Electronics

Theory, Devices, and Circuits

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Preface

The word electronics can be applied to a very wide range of devices, circuits, and systems, and in an introductory textbook of this nature it is not possible to cover all aspects of the subject. Selection of material has been made with the aim of describing, in reasonable detail, those devices and circuits that are found in general purpose applications. One exception is the area of digital electronics. This area requires separate courses of study in most electronics programs, and therefore only a summary of some of the more common logic circuits is included here.

The book is intended for students in technology programs, and the prerequisites are a good knowledge of electric circuit fundamentals; algebra, trigonometry, complex numbers and simple calculus applied to electric and electronic circuits; and some basic semiconductor physics. The emphasis of the book is on circuit analysis and applications, and therefore devices are characterized in terms of measurable circuit properties and parameters sepcified in data sheets. For small signal applications the transconductance model is used throughout. The advantages of this model are that it can be related directly to the physical structures of devices, it applies equally well to bipolar junction transistors and field effect transistors, and the low-frequency model is easily extended to high-frequencies.

Our thanks go to the many manufacturers who provided data sheets, handbooks, and many practical details of devices and circuits; to the reviewers who suggested improvements and rearrangements of the first draft; and to Ellen Cherry of Reston Publishing Company who so ably handled production of the book.

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1 Introductory Semiconductor Theory

1.1 INTRODUCTION

The word *semiconductor,* which features so prominently in present-day electronics, means rather generally a material which has electrical conductivity halfway between that of a metallic conductor, and that of an insulator. However, there are some specific properties that distinguish semiconductors used for electronic devices from materials which generally might be said to have semiconducting characteristics (for example, a wet insulator may very well be a semiconductor in some general sense, but it is regarded as hazardous rather than as useful electrically).

1.2 INTRINSIC SILICON

Silicon is the most widely used of semiconductors. In the earth's crust, it is the second most plentiful element, next to oxygen, but it appears only in oxide compounds known as *silicates*. Quartz is one form of silicon oxide, and sand, that very common stuff, is mostly composed of fine particles of silicon oxide. To be useful for electronic device manufacture, the silicon must be obtained in its elemental form, that is, free of oxygen, and also in its single crystal form. Single crystal means that the atomic lattice structure making up the silicon is regular throughout; in effect, the lattice as "seen" from any lattice point within the silicon appears the same in all directions. Other impurities, especially boron which associates easily with silicon, must be removed or reduced to negligible levels. Fig. 1-1 shows a picture of a silicon rod typical of those produced for electronic

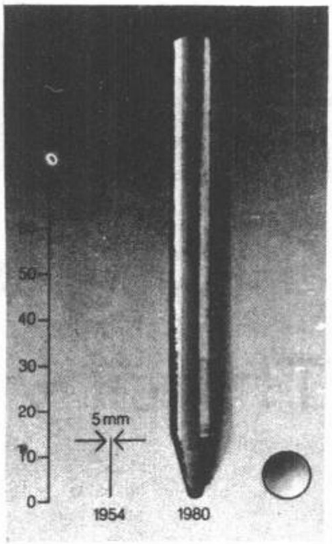

Fig. 1-1. Large diameter silicon rod. (Courtesy of *Siemens Review* and Eberhard Spenke and Walter Heyward.)

applications. The high-purity silicon is specified as *semiconductor grade silicon*. In later stages of processing, certain chemical elements, or impurities, are purposely added again in precisely controlled amounts to alter the electrical conductivity.

