# of Transistors, Semiconductors, Instruments, and Microelectronics

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HANDBOOK of Transistors, Semiconductors, Instruments, and Microelectronics

HANDBOOK

Preface

This book provides factual and procedural tools for the working engineer, the circuit designer, and the laboratory technician. It does this for each semiconductor device by a similar technical approach:

1. Physics of operation (plus some background)
2. Formation and fabrication
3. Ratings, characteristics, and parameters
4. Circuitry and applications

Although the first three chapters do not directly concern practical, usable engineering material, they document a generous amount of fundamental electronic background, and much of the technical nomenclature is drawn from the very processes and construction of the various types of diodes and transistors.

Component and device ratings and characteristics are heavily emphasized, for these are the tools that the circuit designer or operating-technician support personnel must use for reference and in testing.

Beyond conventional diodes and transistors, the material gives special attention to:

1. SCR's and FET's—two major and widely used components.
2. Special diodes—particularly those used in switching and in microwaves. About a dozen of these are covered according to the basic approach outlined above.

Under applications and usage, Chapters 10, 11, 12, and 14, we have:

1. Test and measurement of diodes and transistors
2. Solid-state equipment and instruments
3. Digital switching and pulse circuits

These cover modern hardware, particularly, with concentration on digital voltmeters, counters, and oscilloscopes.

Chapter 13 covers less-coventional opto-electronic, thermal, and microwave devices.

Chapter 14 describes the field of microelectronics and integrated circuits. This chapter crystallizes the technology covered in earlier chapters since microminiature fabrication, characteristics, and operation closely resemble those in full-size semiconductors.

Specialized appendices include parametric amplification, laser types, unijunction transistors, FET's, and wide-band amplifiers.

Harry E. Thomas

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HANDBOOK of Transistors, Semiconductors, Instruments, and Microelectronics

SOLID-STATE TRANSISTOR-DIODE TECHNOLOGY

stems from
SURFACE PHYSICS

It basically concerns
SEMICONDUCTOR CRYSTALS
of

Germanium (Ge)
Silicon (Si)
Indium (In)
Gallium (Ga)
Aluminum (Al)
Selenium (Se)

which have been specially
REDUCED AND REFINED,
TREATED WITH IMPURITIES (DOPED),
GROWN (by epitaxy and molten-state crystal pulling)
in order to form

JUNCTION TYPES OR ASSEMBLED "SANDWICHES":

Grown (during crystal pulling)
Surface-fused (or alloying of pellets)
Diffused (impurity injection while heating)
Epitaxial (or crystal surface grown)
Electrochemical (by plating and etching with streams of electrolyte)

TRANSISTOR CONSTRUCTION GEOMETRY

Mesa
Coaxial
Planar
Homotaxial
Annular
Interdigitated

Semiconductor Physics 1

1-1 INTRODUCTION

A major breakthrough occurred in the world's electronic development with the entry of applied science into solid-state technology. The electronic innovations created by the invention of the transistor have made a major technical and economic impact upon an entire industry.

It all started with a theoretical and experimental examination of electronic conduction in semiconductors and, most particularly, in germanium and silicon. Specifically, when the lattice-like atomic-electron orbital shell structure of semiconductors was examined, it was found that atoms and their electrons, particularly those having covalent shells, could be displaced by impurity atom-electron combinations whose covalent shells contained one more or one less electron than in the base semiconductor atoms.

Thus, if we introduce minute quantities of indium (trivalent, acceptor electron shells) or of arsenic (pentavalent, donor electron shells) into silicon or germanium crystals, both of which have four electrons in each electron shell, we will upset the regularity of the atomic structure, and only partial recombination of the lattice structure will result. We would, therefore, structurally warp the atomic buildup and cause loose or free electrons (or loose or free vacancies or holes) in the main crystal, giving rise to a whole series of new phenomena.

This loosening of the atomic structure opened up an amazing innovation—that of current flow by means of hole conduction. Electronics was thus offered a whole new technology of crystal surface physics, applying most specifically to semiconductors.

