ELEC4705 – Fall 2009

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LECTURE 13
The Diode

Contents

The first device we will look at is the diode. The diode is a non-linear device (I is not proportional to V) formed by creating a device from a metal and a semi-conductor (Schottky diode) or two types of semi-conductor one n and the other p type (pn diode).

13.1. Schottky Barriers (Metal-Semiconductor Junctions)

Schottky diodes (see figure 1) are the oldest semiconductor devices used as rectifiers in "crystal" radios. Later they were replaced by pn-junctions. A Schottky diode is a special type of diode with a very low forward-voltage drop which are based on a metal-semiconductor junction. When current flows through a diode there is a small voltage drop across the diode terminals. A normal diode has between $0.7 - 1.7$ volt drops, while a Schottky diode voltage drop is between approximately $0.15 - 0.45$ volts.

They still have a number of uses and the physical effects on which their operation is based are present in many situations.

The lower voltage drop translates can translate into higher system efficiency.

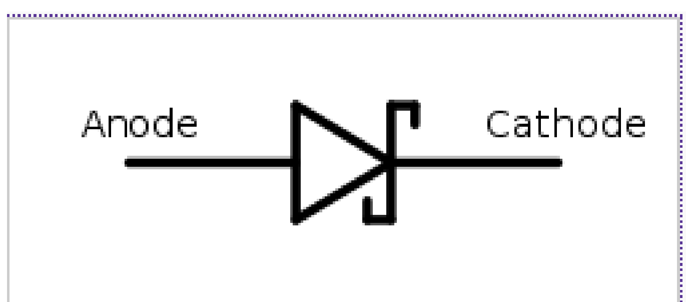


Figure 1. Symbol of a Schottky Diode

13.1.1. Material Band Structures

At surface of any solid there is an energy barrier holding in the electrons (work function), i.e. the work function is the minimum energy needed to remove an electron from a solid to a point immediately outside the solid surface (or energy needed to move an electron from the Fermi energy level into vacuum).

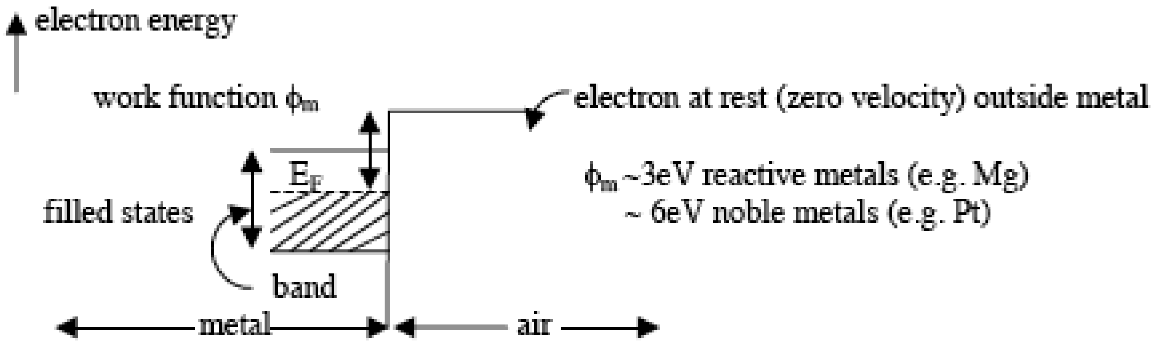


Figure 2. Metal Band Structure

13.1.1.1. *Metal Band Structure (half filled band).* See figure 2.

- ϕ_m is the work function or (ionization energy) which is the energy to remove the electron from the Fermi level to vacuum level.
- The work function ϕ_m is strongly dependent on surface preparation and is not a precisely defined quantity (varies depending on surface).

13.1.2. Semiconductor Band Structure (conduction and valance band, n-type)

See figure 3

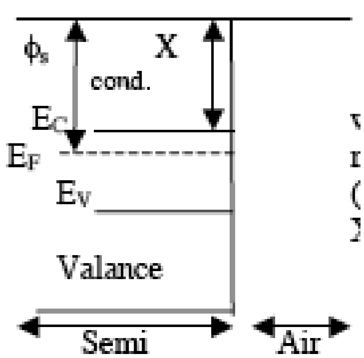


Figure 3. Semiconductor Band Structure

- Work function ϕ_s depends on doping, however it is often more useful to deal with the electron affinity χ (energy to remove electron from conduction band) $\chi_s \approx 4.1eV$ for Si.

13.1.3. Metal-Semiconductor Junction - the thought experiment

As for the pn diode we undertake a thought experiment where we bring the two materials into contact and equilibrate the Fermi energies.

Figure 4 shows the band structures of metal and semiconductor when the materials don't touch and ($\phi_m > \phi_s$).

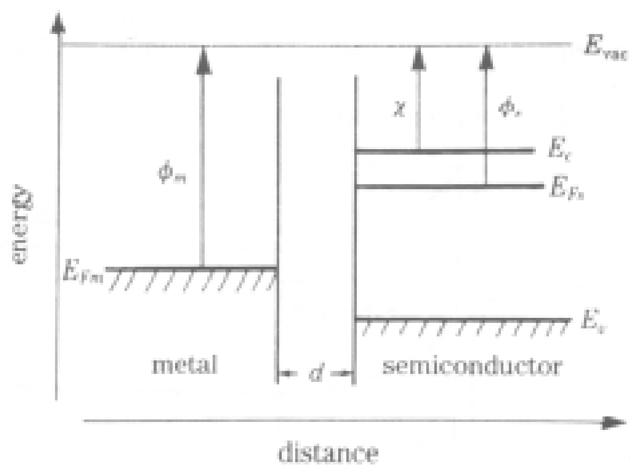


Figure 4. Metal-Semiconductor Band Structure Before Touching

After the metal and semiconductor have been brought into contact, electrons start to flow from the semiconductor down into the metal until the Fermi energies of both solids are equal (equilibrium condition), see figure 5 for the band structure.

