

N-type semiconductor

N-type semiconductors are a type of extrinsic semiconductor where the dopant atoms are capable of providing extra conduction electrons to the host material (e.g. phosphorus in silicon). This creates an excess of negative (n-type) electron charge carriers.

History of semiconducting systems

Around 1898, Karl Ferdinand Braun invented a type of diode during the development of the radio. He used the rectifying properties of galena crystal (lead sulfide). In 1909, Braun shared the Nobel Prize in physics with Guglielmo Marconi for the development of wireless telegraphy.^[1]

Later, semiconductors found applications in transistors. A transistor is a solid-state electronic device that controls the flow of electric current. Until World War II, most systems used vacuum tubes for the amplification and control of electric current. Those vacuum tubes were bulky and fragile, consumed much power, and tended to overheat. The demands of radar, in particular during World War II, encouraged scientists to look for another method of amplifying and controlling electric current in communication devices.

Basic science of n-type semiconductors

Semiconductors are defined by their unique electric conductive behavior. Metals are good conductors because at their Fermi level, there is a large density of energetically available states that each electron can occupy. Electrons can move quite freely between energy levels without a high energy cost. Metal conductivity decreases with temperature increase because thermal vibrations of crystal lattice disrupt the free motion of electrons. Insulators, by contrast, are very poor conductors of electricity because there is a large difference in energies (called a band gap) between electron-occupied energy levels and empty energy levels that allow for electron motion.

Insulator conductivity increases with temperature because heat provides energy to promote electrons across the band gap to the higher electron conduction energy levels (called the conduction band). Semiconductors, on the other hand, have an intermediate level of electric conductivity when compared to metals and insulators. Their band gap is small enough that small increase in temperature promotes sufficient number of electrons (to result in measurable currents) from the lowest energy levels (in the valence band) to the conduction band. This creates electron holes, or unoccupied levels, in the valence band, and very loosely held electrons in the conduction band.^{[2] [3]} An intrinsic semiconductor is made up ideally of one pure element, typically silicon. At room temperature, the conductivity of intrinsic semiconductors is relatively low. Conductivity is greatly enhanced by a process called doping, in which other elements are added to the intrinsic crystal in very small amounts to create what is called an extrinsic semiconductor. When the dopant provides extra electrons to the host, the product is called an n-type semiconductor. The process of doping is described as it introduces energy levels into band gap; those levels are filled with electrons and lie close to the conduction band so that even slight thermal agitation can release them into the conduction band.^[2]

It should be noted, that the negative charge of the electrons is balanced by an equivalent positive charge in the center of the impurity atoms. Therefore, the net electrical charge of the semiconductor material is not changed.^[4]

