

# Chapter 18

## Semiconductors and Nanotechnology

Semiconductors and nanotechnology have become interconnected, and their development has resulted in new and interesting devices and methodologies.

### 18.1 Semiconductors

#### 18.1.1 Introduction

The basic electronic theory of the semiconductor was developed in two papers in the Proc. Royal Society in 1931. It was based on the existence of potential wells in which the electron can reside. With the application of additional voltage, the electron can leave the well and migrate on the surface of the solid. It did not reach a practical stage until the World War of 1939 when the physicist, R. Ohl, at Bell Laboratories tried to use the cat's whiskers as an electronic amplifier. It was found to work in an unreliable manner and was about to be abandoned when a cracked crystal showed excellent but unpredictable results. This was eventually traced to the junction caused by the crack in the crystal. The research team that was formed developed the solid-state diode—composed of two joined crystals. The diode was made of germanium and became known as the semiconductor.

### 18.2 The Triode

After the war, the team at Bell Laboratories (Shockley, Bardeen, and Brattain) started to develop the amplifying triode. The difficulty lays in the need to have the emitter and collector close to each other without failing. This was eventually achieved by slicing a gold foil on a crystal with a razor blade and adding the needed contact points. The development of the germanium triode was given the name “transistor,” and a team of the three researchers was awarded the Nobel Prize in Physics in 1956. The replacement of the germanium by silicon simplified the production of the transistor by allowing the use of zone melting to purify the silicon and thereby improve upon the product.

The early model for an electron in a metal is shown in Fig. 18.1 and more recently in Fig. 18.2 where  $\varepsilon_w$  is the work function; the difference between the energy of an electron in the Fermi level of the metal,  $E_f$ ; and the energy of an electron,  $e_o$ , outside of the metal:

$$\varepsilon_w = e_o - E_f \quad (18.1)$$

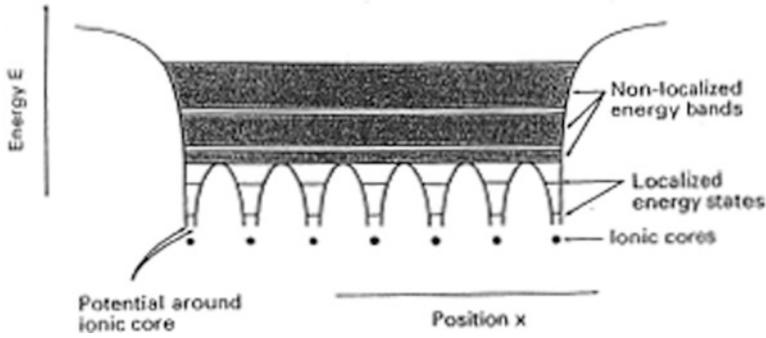


Fig. 18.1 Schematic diagram of energy levels in a one-dimensional structure

$$\phi = E_0 - E_F.$$

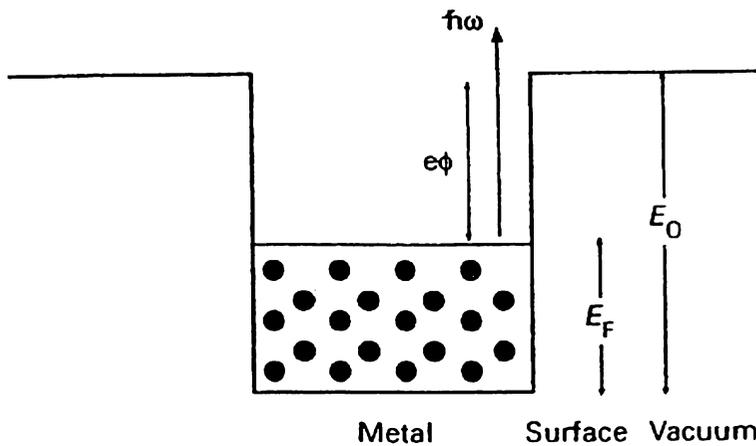


Fig. 18.2 Square-well potential model of a metal. The work function  $\phi$  is equal to the difference in energy between the Fermi level and the energy of an electron outside the material

The semiconductor has been defined in several ways. Two of the most common definitions are based on the limits of two types of measurements: (a) electrical resistance with values between  $10^{-2}$  and  $10^9 \Omega \text{ cm}$  or  $10^3$  and  $10^{-8}$  siemens/cm and (b) the energy gap with electronic excite energy between 0 and 3 electron volts (eV). However, some exceptions to these limits do occur. The best known material for the semiconductor is silicon (Si), but many others include naturally occurring minerals such as zinc blende (ZnS), cuprite ( $\text{Cu}_2\text{O}$ ), and galena (PbS).