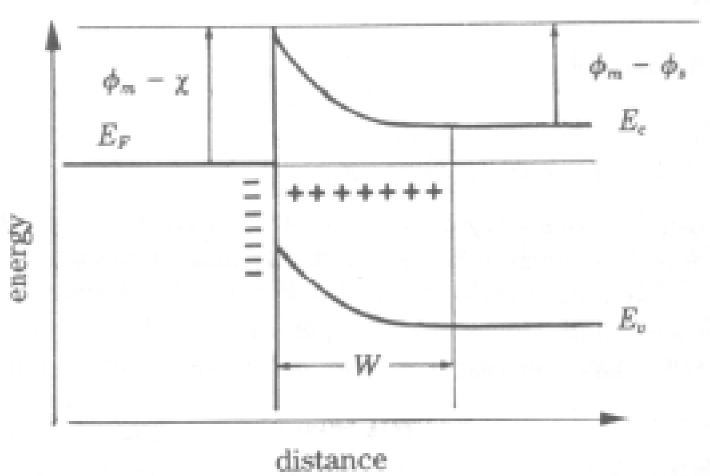


Figure 5. Metal-Semiconductor Band Structure After Touching

- In the semiconductor, a depletion region of width W is formed (uncompensated donors).

$$W = \sqrt{\frac{2\varepsilon_i V_0}{qN_D}} \tag{13.1}$$

- In the metal an electron current forms a negative surface charge layer.
- These in turn produce an electric field is created.
- An electric potential is established and a bending of the bands occurs in the semiconductor.

$$V_0 = \frac{\phi_m - \phi_s}{q} = \frac{KT}{q}\ln(\frac{N_c}{N_D}) \tag{13.2}$$

- V_0 and W both depend on doping concentration (N_D) and temperature.

We have two currents flowing (majority carriers n in this case) one J_{sm} from the semiconductor to the metal over the barrier $\phi_m - \phi_s$ and the other J_{ms} from the metal to the semiconductor over the barrier χ. *The equilibrium is reached when the two equal and opposite electron flow over the barrier and $J = 0$ at $V = 0$.*

13.1.4. Reverse bias ($V < 0$)

If the metal is connected to the negative terminal of a battery, the metal is charged even more negatively than without bias, see figure 17.

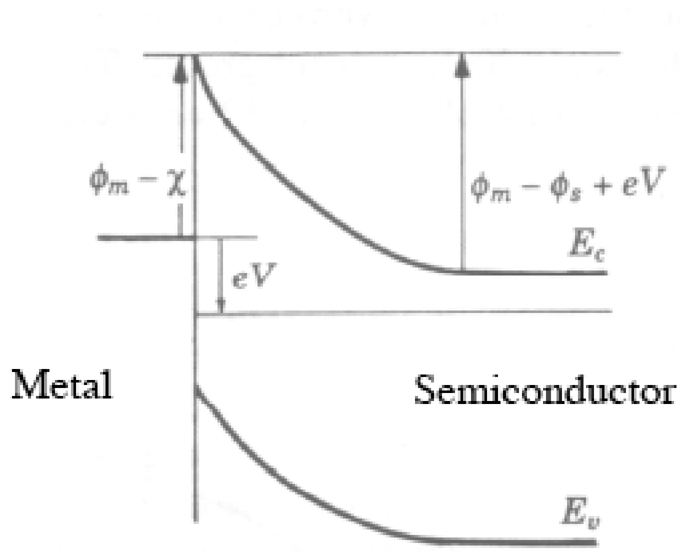


Figure 6. Metal-Semiconductor Band Structure in Reverse Bias

We see similar effects as with the pn diode.

- The electrons in the semiconductor are repelled even more.
  - Depletion region becomes wider.
  - Potential barrier is increased.
- The electron flows are unbalanced since the $J_{sm} \rightarrow 0$.
- A current flows as a result of a few electrons in the metal acquiring enough thermal energy to overcome barrier. This is a small current as barrier $\phi_m - \chi$ has not changed, and J_{ms} is as before.
- At high reverse bias, electrons can tunnel through barrier *"field emission"* and cause a charge current to flow.

13.1.5. Forward Bias

Now consider the case when the polarity of the battery is reversed, i.e. metal is connected to the positive terminal of the battery, see figure 15 for the band structure.

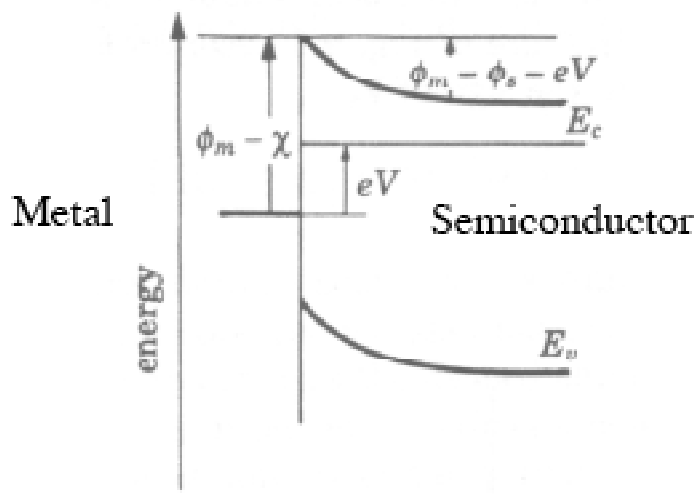


Figure 7. Metal-Semiconductor Band Structure in Forward Bias

- The electrons spill from semiconductor into metal.
  - Depletion region becomes narrower.
  - Potential barrier is reduced.
- We get a large current exponentially related to V flowing in the device.
- To compute the electron flow from semiconductor to metal we use thermionic emission theory. The current that flows from the metal into the semiconductor is given by

$$J_{ms} = \frac{q4\pi m^* K^2 T^2}{h^3} \, e^{-q(\phi_m - \chi)/KT}. \qquad (13.3)$$

