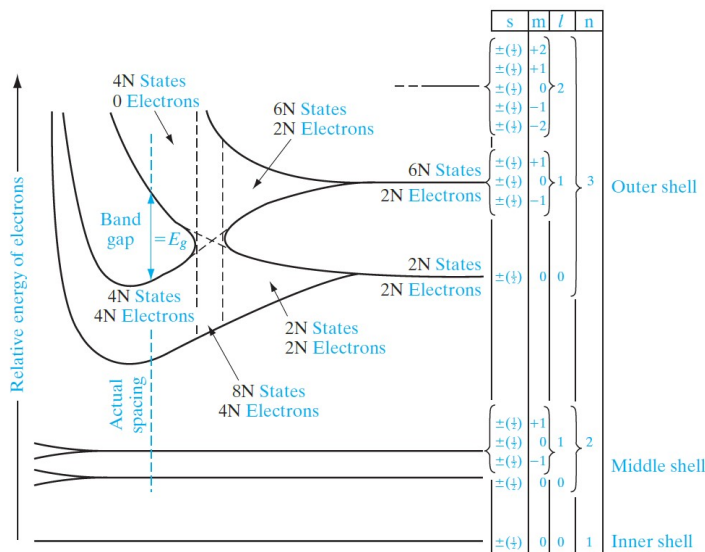

- <u>Direct Semiconductors</u>: The minimum of the conduction band and the maximum of valence band occur for same value of k.
- Thus an electron making a smallest energy transition from the conduction band to valence band without a change in k value.
- Thus electrons make smallest-energy transition
- There is direct band-to-band transition in direct semiconductors.
- During the transition they radiate light energy.
- Applications: Used for LEDs, Laser
- For GaAs the minimum of the conduction band and the maximum of the valence band occur for same value of k =0.
- The band diagram shown during this discussion are cumbersome to draw in analyzing devices. Therefore band diagram discussed during classification of elements are used.
- <u>Indirect Semiconductor:</u> In Indirect Semiconductors the minimum of the conduction band does not occur at the same k value as the valence band is maximum.
- An electron promoted to the conduction band requires a change of its momentum to make the transition to the valence band
- Si has its valance band maximum at a different value of k than its conduction band minimum.

- So the transition from minimum point in conduction band to maximum point in valance band requires some change in k.
- This change in k requires change in momentum of electron.
- So there is no direct band-to-band transition in Si, it must undergo a change in momentum as well as changing its energy.
- It may go through defect state.

(a) Direct   (b) Indirect
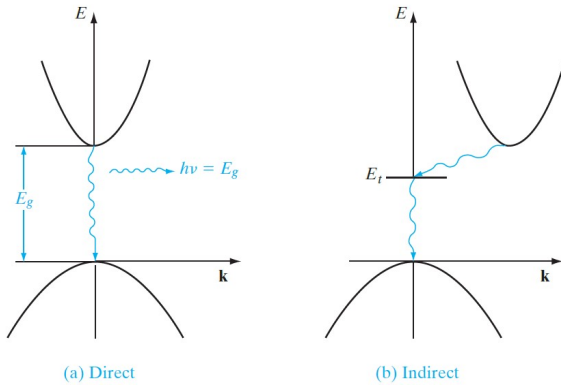
Q2.i) Intrinsic semiconductor:
- A perfect semiconductor without any lattice defects is called an intrinsic semiconductor.
- There are no charge carriers at 0K. At higher temps EHPs are generated which are the only charge carriers.
- Since EHP are created in pair, if the 'n' number of electron concentration (electrons/cm^3) in the conduction band which equals to the 'p' number of hole concentration in the valence band are created. i.e. **n=p=n$_i$**
- Conductivity in a semiconductor depends on two factors
  1. Concentration of electrons and holes. Denoted as n and p and are temperature dependent.
 2. Ability of the electron and holes to travel in the lattice without scattering
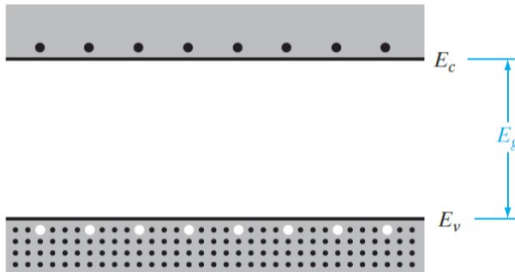
ii)An extrinsic semiconductor is a semiconductor doped by a specific impurity to increase the carrier concentration. Thus there are two types of doped semiconductors, n-type (Major electrons) and p-type (Major holes).
- A n-type semiconductor is created when pentavalent elements P(15), As(33), Sb(51) are used to dope pure semiconductors, like Si and Ge. The impurity atoms are called Donor atoms, since they donate electrons. Thus at about 50–100 K virtually all of the electrons in the impurity level are "donated" to the conduction band. Such an impurity level is called a donor level
- A p-type semiconductor is created when trivalent elements B(5), Al(13), Ga(31)and In(49) are used to dope pure semiconductors, like Si and Ge. When a trivalent atom takes the place of a Si atom, three of its electrons bond with three neighboring Si atoms. However, there is no electron to bond with the fourth Si atom. This leads to a hole or a vacancy between the trivalent and the fourth silicon atom. At low temperatures, enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band. Since this type of impurity level "accepts" electrons from the valence band, it is called an acceptor level.