A recent award to a company producing semiconductors was made by Global Semiconductor Alliance to SiGe Semiconductor, Inc. in recognition of their efforts in advancing the work on silicon-based RF front-end solutions for wireless connectivity applications in consumer electronics and their lead-free initiative for the industry.

Recent developments in semiconductors are in the production of photovoltaic devices that convert solar intensity into electrical energy. There are two classes of semiconductors: the **n**- and the **p**-types. When the doped material releases free electrons, an **n**-type semiconductor is formed with more electrons than holes. When the reverse occurs, that is, more holes than electrons, then the conduction is a **p**-type. When these two materials are brought together, they form the **p-n** junction that favors the flow of electrons in one direction and is referred to as a semiconductor diode.

### 18.3 Applications

Semiconductors are the basic components of modern electronic systems such as radio, computers, telephone, lighting, heating, and cooling as well as communication. Figure 18.3 illustrates the band gap for an electron in three different states of matter. The electrons are considered to be in potential wells from which they can leave when given sufficient energy. When the energy of the wells is not uniform in depth, then the conductor would vary with temperature which when increased permits more electrons with higher energy to leave the well and to move freely on the surface.

The energy of the electron varies with the wave vector  $k$ . However, a more simplified band structure can be used for semiconductors without referring to the value of  $k$ . This approximation is acceptable for limits comparison of semiconductors of different structures and distinguishes between the direct and indirect band gap semiconductor. This is illustrated in Fig. 18.4.

In intrinsic semiconductors, the conductivity,  $\sigma$  ( $\Omega^{-1} \text{ m}^{-1}$ ), increases as the temperature increases and approaches a maximum in conduction at the highest temperatures, Fig. 18.5. A plot of the log  $\sigma$

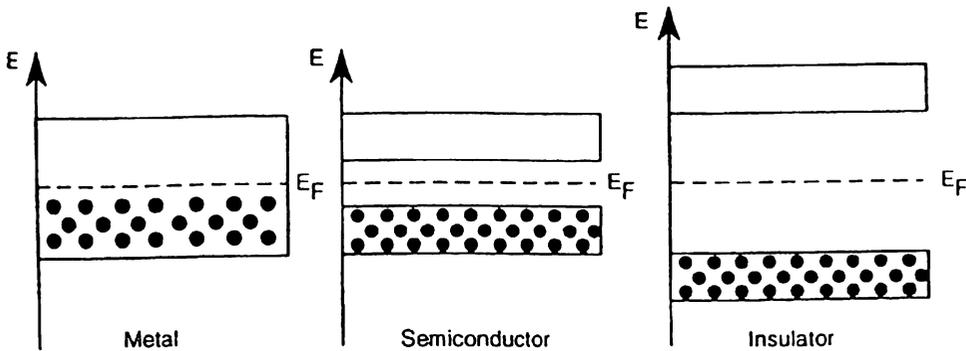


Fig. 18.3 Simplified band structure diagrams of a metal, semiconductor, and insulator. Typical values of the band gap are 0 eV in metals, 0.5–5.0 eV in semiconductors, and 5 eV or greater in insulators

