CS2507 Computer Architecture

Lecture 6

Semiconductors

Resistance, resistivity, conductance and conductivity

We are accustomed by now to measuring the resistance of a circuit element in Ohms. Resistivity accounts for the relationship between the dimensions of the resisting material and its resistance.

For a cuboidal element of length L and cross-sectional area A, its resistance is directly proportional to L and inversely proportional to A, i.e.

$R = \rho L/A$

Here, ρ is the resistivity of the material from which the resisting element is made.

We can write $\rho = RA/L$,

so one can see that if resistance is expressed in ohms (Ω), area in metres squared (m^2) and length in metres (m), the unit of resistivity is the ohm-metre (Ωm).

The reciprocal of resistance is conductance, measured in mhos.

The reciprocal of resistivity is conductivity, σ, measured in mhos per metre.

Solids that are good conductors, chiefly metals, have very high conductivity, of the order of 10^7 mhos/m
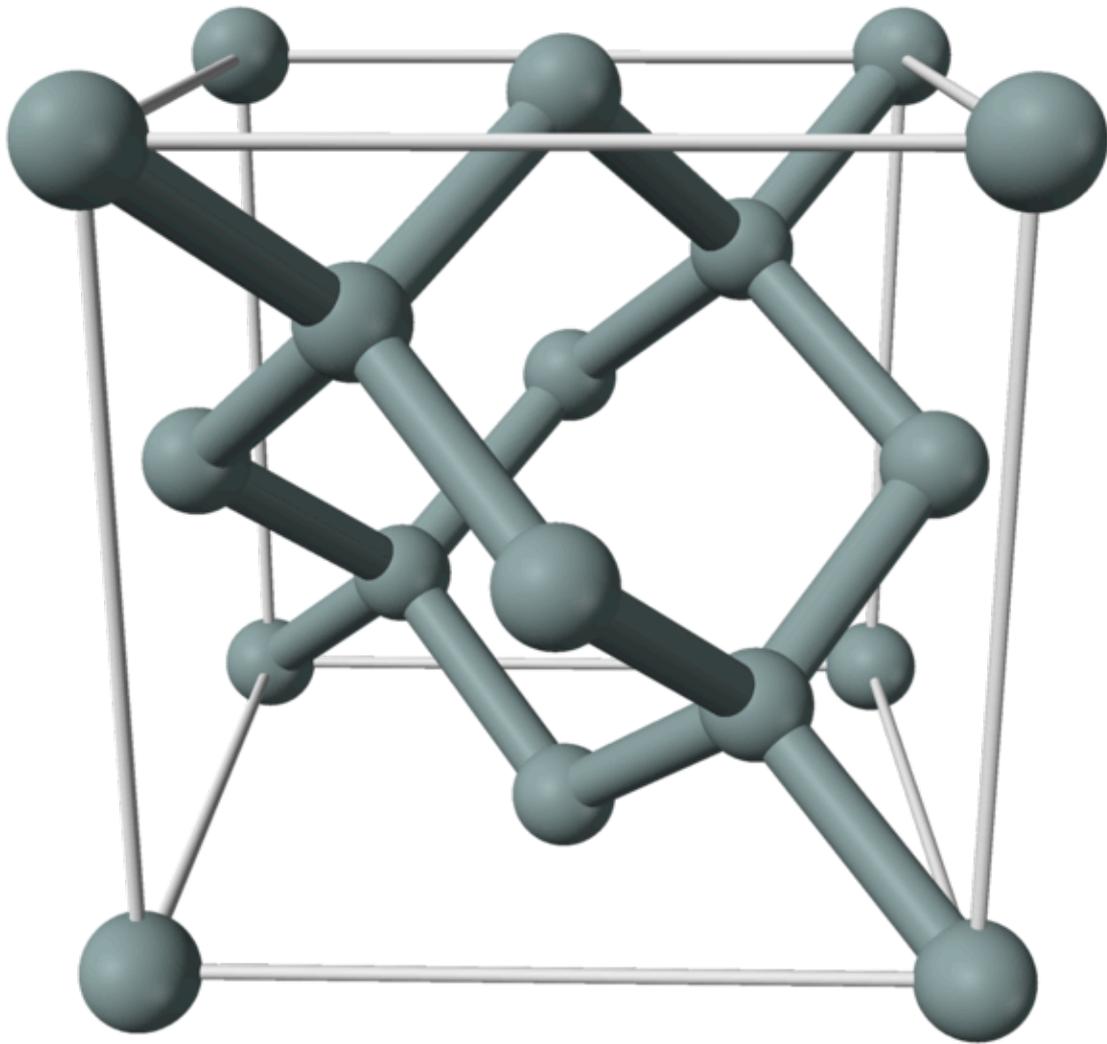
Solids that are insulators or dielectrics have low conductivity, typically 10^{-12} mhos/m

Semiconductors are a group of solids that have intermediate conductivity, between 10^{-3} and 10 mhos/m.
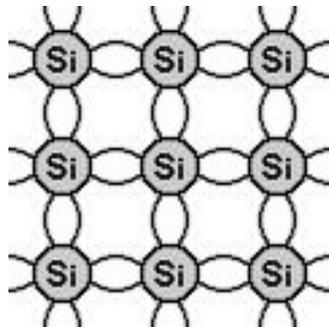
Si is the second most abundant element in the Earth's crust after Oxygen.