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n-type semiconductor   p- type semiconductor

$T = 0\,K$ $T \simeq 50\,K$ $T = 0\,K$ $T \simeq 50\,K$
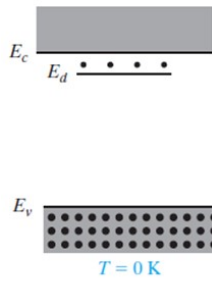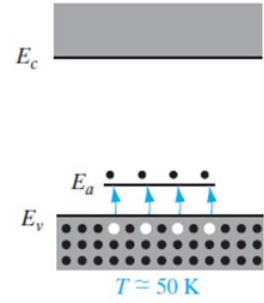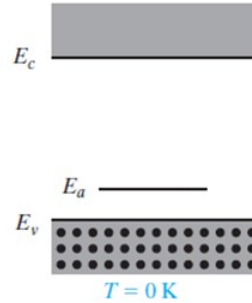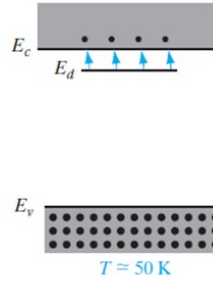
iii) Lattice scattering →scattering by vibration of lattice resulting from temperature. Frequency of scattering ↑by ↑in temperature. Results in mobility↓.

iv) Impurity scattering : Scattering from crystal defects such as ionized impurities becomes the dominant mechanism at low temperatures. Impurity scattering events cause a decrease in mobility with decreasing temperature. With a donor doping concentration of 10^{17} cm^{-3}, however, μ_n is 700 cm^2/(V-s). Thus, the presence of the 10^{17} ionized donors/cm^3 introduces a significant amount of impurity scattering.

- As the concentration of impurities increases, the effects of impurity scattering are felt at higher temperatures. The mobilities due to two or more scattering mechanisms add inversely
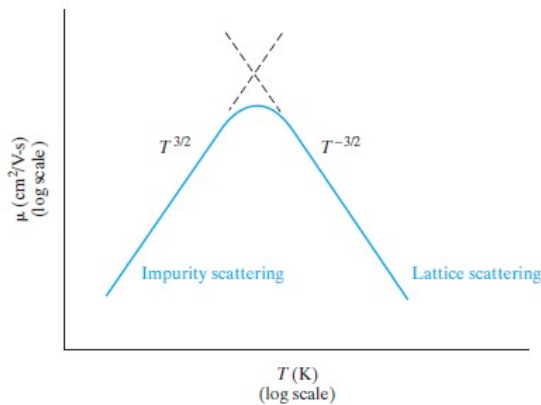

- Q3. Zener Breakdown: When a heavily doped junction is reverse biased, the energy bands become crossed at relatively low voltages. Tunneling of electrons from the p-side valence band to the n-side conduction band constitutes a reverse current from n to p this is the *Zener effect*. It is important that the metallurgical junction be sharp and the doping high, so that the transition region W extends only a very short distance from each side of the junction.
- d becomes smaller as the reverse bias is increased.
- If Zener breakdown does not occur with reverse bias of a few volts, avalanche breakdown will become dominant.
- The Zener effect can be thought of as field ionization of the host atoms at the junction
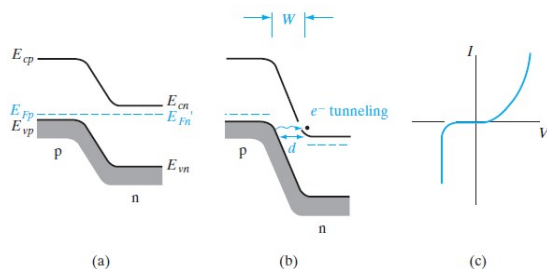
- **Avalanche breakdown:** For lightly doped junctions electron tunneling is negligible, and instead, the breakdown mechanism involves the *impact ionization* of host atoms by energetic carriers.
- An incoming electron may have a collision with the lattice and create an EHP; each of these carriers has a chance of creating a new EHP, and each of those can also create an EHP, and so forth..
- This is avalanche process. Consider a probability P of having an ionizing collision with the lattice.
- Physically, we expect the ionization probability to increase with increasing electric field, and therefore to depend on the reverse bias.
- Measurements of carrier multiplication M in junctions near breakdown lead to an empirical relation
- $$M = \frac{1}{1-(V/V_{br})^n}$$

