- We have seen so far that metal – ntype semiconductors for $\phi_m > \phi_s$ acts as a rectifying contact.
- Similarly, metal contacts to p-type semiconductor for $\phi_m < \phi_s$ acts as a rectifying contact.

EBD for a metal – p type semiconductor contact ($\phi_m < \phi_s$) : (Rectifying contact)

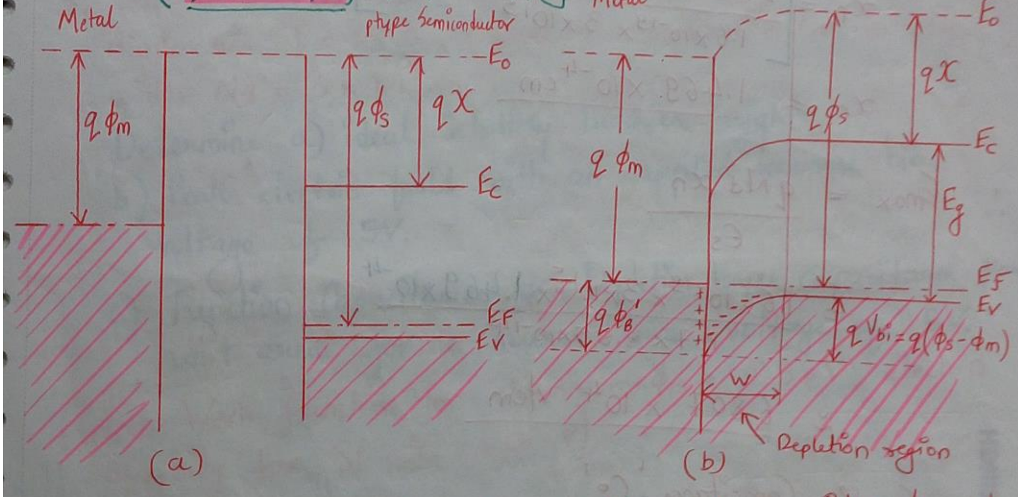

fig 2: EBD of metal – ptype semiconductor with $\phi_m < \phi_s$
a) EBD before contact (ie materials isolated from each other)
b) EBD after the contact is made and thermal equilibrium is reached.

Qualitative theory for fig (2a) and (2b) [Reference!] 19

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1] Fig(2a) depicts the EBD of a metal-ptype semiconductor with $\phi_m < \phi_s$, when metal and ptype semiconductor (SC) are isolated from each other.

2] In fig (2b), when metal and ptype semiconductor are brought into intimate contact, electron flow from metal into the semiconductor until the fermi-level (E_F) is aligned throughout.

- That ie, electrons in metal are at higher energy level thus they flow into semiconductor (where energy level of carriers are lower).
- Each electron flowing into the semiconductor removes a hole from valence band, leaving behind an negatively charged ionized acceptors in the semiconductor,
- creating a depletion region of width 'W'. in the semiconductor. and causes downward bending of bands
- Since the current in a ptype semiconductor is carried by holes, it is a rectifying contact and barrier height $q\phi_B'$ is

$$q\phi_B' = [q\chi + E_g - q\phi_m]$$

Note: Schottky barrier contacts on ptype semiconductor are less frequently used.

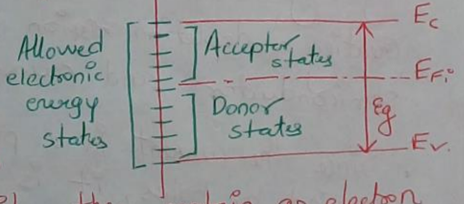
—x—

Non-idealities in Metal-semiconductor contacts

(Non-ideal effects on "Barrier height ϕ_{B0}") [R]

Extra! (Effect of Surface states and Interface)

- In our treatment of Metal-semiconductor (MS) junctions, we have so far neglected the presences of
  - a) surface states
  - b) Any interfacial layer betn the M and S.
- These effects can substantially modify the characteristics of a M-S junction.
- "Surface states" are allowed electronic energy states within the energy bandgap (E_g) → created due to the termination of the periodic potential at Semiconductor surfaces.
- There are two types of surface states, 1) Donor states 2) Acceptor states



- Donor states are neutral if they contain an electron and becomes +vely charged when no electron is present.
- Acceptor states are neutral when they do not contain an electron, but becomes negatively charged when an electron occupies such a state.

