Day 14: Thursday – 110 minutes

Semiconductor Properties and Devices

We have seen that the dominant feature of the electronic structure of semiconductors is the energy gap between the highest occupied valence electron states and the conduction states. The conduction states are not occupied in pure (intrinsic) semiconductors at $T = 0$. This electronic structure has profound implications for the physical properties of semiconducting materials. These properties, in turn, make possible the many practical devices based on semiconductor technology. We can only consider a few examples here but, it is hoped, these will stimulate your curiosity and lead you to further study in other courses, or on your own.

Optical Absorption in Semiconductors

The energy gap in a semiconductor is responsible for the fundamental optical absorption edge. The fundamental absorption process is one in which a photon is absorbed and an electron is excited from an occupied valence band state to an unoccupied conduction band state. If the photon energy $\hbar \omega$ is less than the gap energy, such processes are impossible and the photon will not be absorbed. That is, the semiconductor is transparent to electromagnetic radiation for which $\hbar \omega < E_{\text{gap}}$. For $\hbar \omega > E_{\text{gap}}$ on the other hand, such interband absorption processes are possible (with a qualification that we will discuss shortly). In high quality semiconductor crystals at low temperatures, the density of states rises sharply at the band edge and consequently the absorption rises very rapidly when the photon energy reaches the gap energy. Observation of the optical absorption edge is the most common means of measuring the energy gap in semiconductors.

As an example, consider the semiconductor GaAs commonly used in electro-optical applications. The band gap energy is $E_{\text{gap}} = 1.4$ eV. This corresponds to a photon frequency $\omega = 2.1 \times 10^{14}$ Hz and a wavelength $\lambda \approx 0.9 \times 10^{-6}$ m $\approx 900$ nm. This wavelength lies just outside the visible range in the very near infrared. This tells us that
GaAs is transparent to infrared light, but is opaque (strongly absorbing) in the visible. This is true of many common semiconductors because their energy gaps are of order 1 eV or less.

There is a complication to the fundamental absorption process that limits the usefulness of some semiconductors for optical applications. These include, unfortunately, silicon, the most ubiquitous material in semiconductor applications. Recall that when we studied the optical phonon modes, we found that the intersection of the photon’s dispersion relation and that of the optical modes occurs very close to $k = 0$. This is because the photon wavelength $\lambda_{\text{photon}}$ at the relevant frequency is much longer than a typical interatomic spacing, $a$, in the crystal lattice. Thus $k_{\text{photon}} = \frac{2\pi}{\lambda_{\text{photon}}}$ is very small on the scale of the Brillouin zone ($k_{\text{BZ}} = \frac{\pi}{a}$).

Now considering an interband electronic transition, we see that such transitions must be essentially vertical on the band diagram. This is required if the process is to conserve momentum: $\hbar k_{\text{photon}} = \hbar \Delta k_{\text{electron}}$. This condition is readily satisfied if the maximum of the VB and the minimum of the CB occur at the same $k$-value (often $k = 0$ as in the diagram below). If the band structure has this feature, the gap is said to be \textit{direct}. Such semiconductors are very useful for electro-optical applications.
What if the VB maximum and CB maximum do not occur at the same $k$-value? In this case the gap is said to be an *indirect gap*. Absorption over the band gap cannot conserve energy and momentum without the participation of another particle, usually a phonon. The process then corresponds to photon $\rightarrow$ conduction electron plus phonon. Energy conservation requires $\hbar \omega = E_{\text{gap}} + \hbar \Omega$ where $\Omega$ is the frequency of the phonon created in the process. To conserve momentum, the phonon must have a wavevector $k_{\text{phonon}} = k(\text{CB max}) - k(\text{VB min})$ since $k_{\text{photon}} \approx 0$. Indirect absorption processes are possible (after all they satisfy the necessary conservation conditions), but because of the participation of a third particle (the phonon), their transition probabilities are much lower than those of direct processes. This kind of absorption process is illustrated in the diagram below.

