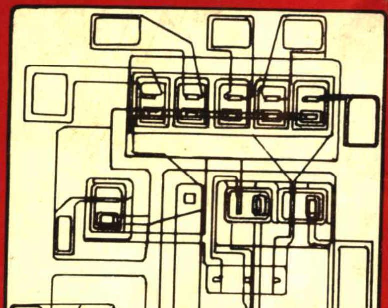
Semiconductor & Integrated Circuit Fabrication Techniques



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Preface

The purposes of this text are to provide a single source of reference to those individuals involved in the processing of semiconductors, and to introduce students of other technologies to the technology of semiconductor processing. The text arose from a sequence of college courses for the semiconductor technician, and was expanded to include many aspects of process design of interest to the processing engineer.

The more complex lessons in the text are approached at two levels of detail. The first level covers the basics of the particular topic and terminates at the technician level. The second level covers more advanced material and should be used at the engineering level.

Each lesson should take an average of two hours to complete. For such self-paced study audio cassettes are available. The set may be purchased from Fairchild Camera & Instrument Corporation, Corporate Training, Mountain View, California.

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1

Semiconductor Physics I

1-1 ATOMIC STRUCTURE

Early structural models of the atom pictured it as having a nucleus composed of positively charged protons and electrically neutral neutrons, surrounded by orbitals or shells containing negatively charged electrons. (Figure 1-1). This model of the atom is being continuously refined by atomic physicists, but the features of the model are sufficient to explain many of the physical phenomena observed in many materials, including most semiconductors.

An atom that has the same number of electrons and protons is electrically neutral. However, the gain or loss of electrons from the orbitals surrounding the nucleus produces an atom that is charged either positively or negatively. An atom charged in such a fashion is called an ionized atom or an ion. The majority of the physical and chemical properties of an atom are determined by the number of electrons in the outermost orbital, since these electrons are the means by which the atom interacts with the outside world.

All atoms with the same number of protons (regardless of the number of neutrons or electrons) are the same element. Unionized atoms with the same number of protons must also have the same number of electrons. Hence, only the number of neutrons contained in the nucleus can differ. Atoms with the same number of protons but a different number of neutrons are isotopes of the element.

Studies by several nineteenth century chemists detected similarities in the physical and chemical properties of elements having

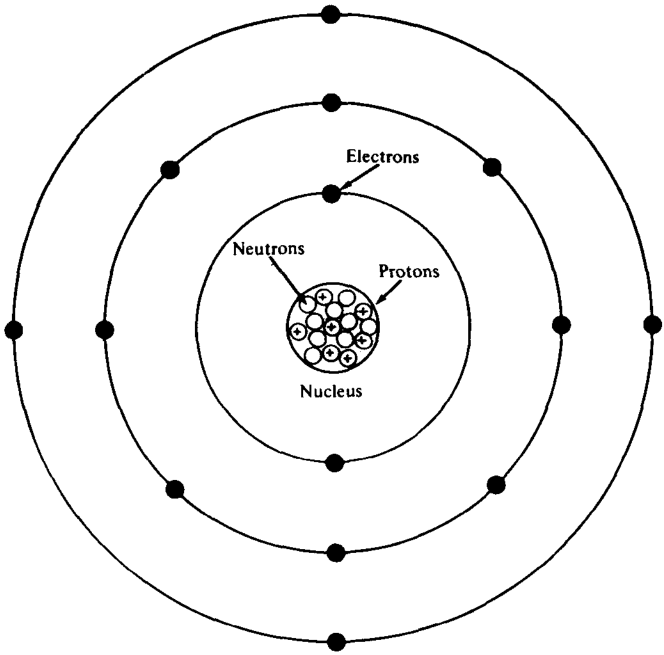

Figure 1-1 A silicon atom.

different densities. Grouping of elements with similar properties based on their densities led to the Periodic Table (Figure 1-2). This table was arrived at largely by experimental means, but it offers large insights into the behavior of materials. The uncomplicated but accurate picture of semiconductors obtained through use of the Periodic Table is sufficient for all but advanced work in semiconductors.

