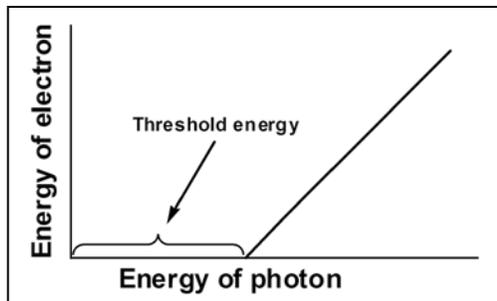


## The Photoelectric Effect, Photovoltaic Systems, and Solar Cells

### The Photoelectric effect

The **photoelectric effect** occurs when light strikes the surface of a (pure metal) substance and if threshold energy is exceeded then electrons are raised to a higher energy level and are emitted from the surface. The greater the energy of the light, the greater the energy of the emitted electron.



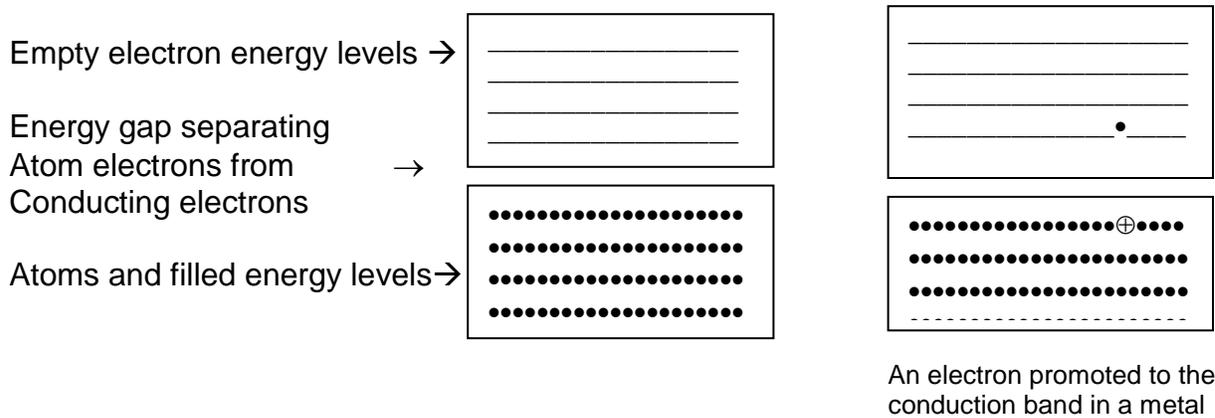
With low frequency light (low energy light since  $E = h\nu$ ) no electrons are emitted below a specific threshold energy (threshold frequency) regardless of the intensity of the light. Greater quantity of photons striking the surface did not effect whether electrons left the surface or not. If the threshold energy was exceeded then the number of electrons emitted increases with the intensity of light. The kinetic energy of each emitted electron increases linearly with the increased frequency of the light (see graph above).

$$\text{Kinetic Energy of electron} = \frac{1}{2} m v^2 = h\nu - h\nu_0 =$$

$$\text{Kinetic energy of electron} = \text{energy of incident photon} - \text{threshold energy.}$$

### Conduction of electricity in Metals

Using molecular orbital theory for the bonding in metals leads to valence orbitals on each atom and delocalized over all the atoms (see, below, left). The highest energy filled level at 0 K is referred to as the Fermi level. The gap between the filled levels and empty levels where conduction occurs is very narrow or nonexistent in metals. The metallic bonding is nondirectional between positive metal ions and the surrounding sea of negative electrons. The energy levels in an individual metal atom are shifted when the atoms come closer to each other. The identical energy levels of each atom merge into energy bands, which are closely spaced and are closely related to the energy levels of the individual metal atom. Most of the time the electrons move in a partially filled "**valence band**" that contains the valence electrons and these electrons can be moved by applying a small amount of energy such as a low level electric field. Another band containing higher energy orbitals (the **conduction band**) exists at an energy above the valence band. In a metal, the valence band and the conduction band overlap so electrons can move freely between them. This explains metals electrical conductivity. Metals that have overlapping valence and conduction bands are considered **conductors**. Usually the conductivity of metals decreases with increasing temperature. When the valence band and the conduction band do not overlap the material can be either an **insulator** or a **semiconductor**. The insulators have a very large energy gap between the valence band and the conduction band. In a semiconductor a very *narrow* energy gap separates the valence band from the conduction band. At some temperatures and with some higher applied levels of energy, semiconductors can conduct electricity.