Where $C = q4\pi m^* K^2/h^3$ is defined as Richardson's Constant. So we have the current as

$$J_{ms} = CT^2 \, e^{-q(\phi_m - \chi)/KT}. \qquad (13.4)$$

- The current flowing from the semiconductor into the metal is

$$J_{sm} = CT^2 \, e^{-q(\phi_m - \phi_s - V)/KT}. \qquad (13.5)$$

- The net current is given by

$$J_{net} = J_s(e^{qV/KT} - 1) \quad , \quad J_s = CT^2 \, e^{-q(\phi_m - \phi_s)/KT} \qquad (13.6)$$

As typically there is very little minority carrier injection from semiconductor into metal; Schottky diodes are said to be majority carrier devices.

13.1.6. Applications

13.1.6.1. *Ohmic Contacts to Semiconductors.* In Integrated Circuits the external connections are always metallic. A metal-semiconductor junction, which conducts current in only one direction, may be problematic. Need to make a low resistance contact with linear V-I characteristics, see figure 11(b).

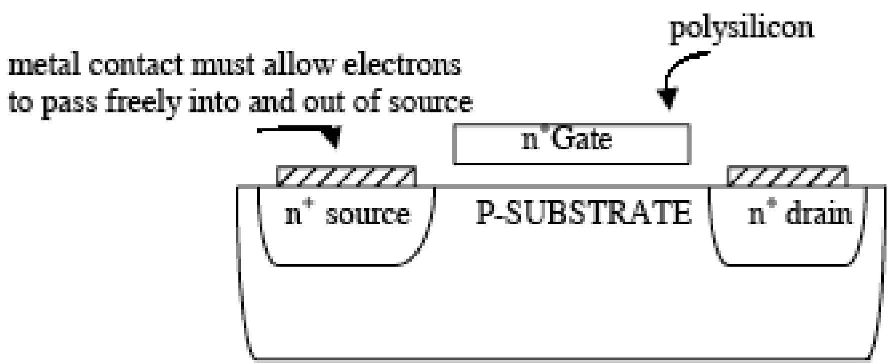


Figure 8. Ohmic Contacts to Semiconductors

In case of $\phi_m < \phi_s$, the electrons flow from the metal into the semiconductor, see figure 9 for the band structure before touching.

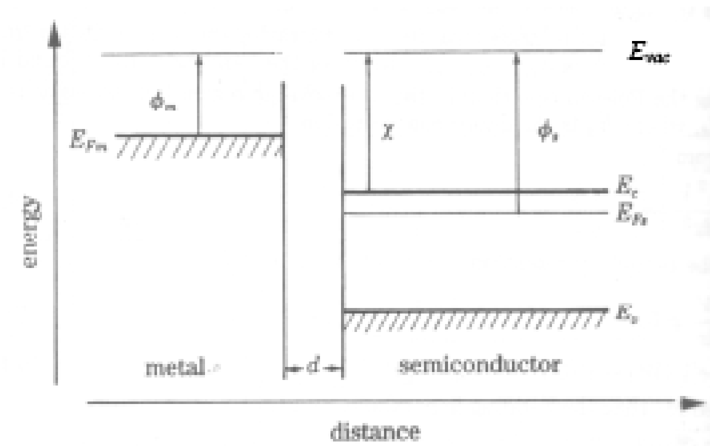


Figure 9. Metal-Semiconductors Band Structure in case of $\phi_m < \phi_s$ before touching

After connecting the two materials we will have:

- In metal, electron current forms a positive surface charge layer.
- An electric field is created (in the opposite direction as before).
- An electric potential and thus a bending of the bands occurs, see figure 10.

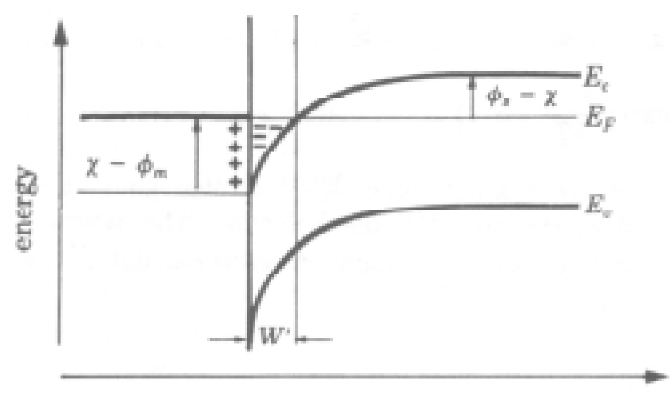
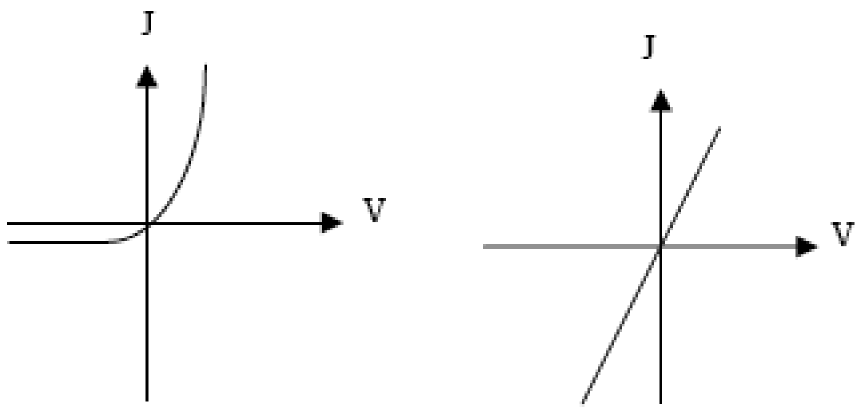


Figure 10. Metal-Semiconductors Band Structure in case of $\phi_m < \phi_s$ after touching

- The bands of the semiconductor bend downward and no barrier exists for the flow of electrons in either direction.
- The current increases linearly with increasing voltage and is symmetric about the origin, see figures 11(a) and 11(b).