The Periodic Table (modified from Mendeleev's) is based upon the arrangement of electrons around the nucleus of an atom. Every atom has orbitals or shells that can be occupied by electrons. The orbitals closer to the nucleus can hold fewer electrons than the orbitals farther away. Electrons fill orbitals starting from the innermost. The rows of elements in the Periodic Table correspond to the filling of an orbital with electrons. When an orbital is filled, a new row in the Periodic Table is begun. Elements that are in the same column in the Periodic Table have the same number of electrons in the outermost orbital. The columns are given "group numbers" which tell the number of electrons in the outer orbital. (We will now concentrate on the Group I elements.)

Atomic weighs are the most recent adopted by the International Union of Chemistry; none are given for artificially produced elements.

GROUP		I	II	III	IV	V	VI	VII	VIII			O
Period	Series											
1	1	1H 1.0080										2He 4.003
2	2	3Li 6.940	4Be 9.013	5B 10.82	6C 12.010	7N 14.008	8O 16.000	9F 19.00				10Ne 20.183
3	3	11Na 22.997	12Mg 24.32	13Al 26.97	14Si 28.06	15P 30.98	16S 32.066	17Cl 35.457				18A 39.944
4	4	19K 39.096	20Ca 40.08	21Sc 45.10	22Ti 47.90	23V 50.95	24Cr 52.01	25Mn 54.93	26Fe 55.85	27Co 58.94	28Ni 58.69	
	5	29Cu 63.54	30Zn 65.38	31Ga 69.72	32Ge 72.60	33As 74.91	34Se 78.96	35Br 79.916				36Kr 83.7
5	6	37Rb 85.48	38Sr 87.63	39Y 88.92	40Zr 91.22	41Nb 92.91	42Mo 95.95	43Tc	44Ru 101.7	45Rh 102.91	46Pd 106.7	
	7	47Ag 107.880	48Cd 112.41	49In 114.76	50Sn 118.70	51Sb 121.76	52Te 127.61	53I 126.92				54Xe 131.3
6	8	55Cs 132.91	56Ba 137.36	6 57-71 Rare earths*	72Hf 178.6	73Ta 180.88	74W 183.92	75Re 186.31	76Os 190.2	77Ir 193.1	78Pt 195.23	
	9	79Au 197.2	80Hg 200.61	81Ti 204.39	82Pb 207.21	83Bi 209.00	84Po 210	85At				86Rn 222
7	10	87Fr	88Ra 226.05	89 Actinide series**								

*Rare earths:	57La 132.92	58Ce 140.13	59Pr 140.92	60Nd 144.27	61Pm	62Sm 150.43	63Eu 152.0	64Gd 156.9	65Tb 159.2	66Dy 162.46	67Ho 164.94	68Er 167.2	69Tm 169.4	70Yb 173.04	71Lu 174.99
**Actinide series:	89Ac 227	90Th 232.12	91Pa 231	92U 238.07	93Np	94Pu	95Am	96Cm	97Bk	98Cf					

Figure 1-2 Periodic table of the elements.

Dimitri Ivanovich Mendeleev, the Russian chemist who devised the Periodic Table, noted that atoms with eight electrons in their outer orbitals are chemically inert. The observation that atoms have a complete set of electrons when they have eight electrons in the outer shell, explains the way elements reacted to form compounds. Group I elements (with one electron in their outer shell) react with Group VII elements (with seven electrons in their outer shell). The Group VII atom "borrows" the electron to complete its outer shell, leaving the Group I atom with zero electrons in its outer shell, but with completed shells beneath. Each element then has a full complement of electrons in its outer shell. The atoms are held together by the electric force between the atoms with one extra electron and the atom with one less electron. This type of bonding is known as ionic bonding.

If a Group II and a Group VI element combine, each atom satisfies its need for electrons. However, the Group VI atom has difficulty capturing the extra electrons, so it shares them instead. The bond formed is less ionic (electron-taking) and more covalent (electron-sharing). In a similar fashion, Group III atoms combine with Group V atoms, and group IV atoms combine with Group IV atoms. A Group IV atom will share one of its four electrons with each of its four nearest neighbors part of the time, and borrow one electron from its neighbors part of the time.

1-2 CLASSIFICATION OF MATERIALS

One method used by scientists to classify materials is to group them by their ability to conduct electricity. Three broad classifications of materials are:

1. Insulator—does not conduct electricity to an appreciable degree.
2. Metal—conducts electricity easily.
3. Semiconductor—conducts electricity poorly when pure.

