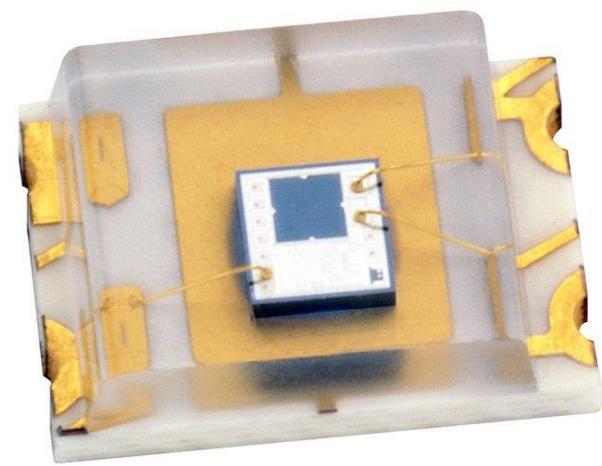
METAL-SEMICONDUCTOR CONTACTS

1. Why?

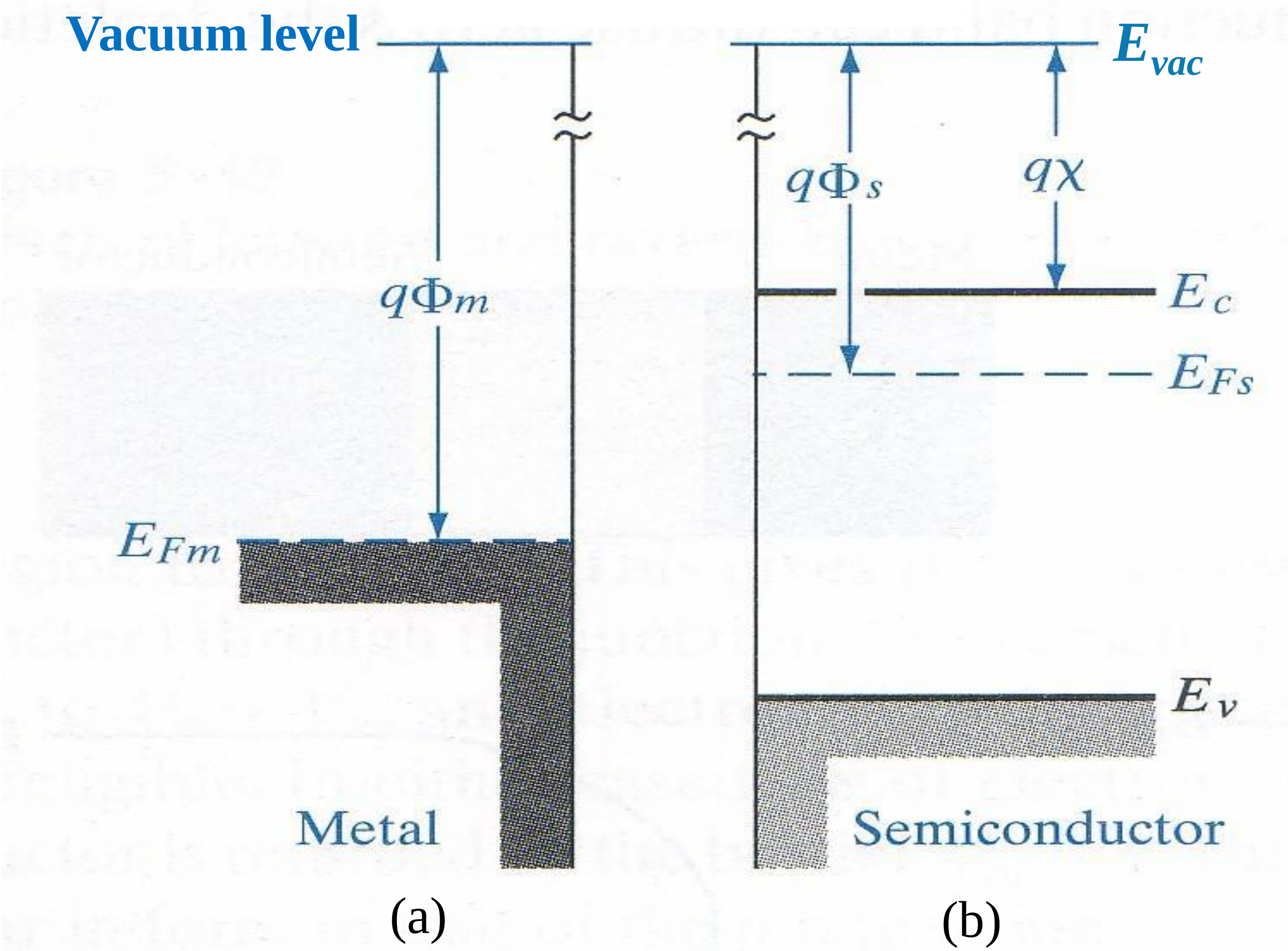
Important consideration from device viewpoint as metal contacts must always be made to devices in order to provide a reliable connection to the external circuitry. There are two types of metal-semiconductor contact that can be formed.

a) **Schottky contact** – Also known as <u>rectifying contacts</u>. It allows current to flow in one direction only, similar to a pn junction. In fact, it is also used as a diode, called the <u>Schottky diode</u>.

a) **Ohmic contact** – Also known as <u>non-rectifying contacts</u>. It allows current to flow freely with small resistance in both directions. This is the usual contact we want for connection from the devices to external circuitry.



Metal-Semiconductor Contacts



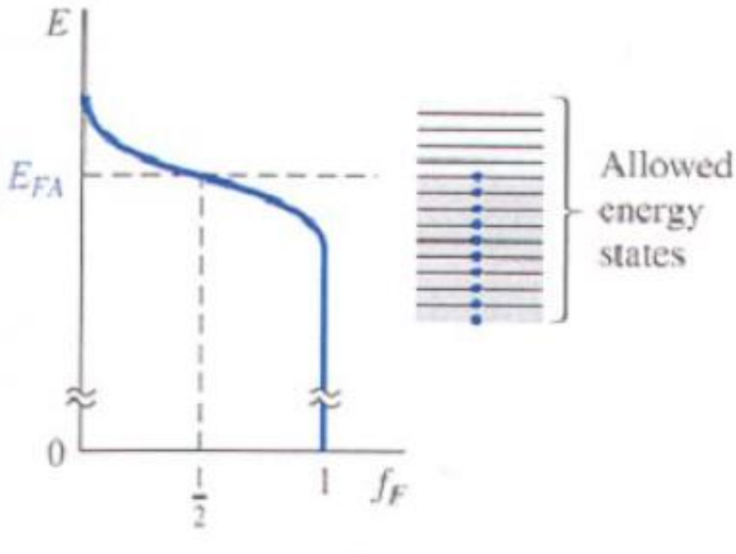
Energy band diagrams for isolated (a) metal and (b) n-type

Terminology in MS contacts:

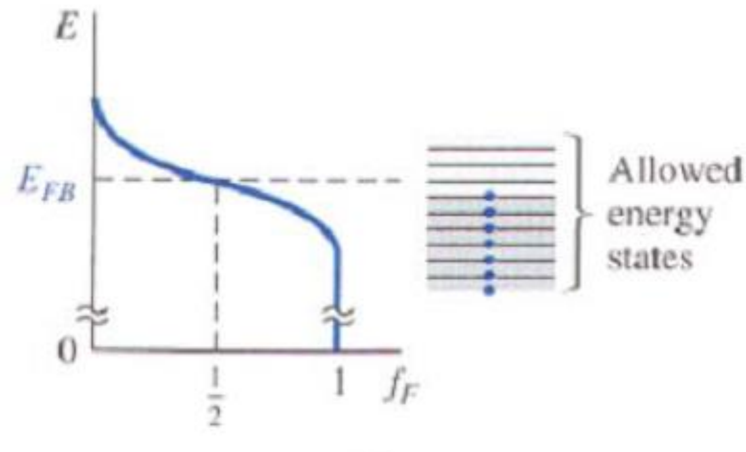
E_{vac}	**Vacuum Energy Level** – Energy level used as a reference in all energy band diagrams. It is the energy at which an electron is free from the material, i.e. can wander off and be emitted away. Convenient energy reference to compare dissimilar materials.
E_{Fm}	**Fermi Energy level** in the metal
E_{Fs}	**Fermi Energy level** in the semiconductor (n-type semiconductor shown)
$q\phi_m$	**Work function of the metal** (units ϕ : volts, $q\phi$: eV) – the amount of energy in eV required for an electron to escape from the metal to vacuum. It is the fundamental property of a metal, e.g., $q\phi = 4.3$ eV for Al.
$q\chi$	**Electron Affinity**(units χ : volts, $q\chi$: eV) – used only for semiconductors. It is the amount of energy in eV required for an electron at the CB edge to escape into vacuum. <u>It is the fundamental property</u> of a semiconductor, <u>independent of doping,</u> e.g., $q\chi = 4.05$ eV for Si). $$q\chi = E_{vac} - E_c \qquad (J)$$
$q\phi_s$	**Work function of the semiconductor** (units ϕ : volts, $q\phi$: eV) – the amount of energy in eV required for an electron to move from E_{Fs} to vacuum. This varies depending on the doping density and type of semiconductor.