The manner in which the conductivity is altered is all-important in determining the characteristics of devices fabricated in the silicon, but before we consider this, we shall compare the resistivity of intrinsic silicon with that of a good electrical conductor, copper, and that of a good electrical insulator, ceramic. Within an order of magnitude, the volume resistivities are

Copper	10^{-4} ohm-meters (Ω-m)
Intrinsic silicon	10^{3} ohm-meters
Ceramic	10^{10} ohm-meters

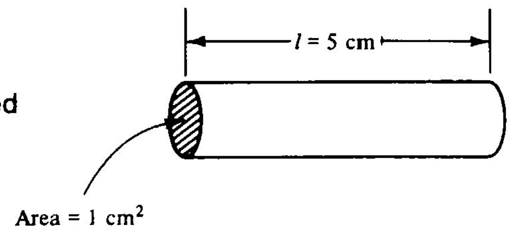

Fig. 1-2. Rod dimensions used in Example 1.1.

EXAMPLE 1.1 Calculate the resistance between the ends of a rod (Fig. 1-2) 5 cm long, and of cross-sectional area 1.0 cm², for each of the materials listed above.

Solution

$$R = \rho \frac{l}{A}$$

For copper:

$$R = 10^{-4} \times \frac{5 \times 10^{-2}}{1 \times 10^{-4}}$$

$$= \mathbf{0.01\ ohm.}$$

For intrinsic silicon:

$$R = 0.01 \times \frac{10^{3}}{10^{-4}}$$

$$= \mathbf{100\ k\Omega.}$$

For ceramic:

$$R = 0.01 \times \frac{10^{10}}{10^{-4}}$$

$$= \mathbf{10^{12}\ ohms\ (or\ 1.0\ T\Omega).}$$

In the three cases just considered, conduction, to the extent that it does occur, is a result of the movement of electrons under the influence of an applied electric field. In copper, there is an abundance of what are termed *conduction-band* electrons, which are only very loosely bound to parent atoms. These move relatively freely under the influence of any externally applied electric field, and account for the high conductivity of copper. In ceramic, almost all electrons are very tightly bound to parent atoms. The density of conduction-band electrons is negligible, with the result that conductivity is also negligible. Of course, the function of an insulator is to prevent conduction, and most practical problems with insulators result from unwanted conduction through surface contaminants.

With intrinsic silicon, two distinct conduction mechanisms must be taken into account. Conduction-band electrons are present which contribute to conduction, although the density is many orders of magnitude less than that in copper. These conduction-band electrons originate by being shaken loose, so to speak, from parent atoms, by the thermal energy which is present naturally because the semiconductor is at a finite (e.g., room) temperature. The electron energy band from which they are shaken loose is termed the *valence band.* Vacancies, or holes, will be left in the valence band by those electrons which leave, and these holes allow the valence-band electrons to contribute to conduction also, by a "hopping" process under the influence of an applied electric field. Rather than describe the process as one of electrons hopping from atom to atom wherever holes permit this, it is vastly more convenient to describe it in terms of the movement of holes. In this way, the concept of *hole conduction* arises.

The two distinct conduction mechanisms in intrinsic silicon are known, therefore, as electron conduction, and hole conduction.

For intrinsic silicon, the volume density n_i of conduction-band electrons at room temperature is known to be approximately:

$$n_i = 1.4 \times 10^{16} \text{ m}^{-3} \quad (1.1)$$

The units for n_i are simply stated as m^{-3}, meaning "electrons per cubic meter." The hole density, p_i, in the valence band must be the same as the conduction-band electron density, since in intrinsic material the conduction-band electrons originate from the valence band:

$$p_i = n_i = 1.4 \times 10^{16} \text{ m}^{-3} \quad (1.2)$$

The conduction-band electrons move more freely than the valence-band holes when an electric field is applied. (This might have been expected from the nature of the two processes.) The average velocity in either case is proportional to the applied electric field, the constant of proportionality being termed the drift mobility. Let μ_e represent the electron drift mobility, and μ_h the hole drift mobility; then the average drift velocity in either case is related to the applied electric field E by:

$$\text{Electron velocity:} \quad v_e = -\mu_e E \quad (1.3)$$

$$\text{Hole velocity:} \quad v_h = \mu_h E \quad (1.4)$$

The minus sign in Eq. (1.3) is to show that electrons, being negatively charged, move in a direction opposite to the electric field direction.

