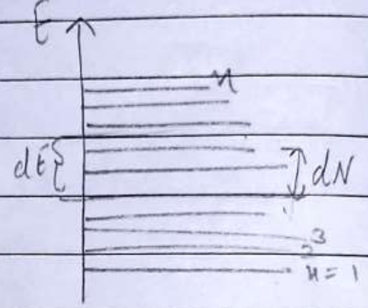
Unit → 1.

Density of States in 3D, 2D, 1D.

↓

[Number of quantum states per unit energy range] per unit length (1D), Area (2D), volume (3D)

$$D(E) = \frac{dN}{dE}$$

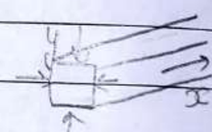



$$\int dN = \int f(E) \cdot D(E) dE$$

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

1-D. [Wire]

$$D(E) = \frac{1}{L}\frac{dN}{dE} \rightarrow (1)$$




dN ⇒ number of quantum states present in energy range

$$N = \frac{2KL}{\pi} \rightarrow (2)$$

Each quantum state contains two electronic states;

$$D(E) = \frac{1}{L}\frac{dN}{dK} \times \frac{dK}{dE}$$

From eq (2)

$$\frac{dN}{dK} = \frac{2L}{\pi} \rightarrow (4).$$

As; $E = \frac{\hbar^2 K^2}{2m} \Rightarrow \frac{dE}{dK} = \frac{\hbar^2 K}{m}$

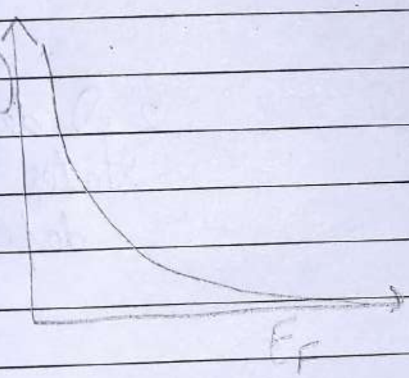
$$\frac{dK}{dE} = \frac{m}{\hbar^2 K} \qquad \left[K = \frac{\sqrt{2mE}}{\hbar}\right]$$

$$d(E) = \frac{1}{L} \times \frac{2L}{\pi} \times \frac{m}{\hbar^2} \frac{\hbar}{\sqrt{2mE}}$$

$$D(E) = \frac{\sqrt{2}}{\pi\hbar} m^{\frac{1}{2}} E^{-\frac{1}{2}}$$

$$d(E) = \frac{2\sqrt{2}}{h} m^{\frac{1}{2}} E^{-\frac{1}{2}} \qquad \left[\hbar = \frac{h}{2\pi}\right]$$

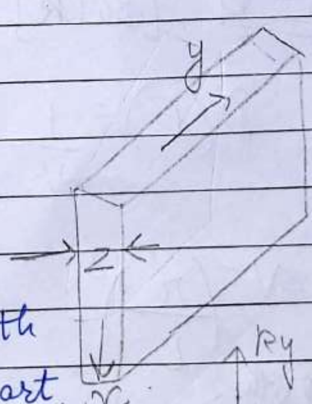
$$D(E) \propto E^{-\frac{1}{2}}$$




It shows that all the states up to fermi-level are filled at 0 K.

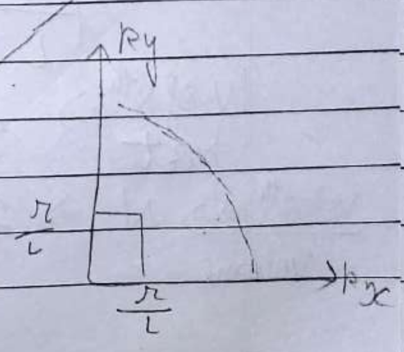
⇒ 2-D [Slab].

$$d(E) = \frac{1}{A} \frac{dN}{dE}$$




$$A = \left(\frac{\pi}{L}\right)^2$$

$A \Rightarrow \frac{\pi K^2}{4} \Rightarrow$ Area of 4th part.