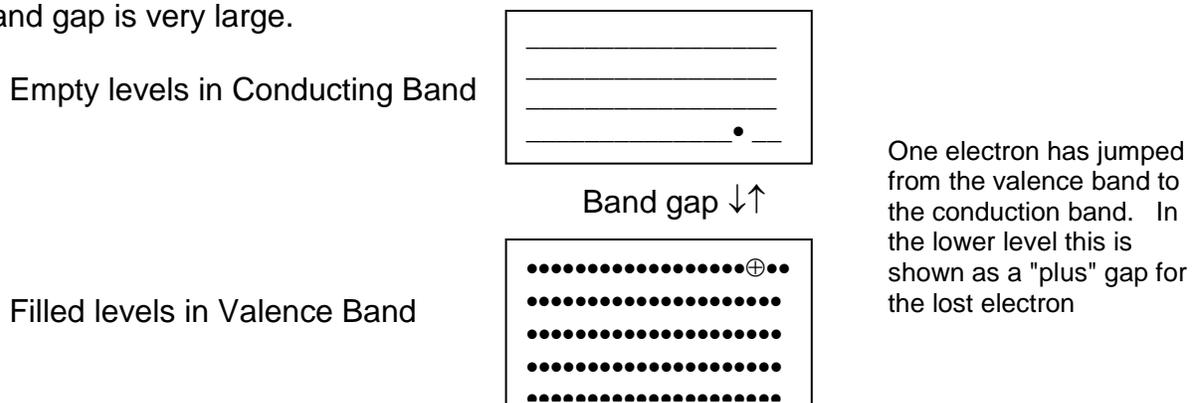
In metals at temperatures above zero Kelvin, thermal energy will cause some electrons to move to higher energy orbitals. When an electron is promoted into the conduction band, two characteristics result. In the conduction band there is a negative electron that is free to move. In the metal below the Fermi level there is a positive "hole" where the electron used to be. Both of these charged areas can move resulting in the conductivity found in most metals. The electrical conductivity arises from the movement of electrons and holes upon the application of an externally applied electric field.

The energy gaps between levels in the conduction band are very small and can be assumed to be continuous. This means the metal can absorb light energy of nearly all wavelengths. When light is absorbed, electrons move to higher energy levels. The now excited electron can immediately emit light of the same wavelength as the electron returns to the original ground state. The observed result of the rapid absorption and reemission of light causes polished metal surfaces to appear highly reflective and shiny.

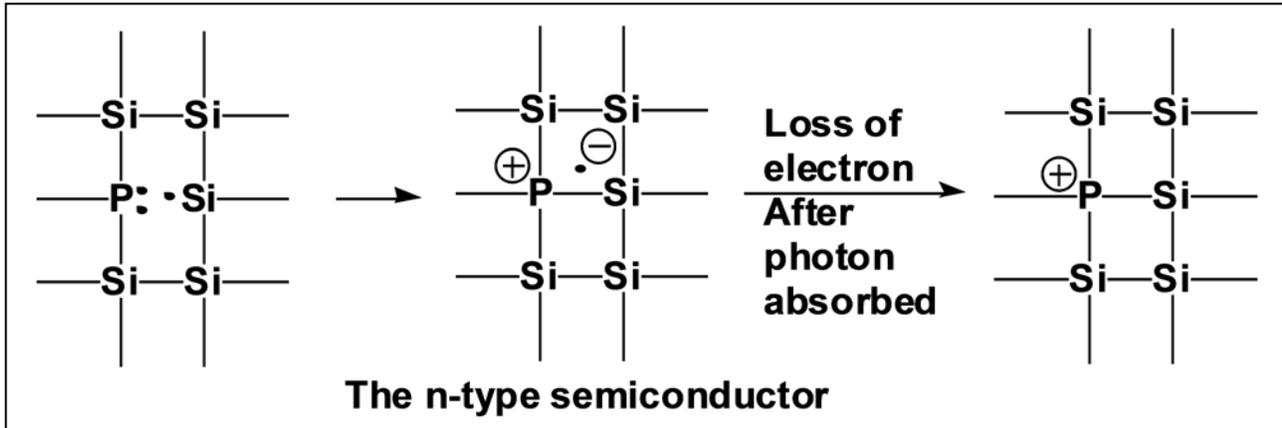
Other physical characteristics of metals can be partially explained by the delocalized bonding in metals. Metals are malleable (capable of being rolled into flat sheets) and ductile (capable of being pulled into long wires) this can be considered a direct consequence of the metal atoms being able to freely move with respect to their nearest neighbors, due to their localized bonds. The atoms can thus slip past each other easily.

### Semiconductors

Metalloids (semiconductors) actually are interconnected via covalent bonds and thus electrons have a more difficult time in moving compared to metals. This causes the conduction band of metalloids to be significantly different from the filled valence band of metallic elements. In contrast to metals, the band of filled levels (the valence band) is separated from the empty conducting band (which has many widely separated levels) by a fairly large gap. For insulators, this band gap is very large.

