

Analysis of semiconductors and their uses engineering essay

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A semiconductor is a material that has an electrical conductivity between that of a conductor and an insulator, that is, generally in the range 10^3 siemens per centimeter to 10^{-8} S/cm. Devices made from semiconductor materials are the foundation of modern electronics, including radio, computers, telephones, and many other devices. Semiconductor devices include the various types of transistor, solar cells, many kinds of diodes including the light-emitting diode, the silicon controlled rectifier, and digital and analog integrated circuits. Solar photovoltaic panels are large semiconductor devices that directly convert light energy into electrical energy. An external diode, the silicon controlled rectifier, and digital and analog integrated circuits. Solar photovoltaic panels are large semiconductor devices that directly convert light energy into electrical energy. An external electrical field may change a semiconductor's resistivity. In a metallic conductor, current is carried by the flow of electrons. In semiconductors, current can be carried either by the flow of electrons or by the flow of positively-charged "holes" in the electron structure of the material. Common semiconducting materials are crystalline solids but amorphous and liquid semiconductors are known, such as mixtures of arsenic, selenium and tellurium in a variety of proportions. They share with better known semiconductors intermediate conductivity and a rapid variation of conductivity with temperature but lack the rigid crystalline structure of conventional semiconductors such as silicon and so are relatively insensitive to impurities and radiation damage. Silicon is used to create most semiconductors commercially. Dozens of other materials are used, including germanium, gallium arsenide, and silicon carbide. A pure semiconductor is

often called an "intrinsic" semiconductor. The conductivity, or ability to conduct, of common semiconductor materials can be drastically changed by adding other elements, called "impurities" to the melted intrinsic material and then allowing the melt to solidify into a new and different crystal. This process is called "doping".

Energy bands and electrical conduction

The electrons in semiconductors can have energies only within certain bands (i. e. ranges of levels of energy) between the energy of the ground state, corresponding to electrons tightly bound to the atomic nuclei of the material, and the free electron energy, which is the energy required for an electron to escape entirely from the material. The energy bands each correspond to a large number of discrete quantum states of the electrons, and most of the states with low energy (closer to the nucleus) are full, up to a particular band called the valence band. Semiconductors and insulators are distinguished from metals because the valence band in the semiconductor materials is nearly filled under usual operating conditions, thus causing more electrons to be available in the "conduction band," which is the band immediately above the valence band. The ease with which electrons in a semiconductor can be excited from the valence band to the conduction band depends on the band gap between the bands, and it is the size of this energy bandgap that serves as an arbitrary dividing line (roughly 4 eV) between semiconductors and insulators. In the picture of covalent bonds, an electron moves by hopping to a neighboring bond. Because of the Pauli exclusion principle it has to be lifted into the higher anti-bonding state of that bond. In the picture of delocalized states, for example in one dimension - that is in a nanowire, for every energy there is a state with electrons flowing in one direction and one

state for the electrons flowing in the other. For a net current to flow some more states for one direction than for the other direction have to be occupied and for this energy is needed, in the semiconductor the next higher states lie above the band gap. Often this is stated as: full bands do not contribute to the electrical conductivity. However, as the temperature of a semiconductor rises above absolute zero, there is more energy in the semiconductor to spend on lattice vibration and — more importantly for us — on lifting some electrons into an energy states of the conduction band. The current-carrying electrons in the conduction band are known as " free electrons", although they are often simply called " electrons" if context allows this usage to be clear. Electrons excited to the conduction band also leave behind electron holes, or unoccupied states in the valence band. Both the conduction band electrons and the valence band holes contribute to electrical conductivity. The holes themselves don't actually move, but a neighboring electron can move to fill the hole, leaving a hole at the place it has just come from, and in this way the holes appear to move, and the holes behave as if they were actual positively charged particles. One covalent bond between neighboring atoms in the solid is ten times stronger than the binding of the single electron to the atom, so freeing the electron does not imply destruction of the crystal structure. Holes: electron absence as a charge carrier