(a) Schottky barrier (b) what we need for an ohmic contact

Figure 11. I-V characteristics for a Schottky junction and an Ohmic contact

13.1.6.2. *Notes on the applications.*

- Since only majority carriers are involved, no mutual annihilation (recombination) of electrons and holes can occur. This results in faster devices.
- The metal base provides better heat removal and is helpful in high power devices.
- Used for detection of long wavelength IR (low energy photons). This is useful in temperature sensors.

13.2. PN Junction

The device operation can be best explained by its band structure and carrier concentrations. We can understand this using a thought experiment where we bring together two pieces of material one n and the other p as shown in figure 12.

Due to diffusion we have two effects:

- Electrons pour out of n-type material, leaving behind uncompensated donors (+ ions)
- Holes pour out of p-type material, leaving behind uncompensated acceptors (- ions)

These electrons and holes then recombine, producing a region around the interface depleted of free carriers, leaving only fixed charges (ionized donors and acceptors). However the diffusion process can not continue indefinitely as this space charge creates an electric field that opposes the

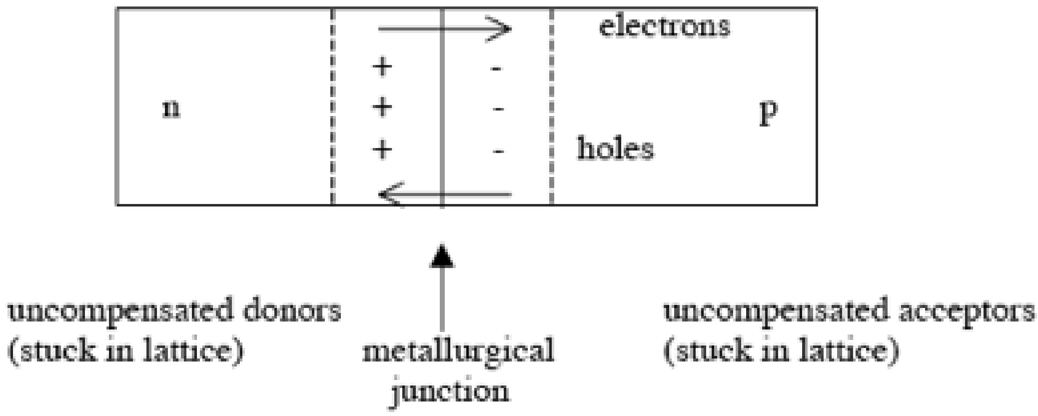


Figure 12. PN Junction

diffusion of majority carriers (electrons in n type and holes in p type), though such diffusion is not prevented altogether as shown in figure 13. The electric field will sweep minority carriers (holes in $n-type$ and

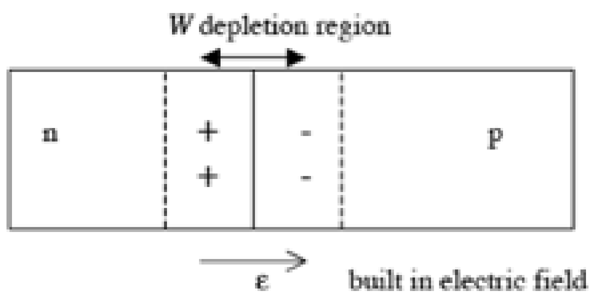


Figure 13. Built in electrin field

electrons in $p-type$) across the junction so that there is a drift current of electrons from the $p-$ to the $n-$ type side and of holes from the $n-$ to the $p-$ type side which is in the opposite direction to the diffusion current. The junction field builds up until these two current flows are equal and equilibrium is achieved (no net current flow).

It is a basic result of thermodynamics that in equilibrium the Fermi energy must be the same throughout the system.

The induced electric field establishes a contact potential ϕ between the two regions and the energy bands of the $p-type$ side are displaced relative to those of the $n-type$ side. This produces the Energy Band Diagram for a p-n Junction as shown in figure 14.

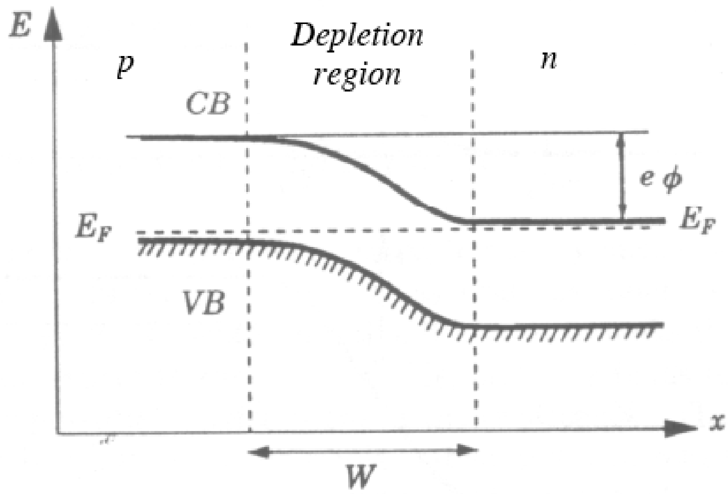
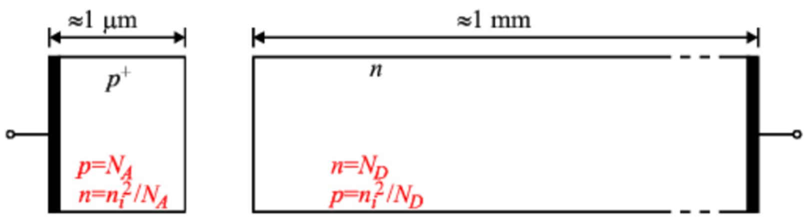


Figure 14. Band structure of a diode

Now lets look at the carrier concentrations in the device during the thought experiment.