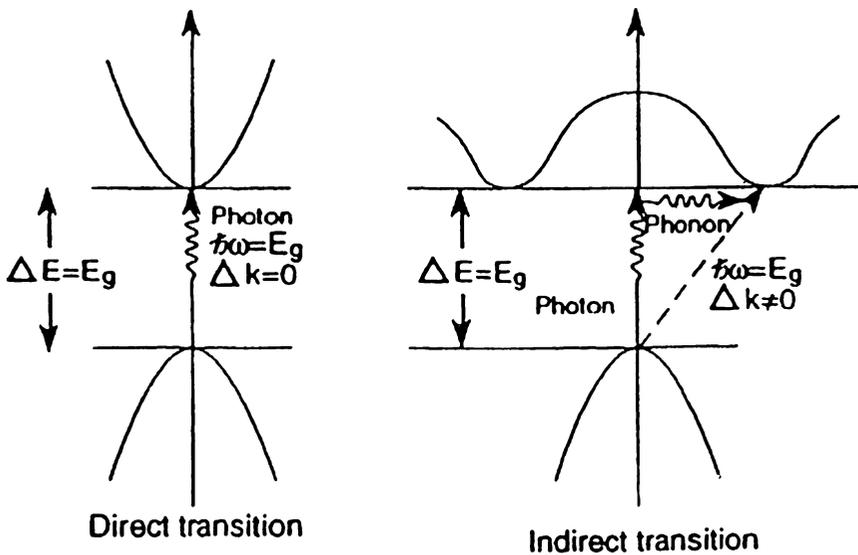


Fig. 18.4 Direct and indirect band gaps in semiconductors

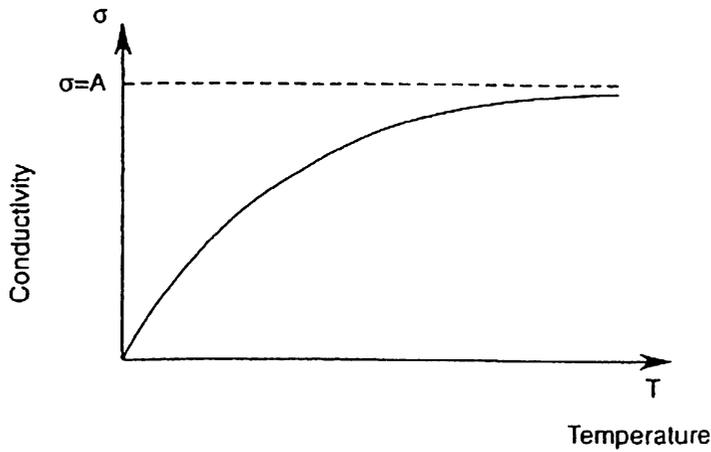


Fig. 18.5 Variation of the conductivity of an intrinsic semiconductor as a function of temperature

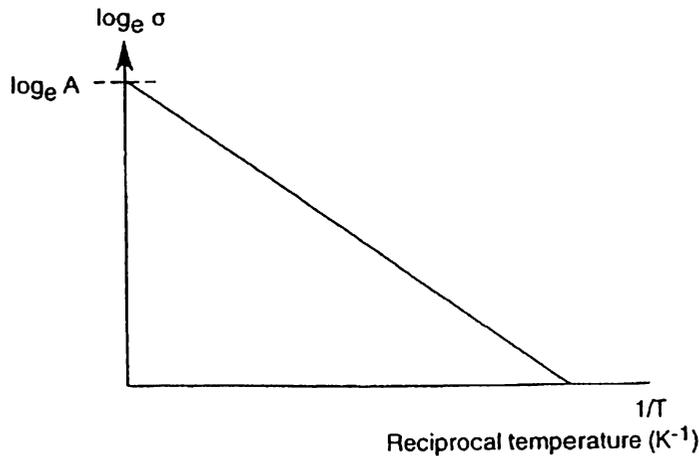


Fig. 18.6 Variation of  $\log \sigma$  with  $1/T$  for an intrinsic semiconductor

against  $1/T$  is shown in Fig. 18.6. In the extrinsic semiconductor trace, impurities of the Group 5 elements form n-type semiconductors or when doped with Group 3 elements such as B, Al, Ga, or In, will form p-type semiconductors. The effect of temperature on the number of charge carriers as a function of temperature of extrinsic semiconductors is shown in Fig. 18.7. The effect of temperature on the conductivity is shown in Fig. 18.8, where comparison is also made with the intrinsic semiconductor. At higher temperatures, the extrinsic conductor usually converts to an intrinsic semiconductor.

## 18.4 Optical Effects

Light is emitted from an object when heated to high temperatures. The light bulb is a simple example of such a source. Luminescence is an alternate method of generating light by allowing an electron in a higher energy state to return to a lower ground state emitting the excess energy in the form of photons.