If we look at the electron structure of these three classifications of materials (Figure 1-3), we see that:

1. Insulators have all electrons tightly bound, so none are free to carry current.
2. Metals have many electrons readily available to carry current.
3. Semiconductors have some electrons free to carry current.

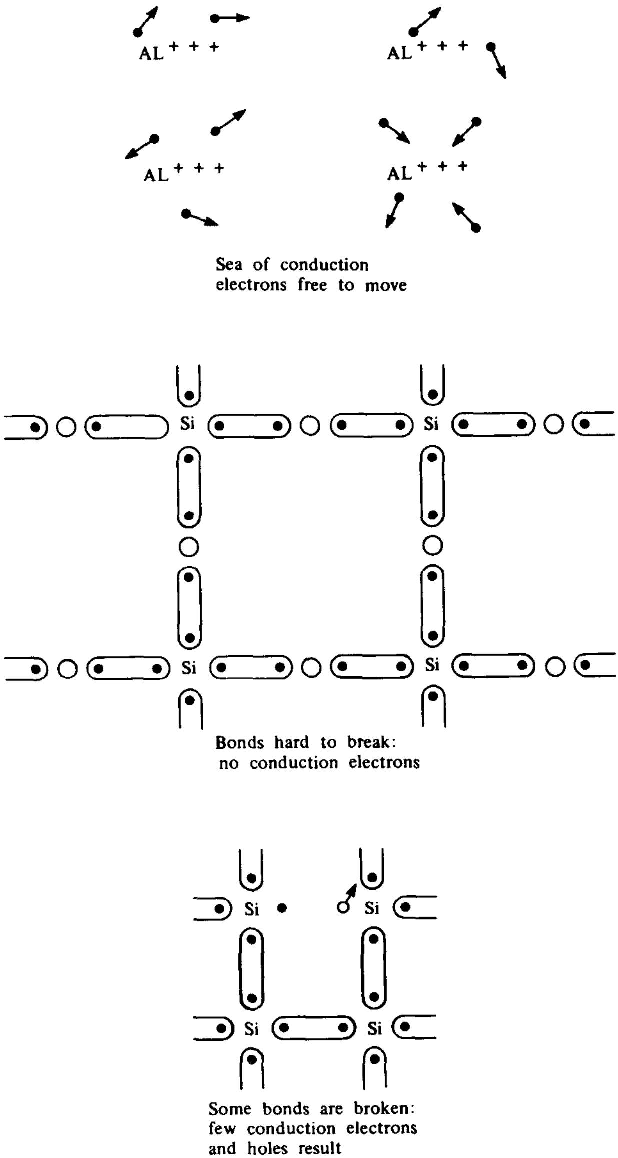

Figure 1-3 Bonding diagrams of a metal, an insulator, and a semiconductor.

Taking a closer look at semiconductors, of which silicon and germanium are the most widely used, we see that they both belong to Group IV in the Periodic Table. When these elements are crystalline, an atom shares one of its four electrons with each of its nearest neighbors (Figure 1-4a). However, at any temperature greater than absolute zero (0°K), some of the bonds linking the atoms are broken (Figure 1-4b). The broken bonds produce electrons free to conduct electricity. In addition, the broken bond corresponding to the absence of an electron is also free to move in the lattice (Figure 1-4c). (The absence of an electron is called a hole; this concept is similar to that calling the absence of water a bubble.) In a pure semiconductor crystal, the number of broken bonds depends only on the temperature. Since every broken bond produces both a hole and an electron, they are present in