Note: χ (pronouns as Chi), ϕ (pronouns as Phi), ξ (pronouns as Xi) and ψ (pronouns as Psi).

EF must be equal when different systems are in contact and in thermodynamic equilibrium



(a)

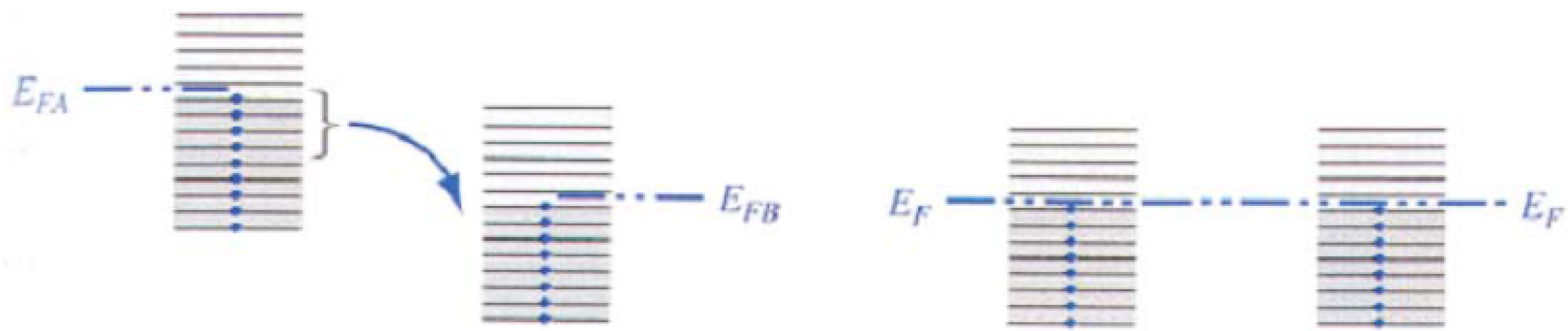


(b)

Consider a material A, with Fermi level E_{FA}. Bands below E_{FA} are full and above are empty.

material B with Fermi level E_{FB}.

EF must be equal when different systems are in contact and in thermodynamic equilibrium

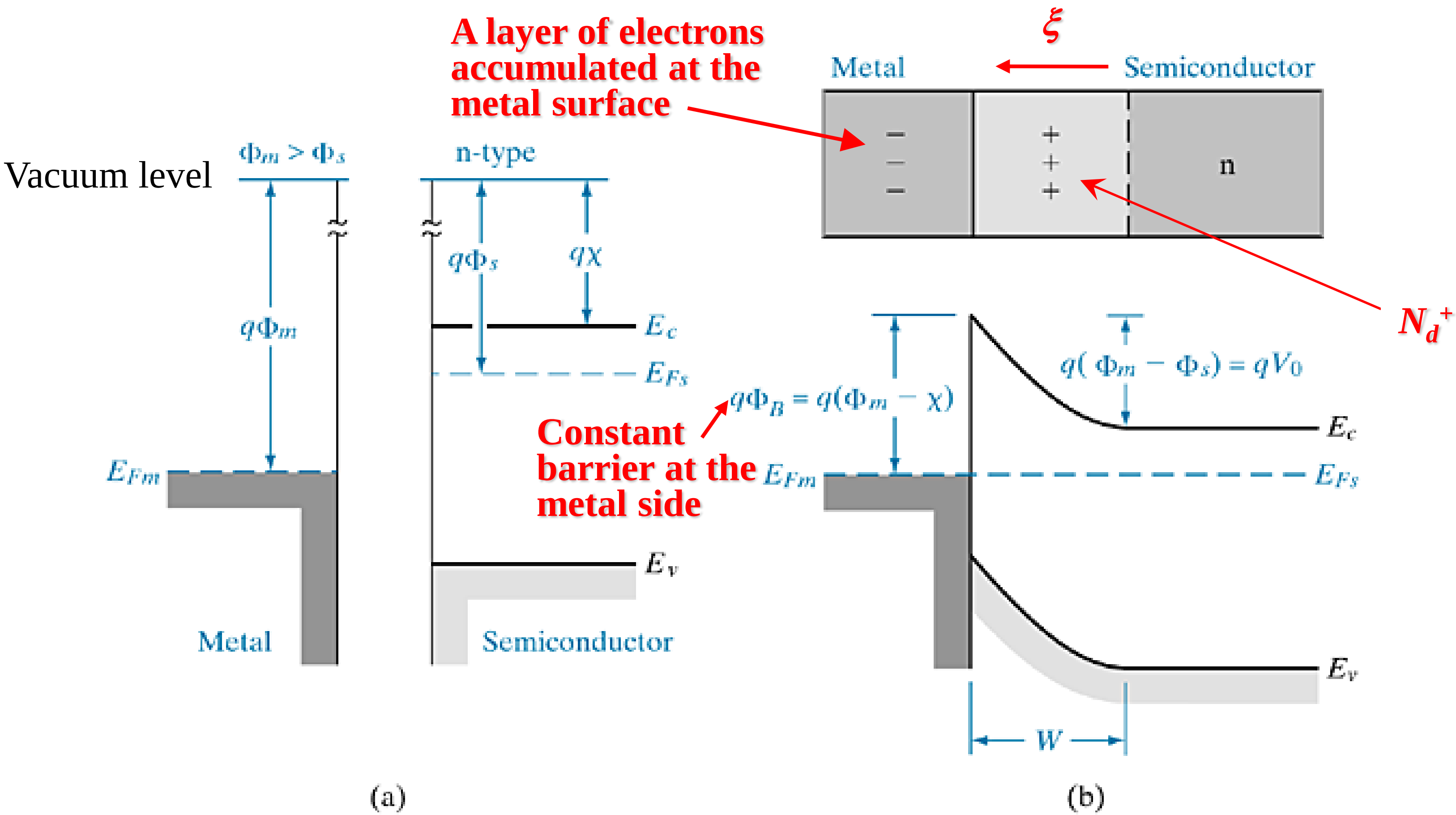


- When A and B are brought in contact, electrons will flow from A into lower energy states of B, until thermal equilibrium is reached.

- Thermal equilibrium → E_F same in A & B

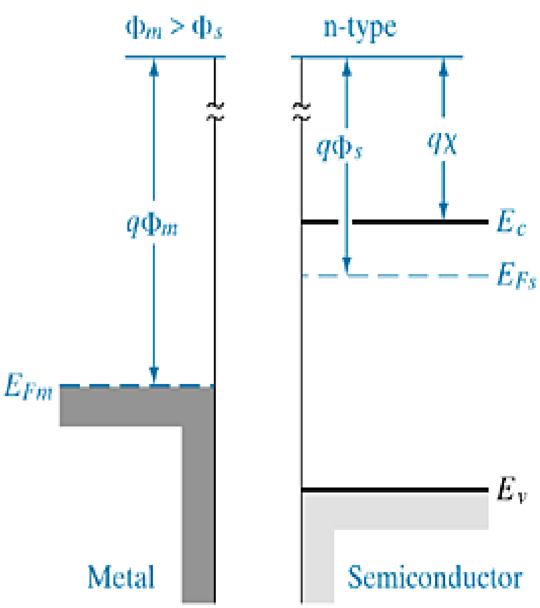
2. Schottky Contact

Consider a metal with a work function $q\phi_m$ brought into intimate contact with a semiconductor **(n-type)** with a work function $q\phi_s$ such that $q\phi_m > q\phi_s$.



A Schottky barrier formed by contacting an n-type semiconductor with a metal having a larger work function: (a) band diagrams for the metal and the semiconductor before joining; (b) equilibrium band diagram for the junction.

$q\phi_m > q\phi_s$



N-type semiconductor

The semiconductor Fermi level is initially higher than that of metal before the contact is made. At the instant when the contact is made, electrons in the CB of semiconductor can easily cross into the metal as they face no potential barrier.

On the other hand, electrons in the metal see a barrier $\boldsymbol{q(\phi_m - \chi)}$, i.e., the Schottky barrier, $\boldsymbol{q(\phi_B)}$, in crossing into the semiconductor. As a result, there will be less electrons flowing from the metal to the semiconductor. Overall, there will be a net transfer of electrons from the semiconductor to the metal.

With the electrons leaving the n-type semiconductor, the donor ions (N_d^+) will be uncompensated. A depletion region (or space charge region) of width $\boldsymbol{W}$ is thus formed in the semiconductor near the contact. The electrons that flow into the metal will be accumulated at the metal surface as a layer of surface charge.

Hence, the semiconductor is positively charged due to $\boldsymbol{N_d^+}$, whereas the metal is negatively charged due to the transferred electrons.

The +ve charge due to uncompensated donor ions within $\boldsymbol{W}$ matches the -ve charge on the metal.