$$N \Rightarrow 2 \times \frac{\pi K^2}{4} \left(\frac{L}{\pi}\right)^2$$

$$\frac{dN}{dk} = \frac{L^2 K}{\pi} \rightarrow (1).$$

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

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \Rightarrow \frac{dk}{dE} = \frac{m}{\hbar^2 k} \rightarrow (2)$$

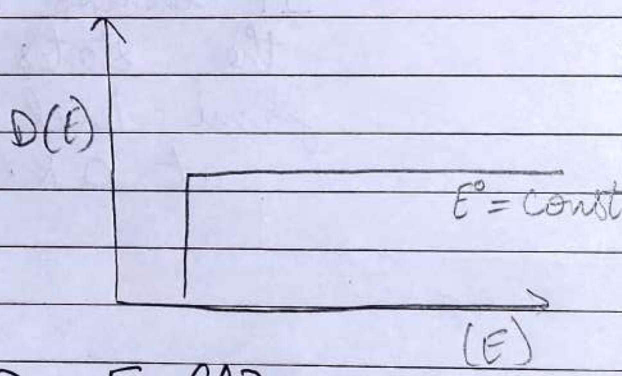
$A \Rightarrow L^2$

$$d(E) = \frac{1}{\cancel{L^2}} \frac{\cancel{L^2}\cancel{k}}{\pi} \times \frac{m}{\hbar^2 \cancel{k}}$$

$$D(E) = \frac{m}{\pi \hbar^2} \qquad \left[\hbar = \frac{h}{2\pi}\right]$$

$$D(E) = \frac{4\pi m}{h^2}$$

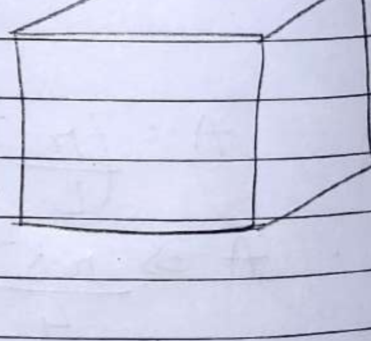
$$D(E) \propto E^0$$




2 D density of states does not depend on energy

⇒ 3-D [Bulk]

$$D(E) = \frac{1}{V} \frac{dN}{dE}$$



$$V = \left(\frac{\pi}{L}\right)^3$$

V of 8th part $\Rightarrow \frac{1}{8} \times \frac{4}{3} \pi k^3$

V of 8th parts / volume $N \Rightarrow 2 \times \frac{1}{8} \times \frac{4}{3} \pi k^3 \left(\frac{L}{\pi}\right)^3 = \pi k^3 \left(\frac{L}{\pi}\right)^3$

$$D(E) = \frac{1}{V}\frac{dN}{dK} \times \frac{dK}{dE}$$

$$\frac{dN}{dK} = \pi K^2 \left(\frac{L}{\pi}\right)^3 \rightarrow (1)$$

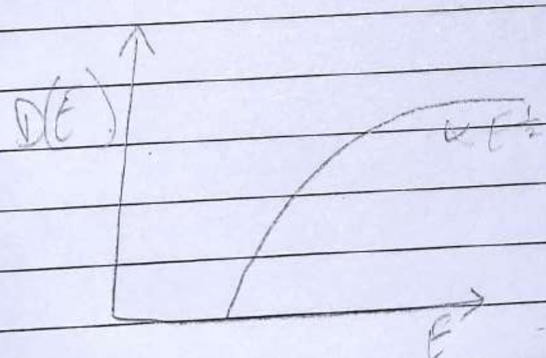
$$E = \frac{\hbar K^2}{2m} \Rightarrow \frac{dE}{dK} = \frac{\hbar^2 K}{m} \Rightarrow \frac{dK}{dE} = \frac{m}{\hbar^2 K}$$

$V = L^3$ $$D(E) = \frac{1}{L^3} \times \pi K^2 \left(\frac{L}{\pi}\right)^3 \times \frac{m}{\hbar^2 K}$$

$$D(E) = \frac{mK}{\pi^2 \hbar^2}$$

$$D(E) = \frac{m}{\pi^2 \hbar^2} \frac{\sqrt{2mE}}{\hbar} \qquad \left[\hbar = \frac{h}{2\pi}\right]$$

$$D(E) \propto E^{\frac{1}{2}}$$




It shows that density of state is a step function with steps occuring at energy of each quantized level.