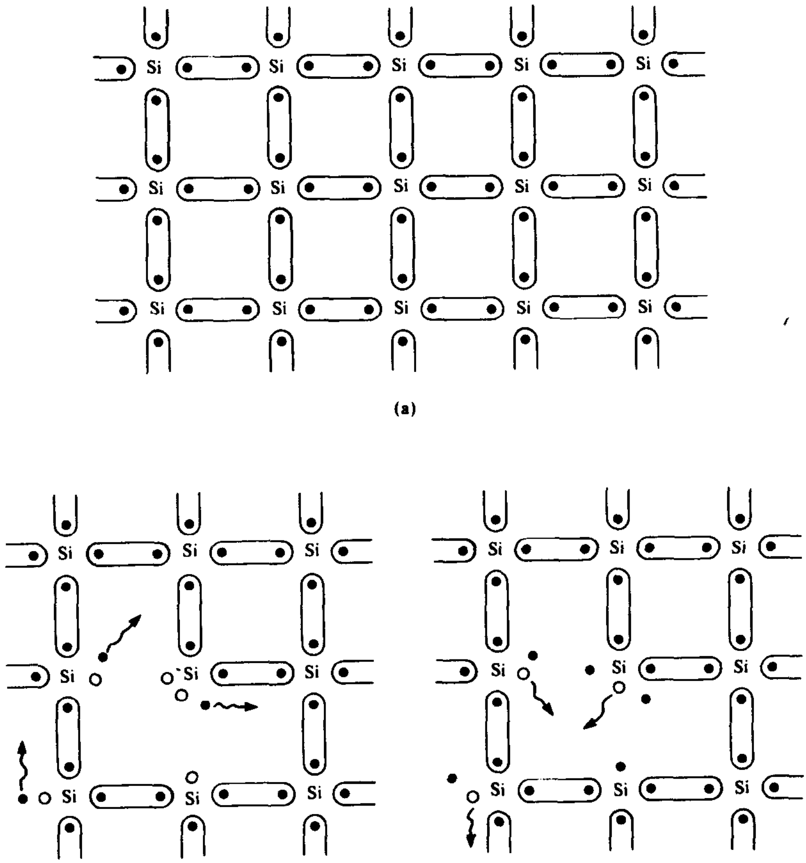

Figure 1-4 *(a)* **Silicon at absolute zero; (b) electron conduction in silicon; (c) hole conduction in silicon.**

equal numbers. The symbol n is used to signify the number of electrons/cm^3 in a semiconductor, while the symbol p signifies the number of holes/cm^3 in a semiconductor. Since they are equal in pure or "intrinsic" silicon, we can say that n equals p. The number of broken bonds in an intrinsic sample is called n_i, and it follows that

$$n = p = n_i, \quad \text{and} \tag{1-1}$$

$$n \cdot p = n_i^2 \tag{1-2}$$

where n_i^2 depends only on temperature. In silicon at room temperature (27° C) $n_i = 1.4 \times 10^{10}/\text{cm}^3$, and $n_i^2 \approx 2 \times 10^{20}/\text{cm}^6$.

The presence of equal numbers of holes and electrons leads to no interesting phenomena, but the ability to increase the number of holes or electrons by adding trace amounts of impurities called dopants, means that regions of semiconductor materials can be altered to perform useful functions. Silicon has four electrons in the outer shell which it shares with its four nearest neighbors. The substitution for silicon of an atom from Group V, for example phosphorus, results in the phosphorus sharing one of its five electrons with each of its four nearest neighbors (Figure 1-5a). The extra electron is not needed for bonding purposes, and is free to conduct electrical current. Semiconductors containing an excess of conduction electrons are called n-type. In an analogous manner, additional holes can be provided by substituting an atom like boron for a silicon atom (Figure 1-5b). Semiconductors containing an excess of holes are called p-type. Atoms supplying additional electrons for the conduction process are called donors; the number of donors/cm^3 in a semiconductor is N_D. Atoms that supply additional holes for the coduction process are called acceptors; the number of acceptors/cm^3 in a semiconductor is N_A. For silicon, potential donor atoms are the atoms of Group V with five electrons in their outer shell.

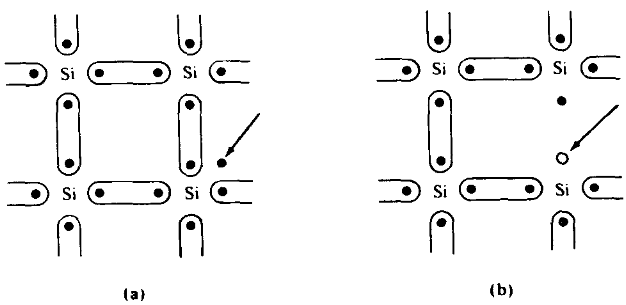

Figure 1-5 **(a) Extra electron easy to remove; (b) extra hole easy to remove.**

The atoms frequently used to dope silicon n-type are phosphorus, arsenic, and antimony. Potential acceptors for silicon are the Group III atoms with three electrons in their outer shell. The atoms used to dope silicon p-type are boron, aluminum, and gallium (boron is used most frequently).