1] Effect of "Localized Surface States"

- Although equation $\boxed{q\phi_{B0} = q(\phi_m - \chi)}$ predics that barrier height ϕ_B varies linearly with ϕ_m.
- In covalently-bonded semiconductors like Si, Ge, GaAs, ϕ_{B0} is almost independent of ϕ_m.

→ In a covalently bonded crystals, the "surface atoms" have no neighbors on the vacuum side with whom they can make covalent bonds.

- Thus, each surface atom has a broken covalent bond known as 'the DANGLING BOND'.
- Dangling bonds gives rise to surface states that are continuously distributed in energy within the forbidden gap.
- These states "pin" the fermi-level at the surface and thus influence the barrier height.
- This process of surface states pinning the fermi level at the surface is known as "Fermi-level Pinning".

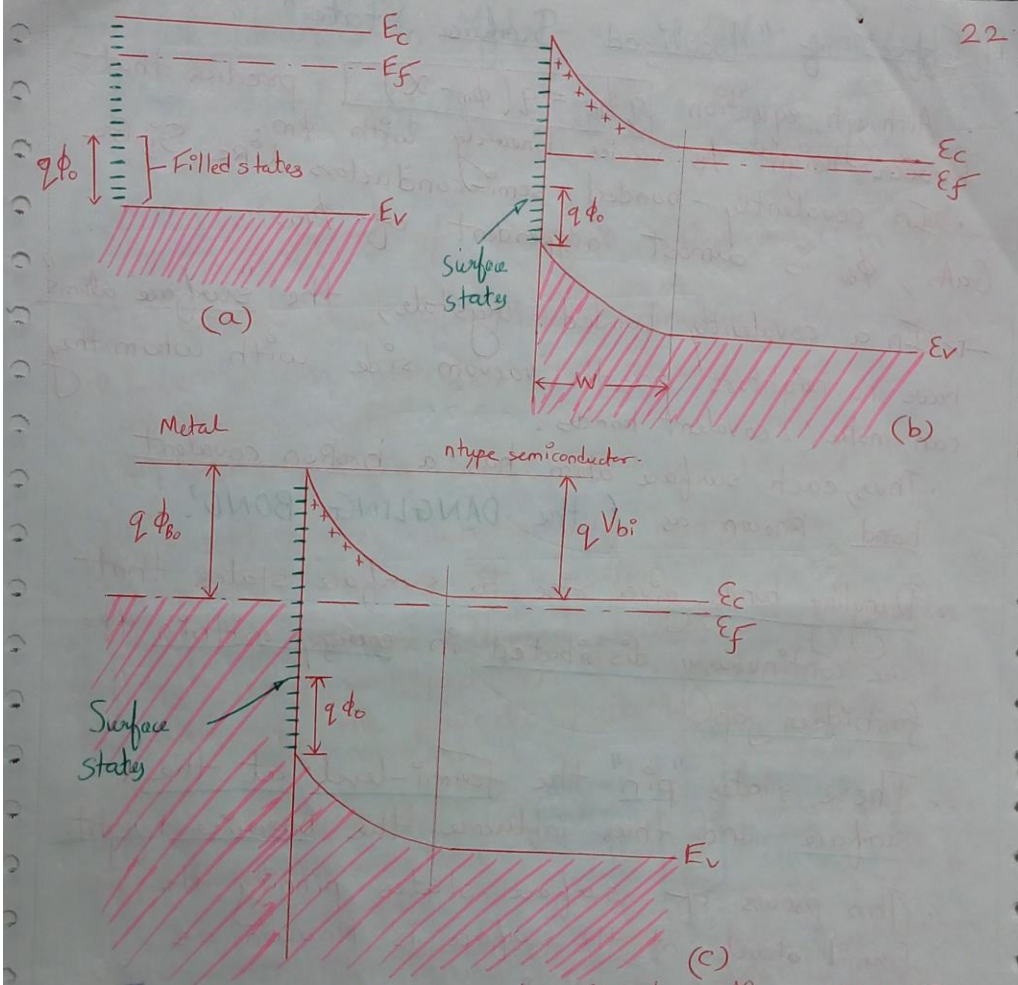


fig 3: EBD illustrating the barrier-formation process on ntype semiconductor with a large density of surface states