The motion of holes, which was introduced for semiconductors, can also be applied to metals, where the Fermi level lies within the conduction band. With most metals the Hall effect reveals electrons to be the charge carriers, but some metals have a mostly filled conduction band, and the Hall effect reveals positive charge carriers, which are not the ion-cores,

but holes. Contrast this to some conductors like solutions of salts, or plasma. In the case of a metal, only a small amount of energy is needed for the electrons to find other unoccupied states to move into, and hence for current to flow. Sometimes even in this case it may be said that a hole was left behind, to explain why the electron does not fall back to lower energies: It cannot find a hole. In the end in both materials electron-phonon scattering and defects are the dominant causes for resistance. Fermi-Dirac distribution. States with energy ϵ below the Fermi energy, here μ , have higher probability n to be occupied, and those above are less likely to be occupied. Smearing of the distribution increases with temperature. The energy distribution of the electrons determines which of the states are filled and which are empty. This distribution is described by Fermi-Dirac statistics. The distribution is characterized by the temperature of the electrons, and the Fermi energy or Fermi level. Under absolute zero conditions the Fermi energy can be thought of as the energy up to which available electron states are occupied. At higher temperatures, the Fermi energy is the energy at which the probability of a state being occupied has fallen to 0.5. The dependence of the electron energy distribution on temperature also explains why the conductivity of a semiconductor has a strong temperature dependency, as a semiconductor operating at lower temperatures will have fewer available free electrons and holes able to do the work. Energy-momentum dispersion In the preceding description an important fact is ignored for the sake of simplicity: the dispersion of the energy. The reason that the energies of the states are broadened into a band is that the energy depends on the value of the wave vector, or k-vector, of the electron. The k-vector, in quantum mechanics, is

the representation of the momentum of a particle. The dispersion relationship determines the effective mass, m^* , of electrons or holes in the semiconductor, according to the formula $m^* = \hbar^2 \left(\frac{d^2 E}{dk^2} \right)^{-1}$. The effective mass is important as it affects many of the electrical properties of the semiconductor, such as the electron or hole mobility, which in turn influences the diffusivity of the charge carriers and the electrical conductivity of the semiconductor.

Typically the effective mass of electrons and holes are different. This affects the relative performance of p-channel and n-channel IGFETs. The top of the valence band and the bottom of the conduction band might not occur at that same value of k . Materials with this situation, such as silicon and germanium, are known as indirect bandgap materials. Materials in which the band extrema are aligned in k , for example gallium arsenide, are called direct bandgap semiconductors. Direct gap semiconductors are particularly important in optoelectronics because they are much more efficient as light emitters than indirect gap materials. Carrier generation and recombination When ionizing radiation strikes a semiconductor, it may excite an electron out of its energy level and consequently leave a hole. This process is known as electron-hole pair generation. Electron-hole pairs are constantly generated from thermal energy as well, in the absence of any external energy source. Electron-hole pairs are also apt to recombine. Conservation of energy demands that these recombination events, in which an electron loses an amount of energy larger than the band gap, be accompanied by the emission of thermal energy (in the form of phonons) or radiation (in the form of photons). In some states, the generation and recombination of electron-hole pairs are in equilibrium. The number of

electron-hole pairs in the steady state at a given temperature is determined by quantum statistical mechanics. The precise quantum mechanical mechanisms of generation and recombination are governed by conservation of energy and conservation of momentum. As the probability that electrons and holes meet together is proportional to the product of their amounts, the product is in steady state nearly constant at a given temperature, providing that there is no significant electric field (which might "flush" carriers of both types, or move them from neighbour regions containing more of them to meet together) or externally driven pair generation. The product is a function of the temperature, as the probability of getting enough thermal energy to produce a pair increases with temperature, being approximately $\exp(-EG/kT)$, where k is Boltzmann's constant, T is absolute temperature and EG is band gap. The probability of meeting is increased by carrier traps—impurities or dislocations which can trap an electron or hole and hold it until a pair is completed. Such carrier traps are sometimes purposely added to reduce the time needed to reach the steady state.

Semi-insulators Some materials are classified as semi-insulators. These have electrical conductivity nearer to that of electrical insulators. Semi-insulators find niche applications in micro-electronics, such as substrates for HEMT. An example of a common semi-insulator is gallium arsenide.

Doping The property of semiconductors that makes them most useful for constructing electronic devices is that their conductivity may easily be modified by introducing impurities into their crystal lattice. The process of adding controlled impurities to a semiconductor is known as doping. The amount of impurity, or dopant, added to an intrinsic (pure) semiconductor varies its level of conductivity.