The electric field and the bending of the bands with $\boldsymbol{W}$ are similar to that of a p^+n junction. For example, the depletion width $\boldsymbol{W}$ can be calculated as

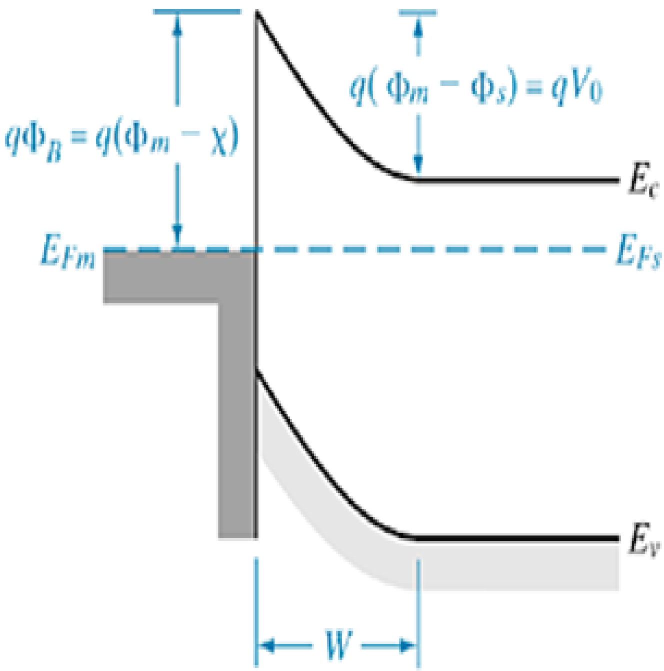
$$\boxed{W = \left[\frac{2\varepsilon V_o}{q} \left(\frac{1}{N_d} \right) \right]^{1/2}} \qquad (1)$$

which is similar to an abrupt p^+n junction ($N_a >> N_d$).

Similarly, the junction capacitance is $\dfrac{A\varepsilon_s}{W}$, identical to that of a p^+n junction.

Recall: $$W = \left[\frac{2\varepsilon V_o}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2}$$

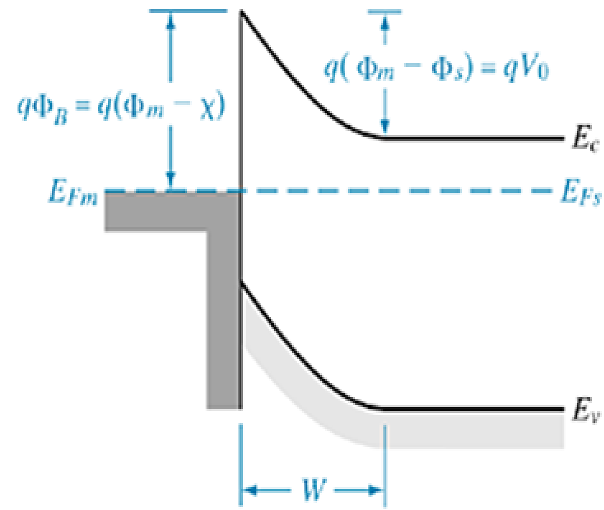
The +ve charges in the semiconductor and the –ve charges in the metal result in a potential difference (PD) $\boldsymbol{V_o}$ across the depletion region, with the potential being higher at the bulk of the n-type semiconductor than at the contact. This is similar to the built-in potential of a pn junction as it is naturally developed when the metal and n-type semiconductor come into contact.



Due to the PD developed, electrons flowing from the semiconductor to the metal will <u>encounter an energy barrier</u> $\boldsymbol{qV_o}$ that reduces its rate of flow. Thermal equilibrium is achieved when this flow is exactly balanced by the flow of electrons from the metal to the semiconductor. This will result in no net electron transfer, viz., no net current flow, as expected at thermal equilibrium.

The equilibrium contact potential $\boldsymbol{V_o}$ prevents further net electron diffusion from the semiconductor CB into the metal. This energy barrier $\boldsymbol{qV_o}$ developed is the difference in the work function potentials $\boldsymbol{\phi_m - \phi_s}$.

$$\boxed{qV_o = q(\phi_m - \phi_s)} \qquad (2)$$



The potential barrier height $\boldsymbol{\phi_B}$ for electron injection from the metal to the semiconductor CB is $\boldsymbol{\phi_m - \chi}$.

$$\boxed{q\phi_B = q(\phi_m - \chi)} \qquad (3)$$

ϕ_B is also referred to as Schottky Barrier Height.

The energy barrier formed that discourages electron flow can also be interpreted in terms of the electric field ξ developed within the depletion region, which opposes the flow of electrons from the semiconductor to the metal.

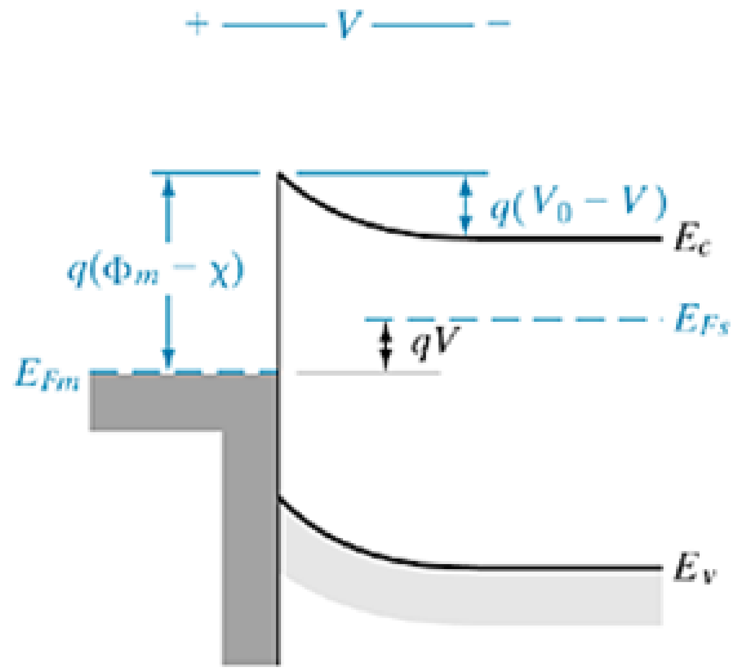
Notice that the discussion for the Schottky contact is very similar to that of a pn junction. Indeed, a metal/n-type Schottky contact is analogous to a p^+n junction, with the conductive metal corresponding to the conductive p^+ region.

As in a pn junction, the energy barrier qV_o can be increased or decreased by applying a FB (+ve bias to metal) or RB (-ve bias to metal) voltage.

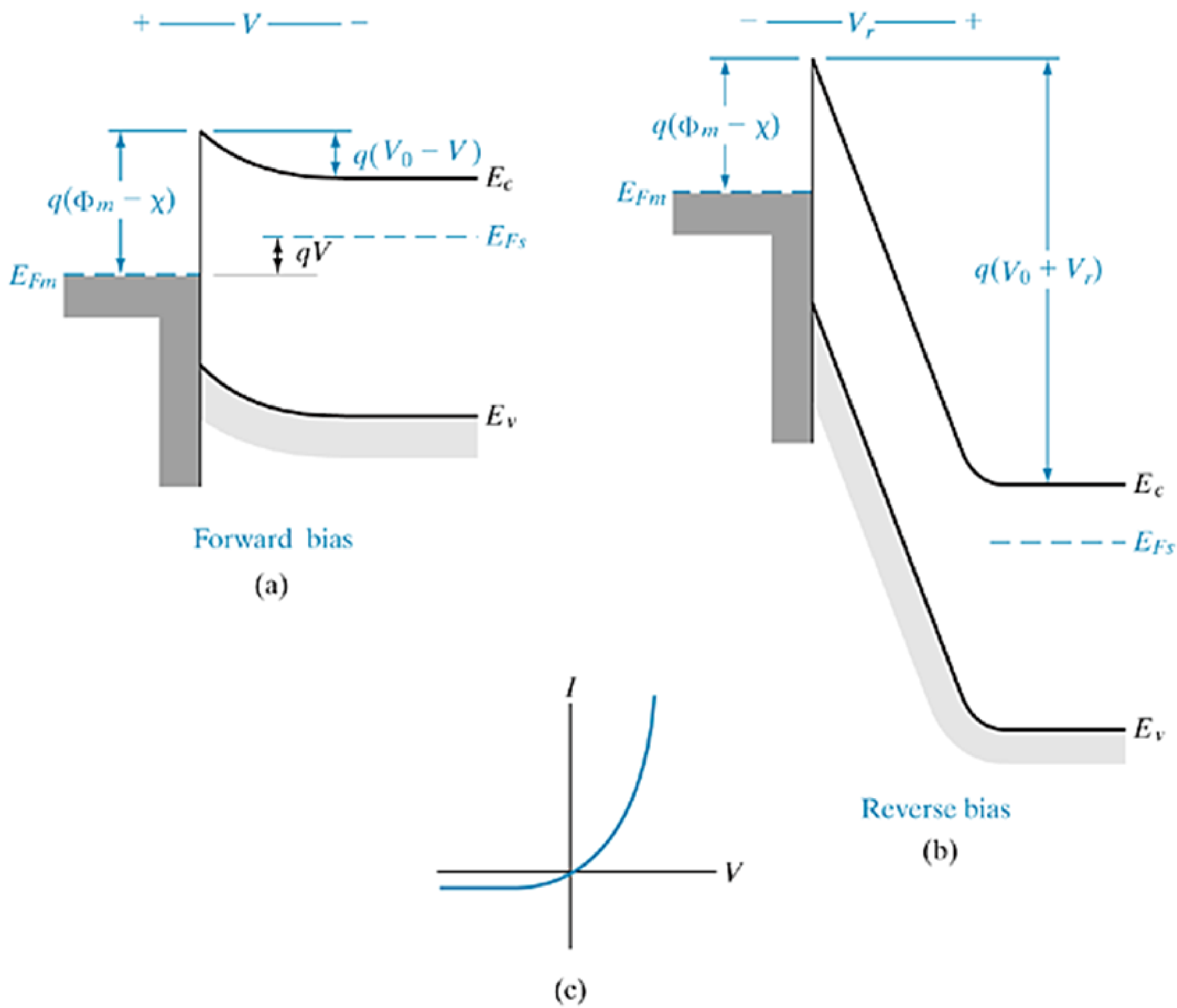
Schottky Contact Under Bias

Consider the Schottky contact under FB with a voltage $\boldsymbol{V}$ (+ve voltage to the metal). This applied voltage will mostly drop across the depletion region due to its larger resistance compared to the metal and the semiconductor bulk region. Thus, the energy barrier will be reduced from $\boldsymbol{qV_o}$ to $\boldsymbol{q(V_o - V)}$.