The units for velocity are meters per second, and for electric field, Volts per meter, so that mobility has the same units as (velocity)/(electric field) or $(\text{meters})^2$ per Volt-second. This is abbreviated $\text{m}^2/\text{V-s}$, and frequently the submultiple $\text{cm}^2/\text{V-s}$ is used. For example, for silicon:

$$\mu_e = 0.145 \text{ m}^2/\text{V-s or } 1450 \text{ cm}^2/\text{V-s}$$

$$\mu_h = 0.05 \text{ m}^2/\text{V-s or } 500 \text{ cm}^2/\text{V-s}$$

The mobility may be considered constant for low to moderate electric fields, and generally speaking, the higher the mobility number the more attractive a semiconductor material is for device applications.

The electric charge carried by an electron is known to have the value

$$q_e = -1.6 \times 10^{-19} \text{ coulombs} \quad (1.5)$$

Since the hole is the absence of an electron, it has an equivalent charge of

$$q_h = +1.6 \times 10^{-19} \text{ coulombs} \quad (1.6)$$

The conductivity of intrinsic silicon, denoted by σ_i, is, in terms of these quantities,

$$\sigma_i = n_i \mu_e q_3 + p_i \mu_h q_h \quad (1.7)$$

Note that both contributions are positive. The conduction-band electrons carry negative charge but move in the opposite direction to the applied field direction, and therefore the product $\mu_e q_e$ is positive in Eq. (1.7).

EXAMPLE 1.2 Calculate the intrinsic conductivity for silicon, at room temperature, showing clearly the individual contributions from electrons and holes. The physical parameters are $n_i = 1.4 \times 10^{16}$ m^{-3}; $\mu_e = 0.145$ m^2/V-s; $\mu_h = 0.05$ m^2/V-s; and magnitude of electron charge = 1.6×10^{-19} C.

Solution

$$\sigma_i = 1.4 \times 10^{16} \times 0.145 \times 1.6 \times 10^{-19} + 1.4 \times 10^{16} \times 0.05 \times 1.6 \times 10^{-19}$$
$$= 0.325 \times 10^{-3} + 0.112 \times 10^{-3} \text{ S/m}$$

Thus the various contributions are

Electrons:	0.325×10^{-3} S/m
Holes:	0.112×10^{-3} S/m
Total:	0.437×10^{-3} S/m

Resistivity is the reciprocal of conductivity:

$$\rho = \frac{1}{\sigma} \tag{1.8}$$

Using the value of conductivity for intrinsic silicon calculated in the previous example, we find that the resistivity for intrinsic silicon is

$$\rho_i = \frac{1}{0.437 \times 10^{-3}}$$
$$= \mathbf{2.29 \times 10^3\ \Omega\text{-m}} \tag{1.9}$$

1.3 EXTRINSIC SILICON

Chemical elements may be added to intrinsic silicon to alter its conductivity. The conductivity is then determined by the volume density of the added element, and is referred to as *extrinsic conductivity*. The added elements are referred to as *impurities*, or *dopants*, and the process of adding them into the silicon is known as *doping*. It may seem strange that the silicon should first be purified at great expense, and then impurities added; however, it is only in this way that a high degree of control can be exercised over the electrical conductivity. The type of conductivity, as well as its magnitude, can be controlled by the type of impurity added.

The orders of magnitude of the quantities involved are quite interesting. Statistical calculations have been made which show that silicon has roughly 5×10^{28} atoms per cubic meter. For semiconductor grade silicon, the impurity concentration must be not more than 1 part in 10^9, that is, one impurity atom for every billion silicon atoms on average. (The population of the earth is about 4×10^9. If the population were required to be healthy to this degree, only four persons at most could be sick.) A typical doping density is 10^{21} dopant atoms per cubic meter, which for silicon means about one impurity atom every fifty million silicon atoms per cubic meter on average. An impurity atom *substitutes* for a silicon atom at this ratic, and the nature of the impurity atom determines the conductivity of the silicon.

