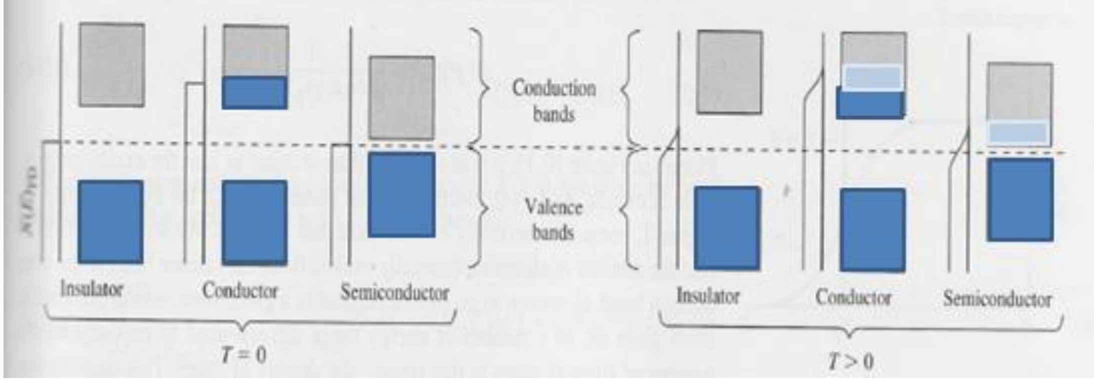
PH102, 2012W, Lecture Notes: February 22, Wed, Class 17

Conduction-Valence Band Gap

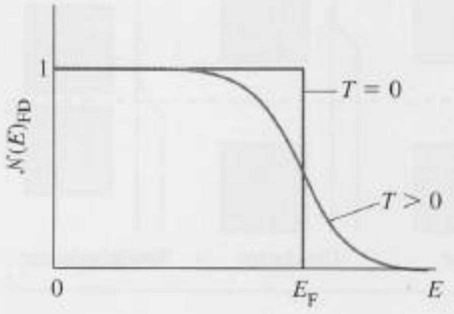
Figure 10.32 Band filling for an insulator, a conductor, and a semiconductor at zero and nonzero temperature. When $T > 0$, a semiconductor will have some electrons in the conduction band.



As shown in the Figure above, at T=0, there are no electrons in the conduction bands of insulators and semiconductors. The gap between conduction and valence band is much larger for insulators than for semiconductors. Substance with a conduction-valence band gap of lower than 2 eV is considered a semiconductor. The gap for an insulator is much bigger, for example, diamond, an insulator, is 5.4 eV.

At T>0, the occupation number for electrons in a solid changes from the T=0 distribution as shown in the diagram on the right.

Figure 10.33 The Fermi-Dirac distribution, the number of electrons per state at temperature T.



$$\mathcal{N}(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

Let’s consider the proportion of electrons that will be excited to be in the conduction band at T>0.

- Consider Density of Energy states $D(E)$ = D (constant)
- The number of electrons in the valence band at T=0:

$$N_{Valence} = \int_{E_{valence-bottom}}^{E_{valence-top}} \mathcal{N}(E)D(E)dE = \int_{E_{valence-bottom}}^{E_{valence-top}} 1 \cdot DdE = D\Delta E_{Valence}$$

- At T>0, the number of electrons that will be excited to be in the conduction band:

$$N_{Excited} = \int_{E_F+\frac{1}{2}E_{gap}}^{\infty} \mathcal{N}(E)D(E)dE$$

$$= \int_{E_F+\frac{1}{2}E_{gap}}^{\infty} \frac{D}{e^{(E-E_F)/k_BT} + 1} dE = Dk_BT\ln(1 + e^{-E_{gap}/2k_BT}) \sim Dk_BTe^{-E_{gap}/2k_BT}$$

Since $e^{-E_F/2k_BT}$ is small and thus $\ln\left(1+e^{-\frac{E_{gap}}{2k_BT}}\right)\sim e^{-\frac{E_{gap}}{2k_BT}}$

$$\frac{N_{Excited}}{N_{Valence}}=\frac{Dk_BTe^{-E_{gap}/2k_BT}}{D\Delta E_{Valence}}=\frac{k_BT}{\Delta E_{Valence}}e^{-E_{gap}/2k_BT}$$