Due to the lower barrier, electrons from the semiconductor can now cross into the metal. This will lead to <u>a forward current flowing from the metal to the semiconductor.</u>

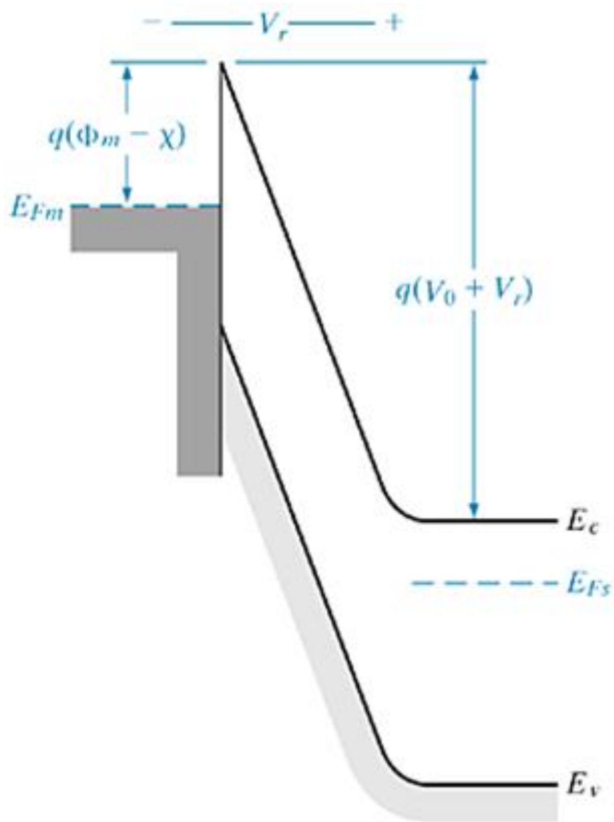


Forward bias



Effects of forward and reverse bias on Schottky contacts to n-type semiconductor (a) forward bias; (b) reverse bias; (c) typical current-voltage characteristic.

Under RB with a voltage V_r (-ve voltage to the metal), the energy barrier is increased from qV_o to $q(V_o + V_r)$. Electron flow from the semiconductor to the metal is now inhibited. However, there is still a continuous flow of electrons from the metal into the semiconductor, giving rise to a reverse current flow.



Reverse bias

This current is small due to the energy barrier $q(\phi_m - \chi)$ (the Schottky barrier height) encountered by electrons in crossing from metal to the semiconductor. It is also independent of the applied bias V_r since the Schottky barrier height is unaffected by the bias voltage (recall that $q\phi_m$ and $q\chi$ are fundamental properties of the metal and semiconductor respectively, and hence they are constant).

This current is the reverse saturation current I_o of the Schottky diode, similar to the reverse saturation current flowing in a pn junction under RB.

The resulting IV characteristic of a Schottky diode can be shown to be similar to that of a pn junction

$$\boxed{I = I_o\left(e^{qV/kT} - 1\right)} \qquad (4)$$

where ***V*** is bias voltage (+ve for FB and –ve for RB) and $\boldsymbol{I_o}$ is the reverse saturation current whose magnitude depends on the Schottky barrier height.

In fact it can be shown that

$$\boxed{I_o = AA^{**}T^2\left(e^{-q\phi_B/kT}\right)} \qquad (5)$$

where A is the area of the diode, A^{**} is the effective Richardson constant and $\boldsymbol{\phi_B}$ is the Schottky barrier height.

Actual *I*-*V* measurements are normally found to fit the expression

$$\boxed{I = I_o\left(e^{qV/nkT} - 1\right)} \qquad (6)$$

where ***n*** is called the <u>ideality factor</u> and represents departure from an ideal Schottky junction (***n*** = 1). Actual Schottky barriers on moderately doped semiconductors usually have ***n*** values in the range 1 to 2. It is also observed that ***n*** increases with the doping density of the semiconductor.

Schottky diode is a majority carrier device as the conduction of current is by the majority electrons in the n-type semiconductor. This is in contrast to a pn junction, which is a minority carrier device, as the current flow is due to the diffusion of minority carriers in each side of the junction.

As such, Schottky diode does not have any minority carrier pile-up, and hence no charge storage capacitance C_s. Hence, there is no delay related to the build-up (during turn-on) and removal (during turn-off) of minority carriers. This results in better high frequency performance and faster switching speed than a pn junction diode.

MS contacts are normally made by depositing an appropriate metal on a clean semiconductor surface and defining the pattern using photolithography. These devices are particularly suited for densely packed ICs as they require fewer steps compared to conventional pn junction devices.

Schottky contact with a p-type semiconductor ($q\phi_m < q\phi_s$)

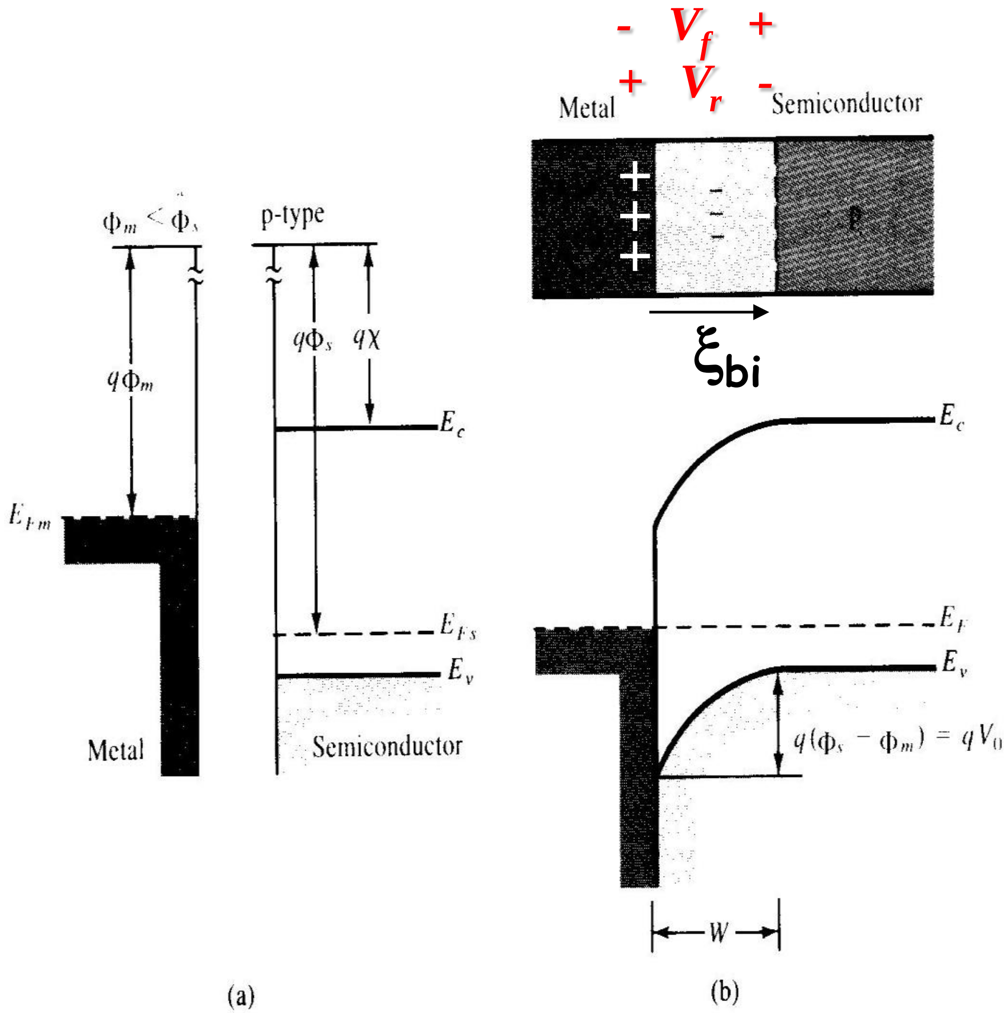
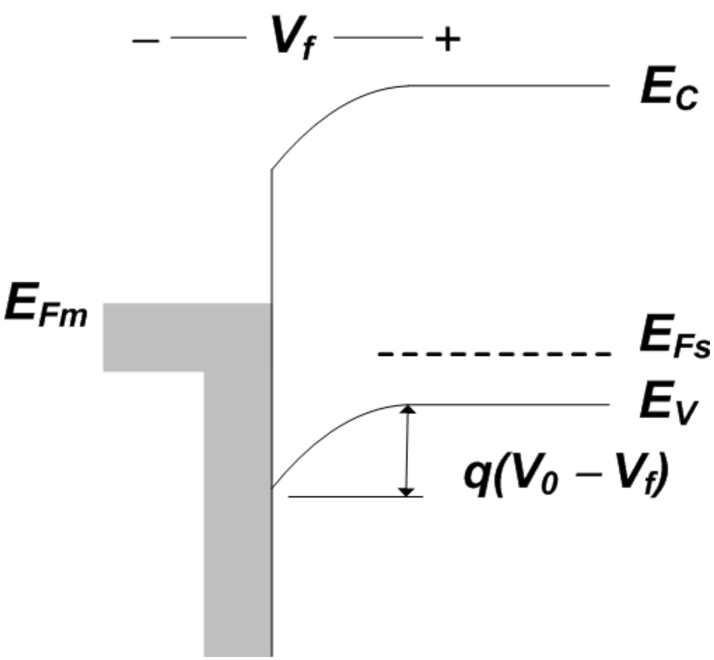