1-2 ELECTRONS IN CONDUCTORS AND SEMICONDUCTORS

Electron conduction in solid material depends upon the composite interaction of all electronic and chemical factors and the physical or electrical forces concerned with interatomic quantities. A summary can best be presented by a discussion of the three major factors pertaining to an atom's basic electronic content and associated forces:

1. Atomic structure
2. Electron mobility and conduction
3. The resulting energy bands and levels

1-2.1 ATOMIC STRUCTURE

All metals and semiconductors exist in crystalline form, a condition which induces them to act like oversized molecules, with each nucleus having a surrounding periodic or planetary array of electrons orbiting by groups in different shells (all electrons within a shell possessing approximately equal energies). Physically, the haze-like fog or solution of moving electrons forms the "glue" which binds the various nuclei-electron combinations together. It is the number of free or excess electrons in the "glue" that determines the material's physical structure and whether it will be a conductor, an insulator, or a semiconductor.

As an aid to understanding the complexities of the atomic structures of all materials, we can list all elements numerically by arranging them in rows and columns according to their atomic numbers (the number of units of free positive electricity in the nucleus). This universal tabulation is the Periodic Table of Elements shown in Fig. 1-1. By inspection of the respective positions of the elements, we can make a number of pertinent chemical, physical, and electronic deductions or predictions.

Figure 1-2(a) illustrates typical atomic construction of the aluminum atom with a pseudo-physical arrangement of electrons and their various shells; Fig. 1-2(b), (c), (d) shows the structure of hydrogen, phosphorous, and germanium atoms. For more specific analysis of atomic relationships, energies, etc., the shells of each element are labeled *L*, *M*, *N*, etc., for successive shell areas progressing outward from the nucleus.

Table 1-1 lists the first 36 elements according to atomic number and the content of electrons within the various shells. Since electrons may have elliptical as well as circular orbits within their shells, they must also be classified according to the state ($n - 1$, $n - 2$, $n - 3$, $n - 4$) in which they exist within a shell structure. This is done to satisfy all of the energy levels which the electrons possess.

Before discussing the energy bands associated with an atom's electrons, we should note a few of the predictive areas afforded by the periodic system of classifying elements:

1. Chemically, it is noted that alkali elements having only one outer electron (Li, Na, K, etc.) all behave the same way. Ionization and valence influences are also noted by a study of the outer shells.

2. Electronically, it was predicted that the stability of the atom and the looseness of the valence or outer shell electrons in germanium and in silicon would make them promising elements for transistor research. In fact, portions of semiconductor elements under groups IIIB, IVB, VB, and VIB all having similar useful properties in electronics fall within a single area on the periodic table (see dotted line enclosure in Fig. 1-1).

3. In metals, the valence electron mobility is high because these electrons readily share themselves with all atoms; hence, their parent metals have high conductivity.

1-2.2 MOBILITY AND CONDUCTION

Electrons within a solid are free to move and, in fact, are continually changing position if only under the influence of ambient temperature. This mobility depends upon the electron mass *m*, its free charge *e*, the free electron population within, and the electric field supplied to, the material in which they exist. Above all, the electron's free movement depends upon the lattice structure of its parent material, that is, on how difficult it becomes for the electron to thread or drift its way through the electronic obstacle course making up the conductor or semiconductor.

Quantitatively, we may express mobility as the magnitude of the average drift velocity per unit field. Expressed this way, the resistivity, ρ, and the conductivity, σ, are:

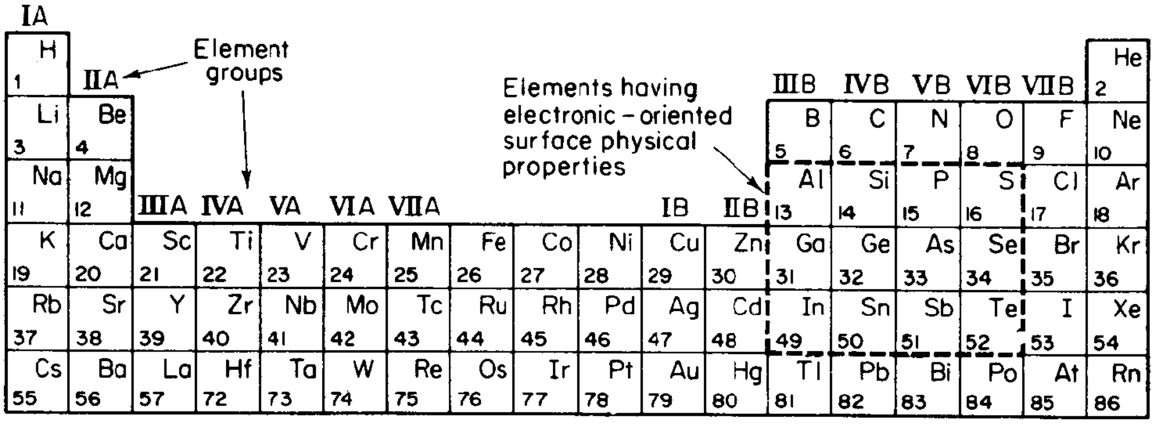
$$\sigma = \frac{1}{\rho} = \frac{n \times e^2 \times r}{m} = -en\mu \qquad (1\text{-}1)$$