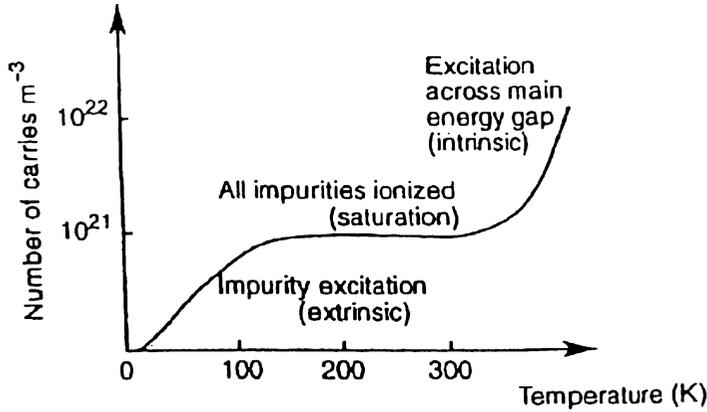


Fig. 18.7 Variation of conductivity of an extrinsic semiconductor with temperature

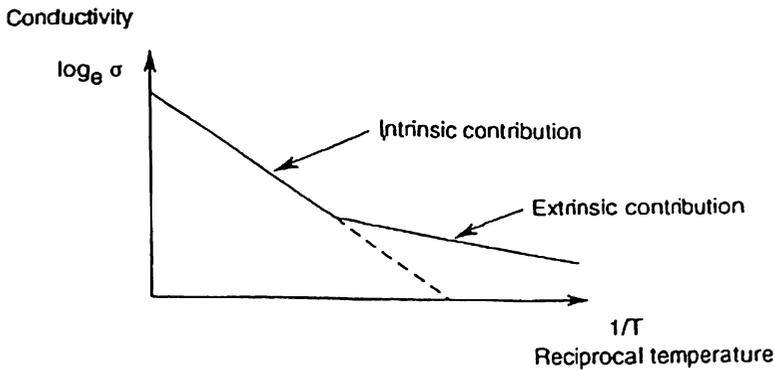


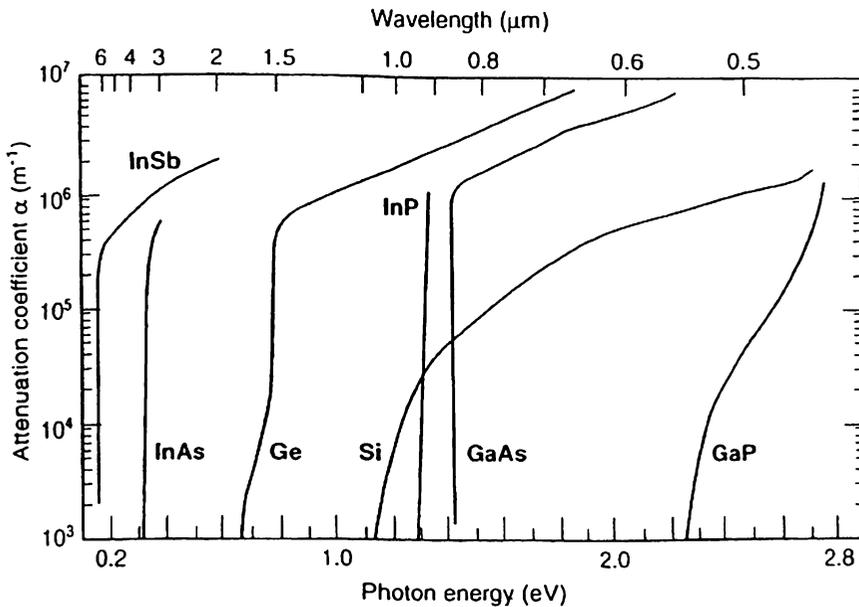
Fig. 18.8 Variation of  $\log \sigma$  with  $1/T$  for an extrinsic semiconductor

Such diodes are called LEDs, light-emitting diodes, and are usually formed when a current provides electrons that combine with holes and return to a lower energy level and emit photons. Figure 18.9 shows the emitted spectra of several semiconductor systems that have been studied.