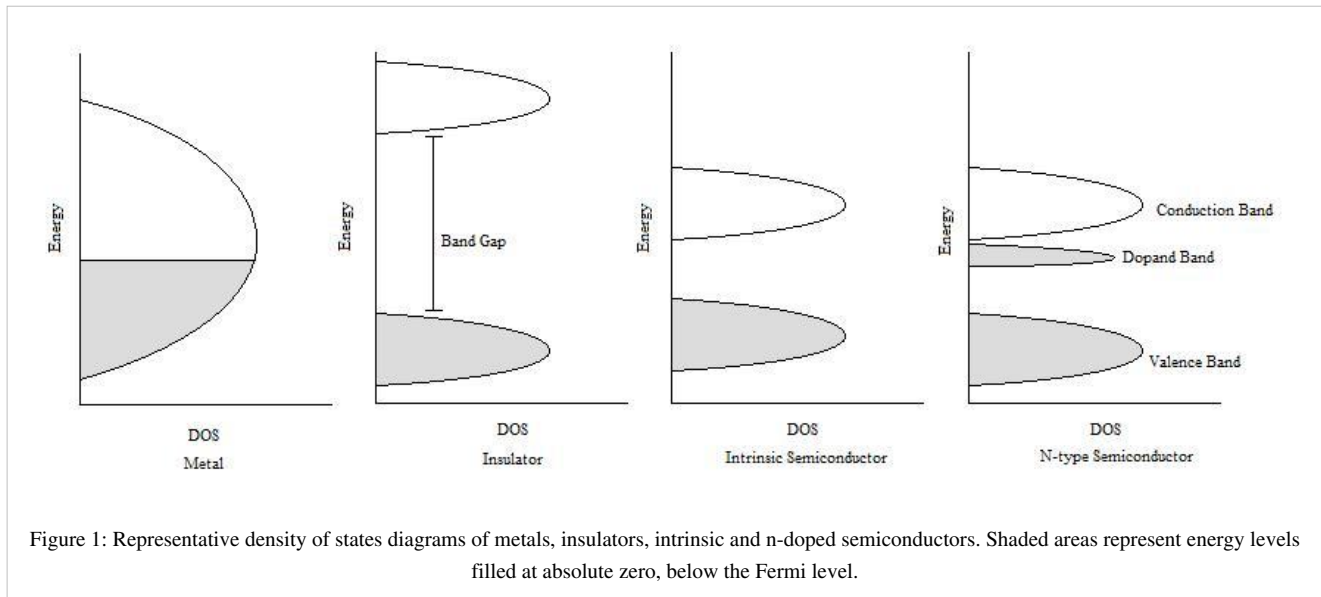
Dopants

The doping atoms usually have one more valence electron than one type of the host atoms. The most common example is atomic substitution in group IV solids (silicon, germanium, tin which contain four valence electrons) by group V elements (phosphorus, arsenic, antimony) which contain five loosely bound valence electrons. The situation is more uncertain when the host contains more than one type of atoms. For example, in III-V semiconductors like gallium arsenide, silicon can be a donor when it substitutes for gallium and acceptor when it replaces arsenic. Some

donors have fewer valence electrons than the host, such as alkali metals, which are donors in most solids.

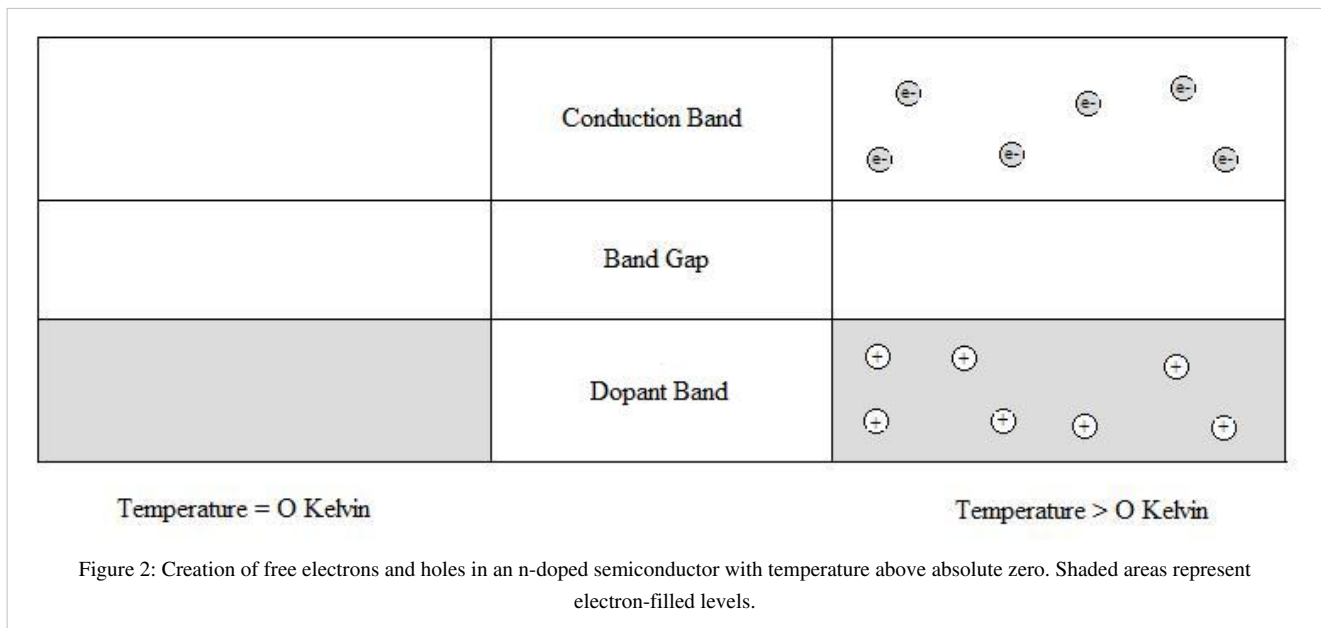
The Fermi level

The Fermi level plays an important role in describing the behavior of doped semiconductors. A substance's Fermi level is defined as the highest occupied energy level found in that substance at absolute zero temperature (0 kelvins or $-273\text{ }^{\circ}\text{C}$). At higher temperatures, energy from heat is available to promote electrons into slightly higher energy levels. However, picturing density of states to be filled to the Fermi level helps scientists understand different behaviors between insulators, metals, and intrinsic and extrinsic semiconductors. As seen in figure one, the Fermi level of n-type semiconductors is elevated from that of the corresponding un-doped intrinsic semiconductor. This makes the conduction band much more thermally accessible at temperatures above absolute zero.^[3]