(a)

(b)   (c)
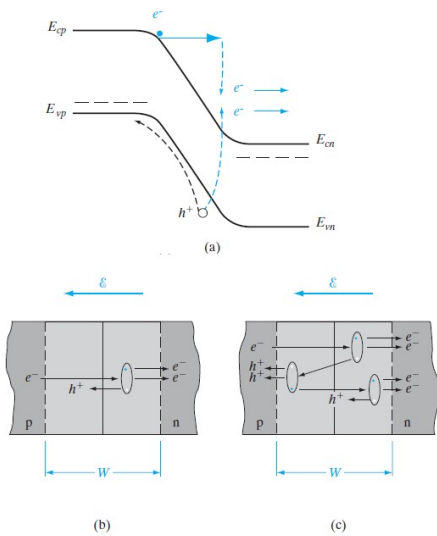
Q.4. If electric field E_x is applied each e^{-n} experiences the force $-qE_x$ Net motion of all electrons is in direction of x.

If P_x the total momentum of all group electrons in the x direction

The force of electric field experienced by n electrons $-q\, nE_x = dp_x/dx$.

- To find total rate of change in momentum we must investigate collision probabilities.
- For random collisions → constant probability of collisions.
- Assume group of N_0 no. of electrons at time t=0.
- Assume N(t) no. of electrons does not take part in collision by time t

Field

$v_x = -\mu_n \mathcal{E}_x$
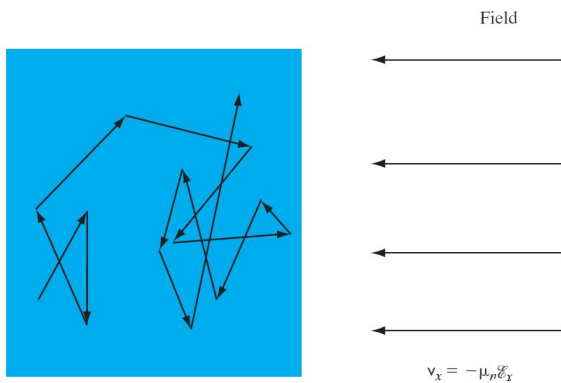
$$-\frac{dN(t)}{dt} = \frac{1}{\bar{t}}N(t)$$

where $\bar{t}^{-1}$ is a constant of proportionality.

The solution of this equation is $N(t) = N_0 e^{-t/t}$ $\bar{t}$ is mean time between scattering events.

The probability that any electron has a collision in the time interval dt is dt/t.

- Thus the differential change in momentum Px due to collisions in time dt is

$$dP_x = -P_x\frac{dt}{\bar{t}}$$

- The rate of change of Px due to the decelerating effect of collisions is

$$\left.\frac{dP_x}{dt}\right|_{collisions} = -\frac{P_x}{\bar{t}}$$

- The sum of acceleration and deceleration effects must be zero for steady state.

$$-\frac{P_x}{\bar{t}} - nq\mathcal{E}_x = 0$$

- The average momentum per electron

$$\langle p_x \rangle = \frac{P_x}{n} = -q\bar{t}\mathcal{E}_x$$

- *The average* a constant net velocity in the negative x-direction

$$\langle v_x \rangle = \frac{\langle p_x \rangle}{m_n^*} = -\frac{q\bar{t}}{m_n^*}\mathcal{E}_x$$

- This drift speed is usually much smaller than the random speed due to the thermal motion.
- The current density resulting from this net drift is just the number of electrons crossing a unit area per unit time.

$$J_x = -qn\langle v_x \rangle ,$$

$$J_x = \frac{nq^2\bar{t}}{m_n^*}\mathcal{E}_x \qquad J_x = \sigma\mathcal{E}_x, \quad \text{where } \sigma \equiv \frac{nq^2\bar{t}}{m_n^*}$$

The conductivity $\sigma(\Omega\text{-cm})^{-1}$ can be written

$$\sigma = qn\mu_n, \quad \text{where } \mu_n \equiv \frac{q\bar{t}}{m_n^*}$$

Q4b.)