where

n = number of free electrons/m^2
e = electron charge
r = relaxation time of electrons
m = electron mass
μ = the electron mobility

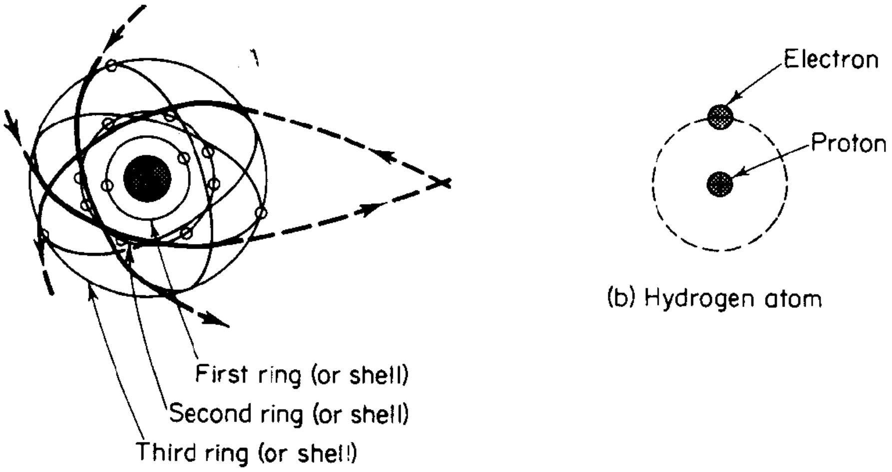
In a conductor the structure is loose and the passage is relatively easy because the population of free or drift electrons in a typical metal is relatively high, of the order of 10^{23} per cubic centimeter. In an insulator it may be one hundred millionth (10^8) of this number. For instance, silver has an *R*/ohm^3 of 10^{-6} ohm while pure germanium is 50–60 ohms per cubic centimeter.

These facts of lattice structure and of electron population and mobility reduce the



IA	IIA	IIIA	IVA	VA	VIA	VIIA				IB	IIB	IIIB	IVB	VB	VIB	VIIB	
H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86

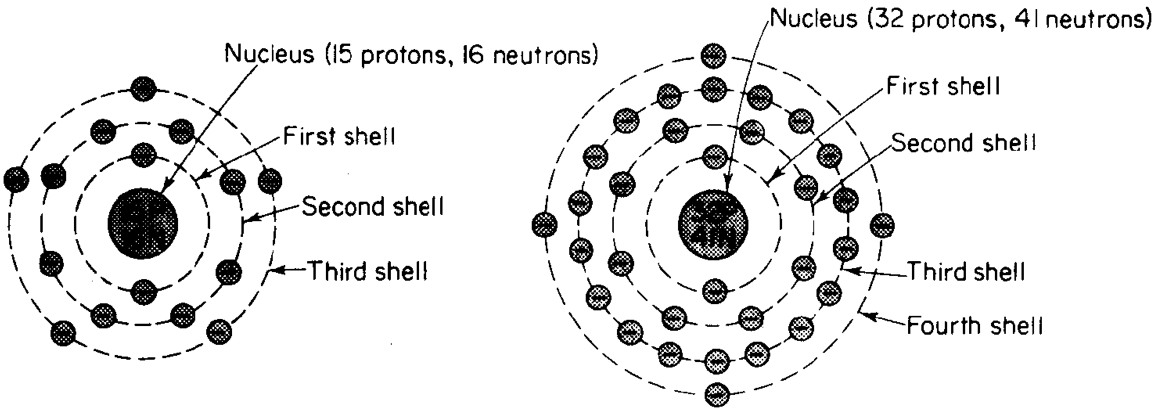
Fig. 1-1 ABBREVIATED PERIODIC TABLE



(b) Hydrogen atom

Nucleus: (13+) positive charges
First shell: (2−) bound electrons
Second shell: (8−) electrons
Third shell: (3−) electrons