a) ntype semiconductor with surface states
b) Surface in thermal equilibrium with the bulk
c) Semiconductor in contact with a metal.

)- Explanation for figure 3:

1] In fig 3a, no net charge exists either in the surface states or in the bulk semiconductor.

· The surface states are characterized by a neutral level $q\phi_0$ such that all states below $q\phi_0$ are occupied while those above it are empty.

2] Equilibrium is reached when electrons from the semiconductor adjacent to the surface occupy states above $q\phi_0$ and fermi level becomes constant throughout (as in fig 3.b)

• Thus, the surface becomes -vely charged and a depletion region is created within the semiconductor near the surface. (as seen in fig 3.b)

3] If a metal is now brought into contact with the semiconductor, → exchange of electrons takes place largely between the metal and the semiconductor surface states.

Thus, the depletion region charge remains practically unaffected and barrier height becomes insensitive to metal work function (ϕ_m).

Extra!

Only in case of covalently-bounded semiconductors, in the limit that density of surface states becomes infinitely large, $q\phi_B$ becomes

$$q\phi_B \approx E_g - q\phi_0 \approx \frac{2}{3}E_g \rightarrow \text{Bardeen approximation}$$

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* Metal-semiconductor contact in presence's of surface states and the "interfacial layer".

- Prior to metal deposition, the semiconductor surface is chemically cleaned. This process invariably leaves a thin insulating oxide layer.

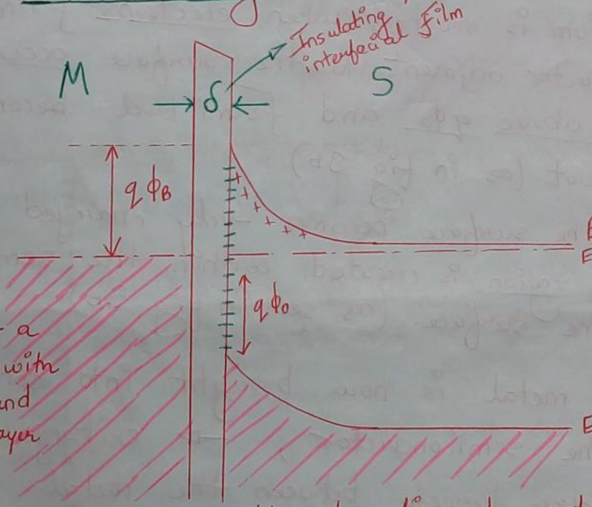

fig 4: EBD of a MS contact with surface states and Insulating oxide layer

- The oxide layer suppresses the tunneling of metal electrons into the semiconductor.
- Fig 4 shows the EBD of a Metal-semiconductor (MS) contact with interfacial oxide layer assuming the oxide to be charge free.
- → It can shown that if density of interface states at the oxide-semiconductor interface is large, → the barrier height (ϕ_{B0}) becomes insensitive to the metal work function. (ϕm)

2) <u>Schottky Effect or Image-force induced lowering of the potential barrier.</u> 25