Si is a popular semiconductor because it remains a semiconductor at a higher temperature than Germanium and because it is easily handled in industrial processes.

Figure 1   Periodic table of elements

Semiconductor bonds

Si, as a pure semiconductor, has 4 valence electrons, i.e. 4 electrons in its outer shell (electron orbit). Figure 1 shows Si positioned in a periodic table of elements.

The silicon atom arranges itself in a solid to share valence electrons with four neighbouring atoms. The resulting crystalline structure takes the same shape as the diamond form of Carbon (see Figure 2). For convenience, it is usually shown in 2-D form as in Figure 3.

Figure 2   Diamond cubic crystalline structure of Silicon

Figure 3   2-dimensional representation of Silicon lattice

In this structure, each element has four equidistant neighbours.

The covalent bonds of a semiconductor can be broken if sufficient energy is imparted to an electron.

For an intrinsic (i.e. ideally pure) semiconductor, the amount of energy needed to break a covalent bond at 300K is at least 1.1 eV for Si and 0.7 eV for Ge.

This energy can be obtained in several ways, such as from thermal energy or electromagnetic radiation. Once a bond is broken, an electron is free to move about the solid and take part in current conduction.

A second conduction mechanism exists in semiconductors: once a covalent bond is broken, nearby electrons can easily move into the vacancy caused by ionization of the atom. Thus, the vacancies in covalent bonds due to ionization can move about the solid in a random motion in a similar way to that in which free electrons move about. This movement of vacancies involves electron motion within the valence band without recourse to an ionization process. The vacancy movement can be modeled by a fictitious particle called a hole which is of equal mass to the electron but is opposite in charge.

Doping

The introduction of impurities into an intrinsic (pure) semiconductor is called doping. It involves replacing intrinsic atoms in the lattice structure with atoms of a doping material, usually with valence 3 or 5.

Assume that Si is doped with a small amount of Phosphorus (P), which has valence 5. If an atom of P occupies a vertex in the lattice and forms covalent bonds with 4 neighbours, one of the P electrons is unbonded, is only lightly attached to its parent atom and, at usual temperatures, escapes and is free to move about in the solid.

The introduction of such an impurity greatly increases the density of free electrons and consequently the electrical conductivity of the material.

A semiconductor that has been doped in a controlled manner with an impurity is called an extrinsic semiconductor. When the impurity is of valence 5, the extrinsic semiconductor is called n-type, because it contains many more free electrons than the intrinsic semiconductor. The impurity itself is called a donor.

The hole density in an n-type semiconductor is not only less than the electron density, but also it is less than the hole density in the intrinsic semiconductor.

Acceptor Doping

If intrinsic semiconductor is doped with a small amount of Boron (B) or Aluminium (Al), the three valence electrons of Boron (say) will make covalent bonds with 3 of its neighbours but no fourth bond can be made and holes will exist in the material with larger density than that of the intrinsic semiconductor. The extrinsic semiconductor is called p-type, because of its surplus holes. Holes exist in the p-type semiconductor with a density larger than that of intrinsic semiconductor. Because the impurity atom can accept electrons from adjacent covalent bonds of the parent material, this impurity is called an acceptor.

The pn Junction

It is possible to place p-type extrinsic semiconductor in contact with n-type extrinsic semiconductor. It is necessary to accomplish the transition from p-type to n-type material without a change in the basic lattice structure of the semiconductor. Therefore, it is not possible simply to attach n-type material to p-type material. The correct p-n junction can be formed for instance by diffusing other impurity atoms into an already doped semiconductor. Thus, for example, B atoms can be diffused into n-type Si in a complex manufacturing process to create a p-type extrinsic region.

Potential barrier of a pn junction

An idealised pn junction has a very high density of holes in the p region and a very high density of electrons in the n region. Holes are majority carriers in the p region and electrons are majority carriers in the n region.

There is a low density of electrons in the p region and a low density of holes in the n region. Electrons are minority carriers in the p region and holes are minority carriers in the n region.

Assume that the p region and the n region are brought together in a perfect matching of the semiconductor crystal structure.

Because of the greater density of holes in the p region, diffusion of holes towards the

n region occurs. Similarly, there is a diffusion of electrons from the n region towards the p region. As holes flow to the n region and electrons to the p region, the potential of the n region must become greater than that of the p region. This potential creates an electric field that opposes further diffusion of holes and electrons.The potential barrier does not completely halt the diffusion flows, as some electrons and holes have very high energies and can flow by diffusion over any barrier of finite height. However, an equilibrium is established because the electric field causes a drift of minority carriers between the p and n regions. The magnitude of the potential barrier is the value for which the diffusion flow of the high-energy holes and electrons equals the drift flow of the minority carriers.

Another effect of diffusion is that it gives rise to a depletion of majority carriers in the vicinity of the pn junction and hence, the region near the junction is called the depletion region.