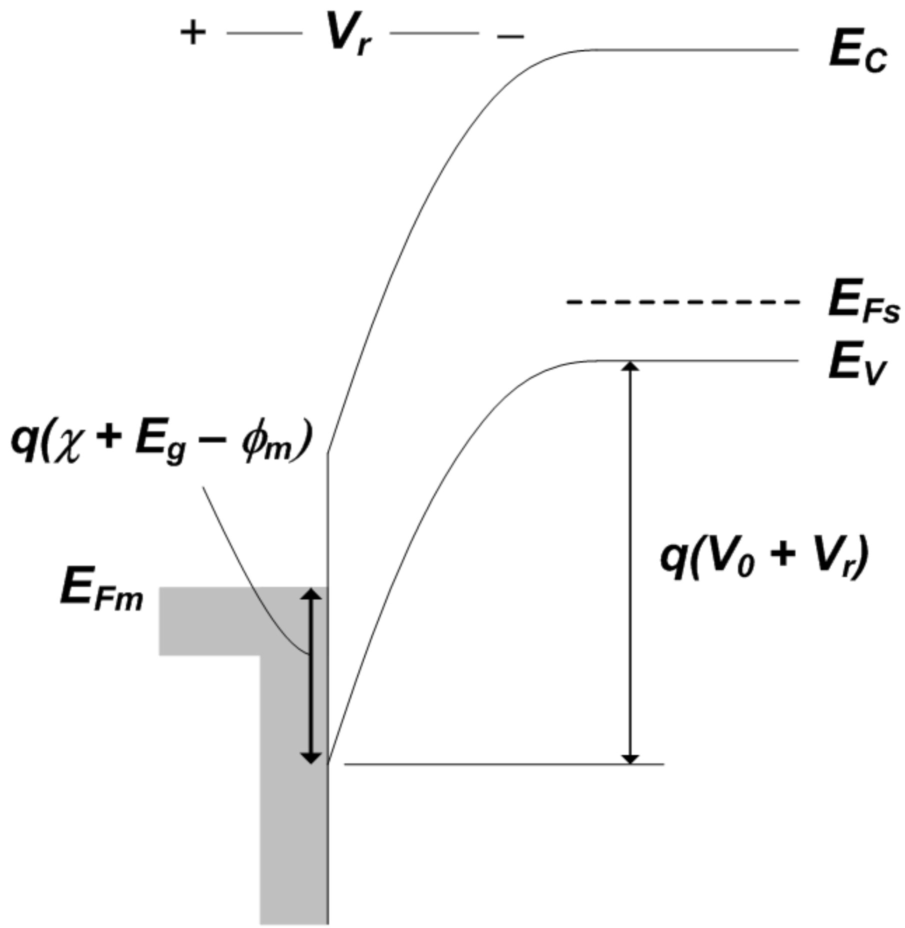
Figure 5-32 Schottky barrier between a p-type semiconductor and a metal having a smaller work function: (a) band diagrams before joining; (b) band diagram for the junction at equilibrium.

†While the properties of the Schottky barrier depletion region are similar to the p+-n, it is clear that the analogy does not include forward-bias hole injection, which is dominant for the p+-n but not for the contact of Fig. 5-31.

Schottky Contact – P-type Semiconductor



forward bias

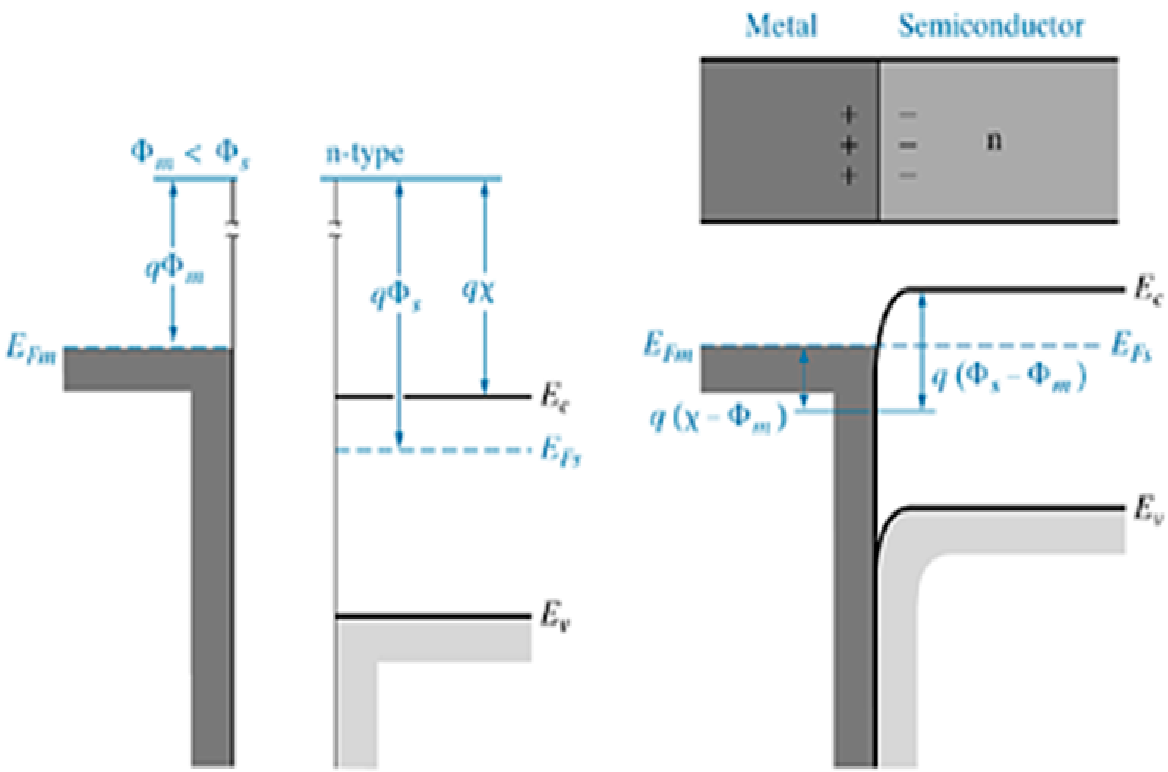


reverse bias

3. Ohmic Contacts

Consider a metal in contact with a **n-type semiconductor** such that

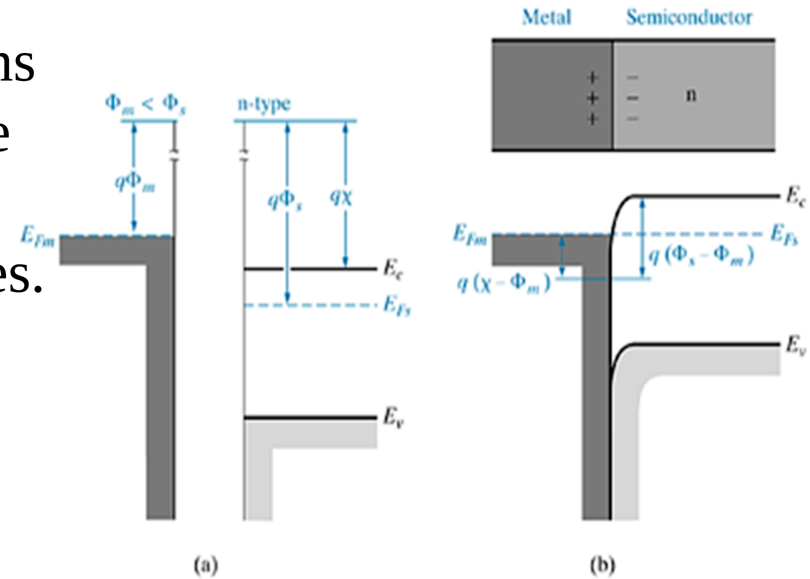
$$\boxed{q\,\phi_m < q\,\phi_s}$$



(a) (b)

At the instant of contact, the more energetic electrons in metal see no barrier in crossing into the CB of the n-type semiconductor. Hence, they can readily flow into the semiconductor to take up lower energy states.

On the other hand, electrons in the semiconductor conduction band see a barrier $\boldsymbol{q(\chi - \phi_M)}$ in crossing into the metal.

