

Semiconductor Diodes and the Absorption of Photons

Photons absorbed by a crystal create negatively-charged electrons (e^-) in the conduction band and positively-charged *holes* (h^+) in the valence band. But there is no preferred direction of motion for either type of charge. So, electrons will not flow from one side of the crystal through an external circuit, perhaps containing a machine that converts the potential energy of the electrons into mechanical work, and back into the other side of the crystal. In order to physically separate the positive and negative charges created upon absorption of a photon, an electric field must be built into the crystal, thereby driving the electron in a direction opposite to the field and the hole or positive charge in the same direction as the field.

Such a field can be created by adding *n-type* impurities into one side of the crystal and *p-type* impurities into the other side. For a silicon (Si) crystal, an n-type impurity, such as arsenic (As), must release one of its electrons in order to fit nearly into the silicon lattice, which requires that it form four bonds. The liberated electron can go only into the conduction band because all the lower energy states in the valence band are already occupied. Thus, the crystal become somewhat conductive, a *semiconductor*. A p-type impurity, such as boron (B), must snatch an electron from one of the bonds holding the crystal together in order to have enough electrons of its own to make four bonds to neighboring Si atoms. The hole created in the conduction band is free to hop around the entire crystal. Again, the crystal become somewhat conductive.

Crystals can be made in which there is a sharp junction between the p- and n-type regions. Semiconductors with such pn junctions are referred to as *diodes*. In a thin ($< 1\mu m$) region about the junction, referred to as the depletion region, the mobile electrons and holes will combine, and the mobile charge vanishes. However, the fixed charges due to the impurities remain. The n-type dopants are positively-charged and the p-type dopants are negatively charged. So an electric field is created, pointing from the n side toward the p side. This electric field introduces the directionality desired for energy conversion schemes.

The inherent electric field in the depletion region will sweep a photo-generated e^- into the n side and the complementary h^+ into the p side. Since the force due to the electric field arises from a change in the potential energy of an electron over this short distance, one can speak in terms of the change in electrostatic potential energy that an electron experiences if it moves from the n side to the p side. Thus, both the conduction and valence bands rise in energy as one moves from the n side to the p side, as shown in Figure 1. Notice that in Figure 1, the energy of an electron increases in the upward direction, while the energy of a hole increases in the downward direction. So, since particles always seek positions of minimum energy, electrons try to move downward to some available energy state while holes try to move upward.

When a photon is absorbed in the pn junction region, the electron promoted to the conduction band will move toward the n-type side and the hole will move toward the p-type side. A wire connecting the n and p sides will conduct a current I , which is defined as a flow of positive charges. A diode designed to absorb light is called a *photodiode* or *photovoltaic cell*. Each absorbed photon creates one conduction band electron, so the current in Amperes is $I = e \times N$, where $e = 1.6 \times 10^{-19}C$ and N is the number of photons absorbed per second. Each electron is delivered at the same potential difference relative to the valence band, $\Delta\Phi = E_g/e$. The power delivered by a photodiode is $P = NE_g = IE_g/e = I\Delta\Phi$. Consider the fact that for green light a power of $1Watt$ corresponds to 2.5×10^{18} *photons/second*.

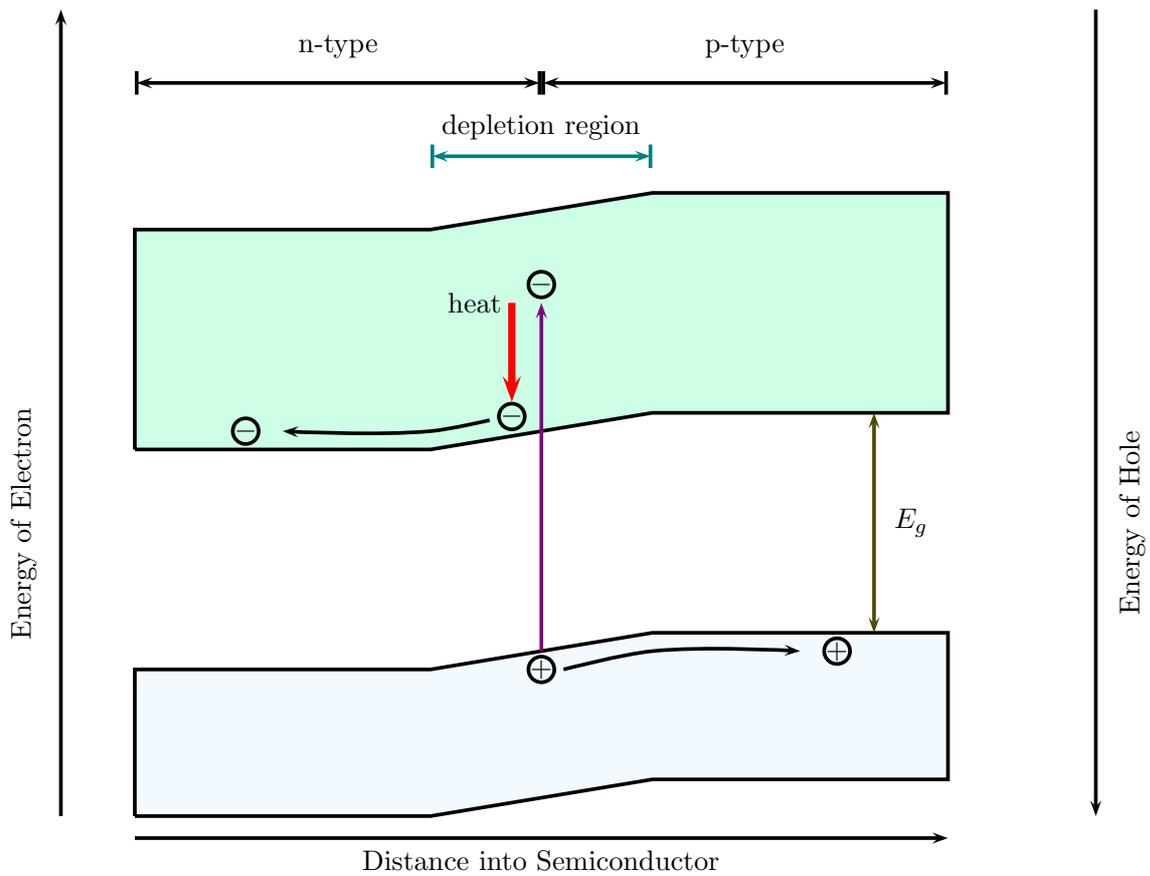


Figure 1: Conduction and valence bands in the vicinity of a pn junction in a crystal with a band gap energy E_g . A photon of energy $> E_g$ absorbed in the pn junction region will create a conduction band electron which will move left toward a region of lower energy for a negative charge. The hole left behind in the valence band will move toward the right, a region of lower energy for a positive charge.