Given L=4 µm, A=0.01 cm², n=10^{17} cm⁻³, V= 2 V

$$I = A \cdot J = A.(qnv) \quad \therefore \varepsilon = \frac{V}{L} \quad \therefore \varepsilon = \frac{2}{4 \times 10^{-4}} = 0.5 \times 10^4 \, V/cm$$

Drift velocity= $1350 \times 0.5 \times 10^{-4}$. $v = 6.75 \times 10^6$ cm/s

$\therefore I = A.(qnv)$ = 1×10^{-2}. 1.6×10^{-19}. 10^{17}. 6.75×10^6.

$\therefore I = 1080A$

Voltage is increased $\varepsilon = 100V/4 \times 10^{-4}$ cm,

$\varepsilon = 2.5 \times 10^5$ V/cm

$\therefore$Drift velocity $v = 10^7$ cm/s

$\therefore I = A.(qnv)$ = 1×10^{-2}. 1.6×10^{-19}. 10^{17}. 10^7.

$\therefore I = 10800A$

Increase in Voltage cause in increase current.

Q.5.a. The Hall effect is the production of voltage difference (the Hall voltage) across a current carrying conductor(in the presence of magnetic field), perpendicular to both current and the field. In the y-direction the force is $F_y = q(\varepsilon_y - v_x B_z)$
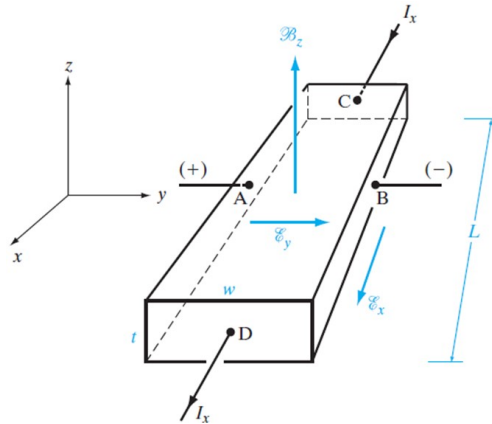
- An electric field ε_y is established along the width of the bar
- This is called as hall effect.
- The Hall Field is proportional to product of current density and magnetic flux density.
- To maintain a steady state flow of holes F_y must be zero. $\varepsilon_y = v_x \mathcal{B}_z$
- V_{AB} is the Hall voltage established. $V_{AB} = \varepsilon_y w$
- Now for holes, the current density is given by $J_x = q p_0 v_x$

$$\varepsilon_y = \frac{J_x}{q p_0} \mathcal{B}_z = R_H J_x \mathcal{B}_z, \quad R_H \equiv \frac{1}{q p_0}$$

- We see that the Hall Field is proportional to product of current density and magnetic flux density.

5.b.
W=0.01cm, t=10×10⁻⁴cm, $\mathcal{B}_z = 10^{-4}$Wb/cm² L=0.6cm, I_x=1×10⁻³A,
V_{AB}=-2×10⁻³ V, V_{CD}=100×10⁻³V.

From sign we can say that majority carriers are electrons.

$$\therefore n_0 = \frac{I_x}{q t V_{AB}} \mathcal{B}_z = \frac{(10^{-3})(10^{-4})}{1.6 \times 10^{-19}(10^{-3})2 \times 10^{-3}}$$

$$\therefore n_0 = 3.125 \times 10^{17} cm^{-3}$$

$$\therefore \rho = \frac{V_{CD}/I_x}{L/wt} = \frac{(0.1)/(10^{-3})}{0.5/(0.01) \cdot (10^{-3})}$$

$$\mu_n = \frac{\sigma}{q n_0} = \frac{1}{\rho q n_0} = \frac{1}{(2 \times 10^{-3})(1.6 \times 10^{-19})3.125 \times 10^{17}}$$

$$\mu_n = 10000 cm^2/(V-s)$$

Q6. One useful feature of a p-n junction is that current flows quite freely in the p to n direction when the p region has a positive external voltage bias relative to n (forward bias and forward current). Whereas virtually no current flows when p is made negative relative to n (reverse bias and reverse current).
Rectification is an important application. Biased p-n junctions can be used as voltage-variable capacitors, photocells, light emitters, and many more devices which are basic to modern electronics. We shall concentrate on qualitative description of current flow in a biased junction.