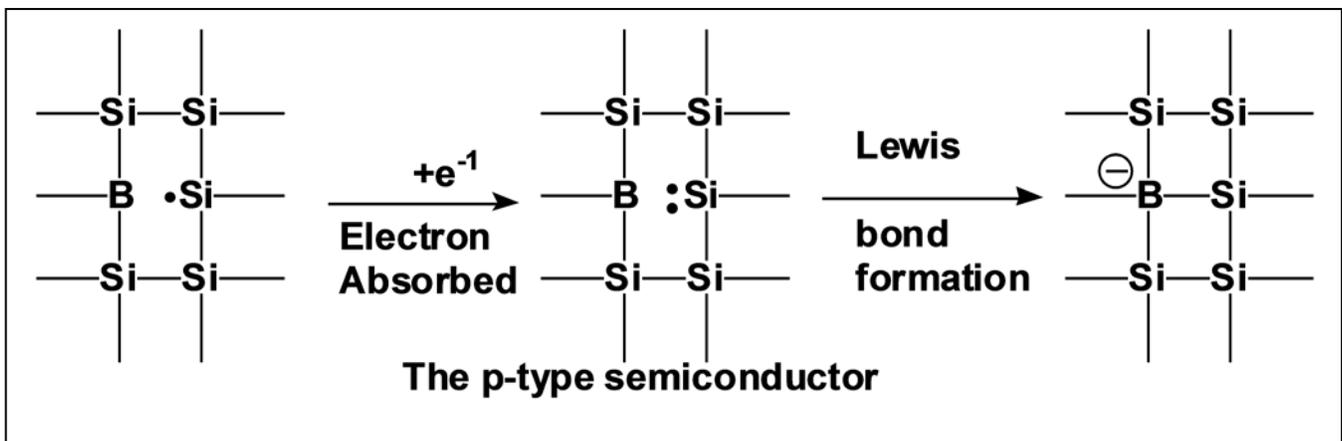


The emission of electrons from pure silicon involves the removing electrons from silicone-silicon bonds. Like most semiconductors, high purity silicon only conducts current when a fairly high electrical voltage is applied. This is the energy needed to jump electrons from the valence band to the conduction band. At high voltages silicon is a good conductor. A process known as doping can improve the semiconducting properties of silicon significantly.



The process of doping involves adding tiny amounts of some other element (dopant) to the silicon. Generally the silicon is doped in two ways; one way adds extra electrons to the silicon by using elements in Group 5A such as phosphorus or arsenic. This is called **n-type** (for negative type) since it has one more electron than silicon (Group 4A) and the extra electron causes the doped silicon to have a slight negative charge and hence readily promotes electrons to the conduction band. This is illustrated in the above diagram showing the 2 nonbonding electrons of phosphorus and the remaining single nonbonded electron from silicon which leads to the formation of a covalent bond with 1 electron left over. This "extra" electron is very easily promoted to the conduction band since it is "free floating", that is it is not directly involved in any (covalent) bond. Thus the n-type semiconductor has electrons that can easily be promoted to the conduction band by low energy light.

Using elements in Group 3A such as boron, aluminum or gallium makes the other type of semiconductor. This is called **p-type** (for positive type) since it lacks one electron and needs one more electron to be able to form a complete bond between silicon and boron (illustrated below). It thus acts like it has a "positive" hole that needs to be filled in order to create a complete bond.



## Solar Cells

Putting these two pieces together results in the creation of solar cells, which have to satisfy several criteria. The surface of the doped silicon layers must be protected hence a sealed glass or other transparent surface and an antireflective coating is added to ensure the maximum of light striking the n-type semiconductor. The electrons accumulating in the conduction band in the n-type semiconductor are then removed through an external circuit and after performing work, charging batteries, etc. are then transported to the p-type semiconductor layer. As the p-type semiconductor layer accumulates electrons, it becomes increasingly more negatively charged. The strongly repelled extra electrons return *internally* back into the n-type layer (which has become positive because of the extensive loss of electrons via the conduction band and removal of electrons via the circuits). One explanation of how electrons pass through the barrier is via "quantum mechanical tunneling". Because electrons are subatomic particles and move in waves (de Broglie) and are subject to Heisenberg uncertainty principle, and if there is sufficient potential difference between the p-type and n-type semiconductor bands the electrons will "jump" the "impenetrable" gap. Basically the electron appears on one side and then suddenly appears on the other side of the gap without spending any time within the gap!

**Extra** ("excited" electrons)

Electrons leave in order to do work. ←

electrons ↑

electrons ↑

**Extra**

Electrons returned after doing work →

Transparent surface, either glass, plastic or other medium
Antireflective coating to ensure that maximum amount absorbed
The n-type semiconductor such as phosphorus doped silicon
The barrier to prevent electrons from returning from p to n type
The p-type semiconductor such as boron doped silicon
Metal conducting strip to carry the extra electrons away (-)

**The basic process** starts when a photon is absorbed. The photon excites an electron to a higher energy conduction band or orbital. This allows the electron to be conducted from the n-type silicon layer and flow through the external circuit to the p-type layer. As the p-type layer becomes more negative (because of added electrons), the increased number of negative charges creates an internal repulsion. The repelling negative charges cause electrons to "jump" the gap internally back into the n-type layer (which has become positive due to loss of electrons via the circuit). This cycling of electrons can continue as long as the silicon layers are exposed to sunlight and the circuit is closed.