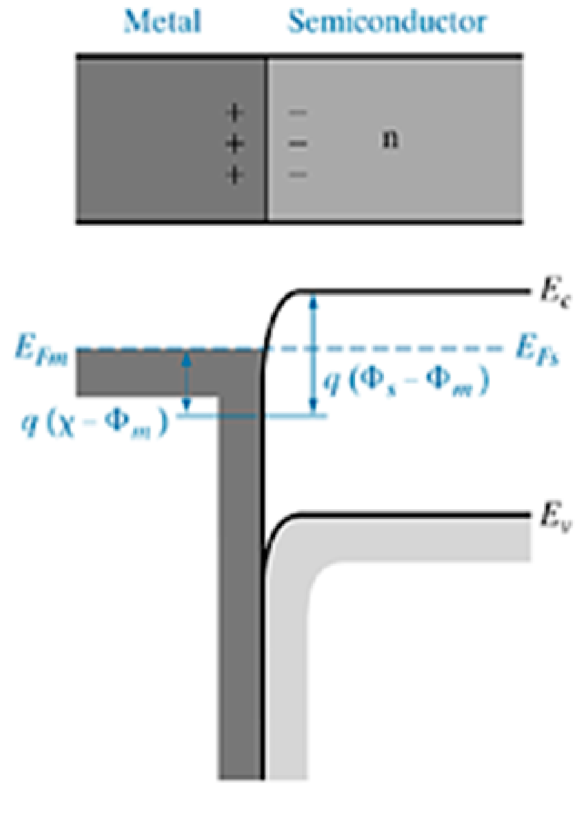


∴ there will be a net transfer of electrons from metal to semiconductor. The excess electron charge in the n-type semiconductor exists essentially as a surface charge density.

The n-type semiconductor will therefore have an accumulation of electrons (majority carriers) near its surface at the contact. On the other hand, due to the loss of electrons, the metal will have a layer of positive surface charge attributed to the metal ions.

Hence, the semiconductor is negatively charged due to the transferred electrons, whereas the metal is positively charged due to the loss of electrons.

Similar to the Schottky contact, these charges will result in a PD across the semiconductor near the contact, and hence an energy barrier that reduces the flow of electrons from the metal to semiconductor. Thermal equilibrium is achieved when the rates of electron flow in both directions are exactly balanced, resulting in no net current flow.



(b)

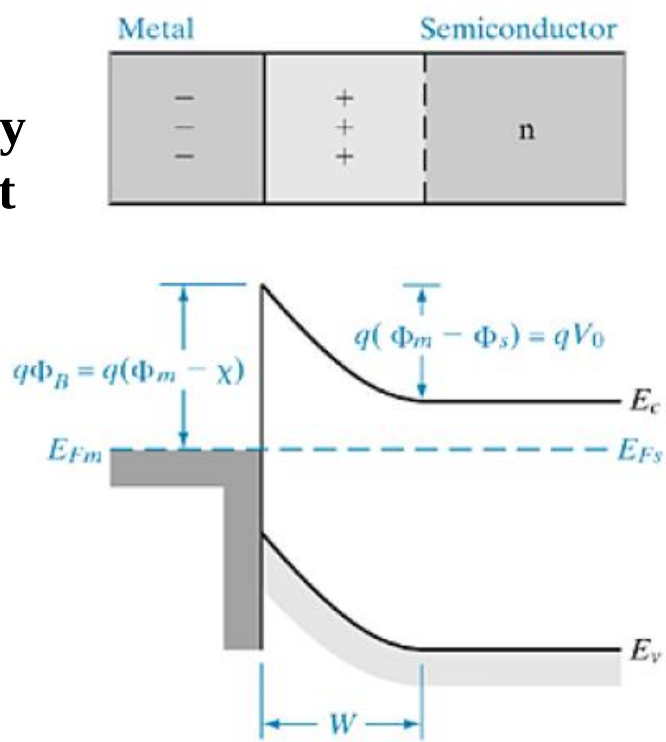
From the energy band diagram, it can be seen that there is a barrier $\boldsymbol{q(\phi_s - \chi)}$ for electrons crossing from the metal to the semiconductor.

So, what is the main difference between a metal/n-type semiconductor Schottky and ohmic contact ?

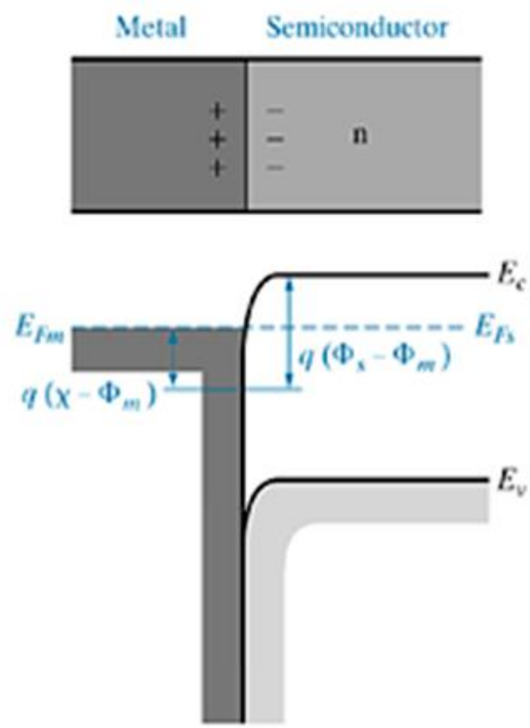
- For the Schottky contact, there is a depletion region formed in the semiconductor, which separates the conducting electrons in the metal from those in the semiconductor.

- For the Ohmic contact, there is an accumulation of electrons (majority carriers) in the semiconductor near the contact and the conducting electrons in the metal and semiconductor are also physically close to the contact. This makes the contact a conductive region.

Schottky Contact

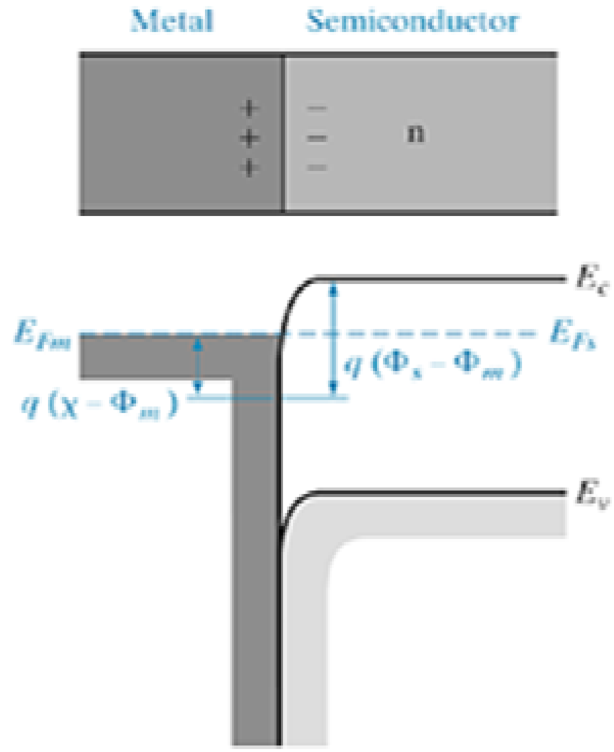


Ohmic Contact



It can be seen that there is practically no barrier for electrons crossing from the semiconductor to the metal.

On the other hand, there is an energy barrier $\boldsymbol{q(\phi_s - \chi)}$ encountered by electrons in crossing from the metal to the semiconductor at equilibrium. From



$$
\boxed{\begin{aligned} q\phi_s &= q\chi + (E_C - E_{Fs}) \\ \Rightarrow q(\phi_s - \chi) &= E_C - E_{Fs} \end{aligned}} \qquad (7)
$$

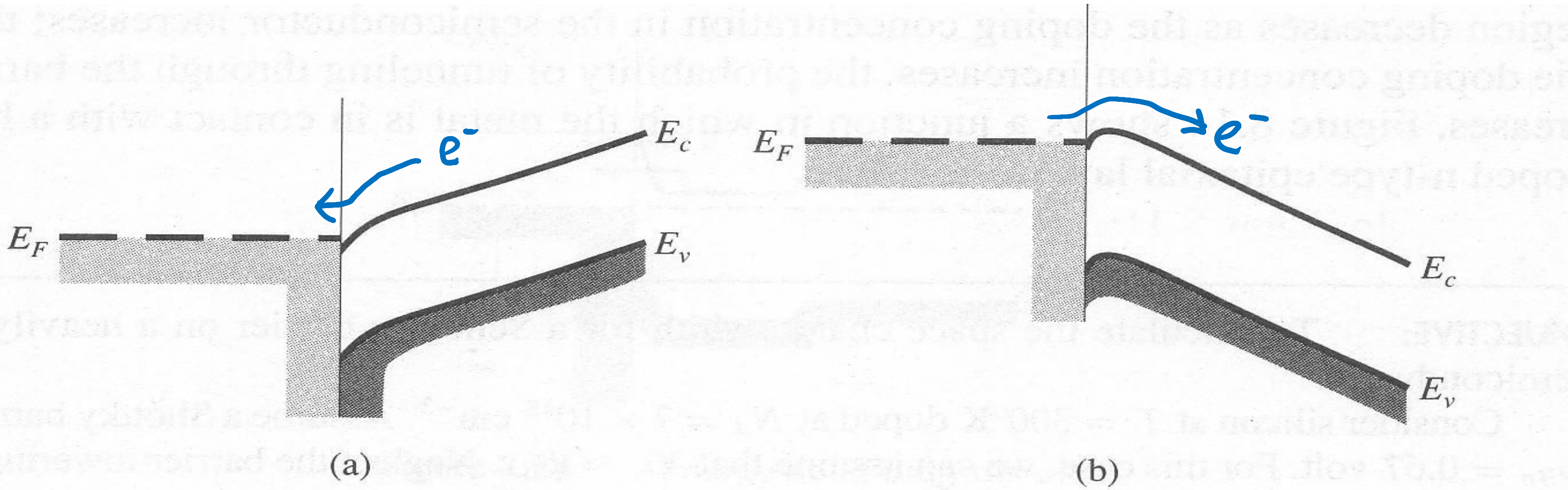
Thus, the energy barrier is equal to $\boldsymbol{(E_C - E_{Fs})}$.