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# * Metal - Semiconductor Junction.

## Need for Metal SC Junction.

- As metal contacts.
- To connect external circuitry with the device.

## Effect of Metal SC Junction.

- Variation in Device Behaviour.
- Control May lost.

## Define

It is a metal and semiconductor junction in which metals and semiconductor are joined together to form electronic devices.

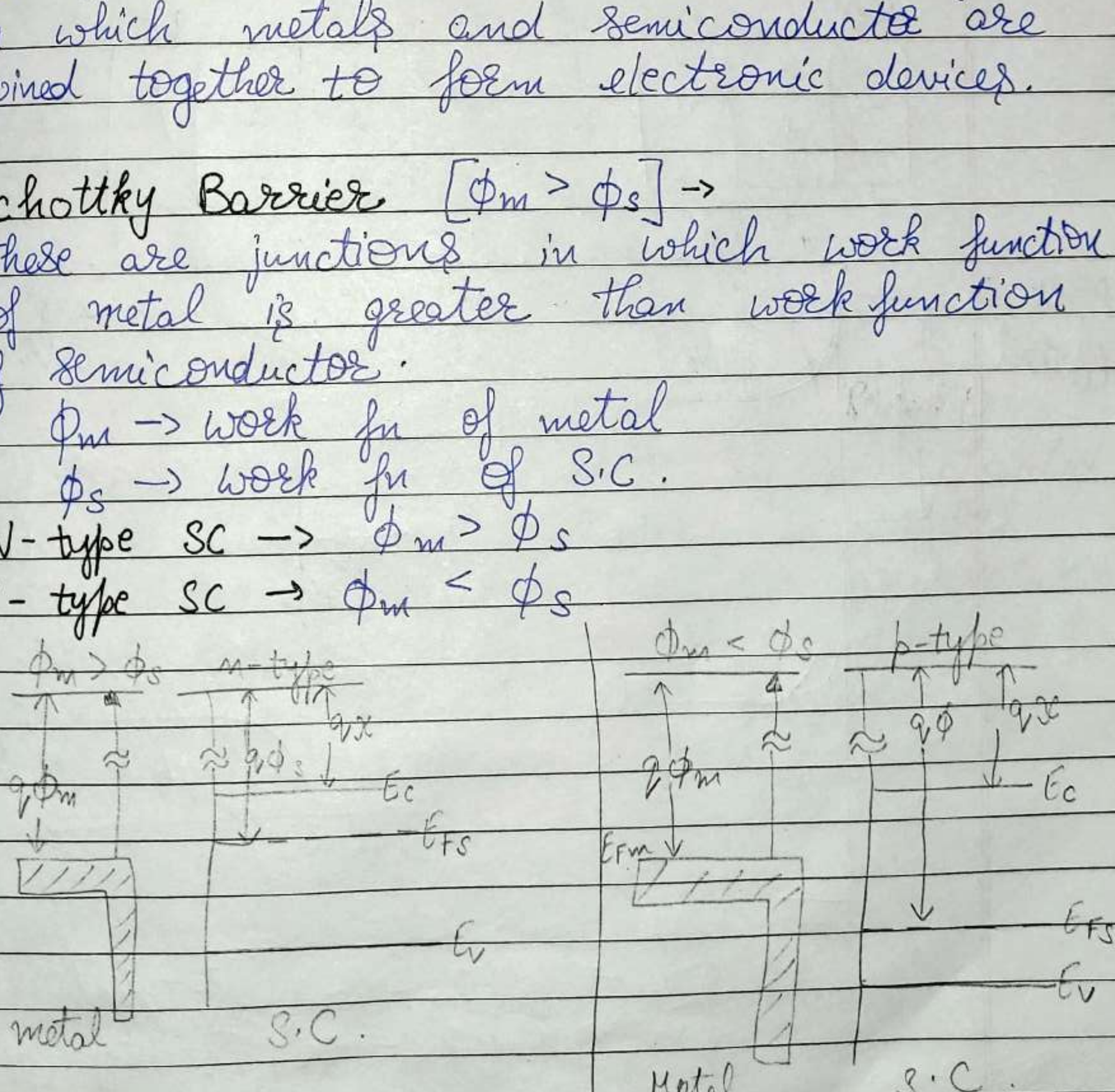
## (1) ⇒ Schottky Barrier $[\phi_m > \phi_s]$ →

These are junctions in which work function of metal is greater than work function of semiconductor.