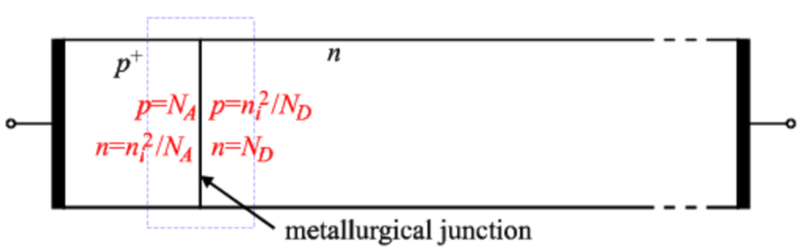
Junction Materials Just Before Connection

- To understand carrier flow in biased diode, first examine behaviour of carriers during establishment of equilibrium between p and n materials
- Start with situation below, where p^+ and n materials are separated, and hence cannot exchange carriers (would be a p^+ implant diffusion into n substrate structure)
- Electrons are majority in n-type (N_D) and minority in p-type (n_i^2/N_A), holes are majority in p-type (N_A) and minority in n-type (n_i^2/N_D)



Junction Materials Immediately After Connection

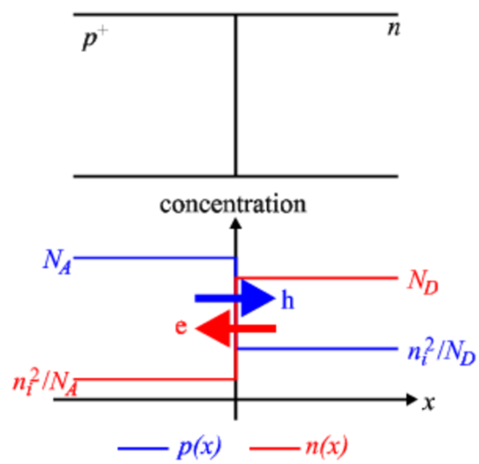
- After materials are connected, they can exchange carriers
- Large concentration gradients exist across the metallurgical junction
- Following slides show enlargement of boxed region



Charge Distributions at $t = 0^+$

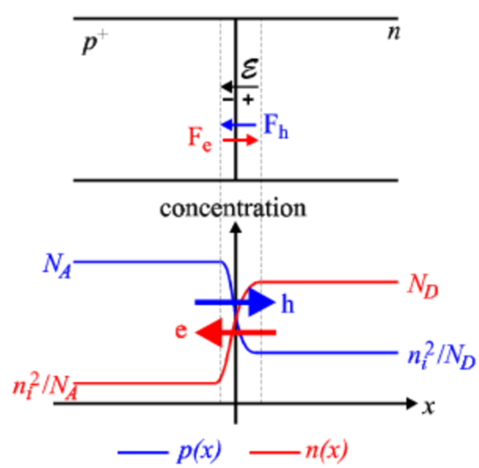
- Just after connection, the hole and electron distributions are flat in each material (uniform doping) and discontinuous across the metalurgical junction
- Large concentration gradients exist, so there will be a large component of carrier flux due to diffusion, recall

$$\Theta = -D\frac{dc(x)}{dx}$$



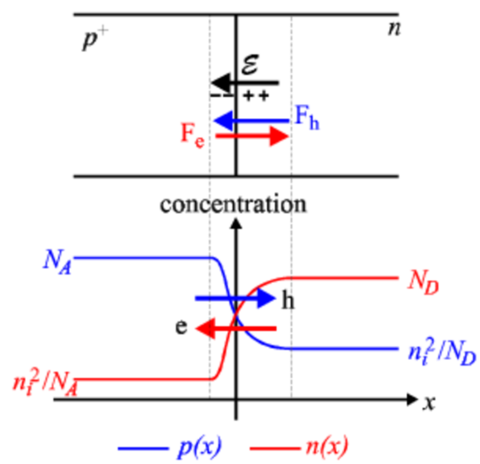
Charge Distributions at Later t

- At some later time, charge redistribution has taken place
- Holes move to *n*-type, creating +ve charge, electrons move to *p*-type, creating -ve charge
- Concentration gradients, and hence diffusion flux, decrease as carriers redistribute
- Charge redistribution causes electric field which also tends to oppose further diffusion of carriers



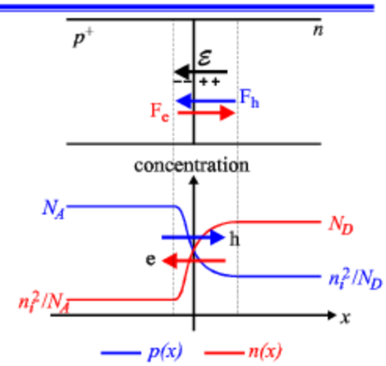
Charge Distributions for t → ∞, Equilibrium