For n-type semiconductor, this energy difference is generally small. In practical ohmic contacts, the n-type semiconductor will be heavily doped, viz., make $\mathbf{n^+}$, to further reduce $\boldsymbol{(E_C - E_{Fs})}$ and result in a very small energy barrier.

Essentially, there is **negligible barrier for electron flow in either direction**. Hence, with a bias, current can flow freely in either direction across the contact region.

Effects of Bias on Ohmic Contact

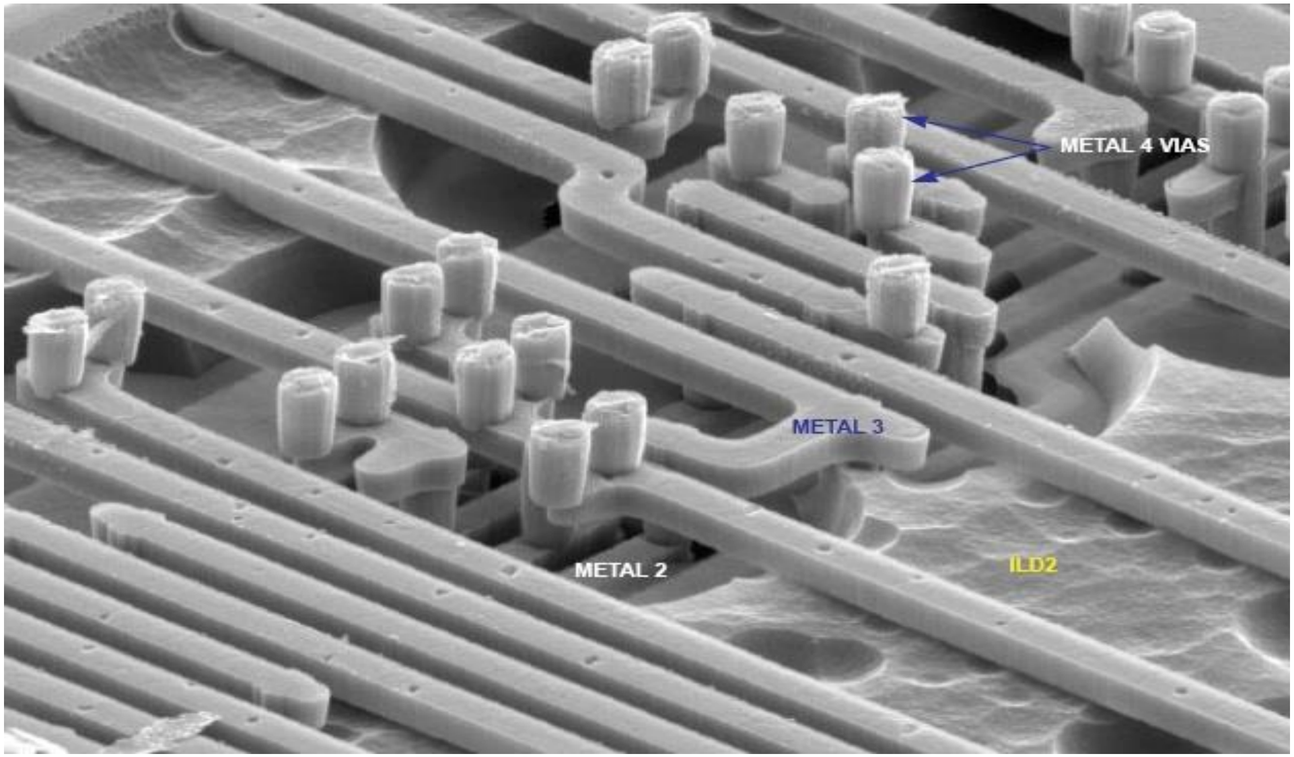
As the contact region is very conductive, the applied voltage in an ohmic contact will drop mostly across the bulk of the semiconductor, which is now the most resistive part of the entire structure, compared to the metal and the contact region.



Ideal energy-band diagram of a metal–n-semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor

- When a +ve voltage is applied to the metal, electrons can flow down-hill from the semiconductor into the metal.
- When a +ve voltage is applied to semiconductor, electrons can easily flow over the (small) barrier from the metal into the semiconductor.
- Hence, this contact is called an ohmic contact.

Ohmic contacts, having linear *I-V* characteristics in both biasing directions, are a common feature in integrated circuits (ICs). In ICs, the surface is a maze of p and n regions, which must be properly contacted and interconnected. It is important that these contacts be OHMIC, with minimal resistance and no tendency to rectify signals.

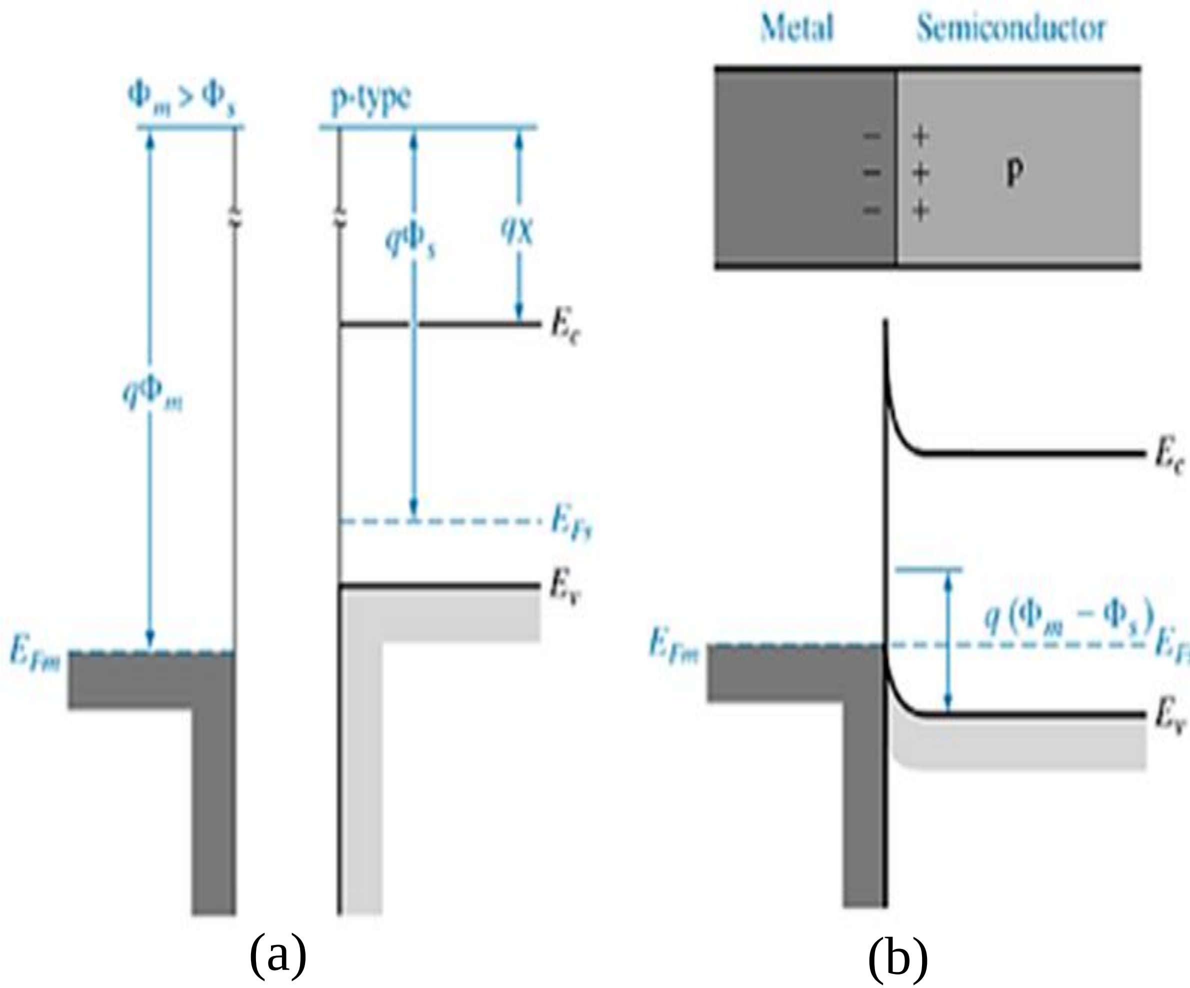


Forming Ohmic Contacts

A practical way of forming ohmic contacts is by doping the semiconductor heavily in the contact region. This further reduces the small barrier $\boldsymbol{q(\phi_s - \chi) = E_C - E_{Fs}}$ for electron flow from metal to semiconductor.