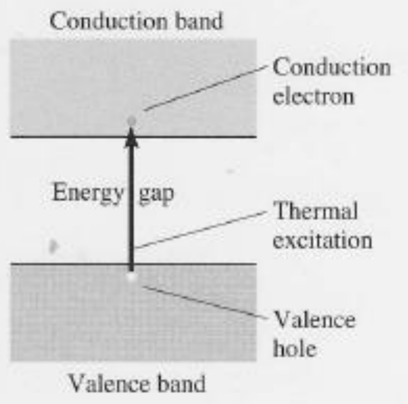
- ➔ k_BT at room temperature ~ .026 eV
- ➔ $\Delta E_{Valence}\sim 10$ eV
- ➔ $\frac{k_BT}{\Delta E_{Valence}}\sim .0026$ eV
- ➔ Insulator (assuming 5eV): $e^{-E_{gap}/2k_BT}\sim e^{-5/2\cdot.026}\sim e^{-100}\sim 10^{-42}$ → no electrons in the conduction band at the room temperature
- ➔ Semiconductor (assuming 1 eV): $e^{-E_{gap}/2k_BT}\sim e^{-1/2\cdot.026}\sim e^{-20}\sim 10^{-8}$ → considering the number of electrons is at the order of 10^{23}, a significantly large amount of electrons can be expected in the conduction band of a semiconductor at the room temperature.

Semiconductor Theory

Two types of charge carriers:

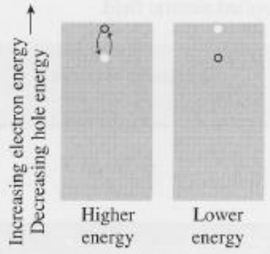
- **Electrons** in the conduction band
- **Holes** in the valence band.
    - Holes are created by electrons in the valence band move to the conduction band when T>0. See the diagram on the right. Holes mean absence of electrons in the band otherwise filled.
    - Holes behave as if they carry positive charges.
    - Holes are free to move around in the valence band while the movement of electrons in the valence band is limited to the emptied state that is available.

Figure 10.35 Thermal excitation creating a pair of charge carriers.



- The lower energy requirement make holes float near the top of the valence band. See Figure 10.36.

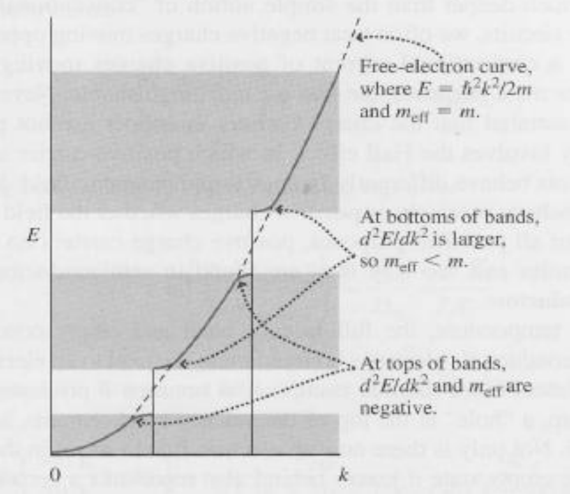
Figure 10.36 Holes float.



Effective mass: the ratio of the external force that we can control to the acceleration of electron.

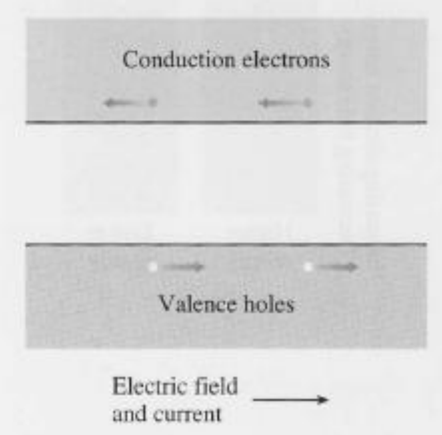
$$m_{eff} = \hbar^2 (\frac{d^2E}{dk^2})^{-1}$$

Figure 10.37 Energy versus wave number for electrons in a one-dimensional crystal. An electron's effective mass depends on what state it occupies.



- Figure 10.37 shows energy bands over k. The parabolic curve represents the free electron case:
    - $E = \frac{\hbar^2 k^2}{2m}$
- At the bottom of each energy band
    - $\frac{d^2E}{dk^2}\Big| bottom > \frac{d^2E}{dk^2}\Big| free\ electron$
    - $m_{eff} < m$
- At the top of each energy band
    - $\frac{d^2E}{dk^2} < 0$ thus , $m_{eff} < 0$
- In a conductor, electrons in the conduction band fill energy states around the middle energy band. Therefore, electrons move like free particles of mass m.
- In a semiconductor, electrons fill to the top of the valence band where effective mass is negative. This means that electrons' acceleration is opposite to the external force. If we use holes, instead of electrons, then holes will have a positive effective mass, meaning holes will be accelerating in the same direction as the external force is applied.

Figure 10.38 In a semiconductor at $T > 0$, both holes and electrons contribute to current in the direction of an applied electric field.