$\phi_m$ → work fn of metal
$\phi_s$ → work fn of S.C.

N-type SC → $\phi_m > \phi_s$
P-type SC → $\phi_m < \phi_s$

⇒ Before contact




$q\chi$ → Electron Affinity.

## Formation of Junction ⇒

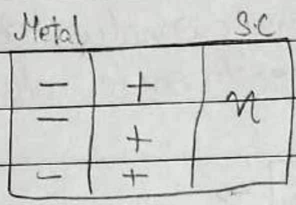
- Fermi level aligning at ≡m.
- To align two fermi-levels; a contact potential ($V_0$) was created.
- Potential Barrier →

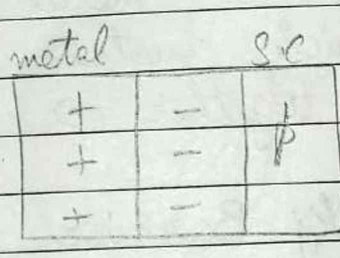
  n-type. To retard electron diffusion.

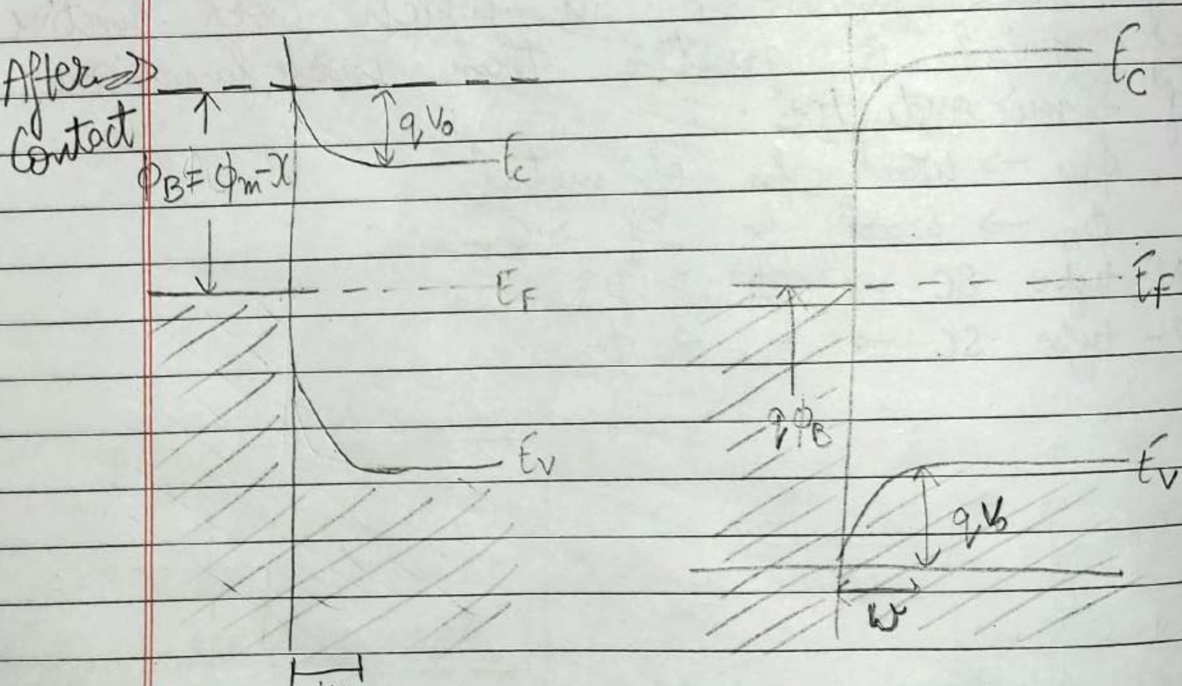
  $V_0 = \phi_m - \phi_S$.

  p-type. To retard hole diffusion

  $V_0 = \phi_S - \phi_m$.
- Potential Barrier for ē injection = $\phi_B$.
- This barrier is called Schottky barrier.