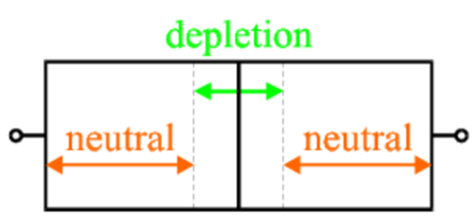
- After a long time, charge will have redistributed so that the forces due to the concentration gradient and the electric field balance
- Forces due to diffusion and electric field are still present, but exactly balance
- If electrons and holes were not charged, this would not occur (no charge separation, no $\mathcal{E}$)
- Note that areas away from metallurgical junction are unaffected



Diode Regions

- Identify two distinct regions in the *pn*-junction structure:
  - The neutral regions are those which are essentially unaffected by the charge redistribution
  - The depletion region is the transition region where charge redistribution has taken place





13.2.1. Values for ϕ and W

The electrostatics and the fact that at equilibrium the current through this device must be zero can be use to solve for the built in potential and the width of the depletion region.

For a uniform junction $N_d = Const.$ and $N_A = Const.$ the built in potential (ϕ) and the width of the depletion region (W) are as follows.

$$\phi = \frac{K_B T}{q} \ln(\frac{N_A N_D}{n_i^2}) \tag{13.7}$$

$$W = \sqrt{\frac{2\varepsilon_{Si}\phi}{q}} \sqrt{\frac{N_A + N_D}{N_A N_D}} \tag{13.8}$$

Notes:

- ε_{Si} is the electric permitivity of Silicon.
- The built in potential (ϕ) depends on doping and temperature.

13.2.1.1. *A special case.* In practice, we often encounter one-sided (one side much more heavily doped than the other) abrupt junctions and then for the depletion width (equation 13.8)we will have

$$W = \sqrt{\frac{2\varepsilon_{Si}\phi}{q N_B}} \tag{13.9}$$

$$N_B = N_A \quad if\ N_D \gg N_A$$
$$N_B = N_D \quad if\ N_A \gg N_D$$

NOTE:
Even for zero bias, there are electron and hole flows across the junction which exactly balance, i.e.

$$J_e(drift) + J_e(diffusion) = 0$$
$$J_h(drift) + J_h(diffusion) = 0$$

13.2.2. Forward Bias

Consider now the case when the $n - side$ is connected to the negative terminal of the dc source, then the depletion region narrows,as shown in figure 15. This has the effect of lowering the height of the potential

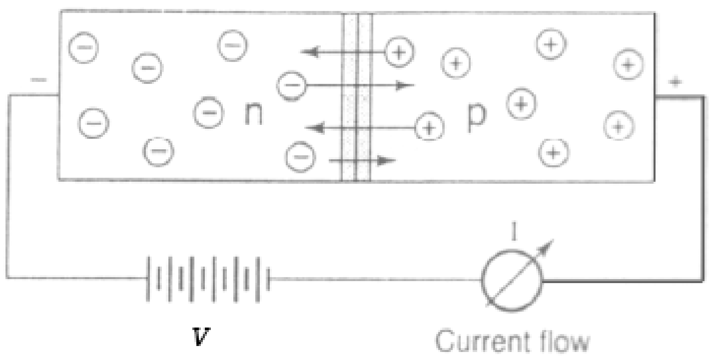


Figure 15. Forward Bias

barrier to $(\phi - V)$. Consequently, majority carriers are able to surmount the potential barrier much more easily than in the equilibrium case so that the diffusion current becomes much larger than the drift current. See figure 16 for the band structure in forward bias.

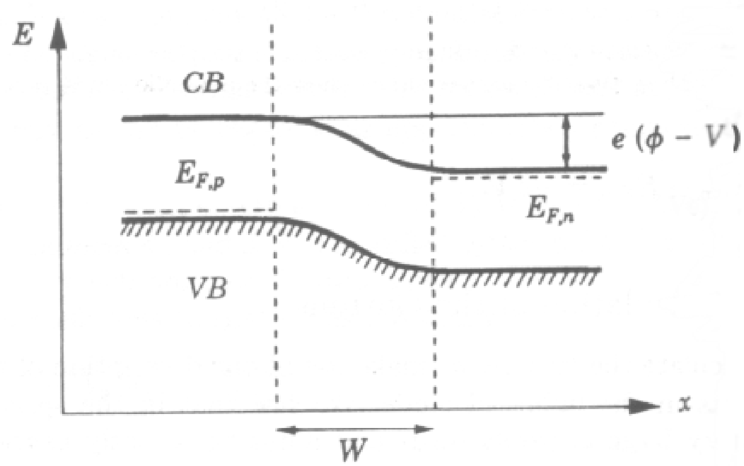
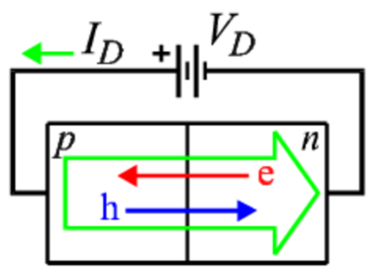


Figure 16. Forward Bias

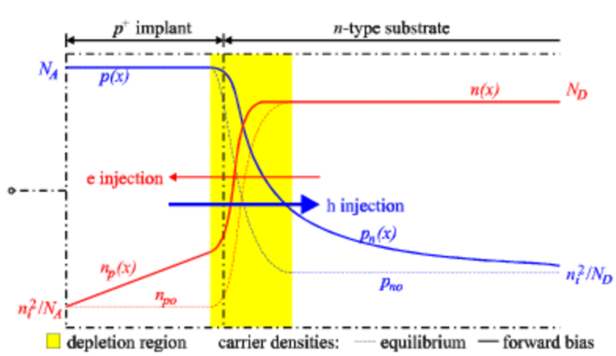
Forward Bias Injection Components

- Forward bias raises potential of p with respect to n, causes current flow from p to n
- Two current components:
  - Injection of holes from p to n, in the direction of current
  - Injection of electrons from n to p, in the opposite direction to current
- Note that electrons injected into p, holes injected into n, hence the term minority carrier injection for forward bias



Forward Bias Carrier Density Profiles

- In forward bias, injection of carriers raises the value of the carrier density throughout the device - note linear behavior in thin p^+ region
- In the neutral regions, the increase is negligible compared to the doping level for moderate bias levels
- This is therefore a low level injection situation



13.2.3. Reverse Bias

Consider figure 17 and 18, if we apply a bias $V < 0$, a very small current will flow.