An increase in the number of conduction electrons present in a semiconductor causes a corresponding decrease in the number of holes, and vice versa. The equation $n \cdot p = n_i^2$ is valid even when n does not equal p $(n \neq p)$. If only donor atoms have been added to silicon and the number of donors is less than $10^{19}/\text{cm}^3$, $(N_D < 10^{19}/\text{cm}^3)$, all of the donors produce conduction electrons. It follows that, in this case, $n = N_D$, and $p = \frac{n_i^2}{N_D}$. In a similar fashion, if only acceptors are added to a bar of silicon, and their number is less than $10^{19}/\text{cm}^3$, $(N_A < 10^{19}/\text{cm}^3)$, each acceptor atom produces one hole. In this case, $p = N_A$, and $n = \frac{n_i^2}{N_A}$.

When both donors and acceptors are added to a semiconductor, they tend to cancel each other out. When more donor than acceptor atoms are added, $(N_A < N_D)$, the donor atoms cancel out the effect of all of the acceptor atoms, and the number of electrons is the difference between the number of donors and the number of acceptors $(n = N_D - N_A)$. In an analogous manner, if more acceptor atoms are added than donor atoms, the acceptor atoms cancel out the effect of all of the donor atoms, and the number of holes is the difference between the number of acceptors and the number of donors $(p = N_A - N_D)$. In both cases, the product of $n \cdot p$ remains constant, so the carrier type in the minority can be determined using the formula $n \cdot p = n_i^2$.

The amount of dopant present in a semiconductor is determined by measuring its conductivity or resistivity. The resistivity of a material is the opposing force a material has to a voltage placed across it. The symbol for resistivity is the Greek letter ρ. The units of resistivity are ohm-centimeters (Ω-cm). The conductivity is related to the resistivity by the equation

$$\sigma = \frac{1}{\rho} \tag{1-3}$$

The conductivity of a sample depends upon the number of free carriers (holes and/or electrons) and their mobility or the ease with which they move through the sample. If the resistivity (or the conductivity) of a material is known, the resistance of a box-shaped piece of material is determined by the formula:

$$R = \frac{\rho L}{A} \qquad (1\text{-}4)$$

where R = the resistance of the material (units of ohms)
L = the length of the material from contact to contact
A = the cross-sectional area of the material (area = height × width)

The resistance of a piece of material is related to the applied voltage (V) and the current that flows (I) by the equation:

$$V = RI \text{ or } R = \frac{V}{I} \qquad (1\text{-}5)$$

In a semiconductor (and in other industrial materials as well) the "sheet resistance" of a material is an often-measured parameter. The symbol for sheet resistance is R_s. Sheet resistance is measured in ohms per square ($\Omega/\square$). The resistance of a resistor made up of n squares laid in a row is nR_s. (For instance, if 10 squares of material are laid in a row with $R_s = 100\ \Omega/\square$, $nR_s = 10R_s = 1000\ \Omega$.) Sheet resistance is measured using a four-point probe. (Figure 1-6.). The formula relating sheet resistance to current and voltage is:

$$R_s = 4.53\frac{V}{I} \qquad (1\text{-}6)$$

This equation is valid when:

1. The thickness of the layer being measured is much less than the spacing between the probes, and
2. The size of the piece of material being measured is much greater in length and width than the probe spacing.

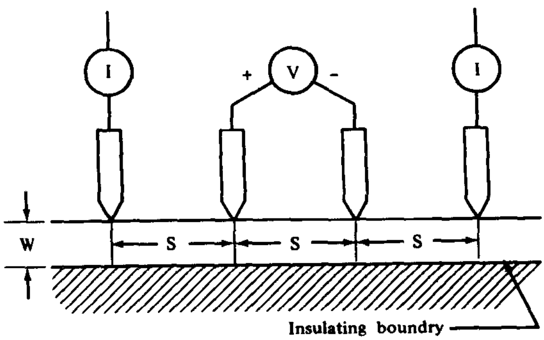

Figure 1-6 Four-point probe.