Doped semiconductors are often referred to as extrinsic. By adding impurity to pure semiconductors, the electrical conductivity may be varied not only by the number of impurity atoms but also, by the type of impurity atom and the changes may be thousand folds and million folds. For example, 1 cm³ of a metal or semiconductor specimen has a number of atoms on the order of 10^{22} . Since every atom in metal donates at least one free electron for conduction in metal, 1 cm³ of metal contains free electrons on the order of 10^{22} . At the temperature close to 20 °C, 1 cm³ of pure germanium contains about 4.2×10^{22} atoms and 2.5×10^{13} free electrons and 2.5×10^{13} holes (empty spaces in crystal lattice having positive charge) The addition of 0.001% of arsenic (an impurity) donates an extra 10^{17} free electrons in the same volume and the electrical conductivity increases about 10,000 times."

Dopants The materials chosen as suitable dopants depend on the atomic properties of both the dopant and the material to be doped. In general, dopants that produce the desired controlled changes are classified as either electron acceptors or donors. A donor atom that activates (that is, becomes incorporated into the crystal lattice) donates weakly-bound valence electrons to the material, creating excess negative charge carriers. These weakly-bound electrons can move about in the crystal lattice relatively freely and can facilitate conduction in the presence of an electric field. (The donor atoms introduce some states under, but very close to the conduction band edge. Electrons at these states can be easily excited to the conduction band, becoming free electrons, at room temperature.) Conversely, an activated acceptor produces a hole. Semiconductors doped with donor impurities are called n-type, while those doped with acceptor impurities are known as p-

type. The n and p type designations indicate which charge carrier acts as the material's majority carrier. The opposite carrier is called the minority carrier, which exists due to thermal excitation at a much lower concentration compared to the majority carrier. For example, the pure semiconductor silicon has four valence electrons. In silicon, the most common dopants are IUPAC group 13 (commonly known as group III) and group 15 (commonly known as group V) elements. Group 13 elements all contain three valence electrons, causing them to function as acceptors when used to dope silicon. Group 15 elements have five valence electrons, which allows them to act as a donor. Therefore, a silicon crystal doped with boron creates a p-type semiconductor whereas one doped with phosphorus results in an n-type material.

Carrier concentration

The concentration of dopant introduced to an intrinsic semiconductor determines its concentration and indirectly affects many of its electrical properties. The most important factor that doping directly affects is the material's carrier concentration. In an intrinsic semiconductor under thermal equilibrium, the concentration of electrons and holes is equivalent. That is, if we have a non-intrinsic semiconductor in thermal equilibrium the relation becomes: where n_0 is the concentration of conducting electrons, p_0 is the electron hole concentration, and n_i is the material's intrinsic carrier concentration. Intrinsic carrier concentration varies between materials and is dependent on temperature. Silicon's n_i , for example, is roughly $1.1 \times 10^{10} \text{ cm}^{-3}$ at 300 kelvins (room temperature). In general, an increase in doping concentration affords an increase in conductivity due to the higher concentration of carriers available for conduction. Degenerately (very highly) doped semiconductors have

conductivity levels comparable to metals and are often used in modern integrated circuits as a replacement for metal. Often superscript plus and minus symbols are used to denote relative doping concentration in semiconductors. For example, n^+ denotes an n-type semiconductor with a high, often degenerate, doping concentration. Similarly, p^- would indicate a very lightly doped p-type material. It is useful to note that even degenerate levels of doping imply low concentrations of impurities with respect to the base semiconductor. In crystalline intrinsic silicon, there are approximately 5×10^{22} atoms/cm³. Doping concentration for silicon semiconductors may range anywhere from 10^{13} cm⁻³ to 10^{18} cm⁻³. Doping concentration above about 10^{18} cm⁻³ is considered degenerate at room temperature. Degenerately doped silicon contains a proportion of impurity to silicon in the order of parts per thousand. This proportion may be reduced to parts per billion in very lightly doped silicon. Typical concentration values fall somewhere in this range and are tailored to produce the desired properties in the device that the semiconductor is intended for effect on band structure. Doping a semiconductor crystal introduces allowed energy states within the band gap but very close to the energy band that corresponds to the dopant type. In other words, donor impurities create states near the conduction band while acceptors create states near the valence band. The gap between these energy states and the nearest energy band is usually referred to as dopant-site bonding energy or EB and is relatively small. For example, the EB for boron in silicon bulk is 0.045 eV, compared with silicon's band gap of about 1.12 eV. Because EB is so small, it takes little energy to ionize the dopant atoms and create free carriers in the conduction or valence