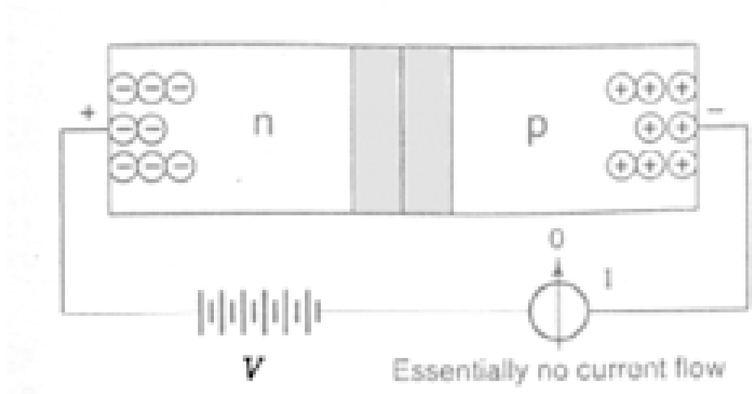


Figure 17. Reverse Bias

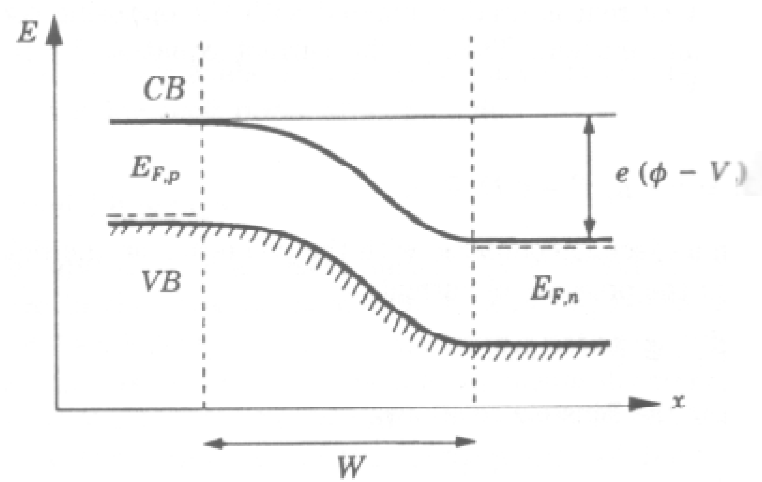
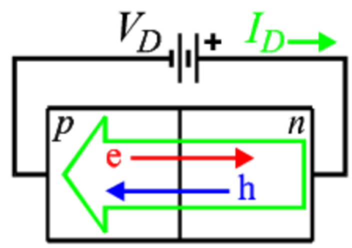


Figure 18. Band Structure in Reverse Bias

Connecting the positive terminal of a *d.c.* source to the $n - side$ withdraws electrons and holes from the depletion area which becomes wider and the potential barrier grows higher. We no longer have an equilibrium situation. The barrier is now so high that few electrons can cross from the $n - type$ to the $p - type$ region reducing the diffusion current. However, electrons are still generated (thermally) in the $p - type$ region. And holes are still generated in the $n - type$ region.

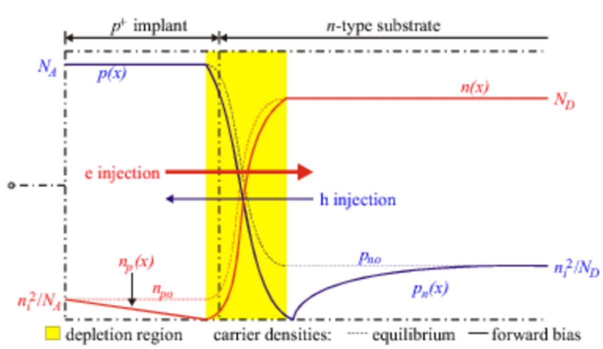
Reverse Bias Injection Components

- Reverse bias raises potential of *n* with respect to *p*, causes current flow from *n* to *p*
- Two current components:
  - Injection of holes from *n* to *p*, in the direction of current
  - Injection of electrons from *p* to *n*, in the opposite direction to current
- Note that electrons injected into *n*, holes injected into *p*, hence the term majority carrier injection for forward bias