$qV_0 \Rightarrow q(\phi_S - \phi_m)$ [p-type]

$qV_0 \Rightarrow q(\phi_m - \phi_S)$ [n-type].

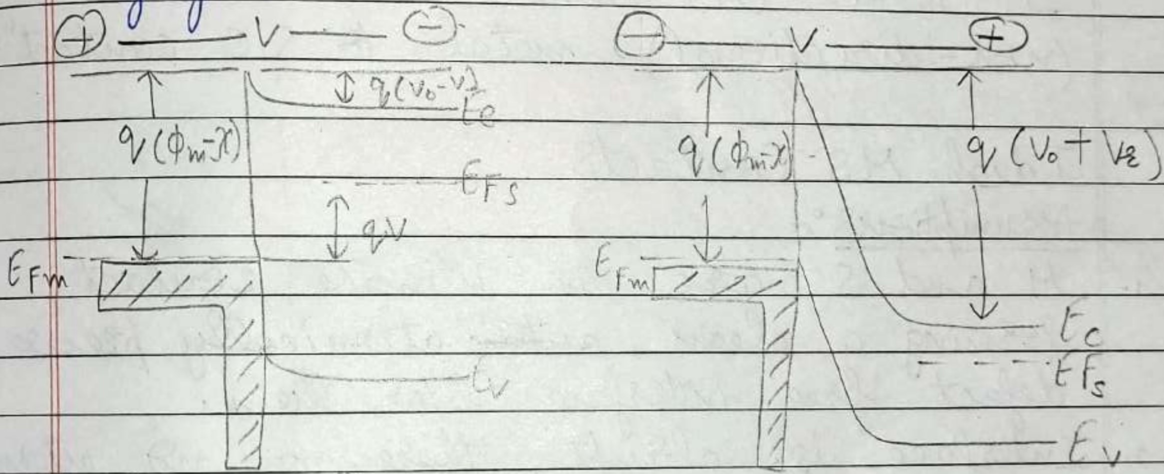
## → Rectifying Contacts

F.B → Forward Biasing.

- $V_0 \rightarrow V_0 - V$
- Electron diffusion becomes easier from SC to Metal.

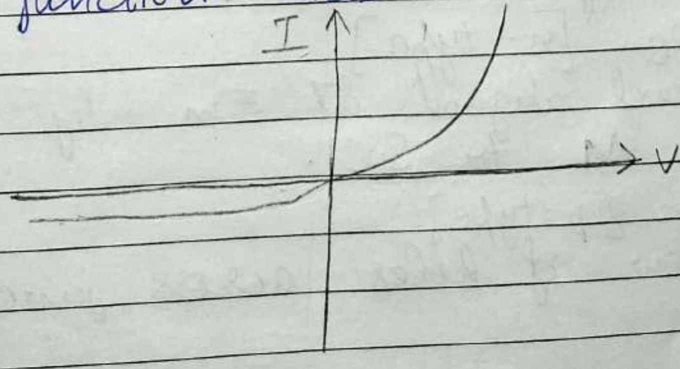
R.B → Reverse Biasing.

- $V_0 \rightarrow V_0 + V$
- Electron flow from SC to Metal becomes negligible.




Forward Biasing

- Electron flow from M to SC is retarded due to barrier $\phi_m - \chi$ in both cases.
- In Schottky diode, the reverse saturation current depends only on size of barrier $\phi_B$.
- Resulting I-V curve is similar to P-n junction diode.



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## (2) → Ohmic Barrier. [$\phi_m < \phi_s$].

- It follows Ohm's law in current conduction. It yields a linear relationship b/w voltage applied and current that flows across the junction.
- These are the junctions in which work function of metal is lesser than work function of semiconductor.
- It is a low resistance and non-rectifying (non-directional) metal to S.C contact.

### Ideal MS Contacts

Assumptions:-

1. M and S are in intimate contact, forming a clean, ~~atom~~ atomically precise, defect free interface b/w them.
2. Interface is abrupt, there is no intermixing b/w M and S.
3. No oxides or charges at interface.