Charge carriers

The concept of free electrons and corresponding holes in a solid semiconductor is a useful tool for understanding conduction through the solid. At temperatures above absolute zero, some electrons in an n-type semiconductor are expected to be excited from the energy level of the dopant into the conduction band. This creates a state with a few loosely held, very mobile electrons occupying some of the large amount of states available in the conduction band. The vacancies left in the dopant band group V ions containing a positively charged "hole" in their valence shell. While the amount of holes per filled levels in the dopant band is low, there is a large number of holes or levels to occupy per electron in the conduction band (see figure 2). The electrons can easily move between these available states and conduct a current. In the case of n-type semiconductors, the electrons are considered to be the majority charge carrier. The holes of the dopant band are considered minority carriers.^[5]



Techniques of doping and synthesis

The synthesis of n-type semiconductors may involve the use of vapor-phase epitaxy. In vapor-phase epitaxy, a gas containing the negative dopant is passed over the substrate wafer. In the case of n-type GaAs doping, hydrogen sulfide is passed over the gallium arsenide, and sulfur is incorporated into the structure.^[6] This process is characterized by a constant concentration of sulfur on the surface.^[7] In the case of semiconductors in general, only a very thin layer of the wafer needs to be doped in order to obtain the desired electronic properties.^[8] The reaction conditions typically range from 600 to 800 °C for the n-doping with group VI elements,^[6] and the time is typically 6–12 hours depending on the temperature.

The p-n junction

Perhaps the most important current use of n-type semiconductors is in p-n junctions. These are p-type and n-type semiconductors brought together in close contact, creating what is called the depletion region. The importance of this contact or junction is the creating of a region between the p and n layers where p-type holes can recombine with n-type free electrons producing light, such as in light emitting diodes (LEDs). P-n junctions form the basis of how a lot of current technology works by creating diodes. In a diode, current can flow easily in one direction but not the other, which is a basis for digital electronics.^[9]

Other applications and continuing research

Rectifying junction

A rectifying junction can be made when certain metals are in contact with a semiconductor crystal. In the case of an n-type germanium crystal in contact with tungsten, current is allowed to flow when the tungsten is held at a positive potential, however, there is negligible current in the case where tungsten is held at a negative potential. The reverse is true in the case of p-type semiconductors.^[7] These junctions have some advantages over the standard p-n junction (diode) in that there is a smaller voltage drop, thus better emulating an ideal diode. Schottky diodes also allow for faster switching times compared to p-n junctions.

The n-type junction (Schottky diode) can also be used in producing a hydrogen fuel cell. Water and hydrogen would combine on a palladium layer and generate a thermionic current sent into an n-type silicon carbide semiconductor

with a potential greater than the Schottky barrier. These solid state fuel cells can potentially allow for integration of fuel cells into portable electronics.^[10]

N-type semiconductors in organic devices

Organic semiconductors have been of great research interest for use in low cost, ultra thin, and flexible products such as displays and solar energy conversion cells. While many p-type organic semiconductors have been thoroughly characterized, n-type organic semiconductors have proven hard to obtain. Both types are needed for the diodes and transistors that make desirable devices possible. N-type organic semiconductors were produced of the arylene diimide family that are resistant to thermal and environmental stresses, which is one of the largest challenges in the field.^[11] Several other compounds are being explored for n-type organic semiconductors for use in organic field-effect transistors (OFET), such as fullerene (C₆₀) and chemically modified oligothiophenes. Semiconductors are made from these compounds by reduction with electron withdrawing groups or, alternatively, by modifying the surface properties to control electron trapping.^[12] Organic thin film transistors (OTFTs) are being explored because their low synthesis temperatures allow them to be deposited on thin plastic substrates without damage, resulting in thin and flexible devices. Some compounds are often considered for use in OFETs and OTFTs.^[13]

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