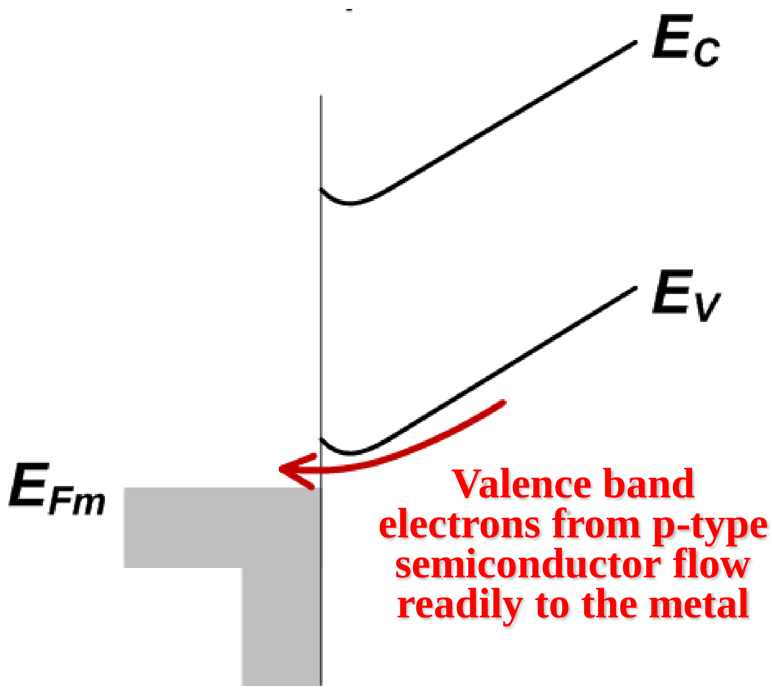
Usually in a pn junction, a p+ surface layer is used for contacting the p-region to the metal and similarly a n+ surface layer for contacting the n-region to the metal. Both p+ and n+ layers form the necessary low resistance ohmic contacts with the metal, thus enabling the connectivity of the pn junction to the outside world.

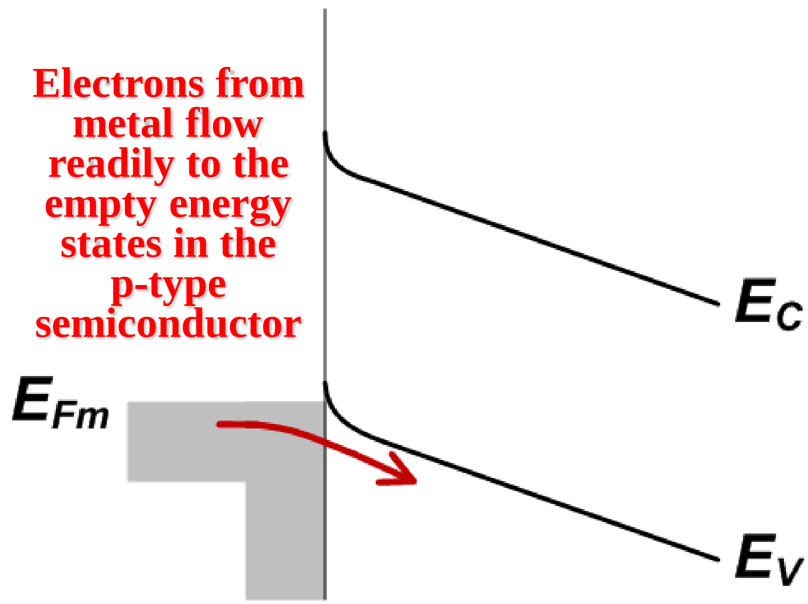
Ohmic contact with a p-type semiconductor ($q\phi_m > q\phi_s$)



Ohmic metal-semiconductor contacts: (a) $\phi_m > \phi_s$ for a p-type semiconductor, and (b) the junction at equilibrium.

Ohmic Contact – P-type Semiconductor





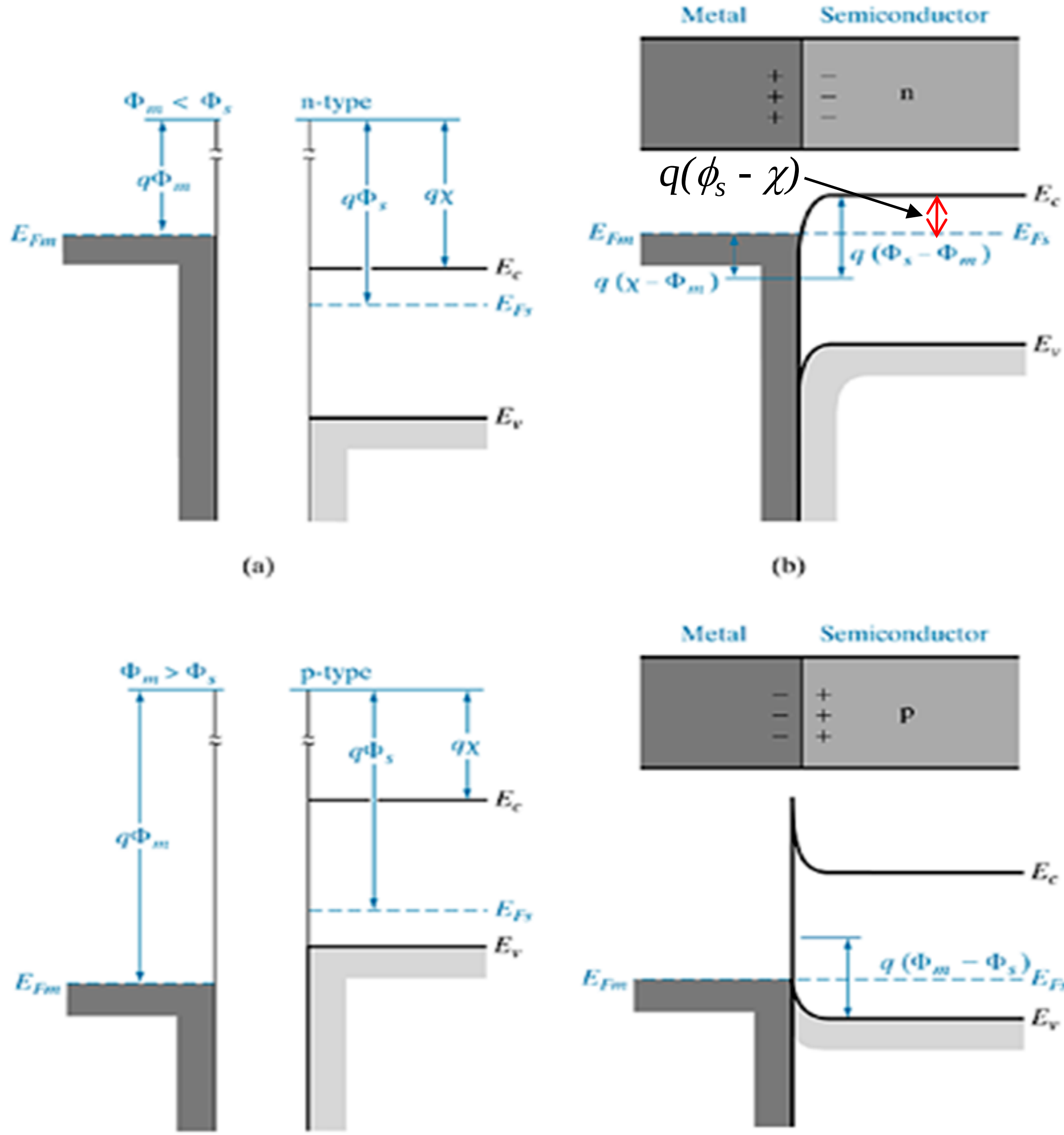
positive voltage applied to the metal; "forward" bias

negative voltage applied to the metal; "reverse" bias

Ohmic Metal-Semiconductor Contacts

(i) $q\phi_m < q\phi_s$
for an n-type
semiconductor

(ii) $q\phi_m > q\phi_s$
for a p-type
semiconductor



Ohmic metal–semiconductor contacts: (a) $q\phi_m < q\phi_s$ for an n-type semiconductor, and (b) the equilibrium band diagram for the junction; (c) $q\phi_m > q\phi_s$ for a p-type semiconductor, and (d) the junction at equilibrium.

Summary on MS Contacts

1. **<u>Schottky contact</u>** is obtained when:
   - $q\phi_m > q\phi_s$ in an n-type semiconductor
   - $q\phi_m < q\phi_s$ in an p-type semiconductor

   <u>Depletion regions are formed in these cases.</u>

2. **<u>Ohmic contact</u>** is obtained when:
   - $q\phi_m < q\phi_s$ in an n-type semiconductor
   - $q\phi_m > q\phi_s$ in an p-type semiconductor

   <u>Accumulation of majority carries occur in these cases.</u>