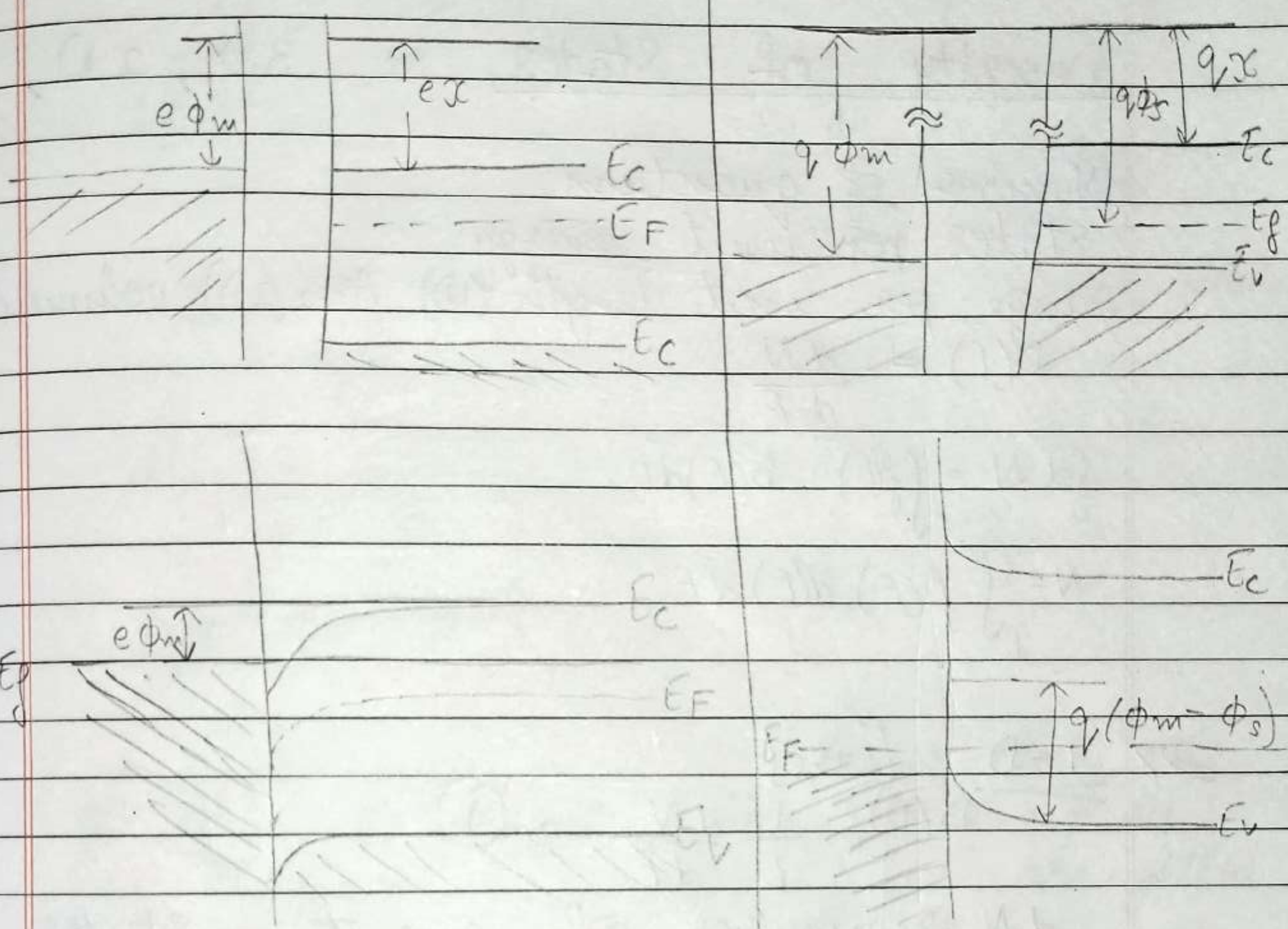
→ Ways to achieve Ohmic MS contacts
- Reduce Schottky Barrier Height.
- Reduce Schottky Barrier Width.