(a) Aluminum atom



(c) Phosphorus atom

(d) Germanium atom

Fig. 1-2 TYPICAL ATOMIC STRUCTURE

20-37

TABLE 1-1 THE ELECTRON CONFIGURATION OF THE FIRST 36 ELEMENTS

		K $n = 1$	*L* $n = 2$		*M* $n = 3$			*N* $n = 4$			
Atomic number Z	*Element*	$l = 0$ *s*	$l = 0$ *s*	$l = 1$ *p*	$l = 0$ *s*	$l = 1$ *p*	$l = 2$ *d*	$l = 0$ *s*	$l = 1$ *p*	$l = 2$ *d*	$l = 3$ *f*
1	H	1									
2	He	2									
3	Li	2	1								
4	Be	2	2								
5	B	2	2	1							
6	C	2	2	2							
7	N	2	2	3							
8	O	2	2	4							
9	F	2	2	5							
10	Ne	2	2	6							
11	Na	2	2	6	1						
12	Mg	2	2	6	2						
13	Al	2	2	6	2	1					
14	Si	2	2	6	2	2					
15	P	2	2	6	2	3					
16	S	2	2	6	2	4					
17	Cl	2	2	6	2	5					
18	A	2	2	6	2	6					
19	K	2	2	6	2	6		1			
20	Ca	2	2	6	2	6		2			
21	Sc	2	2	6	2	6	1	2			
22	Ti	2	2	6	2	6	2	2			
23	V	2	2	6	2	6	3	2			
24	Cr	2	2	6	2	6	5	1			
25	Mn	2	2	6	2	6	5	2			
26	Fe	2	2	6	2	6	6	2			
27	Co	2	2	6	2	6	7	2			
28	Ni	2	2	6	2	6	8	2			
29	Cu	2	2	6	2	6	10	1			
30	Zn	2	2	6	2	6	10	2			
31	Ga	2	2	6	2	6	10	2	1		
32	Ge	2	2	6	2	6	10	2	2		
33	As	2	2	6	2	6	10	2	3		
34	Se	2	2	6	2	6	10	2	4		
35	Br	2	2	6	2	6	10	2	5		
36	Kr	2	2	6	2	6	10	2	6		

resistivities of the various materials as pictured in Fig. 1-3 and have a close relationship to the particular voltage energy levels existing in certain substances.

Mobilities in some semiconductors and their compounds can be increased materially by the addition of impurities. This process, called *doping*, has a profound effect upon the conductivity. In transistors, for instance, by doping with impurities, we can attain resistivities of one or two ohms per ohm-cm, and by substituting the accepted values of 1.7×10^{23} electrons per cubic meter and $e = 1.6 \times 10^{19}$, we obtain an electron mobility of $\mu = 0.36$ m^2/V/s. In the case of pure germanium, the resistivity runs 60 ohms per ohm-cm. Impurities can reduce this resistance to as low as 0.2 to 0.4 ohm per ohm-cm, but design and performance require-