- The current flows freely in the forward direction of the diode
- Almost no current flows in reverse direction
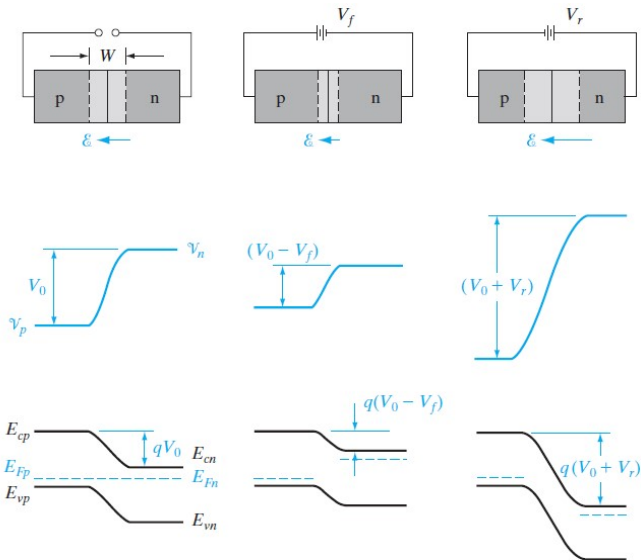
The *electrostatic potential barrier* at the junction is lowered by a forward bias V_f from the equilibrium contact potential V_0 to the smaller value $V_0 - V_f$. This lowering of the potential barrier occurs because a forward bias (p positive with respect to n) raises the electrostatic potential on the p side relative to the n side. For a reverse bias ($V = -V_r$) the opposite occurs; the electrostatic potential of the p side is depressed relative to the n side, and the potential barrier at the junction becomes larger ($V_0 + V_r$).

(1) Hole diffusion   (3) Electron diffusion
(2) Hole drift   (4) Electron drift
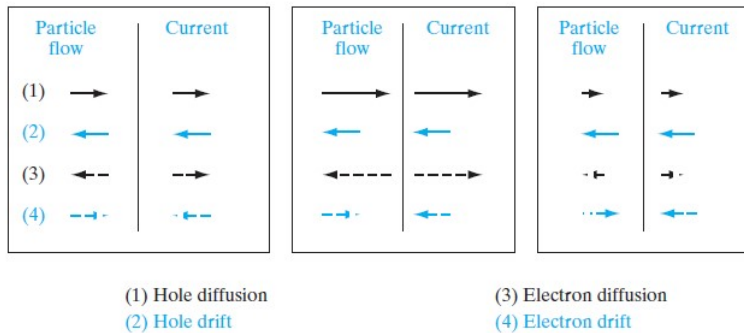
The *separation of the energy bands* is a direct function of the electrostatic potential barrier at the junction. The height of the electron energy barrier is simply the electronic charge q times the height of the electrostatic potential barrier.

- **Diffusion current:** Whenever there is a non-uniform concentration gradient, diffusion takes place from higher concentration to lower concentration. This is called diffusion current.

Drift current: The drift current is independent of the biasing as the no. of minority carrier is independent of the biasing voltages. The supply of minority carriers on each side of the junction required to participate in the drift component of current is generated by thermal excitation of electron–hole pairs.

Total current $I = I$(diff.) - $\cdot$ I(gen.) $\cdot = 0$ for $V = 0$. I_{gen} is generation current, reverse saturation current. The diffusion current under forward bias is given by its equilibrium value multiplied by $\exp(qV/kT)$;

$$I = |I(\text{gen.})|(e^{qV/kT} - 1)$$
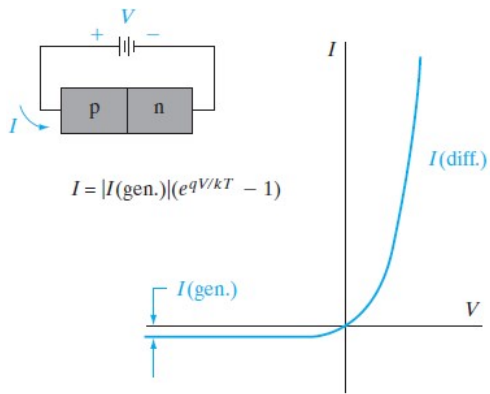
Q7. Major Types of Bonding forces

- <u>Ionic Bonding:</u> Forms ionic **compounds.** Transfer of electron takes place. Electrons are transferred between valence shells of atoms. Ionic compounds are made of ions, not molecules. Ionic compounds are called salts or crystals. A typical example of an ionic bond in Sodium chloride (NaCl). Each Na+ ion exerts attractive force on neighboring Cl- ions. In the lattice NaCl structure all electrons are tightly bound to the atoms.