### Formation of Junction.

(a). $\phi_m < \phi_s$ [n-type].
Fermi level aligned at $\equiv$m by transforming $\bar{e}$ from M to S.C.

(b). $\phi_m > \phi_s$ [p-type].
Easy flow of holes across junction.

n-type | P-type



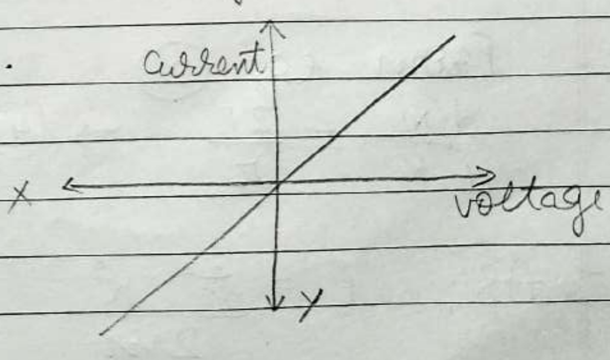

Practical Ohmic Contact.

- most M-S are rectifying.
- contact which can ~~con~~ conduct on both directions.

We doped S.C heavily.

- W is ~~so~~ narrow that carrier can tunnel through barrier. → Tunneling Ohmic Barrier.

\# V-I → Ohmic contact.



# Metal-Semiconductor Junction:-

It is a metal and Semiconductor junction in which metals and Semiconductors are joined together to form electronic devices.

-> Schottky barrier :- Depletion layer is formed in the Semiconductor due to the transfer of electrons from Semiconductor to metal. Thus the Schottky barrier is formed at the junction of N type Semiconductor and the metal.

work function ($\phi_m$) of metals is larger than the work function of Semiconductors ($\phi_{smi}$). $\phi_m > \phi_{smi}$

There is a built in potential formed in the Schottky barrier given by:-

$$eV_0 = \phi_m - \phi_{smi}$$

The distance between the fermi level and the vacuum level is called the work function ($\phi$).

The work function of the metal remain constant but the work function of the Semiconductor depends upon the doping concentration. The barrier which is formed prevents the flow of electrons from metal to Semiconductor and from Semiconductor to metal. It is denotted by $\phi_B$

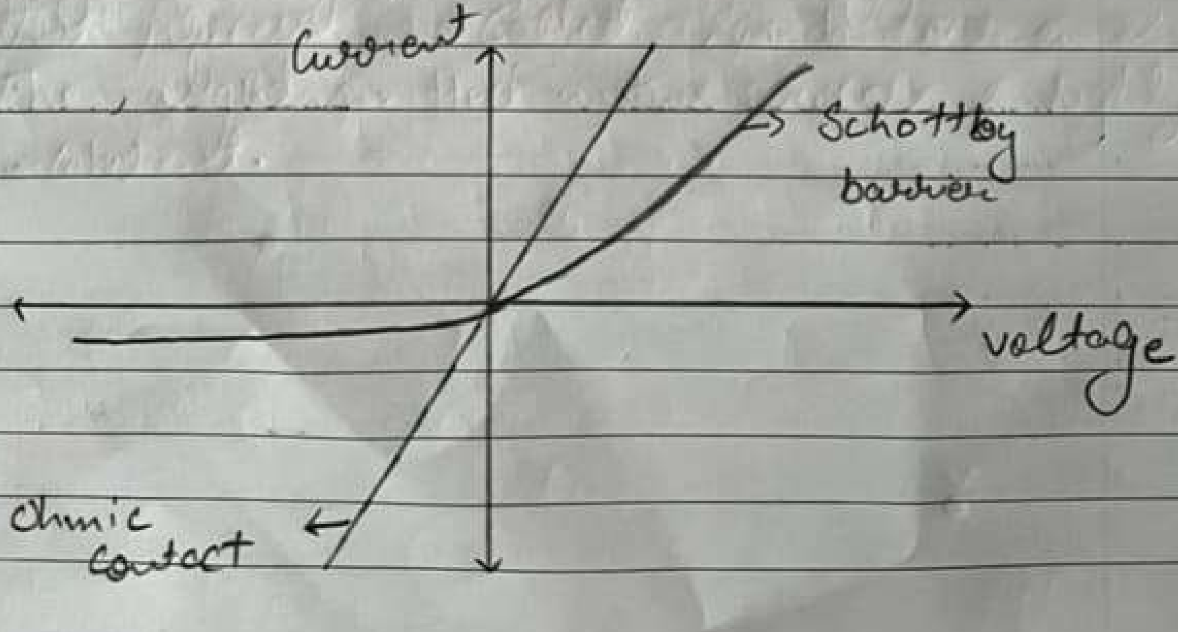
$\phi_B = \phi_m - \chi_n$ , $\chi_n$ is the electron affinity of ntype Semiconductor.