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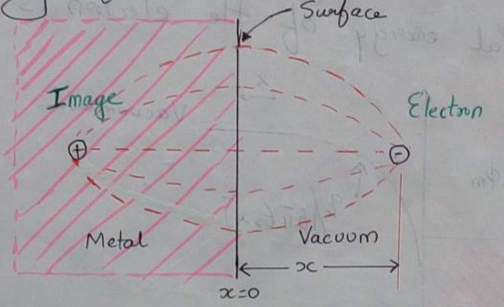
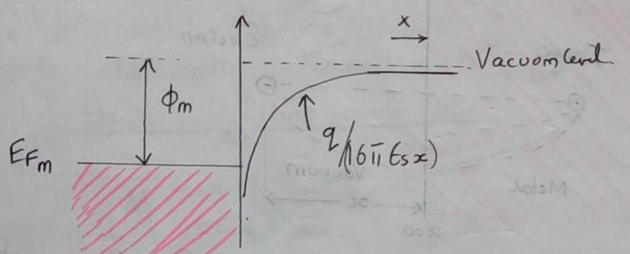


fig 5 a) Electron in vacuum (or dielectric) with image charge in the metal (Image effect)

- An electron in the vacuum (dielectric) at a distance 'x' from the metal surface experiences an attractive force towards the metal.
- ie An electron at a distance 'x' from the metal experiences an electric field perpendicular to the metal surface (as per Gauss's law).
- This electric field may be calculated by assuming a "<u>hypothetical image charge</u> '$+q$' located at a distance $(-x)$ inside the metal.
- The force of attraction between the electron and its image charge is, $F = \dfrac{q^2}{4\pi\epsilon_s(2x)^2}$ — ①
- The electron energy $\phi(x)$ can be obtained by integrating eqn ① from $x = \infty$ to x.

ie $\phi(x) = \dfrac{-q}{16\pi \epsilon_s x}$ — (2)

Now, the potential energy of the electron is $-q\phi(x)$.



(fig 5b) Distortion of potential barrier due to image forces in absence of applied field ($E=0$)

- With an electric field E (V/cm) is present in the dielectric, The energy of an e^- at a distance x from the metal surface then becomes,

$$q\,\phi(x) = -\left(\frac{q^2}{16\pi \epsilon_s x}\right) - qEx \quad \text{— (3)}$$

and the potential is,

$$\phi(x) = -\left(\frac{q}{16\pi \epsilon_s x}\right) - Ex \quad \text{— (4)}$$

From diagram (5c), it is clear that when an external E-field is applied, peak potential barrier is now lowered. to $q\phi_{Bn}$ from $q\phi_{B0}$.

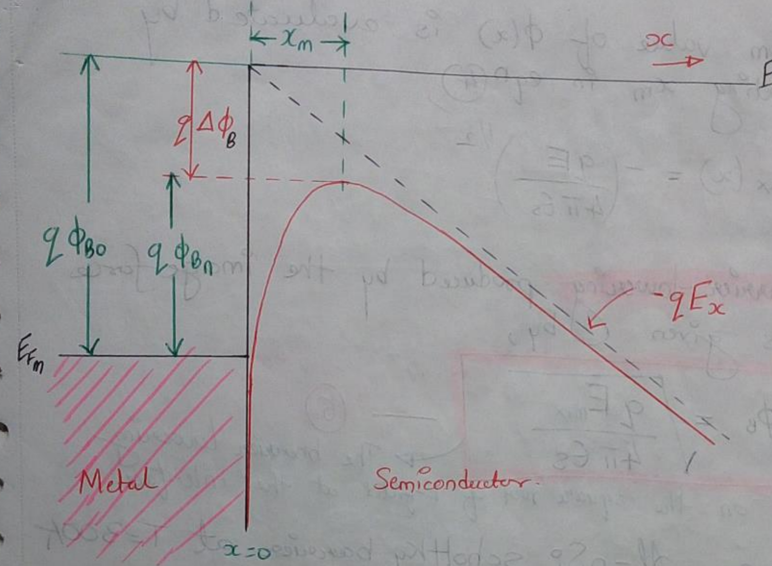


fig 5c) Energy band diagram showing barrier lowering due to image force when an external field E is applied.

- This lowering of the potential barrier is the "Schottky effect" or "Image-force-induced lowering".