Biasing the pn junction: Forward bias

Assume that a positive voltage is applied across a pn junction from p to n. That is, the positive terminal of a voltage source is connected to the p side of the junction and the negative terminal of the same voltage source is connected to the n side of the junction.

In this case, the potential difference of the voltage source opposes the potential barrier caused by diffusion, thus lowering the potential barrier. This causes an increased diffusion flow (of majority carriers) across the pn junction.

The drift of minority carriers is scarcely affected by the applied voltage, since minority carrier availability is small and fixed at thermal equilibrium in the region of the pn junction.

Therefore, there is a net increase in carrier flow across the pn junction due to the applied voltage.

Voltage applied to the pn junction in this manner is said to forward bias the junction. In forward bias, an increase in applied voltage gives rise to an exponential increase in current flow. If voltage is decreased, there is an exponential decrease in current flow.

Reverse bias

If the positive terminal of a voltage source is connected to the n side of the junction and the negative terminal of the same voltage source is connected to the p side of the junction, the voltage applied to the pn junction becomes negative and the junction is subjected to a negative or reverse bias.

This has the effect of raising the potential barrier across the junction above its unbiased value. As a consequence, minority carrier flow across the junction rises above its equilibrium value. However, it is limited by the availability of minority carriers at a given temperature. The result is that a very small current flows from n to p in a reverse-biased junction. In a theoretically ideal scenario, this current, called the saturation current, is independent of the applied negative bias.

The reverse-bias voltage cannot be increased without limit. A breakdown of the junction occurs at large voltages.

Avalanche breakdown occurs when the electrons and holes flowing in the pn junction are accelerated to large velocities. If the energy of the minority carriers is sufficient, ionization of atoms occurs due to collisions. This ionization gives rise to a new hole-electron pair that can in turn be accelerated to cause further ionization, creating an avalanche of ionization that leads to a sudden rapid increase in current from n to p.

The IV characteristics of a typical diode are shown in Figure 4.
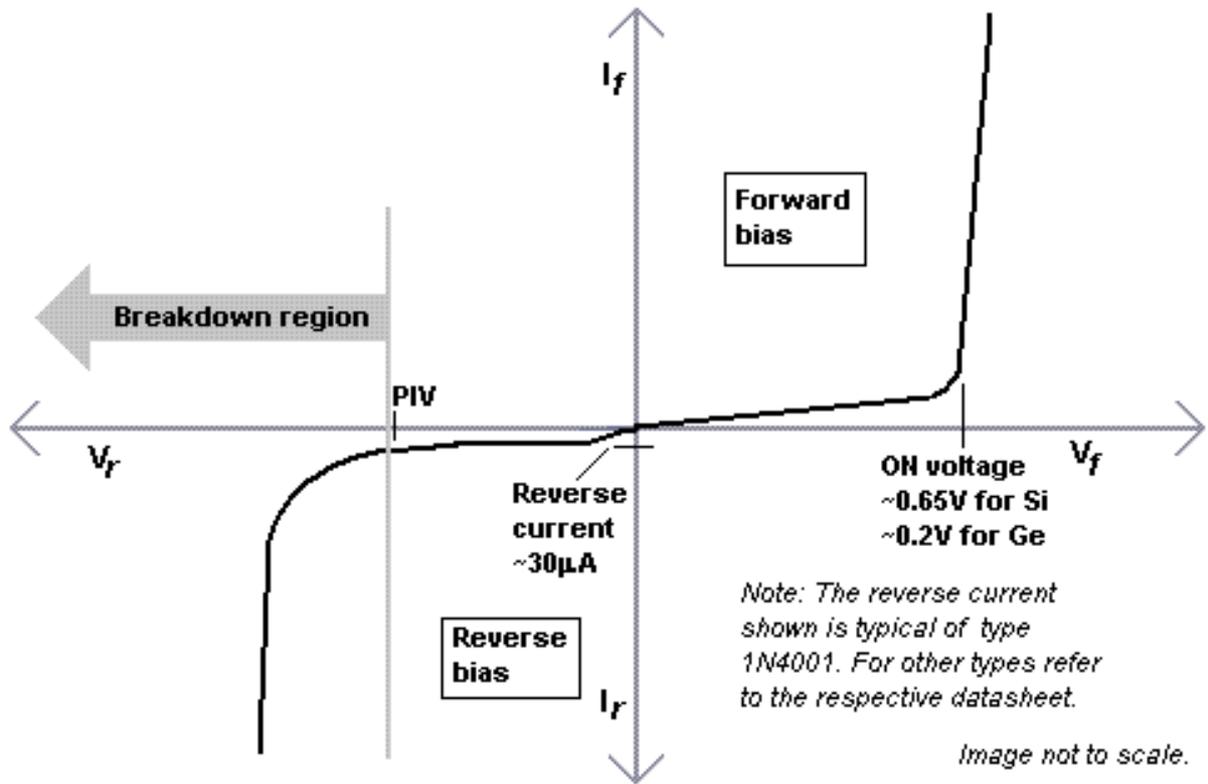
Figure 4   Diode IV characteristics