→ **Ohmic Contact :-** Potential barrier is not formed at all cases when metal and semiconductor is joined. So in that case when no potential barrier is formed, it is called Ohmic Contact or Ohmic junction.

Work function of metal ($\phi_m$) is lesser than the work function of semiconductor ($\phi_{Smi}$).
The electrons move from metal to semiconductor and thus the Fermi level of the semiconductor moves up till equilibrium state is established.
Since there is no barrier even a small forward bias will produce large forward bias current and when reverse bias is applied small barrier is formed but it is removed when the reverse bias is increased further.

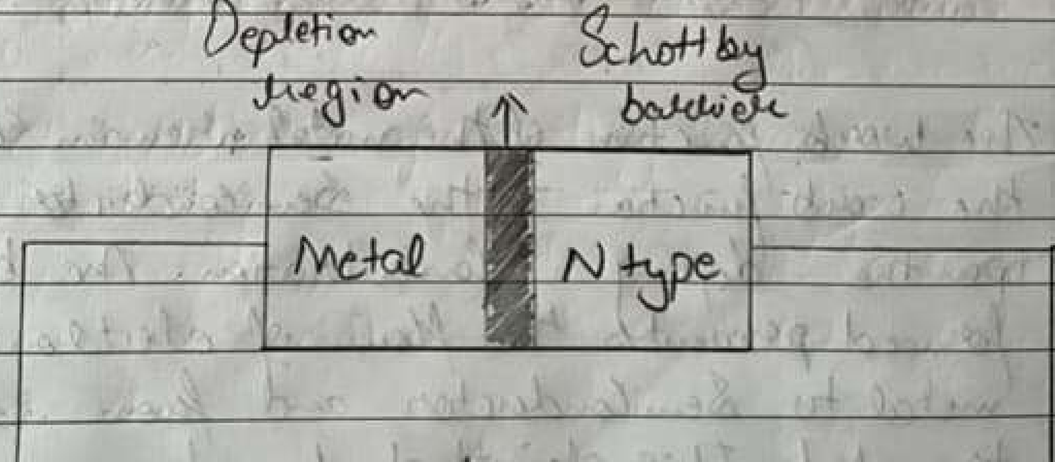
There is a linear relationship between voltage and current and follow ohm's law.

# V-I characteristics of Schottky barrier and Ohmic Contact :-



• <u>Forward bias:-</u> when external voltage is applied, when forward biased, the +ve terminal is connected to the metal and the -ve terminal is connected to the N type semiconductor. The $e^-$ receives more energy to cross the junction barrier and move from N type semiconductor to the metal and thus the current starts to flow. The current is due to the drift of majority charge carriers. Since there is no P type semiconductor, there is no holes and thus no minority carriers.

When forward biased, the Fermi level of the metal is lower than the Fermi level of semiconductor. The Schottky barrier ($\phi_B$) decreases which makes electrons to diffuse easily from semiconductor to metal. Because of this movement of electrons, a +ve current is formed across the junction.



• Reverse bias :- When reverse biased, the +ve terminal is connected to the N type semiconductor and the -ve terminal is connected to the metal. The size of the depletion region increases and the current stops to flow. There is a small amount of leakage current. When the applied voltage is increased further the current increases and when increased further the depletion region breaks down which damages the device permanently.
The Fermi level of the metal is higher than the Fermi level of the semiconductor. So the potential across the barrier increases and blocks the electrons from diffusing from semiconductor to metal.