1.3.1 *n*-type silicon

Silicon has four valence electrons for every atom. When the substitutional impurity has five valence electrons per atom, one electron becomes free, since only four are required to complete the covalent bond. The electron becomes free in fact by receiving sufficient thermal energy from the silicon to excite it into the conduction energy band. Recall that there may be of the order of 10^{21} impurity atoms per cubic meter. The density of conduction-band electrons will increase by this amount, so if it was originally 1.4×10^{16} m^{-3}, the value for intrinsic silicon, the impurity contribution to conduction will be of the order of 10^5 times greater than the intrinsic electron conduction. The impurity atom in this situation is termed a *donor* impurity, because it donates an electron to the conduction process. Typical donor impurities for silicon are arsenic, phosphorous, and antimony.

Equally important is the fact that the impurity atom, or *donor center*, is firmly locked into the silicon crystal structure, and therefore it is not free to move. The donor center will be positively charged, since it gave up an electron (and was originally electrically neutral). Thus, *n*-type material may be represented symbolically as shown in Fig. 1-3(a), and the properties which will be used here summarized as:

Mobile negative charge carriers, or electrons

Fixed positive charges, or donor centers

1.3.2 *p*-type silicon

When the substitutional impurity has only three valence-band electrons per atom, the covalent bonds are completed by the impurity atoms "capturing" valence-band electrons from neighboring silicon atoms. In this way the hole density is increased. Again, for a typical doping density of 10^{21} m^{-3}, the impurity contribution to hole conduction will be of the order of 10^5 times greater than the intrinsic hole conduction. The impurity atom in this situation is termed an *acceptor* impurity, since it accepts an elec-

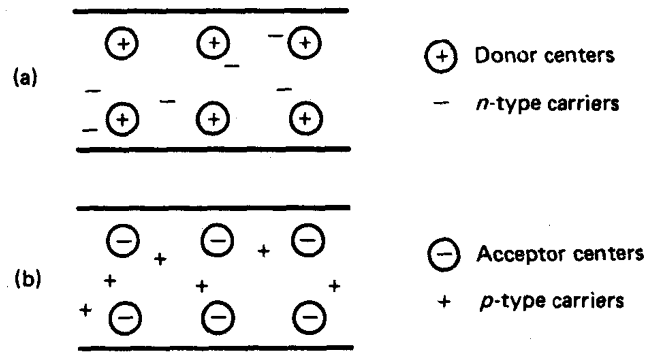

Fig. 1-3. (a) *n*-type material. (b) *p*-type material.

tron from the valence band. Typical acceptor impurities for silicon are gallium, indium, boron, and aluminum. Acceptor centers are negatively charged, since they have, on the average, one extra electron over their natural number. Also, they are firmly locked into the silicon crystal structure. The *p*-type material is represented symbolically as shown in Fig. 1-3(b), and the properties of interest here are

Mobile positive charge carriers, or holes.

Fixed negative charges, or acceptor centers.

1.4 MAJORITY AND MINORITY CARRIERS

The *majority* carriers in *n*-type silicon are electrons. Holes are also present in *n*-type material, and are termed *minority* carriers. In *p*-type material just the opposite occurs. Holes are majority carriers, and electrons the minority carriers. A phenomenon known as *minority carrier suppression* occurs in doped material. It can be shown that, for a wide range of doping densities, a relationship exists between majority and minority carrier densities and the intrinsic carrier density, given by:

$$np = n_i^2 \tag{1.10}$$

where n is the electron density, p the hole density, and n_i the intrinsic carrier density. For example, if silicon, with an intrinsic density of 1.4×10^{16} m^{-3}, is doped *n*-type, the doping density being 10^{21} m^{-3}, then if it is assumed that all the donor atoms are ionized (i.e., each gives up an electron to the conduction band), the electron density will be

$$n = 10^{21} \text{ m}^{-3} \tag{1.11}$$

The hole density in the same material will be