## 18.5 Nanotechnology

Nanotechnology, unlike semiconductors, is a recent addition to the catalog of scientific fields. However, the two topics have become closely linked and appear to be complimentary to each other. The subject matter of nanotechnology was first discussed by Richard Feynman in a speech given at a scientific meeting in Dec. 1959. He predicted that the scientific trend would be moving to the study of smaller groups of atoms and molecules with tools that will be following the transition by the observation of individual atoms and molecules.

The term “nanotechnology” was first used in a paper presented by Norio Taniguchi of Tokyo University in 1974. This title was further developed in the 1980s by K. Eric Drexler in his 1991 MIT Ph.D. thesis (nanosystems, molecules, manufacturing, and computation) in speeches and in books such as “Engines of Creation: The Living Era of Nanotechnology (1986).”



**Fig. 18.9** Absorption coefficient versus photon energy for Ge, Si, GaAs, and selected other III–V binary semiconductors at  $T = 300\text{ K}$

A nanometer (nm) is  $10^{-9}\text{ m}$  or  $1\text{ nm} = 10\text{ \AA}$ . In terms of human parameters, the diameter of the double helix is 2 nm, bacteria are about 200 nm long. Another comparison that has been made is that the ratio of a nanometer to a meter is similar to that of a marble to the diameter of the earth.

The subject matter that can be included in the topic “nanotechnology” is limitless and much has been written on the various subject areas. However, it is not possible to treat each of the topics covered by nanotechnology. It will be useful to itemize the fields that have been subject to nanotechnology treatment

One recent study by Dr. Nayoo in China has shown that the effect of nanoparticles on plant cells such as rice was not invariably beneficial. In fact, the nanomaterial induced the death of plant cells. Caution is advised when nanotubes are injected into plants.

The 2010 Nobel Prize in Physics was awarded to two British physicists at the University of Manchester for groundbreaking experiments regarding the two-dimensional material “graphene” shown in Fig. 16.4 as the two-dimensional sheet of one atomic layer thick. As an electrical conductor, it is as good as copper, and as a conductor of heat, it is superior to most other materials. It is almost completely transparent but impervious to penetration by all gases including the smallest gas—helium atoms.

The future of graphene has been predicted to include its application to electronics, solar cells, and panels. It has been predicted to find applications in strengthening thin materials such as solar panels. When added to plastics, it is argued that the new materials could become good electrical and heat conductors as well and serve in several capacities in satellites and airplanes where low weight is important.

It has recently been shown that it is possible to make super-hydrophobic surfaces that repel water and possess a contact angle of about  $150^\circ$  with water. Normal non-wetting surfaces of glass or plastic can have contact angles with water that can vary from  $60^\circ$  to  $90^\circ$ . The high values of  $100^\circ$  are similar to that obtained for the lotus plant leaves and are attributed to air pockets that form between the water and the rough surface. One immediate application is for wind turbine blades with one caveat—the effect decreases at low temperature—a regular problem facing Canadians.

Examples of nanomaterials can be classified in different ways. Some of the common classes are based on application and consist of the following: carbon nanotubes (fullerenes), nanoparticles, nanorods, and nanoelectronic devices. Other more specific are, for example, medical applications, silicon solar cells, semiconductors, nanoelectromechanical systems (NEMS) or microelectromechanical systems (MEMS), and nanolithography. Another major potential application is in the medical field as nanorobotics.

This new and exciting field of nanotechnology and its many applications have recently been critically evaluated and debunked by showing that the many applications that have been proposed are impractical, excessively expensive, and energy consuming. Ms Georgia Miller at Friends of the Earth (FOE) Australia has been leading the effort of exposing the deception that nano-based developments will reduce the release of greenhouse gases. Her report “Nanotechnology, Climate and Energy: Overheated Promises and Hot Air?” raises some important factors that have yet to be resolved.

Hence, the future of nanotechnology, though full of enthusiastic hope and expectation, may be packed with problems and could become a great disappointment.

### Exercises

1. Describe the physical properties of insulators, semiconductors, and conductors and show how some interchange can be made to occur.
2. Chemical potential wells exist. In what way do these differ with electronic energy wells?
3. In simple chemical reactions at low temperatures, it is possible to observe “tunneling” through the energy barrier. Is there any evidence for this with the electron?
4. To what extent does temperature plays in the current–potential interaction of the electronic systems?
5. In Fig. 18.9, what major characteristics are not mentioned in determining the properties of the semiconductors?

### Further Reading

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