bands. Usually the thermal energy available at room temperature is sufficient to ionize most of the dopant. Dopants also have the important effect of shifting the material's Fermi level towards the energy band that corresponds with the dopant with the greatest concentration. Since the Fermi level must remain constant in a system in thermodynamic equilibrium, stacking layers of materials with different properties leads to many useful electrical properties. For example, the p-n junction's properties are due to the energy band bending that happens as a result of lining up the Fermi levels in contacting regions of p-type and n-type material. This effect is shown in a band diagram. The band diagram typically indicates the variation in the valence band and conduction band edges versus some spatial dimension, often denoted x . The Fermi energy is also usually indicated in the diagram. Sometimes the intrinsic Fermi energy, E_i , which is the Fermi level in the absence of doping, is shown. These diagrams are useful in explaining the operation of many kinds of semiconductor devices. Preparation of semiconductor materials Semiconductors with predictable, reliable electronic properties are necessary for mass production. The level of chemical purity needed is extremely high because the presence of impurities even in very small proportions can have large effects on the properties of the material. A high degree of crystalline perfection is also required, since faults in crystal structure (such as dislocations, twins, and stacking faults) interfere with the semiconducting properties of the material. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the necessary perfection. Current mass production processes use crystal ingots between 100 mm and 300 mm (4-12 inches) in

diameter which are grown as cylinders and sliced into wafers. Because of the required level of chemical purity and the perfection of the crystal structure which are needed to make semiconductor devices, special methods have been developed to produce the initial semiconductor material. A technique for achieving high purity includes growing the crystal using the Czochralski process. An additional step that can be used to further increase purity is known as zone refining. In zone refining, part of a solid crystal is melted. The impurities tend to concentrate in the melted region, while the desired material recrystallizes leaving the solid material more pure and with fewer crystalline faults. In manufacturing semiconductor devices involving heterojunctions between different semiconductor materials, the lattice constant, which is the length of the repeating element of the crystal structure, is important for determining the compatibility of materials.

Application of Semiconductors and Semiconductor Materials Semiconductors and semiconductor materials are used to fabricate microelectronic devices and optoelectronic devices such as transistors, photodetectors and solar cells. Silicon (Si) is the most commonly used semiconductor material today; however, other semiconductor material types are also available. The number of valence shell electrons in a semiconductor material places this category of material between insulators (poor electrical conductors) and metals (good semiconductors). Insulators have a filled valence shell (eight electrons) and a large band gap, which results in poor electrical conductivity. Metals have a partially-filled valence shell and overlapping band gap, which results in free-traveling electrons and high electrical conductivity. Semiconductors and semiconductor materials are useful because their electrical conductivity can

be altered with dopants, an applied electric field, or electromagnetic radiation. There are two basic categories of semiconductors and semiconductor materials: electrical semiconductors and compound semiconductors. Silicon (Si) and germanium (Ge), the most common electrical semiconductors, are used in many semiconductor components. Gallium arsenide (GaAs) and indium phosphide (InP) are examples of composite semiconductors that contain added materials or dopants. Semiconductor doping, the addition of a very small amount of a foreign substance to a pure semiconductor crystal, provides a semiconductor with an excess of conducting electrons or an excess of conducting holes. The first semiconductors and semiconductor materials produced electrical conduction through contact with a metal wire. Subsequent technologies used semiconductor crystals and semiconductor diodes. A semiconductor diode allows current to flow in one direction only. There are many applications for semiconductors and semiconductor materials in materials engineering, such as the fabrication of transistors, photodetectors and solar cells. Major semiconductor manufacturers and providers of semiconductors and semiconductor materials include Lattice Semiconductor Corporation, Xilinx, Altera, Actel and Quicklogic. Other semiconductor manufactures are located across the United States and around the world. In semiconductor manufacturing, transistors are placed together to create a silicon chip. The semiconductor manufacturer then creates a microprocessor from the silicon chip. The term PN junction diode is normally reserved for what may be called the basic form of diode, although in reality the term applies to virtually any form of semiconductor diode. The PNjunction diode gains its name from the