- Position of maximum barrier at a distance x_m from metal surface is

$$\boxed{x_m = \sqrt{\frac{q}{16\pi \varepsilon_s E}}} \quad (5)$$

{ Differentiate eqn 4 w.r.t x & equating it to zero results in value of x_m }

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Now, maximum value of $\phi(x)$ is evaluated by subsituting x_m in eq^n (4),

$$\phi_{max}(x) = -\left(\frac{qE}{4\pi \epsilon_s}\right)^{1/2}$$

Thus, the barrier-lowering produced by the image force in eV is given by,

$$\boxed{\Delta \phi_B = \sqrt{\frac{q E_{max}}{4\pi \epsilon_s}}} \quad \text{--- (6)}$$

The barrier lowering depends on the square root of E-field at the interface.

Ex: Consider an Al-nSi schottky barrier at T=300K with $N_d = 10^{16}/cm^3$, $N_c = 2.8 \times 10^{19}/cm^3$, $\phi_{B0} = 0.55\ V$

a) Determine Schottky barrier height, V_{bi}, x_d and E_{max} at zero bias (Given: $N_c = 2.8 \times 10^{19}/cm^3$)

b) Using the value of E_{max} from part (a), determine $\Delta\phi_B$ and x_m for the schottky barrier lowering

c) Repeat part (b) for the case when a reverse bias of $V_R = 4V$ is applied.

Sol^n: a] i) Schottky barrier height (ϕ_{B0})

$$q\phi_{B0} = q(\phi_m - \chi_s) \approx 0.55V.$$

ii) $V_{bi} = \phi_{B0} - \phi_n$

$$\rightarrow \phi_n = \frac{KT}{q} \ln\left[\frac{N_c}{N_d}\right] = (0.0259) \times \ln\left[\frac{2.8\times10^{19}}{10^{16}}\right]$$

$$\phi_n = 0.206\ V$$

$$\therefore V_{bi} = \phi_{B0} - \phi_n = 0.55 - 0.206 = 0.344\,V$$

iii) $$x_d = \left[\frac{2\epsilon_s V_{bi}}{q N_d}\right]^{1/2} = \left[\frac{2\times 11.7\times 8.85\times10^{-14}\times 0.344}{1.6\times10^{-19}\times10^{16}}\right]^{1/2}$$

$$= 0.211\times10^{-4}\,cm$$

iv) $$|E_{max}| = \frac{q N_d x_d}{\epsilon_s} = \frac{1.6\times10^{-19}\times10^{16}\times 0.211\times10^{-4}}{11.7\times 8.85\times10^{-14}}$$

$$= 32.60\times10^{3}\ V/cm$$

b) $$\Delta\phi_B = \sqrt{\frac{qE}{4\pi\epsilon_s}} = \sqrt{\frac{1.6\times10^{-19}\times 32.6\times10^{3}}{4\pi\times 11.7\times 8.84\times10^{-14}}}$$

$$\Delta\phi_B = 0.02\ V$$

$$\therefore x_m = \sqrt{\frac{q}{16\pi\epsilon_s E}} = \sqrt{\frac{1.6\times10^{-19}}{16\pi\times 11.7\times 8.85\times10^{-14}\times 32.6\times10^{3}}}$$

$$= 0.307\times10^{-6}\ cm$$

c]

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For $V_R = 4V$

$$x_d = \left[\frac{2\epsilon_s (V_{bi} + V_R)}{q N_d}\right]^{1/2}$$

$$= \left[\frac{2 \times 11.7 \times 8.85 \times 10^{-14} (0.344 + 4)}{1.6 \times 10^{-19} \times 10^{16}}\right]^{1/2}$$

$$x_d = .75 \times 10^{-4} cm$$

$$|E_{max}| = \frac{q N_d x_d}{\epsilon_s}$$

$$= \frac{1.6 \times 10^{-19} \times 10^{16} \times 0.75 \times 10^{-4}}{\epsilon_s}$$

$$|E_{max}| = 1.156 \times 10^{5} \ v/cm$$

$$\therefore \Delta\phi_B = \sqrt{\frac{qE}{4\pi\epsilon_s}}$$

$$= 37.8 \times 10^{-3} V$$

$$x_m = \sqrt{\frac{q}{16\pi\epsilon_s E}} = 0.163 \times 10^{-6} cm$$