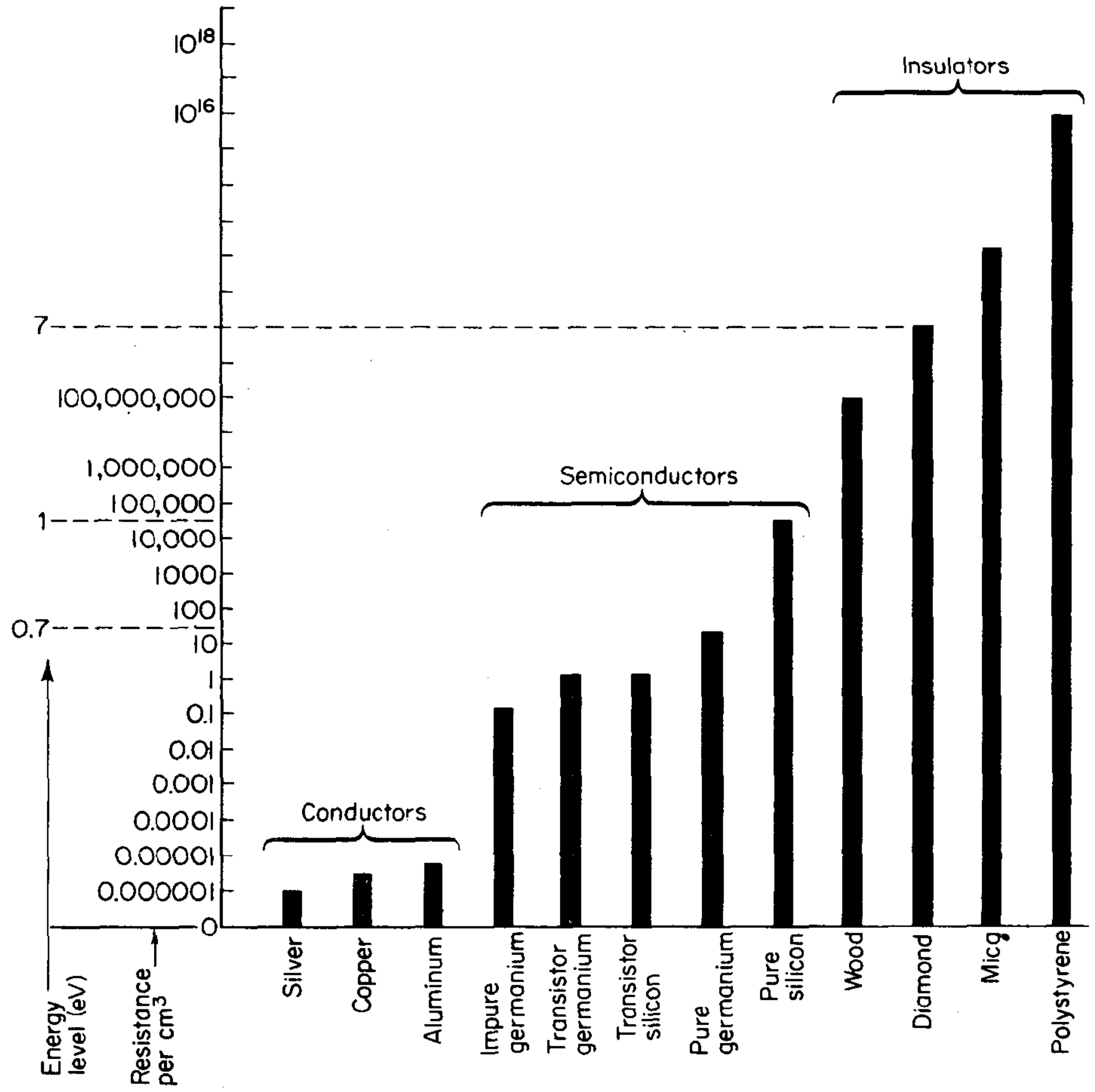


Fig. 1-3 RESISTANCE VARIATION IN MATERIALS

ments call for careful impurity control to attain the values just mentioned

Table 1-2 lists a number of semiconductors and pertinent selected compounds and their energy gaps and mobilities.

1-2.3 ENERGY BANDS AND LEVELS

Internally, most complicated atomic structures possess multiple energy levels due to all nuclei and electron charges, rotations, kinetic forces, orbital speeds, etc. Naturally, energies exist in many different bands or levels for different materials for particular shell position, for temperature, and under other varying conditions. These energies may be determined by quantum mechanics (involving wavelengths, interatomic spacing, etc.); a typical plot of the energy bands for electrons in the near and remote orbits surrounding the silicon nucleus is shown in Fig. 1-4. Note how the energies "smear," forming bands separated by vacant or forbidden energy gaps.

The levels or energy bands (expressed in electron volts) also determine the physical nature of the material. An insulator, for instance, may have a level of several electron volts (ev) while silicon has 1.1 ev and germanium has only 0.7 ev. See Table 1-3. In a metal, the energy bands of conduction and of valence overlap; hence they aid in the passage of current. In a semiconductor, there are several energy bands separated by gaps in which no electron can exist or travel about. These are