Doping

- We can create semiconductors (called extrinsic semiconductors) by doping small amounts of impurities on a crystal. Typical doping would be one of every 10^5 atoms of the intrinsic semiconductors such as Silicon or germanium. This action creates
    - If we use n-type impurities (elements with 5 valence electrons, e.g. phosphorous or arsenic), there will be an extra electron per impurity atom that cannot occupy the valence band. Each impurity atom also has an additional positive charge. These two interact to create new energy levels (called donor states) which will be added just below the conduction band. Typical energy difference between donor states and the conduction band is .05 eV, which is easily executable. Since impurity atoms are sparse, the extra electrons do not form energy bands. Vacated donor states neither form holes nor act as positive charge carriers. In the conduction band, electrons from the donor states are far more abundant than those from electron-hole pairs that require a larger excitation energy. Therefore, in an n-

type semiconductor, the majority charge carriers are conduction band electrons and the minority charge carriers are holes left by the excited electrons from the valence band.
    - If we use p-type impurities (elements with 3 valence electrons, e.g. aluminum or gallium), missing electrons create holes in the valence band which interact with the missing positive charges in the crystal. This adds new energy levels (acceptor states) above the valence band. Electrons in the valence band can be easily excited to acceptor levels, making holes in the valence band free to move. The majority charge carriers in a p-type semiconductor are holes in the valence band. The minority charge carriers are electrons in the conduction band that are excited from the valence band.

Figure 10.39 At $T = 0$, extra electrons in an n-type semiconductor occupy donor states. At $T > 0$, they easily become conduction electrons.

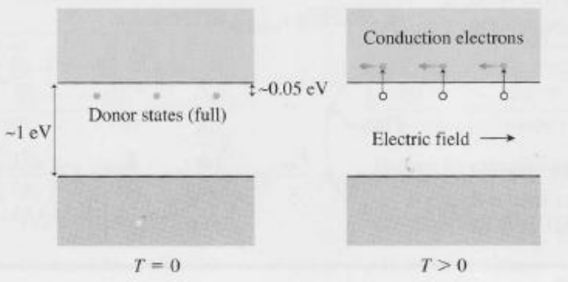
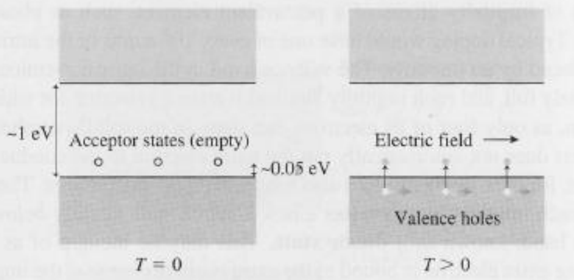


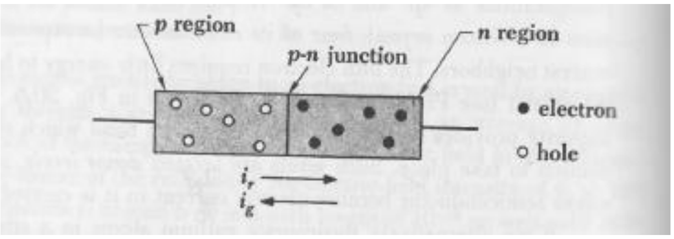
Figure 10.40 At $T = 0$, a p-type semiconductor has empty acceptor states, which at $T > 0$ are filled by electrons from the valence band, freeing holes.

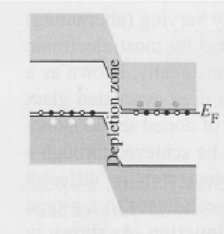


Semiconductor Devices

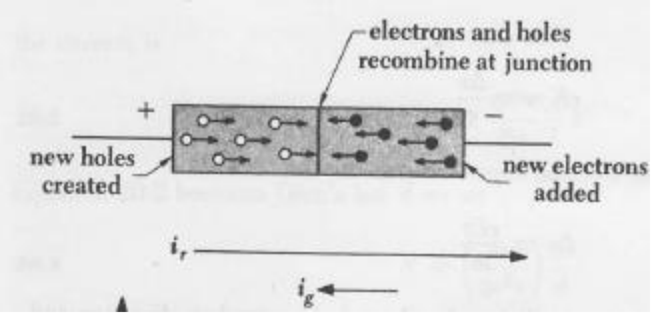
Diode:

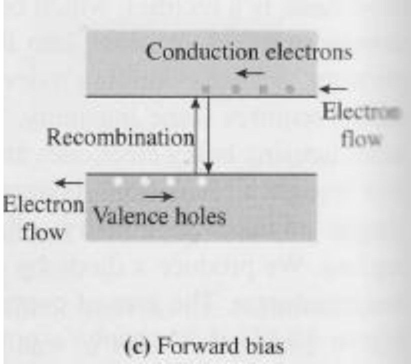
- Diode converts AC (alternating current) supplied by the power plant to DC (direct current) needed to run electronic devices.
- Diode is created by joining an n-type semiconductor to a p-type semiconductor. The area of contact is called a p-n junction.
- At thermal equilibrium (unbiased): a p-type and an n-type semiconductors are joined without an external potential difference. Electrons in the conduction band of the n-type semiconductor diffuse to the p-type side, raising all electron energies by repulsion in the p-type and lowering in the n-type until equilibrium is reached where $E_F$of both sides is the same. Note that electrons fill up to the donor levels and the acceptor levels in both types of semiconductors. As a result, the electron potential energy has changed to look like in the diagram below. Immediately near the p-n junction area called the depletion zone, there are no free charge carriers.





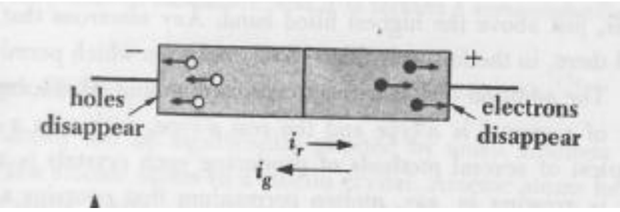
- Forward Bias (Applying potential difference with the p-type at the higher potential): free holes in the p-type and free electrons in the n-type flow toward the junction. When they meet they recombine. Current flows continuously as electrons kept added to the n-type and holes kept added to the p-type (valence electrons re removed). Forward-biasing the diode shifts the n-type conduction band upward, allowing conduction band electrons move to the p-type. So do the holes from the p-type to the n-type. Electrons and holes recombine, meaning the conduction electrons jump down to fill the valence holes. In this process, energy is lost to heat or to light. Therefore, the forward bias needs to shift the band gap for current to flow continuously. A diode of 1eV band needs 1V forward bias before it turns on.

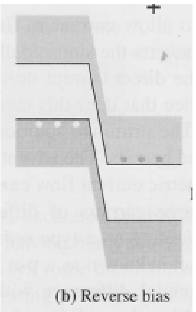




(c) Forward bias

- Reverse Bias (Applying potential difference with the n-type at the higher potential): when the n-type is at the higher potential, both holes and electrons move away from the junction. A region devoid of free charge carriers quickly forms, and current stops almost instantly. Applying a reverse bias makes the potential difference more pronounced. Note that in this condition, still minority charge carriers (electrons in the p-type conduction band and holes in the n-type valence band) would cross the junction. But the numbers for minority carriers that recombine are negligible.





(b) Reverse bias

Transistor

- Joining three extrinsic semiconductors such as npn or pnp.
- For a npn transistor, p the base, one n the emitter and the other n the collector.
    - The emitter-base diode is forward biased, so conduction electrons flow from the emitter into the base. These electrons are discouraged to combine with holes in the base because (1) the base is made small, (2) the base is reverse biased with the collector, and (3) conduction electrons are minority carriers in the base (p-type). So, most electrons move to the collector's conduction band. Only a small fraction of conduction electrons recombine in the base. The fraction of electrons that flows

out the collector side is 100 times greater than that which flows out the base returning to the input circuit.

Figure 10.44 Bands and charge flow in a npn transistor.

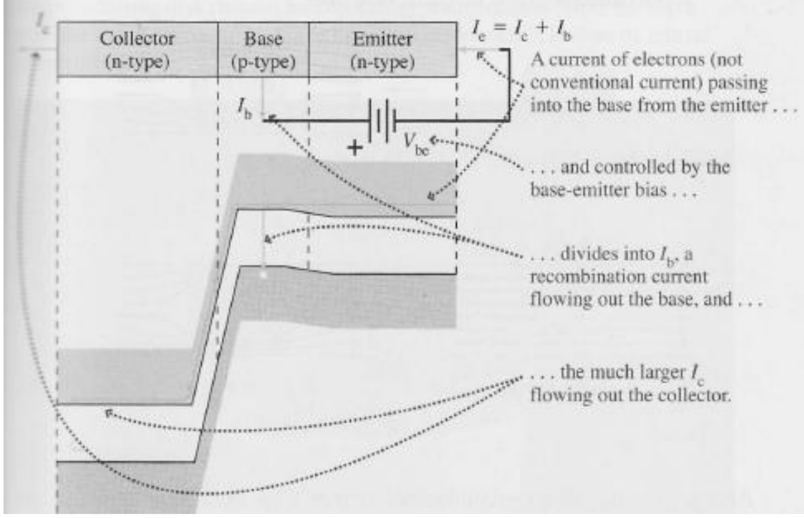


Figure 10.45 The elements of a transistor amplifier.