Reverse Bias Carrier Density Profiles

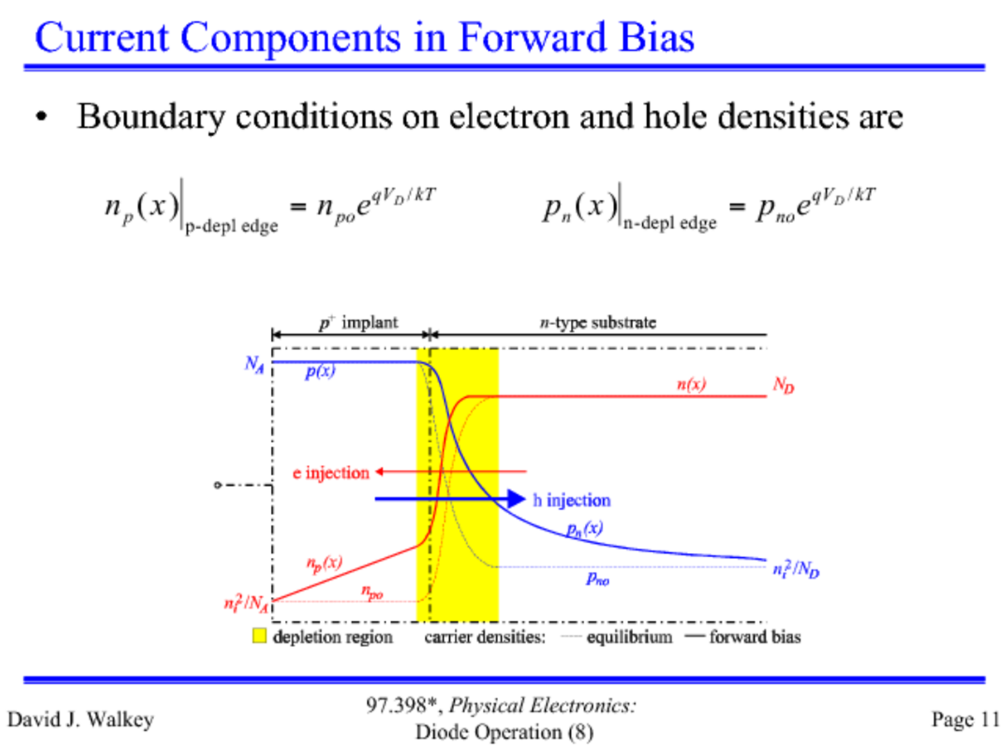
- In reverse bias, injection of majority carriers lowers the value of the minority densities - again note linear behavior in thin p^+ region
- In the neutral regions, the increase is negligible compared to the doping level for moderate bias levels
- This is therefore again a low level injection situation



13.2.4. I-V Characteristics for Diode

We can solve for the current flow through the device by using minority carrier diffusion. For the diffusion current we have $J_{forward} \propto e^{qV_b/K_BT}$.

Excitation of electrons over a barrier is exponential! And proportional to e^{qV_b/K_BT}



Components of Ideal Diode Equation

- Develop expressions for minority densities, then use diffusion relationship to derive current components due to electron injection J_n and hole injection J_p as

$$J_n = \frac{qD_n n_{po}}{w_p}\left(e^{qV_D/kT} - 1\right) \qquad J_p = \frac{qD_p p_{no}}{L_p}\left(e^{qV_D/kT} - 1\right)$$

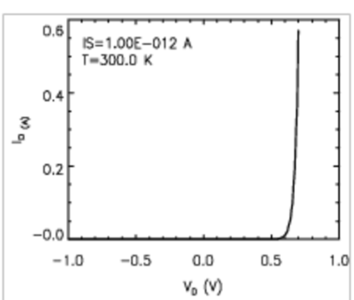
- Total current is sum of individual components, this is the ideal diode equation (for current density) but illustrating the physical components of the saturation term

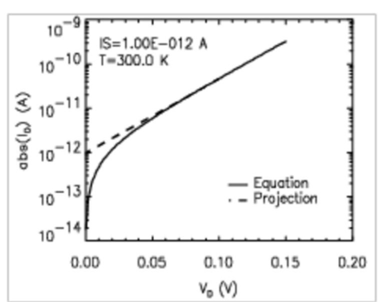
$$J_D = \left(\frac{qD_n n_{po}}{w_p} + \frac{qD_p p_{no}}{L_p}\right)\left(e^{qV_D/kT} - 1\right)$$

Ideal Diode Equation

- Total current is sum of individual components, this is the ideal diode equation (for current density) but illustrating the physical components of the saturation term

$$J_D = \left(\frac{qD_n n_{po}}{w_p} + \frac{qD_p p_{no}}{L_p}\right)\left(e^{qV_D/kT} - 1\right)$$





Summary of ideal diode equation:

- As the ideal diode equation indicates the current is very strong temperature and bias.
- For forward bias (positive V) the net current increases exponentially with voltage.
- For reverse bias (negative V) the current is essentially constant and equal to J_0.
- The reverse bias generation current is small compared with the forward bias current.
- A typical I-V curve for a diode is shown in figure 19. The reverse saturation current $i_0$is equal to J_0 multiplied by the junction cross-sectional area (A).

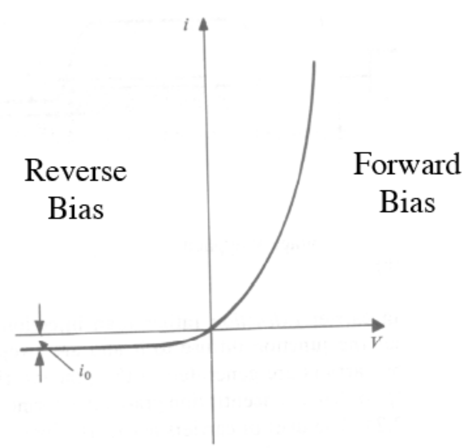


Figure 19. Current- Voltage Characteristic of a *pn* junction diode

There is also the generation of hole/electron pairs in depletion region and these cause small additional current. Therefore we have a small leakage current (equation 13.11)as these electrons and holes are swept across the depletion region (drift current).

$$J_0 = q(\frac{D_h}{L_h}p_n + \frac{D_e}{L_e}n_p) \tag{13.11}$$

- In order to keep J_0 small, the minority carriers (p_n and n_p) have to be kept at low levels. This can be accomplished by selecting semiconductors having a large energy gap and by high doping.
- The drift current is relatively insensitive to the height of the potential barrier since all of the minority carriers generated may diffuse to the depletion region and be swept across it.