fact that it is formed from a semiconductor PN junction and by its nature it only allows current to flow in one direction. However the PN junction diode also has other properties that can be used in many other applications. These range from light emission to light detection and variable capacitance to voltage regulation. Many of these types of diode are described in other pages on this section of the Radio-Electronics. Com website. The basic form of PN junction finds many uses in electronics circuits. The standard PN junction diodes are available in a variety of forms. They are mainly manufactured from silicon, although germanium diodes are also available. PN junction diodes can also be manufactured from other semiconductor materials, but these are generally specialised diodes used for particular applications. The basic PN junction diodes are able to perform a variety of roles in electronics circuits. These range from applications as small signal diodes, to switching, to those required in applications such as power supplies as high current or high voltage rectifiers. PN junction diode circuit basics As the name indicates a diode has two terminals. These are referred to as the anode and cathode. When in circuit, the current flow (conventional current flow) is across the PN junction diode from the anode to the cathode. As the diode is a one way device, current is inhibited from flowing in the other direction. Diode circuit symbol and common package outlines Key PN junction diode specifications There are many parameters that can be specified for any form of diode. Some of the key PN junction diode specifications or parameters are outlined below:

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Semiconductor material: The semiconductor material used in the PN junction diode is of paramount importance because the material used affects many of the major properties of the diode. Silicon is the most widely used material as it offers high levels of performance for most applications and it offers low manufacturing costs. The other material that is used is germanium. Other materials are generally reserved for more specialist diodes.

- Forward voltage drop: Any electronics device passing current will develop a resulting voltage across it. The voltage across a PN junction diode arises for two reasons. The first is of the nature of the semiconductor PN junction. Broadly speaking, 0.6 volts is required for silicon and about 0.2 to 0.3 volts across a germanium diode to enable the depletion layer to be overcome and for current to flow. The second arises from the normal resistive losses in the device. As a result a figure for the forward voltage drop at a specified current level will be given. This figure is particularly important for rectifier diodes where significant levels of current may be passed.
- Peak Inverse Voltage (PIV): This is the maximum voltage a diode can withstand in the reverse direction. This voltage must not be exceeded otherwise the device may fail. This voltage is not simply the RMS voltage of the incoming waveform. Each circuit needs to be considered on its own merits, but for a simple single diode half wave rectifier with some form of smoothing capacitor afterwards, it should be remembered that the capacitor will hold a voltage equal to the peak of the incoming voltage waveform. The diode will then also see the peak of the incoming waveform in the reverse direction and therefore under these circumstances it will see a peak inverse voltage equal to the peak to peak

value of the waveform.

- **Maximum forward current:** When designing a circuit that passes any levels of current it is necessary to ensure that the maximum current levels for the diode are not exceeded. As the current levels rise, so additional heat is dissipated and this needs to be removed.
- **Leakage current:** If a perfect diode were available, then no current would flow when it was reverse biased. It is found that for a real PN junction diode, a very small amount of current flows in the reverse direction as a result of the minority carriers in the semiconductor. The level of leakage current is independent upon three main factors. The reverse voltage is obviously significant. It is also temperature dependent, rising appreciably with temperature. It is also found that it is very dependent upon the type of semiconductor material used - silicon is very much better than germanium.
- **The leakage current for a PN junction diode is specified at a certain reverse voltage and particular temperature.** It is normally measured in microamps or picoamps.
- **Junction capacitance:** All PN junction diodes exhibit a junction capacitance. The depletion region is the dielectric spacing between the two plates which are effectively formed at the edge of the depletion region and the area with majority carriers. The actual value of capacitance being dependent upon the reverse voltage which causes the depletion region to change (increasing reverse voltage increases the size of the depletion region and hence decreases the capacitance). This fact is used in varactor or varicap diodes to good effect, but for many other applications, especially RF applications this needs to be minimised. As the capacitance is of importance it is specified. The parameter is normally detailed as a given capacitance (in pF) at a given voltage or voltages. Also special low capacitance diodes are available for

many RF applications. • Package type: Diodes can be mounted in a variety of packages according to their applications. High power diodes may require packages that can be bolted to heatsinks, whereas small signal diodes may be available in leaded formats or as surface mount devices.

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