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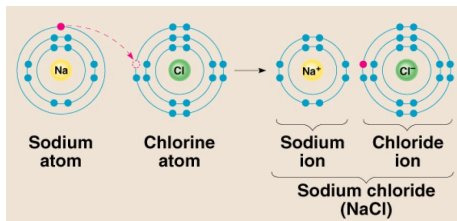
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- <u>Metallic Bonding:</u> Bonds formed in metals. Holds the atoms strongly. There is a cloud of electrons around the atoms.   Good conductors of electricity. Example : Na, Fe, Al, Cu etc.
- There are complicated differences in the bonding forces for various metals, as evidenced by the wide range of melting temperatures. Mercury Hg(80) 234 K, Tungston W(74)3643 K.
- <u>Covalent Bonding:</u> In covalent bonds pairs of electrons are shared between atoms. They are formed between non-metal atoms The electro negativity difference of the atoms should be <1.7. They form poly atomic ions.
  Some key features are :   Between nonmetallic elements of similar electro negativity. Formed by sharing electron pairs. Stable non-ionizing particles, they are not conductors at any state
  Examples; O_2, CO_2, H_2
  Metals,Semiconductors,Insulators.
- An energy band is a range of allowed electron energies. Every solid has its own characteristic energy band structure. The band structure is responsible for the electrical characteristics. We have valence band and conduction band. The energy gap in between is the forbidden gap.
- The energy band in a metal is only partially filled with electrons. Metals have overlapping valence and conduction bands . For an electron to become free to conduct, it must be promoted into an empty available energy state. For metals, these empty states are adjacent to the filled states. Generally, energy supplied by an electric field is enough to stimulate electrons into an empty state. Hence, metals are said to have high conductivity
- Eg. Cu, Ag, Au etc

- Metal   Insulator
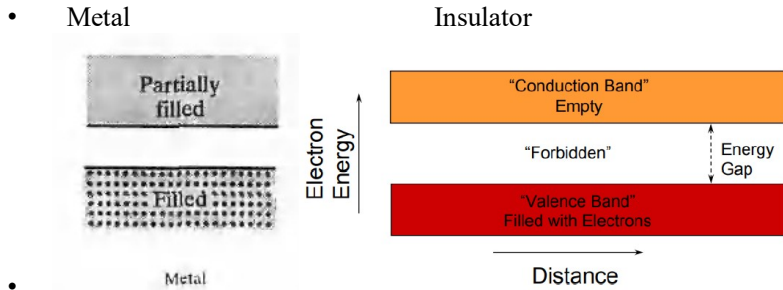
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- Insulators: The valence band and conduction band are separated by a large (> 4eV) energy gap, which is a "forbidden" range of energies. Electrons must be promoted across the energy gap to conduct, but the energy gap is large. So small electric fields are not sufficient to transfer the electrons from valence band to conduction band. When the electric field is very large, then the insulation "breaks down" and starts conducting. e.g. Diamond with band gap 5eV, Silicon dioxide SiO_2 has band gap of 9.0 eV
- Semiconductor:
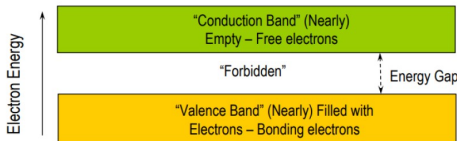
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- They belong to group IV in the periodic table. Semiconductors have resistivities in between those of metals and insulators. If relatively few electrons reside in an otherwise empty band, plenty of unoccupied energy states are available into which electrons can move. If we consider Si, valence band is completely full at 0K and conduction band is empty. Since VB is full, no empty states. So no electron transfer. Since conduction band is empty, no charge transport here also. Hence, Si has high resistivity. In Si band gap is 1.1 eV.

  Since band gap is low, electrons can be transferred from lower energy valence band by thermal or optical energy. At room temp, Si will have significant number of electrons excited thermally into conduction band, whereas in an insulator (gap > 4ev) negligible electrons in conduction band.