![Energy diagram](image)

Despite the inefficiency of electron-hole excitation (interband absorption) in indirect semiconductors, these materials nevertheless have important applications. One example is the crystalline silicon solar cell.
The p-n Junction

Consider a silicon crystal in which one part is doped mainly with acceptors so that the majority carriers are holes (p-type) and the other part is n-type with electrons as the majority carriers:

![Diagram of p-type and n-type regions](image)

In such a crystal, there will be a tendency for some holes to diffuse across the junction and recombine with donors in the n-type materials, and a similar tendency for electrons to diffuse into the p-type material and recombine with acceptors. This will lead to a situation in which there is an excess of ionized donors ($D^+$) and a deficiency of electrons on the n-type side of the junction. Similarly, there will be an excess of ionized acceptors ($A^-$) on the p-type side and a corresponding deficiency of holes. However, as these regions of excess charge build up, they will produce an electric field directed from the n-type side to the p-type side. The field will tend to oppose the flows of electrons and holes that are producing it. Thus an equilibrium will be established in which the deficiencies of carriers is confined to a narrow region near the junction, the so-called “depletion region.” The electric field is called the “built-in field.”
Because the system is at thermal equilibrium, the following relationship will relate the concentrations of n- and p-type carriers throughout the crystal (we have seen this before):

\[ np = N_C N_V e^{-E_g/k_B T} \]

Thus, in regions where the electron concentration is high, the hole concentration will be small (but not zero!) and vice versa as illustrated below.

Just because the crystal is in equilibrium does not mean that there are no currents flowing in the junction – only that any currents flowing from the n-side to the p-side are balanced by currents flowing in the other direction. This is an example of dynamic equilibrium. There are two kinds of currents flowing:

(1) Recombination currents. There will always be a few electrons making their way from the n-side to the p-side to recombine with holes there. In the absence of any applied electric field, we represent this current by the electron current density \( J_{nr}(0) \).

(2) Generation currents. There is also a flow of electrons, \( J_{ng}(0) \), that are generated by thermal excitation on the p-side and are swept across the junction by the electric field.
In dynamic equilibrium these currents are exactly balanced so that \( J_{nr}(0) + J_{ng}(0) = 0 \).

There are similar recombination and generation currents flowing in the opposite directions for holes.

The foregoing describes the situation for the junction in equilibrium in the absence of any applied voltages. Now, suppose that we do apply a voltage \( V \) so that it adds to the built-in electric field. That is, the n-type side of the junction is made even more positive relative to the p-side than at equilibrium. This added potential difference makes it harder for electrons to flow to the p-side to recombine. Only electrons with enough thermal energy to surmount the potential barrier will flow. This will reduce the electron recombination current accordingly:

\[
J_{nr}(V) = J_{nr}(0) \exp\left(-\frac{e|V|}{k_B T}\right)
\]

The generation current on the other hand will not be affected much since the applied voltage favors the flow of electrons from the p-side to the n-side. That is,

\[
J_{ng}(V) = J_{ng}(0).
\]

Under these conditions the junction is said to be reverse biased since the applied voltage reduces the net current flowing across the junction.

Now, suppose that we apply a positive voltage to the p-type side. This will lower the potential barrier for electrons trying to recombine and the electron recombination current will be

\[
J_{nr}(V) = J_{nr}(0) \exp\left(\frac{e|V|}{k_B T}\right).
\]

The junction is now forward biased since the applied voltage favors an increase in the net current flowing across the junction.
Now the net electron current flowing in the junction will be

\[
J_n(V) = J_{nr}(V) + J_{ng}(V) = J_{nr}(0) \exp \left( \frac{eV}{k_B T} \right) + J_{ng}(V) = -J_{ng}(0) \exp \left( \frac{eV}{k_B T} \right) + J_{ng}(0)
\]

The enhanced electron current in the forward biased junction will be accompanied by a corresponding increase in the net hole current (lowering the barrier favors hole current flowing from p-side to n-side).

Combining the electron and hole currents, and using the conventional definition of current in terms of positive charge carriers, we see that the forward current will have the form

\[
I = I_g \left[ \exp \left( \frac{eV}{k_B T} \right) - 1 \right]
\]

The reverse current will have a similar form, but with negative \(V\).

A plot of current versus voltage (the “I-V characteristic”) for the junction diode therefore looks like this:
When the junction diode is “forward biased” (positive voltage on the p-type side), the current increases rapidly with increasing voltage. The junction has a high conductivity and low resistivity. On the other hand, when the diode is “reverse biased,” only a small current flows. Thus the device has the property of rectification, allowing significant current to flow in only one direction. There are many applications in electrical circuitry for devices with this property. These include rectifiers that convert AC to DC and photodiodes.

Perhaps even more important, when two junctions are combined to produce a three-terminal device, the result is a transistor. Current through the two-junction device can be controlled by the current flowing into a third terminal. In contemporary large scale integrated (LSI) circuitry, junction transistors have been replaced by so-called “field effect” transistors. But the idea is the same, i.e. to control a large current through a device by means of a relatively small input current. Exploration of such devices while fascinating and important would take us well beyond the scope of this paradigm.