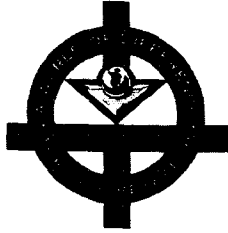# International Rectifier Corporation Engineering Handbook

J. T. CATALDO
and
W. E. WILSON

International Rectifier

Corporation

Engineering Handbook

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A Combination of Theoretical
and Practical Articles on the
Application of Rectifying
Devices to Today's Electronic
and Electrical Equipment.

Acknowledgements

Foreword

Each technical advance in the field of electronics, and particularly semiconductors, brings with it an obvious need for thorough and accurate information on the subject. To be sure, the strides in the semiconductor field in the past few years have been both great and numerous. In the field of rectifiers, significant achievements have been recorded at a startling rate. It is the purpose of this handbook to place in the hands of the design engineer useful, practical information on the application and protection of semiconductor rectifiers.

As each new development appeared, the engineering staff of International Rectifier Corporation has prepared articles of a basic nature to provide a successful foundation for the use of the device. Many of the articles were written for and appeared in the leading technical journals of the industry. Full credit is given elsewhere in this book to both the authors and the publications.

We hope that by transmitting the information in this compact manner, we will provide the solution to many of your application problems.

J. T. CATALDO
Executive Editor

Contents

INDEX TO INTERNATIONAL RECTIFIER CORPORATION SEMICONDUCTOR TYPES

A portion of the International Rectifier Corporation Periodic Table of the Chemical Elements. Highlighted are three elements used in the production of semiconductor rectifiers and photovoltaic devices.

First Principles of Semiconductors

by Dr. C. A. Escoffery, BCE, PhD
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The reader is introduced to some of the main points of semiconductor phenomena. Concepts of wave properties of electrons, discrete energy levels, free electrons in metals, and band theory of solids, show how semiconductors differ from metals and insulators. This is followed by a discussion of doping to create impurity conduction (n and p type), and of the relationship of conductivity to carrier concentration, lifetime, and mobility.

On the basis of electrical conductivity, solids can be broadly classified into metals, semiconductors, and insulators. Because of the rapidly growing prominence of semiconductors in electronic technology, the average engineer has become interested in acquiring a greater understanding of semiconductors but his efforts are hampered by the esoteric language of the physicist. It is hoped that this article may be of aid by presenting a brief review of some of the main points of semiconductor phenomena.

However, in order to obtain a reasonably clear picture of semiconductors, it is necessary to invade the field of solid-state physics and become partially acquainted with the band theory of solids. To do so, a review of some of the present-day concepts of the behavior of electrons, first in individual atoms, then in metals, and finally in semiconductors, must be undertaken.

Wave Properties of Electrons

In dealing with matter of very small dimensions such as atoms, electrons, and protons, modern physics makes it possible and even desirable to consider them as wave motion rather than as particles. Electrons can, in fact, be diffracted (scattered in definitely determined directions) by passing them through thin crystals.

The "wave length" of a moving electron is related to its mass and velocity by the De Broglie equation

$$\lambda = \frac{h}{m v} \tag{1}$$

where h is a very important constant of proportionality known as Planck's constant. Thus, for instance, the wave length of an electron with one volt of kinetic energy (traveling at a speed of $1\frac{1}{2}$ million miles per hour) would be about 12×10^{-8} cm. This is of the same order of magnitude as the spacing between atoms in a crystal, and explains why electrons can be diffracted.

Since electrons can be considered as (mathematical) waves, many of the equations involved in their treatment resemble those used in describing familiar examples of wave motion such as vibrating strings and oscillating electrical circuits.

Now, it is necessary to define discrete energies. A system that can have any frequency of oscillation, such as a spinning wheel, can have any value of energy. But if only certain frequencies are permitted, as in the case of a violin string fastened at both ends, then only certain definite, discrete energies are permitted. In the case of the vibrating string, the permitted frequencies are,

of course, the familiar overtones or harmonics.

The same considerations apply to electrons in an atom. Only certain energy overtones or energy levels are permitted because, like the violin string, the electrons are tied down. The mathematician would say they are subject to boundary conditions.

Electrons in Metals

From chemistry it is learned that only the outermost electrons in an atom determine its chemical valence. In discussing the conductivity of solids, only these electrons are considered "free," the rest being bound rather strongly to the nucleus. Only the "free" valence electrons are capable of conducting an electric current and, therefore, only valence electrons shall be considered from now on.

In order to study the behavior of these electrons in a metal, matters must first be simplified by considering these electrons as being confined to a potential field like that in Fig. 1. Here O, the potential energy of the electrons outside of the metal, is arbitrarily chosen as zero for convenience; inside of the metal, the potential energy A is constant. Because electrons do not ordinarily escape from a metal, they must have a lower (more negative) energy inside than outside. In this simplified
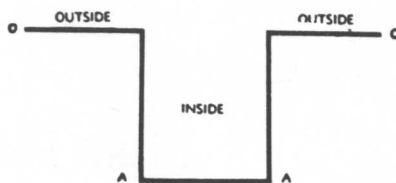
Fig. 1. Potential box of a metal.

model, the electrons move in the field, which is regarded as constant and equal to zero outside of the metal, and constant and equal to A within.

As in the violin string and in the individual atom, so too in Fig. 1 the "boundary restrictions" give rise to a discrete energy spectrum. But now there is a difference: due to the very large number of atoms, we find a very large number of energy levels, all very close together, giving rise to what is known as a quasicontinuous spectrum, as indicated schematically in Fig. 2(A).

In Fig. 2, the occupied levels are indicated by heavy horizontal lines, whereas the empty levels are indicated by light lines.

An examination of Fig. 2(A) reveals that there is a sharp transition between the filled and the vacant levels and, furthermore, that even at the absolute zero of temperature the electrons are distributed over a very wide range of energy. The reason for the latter follows
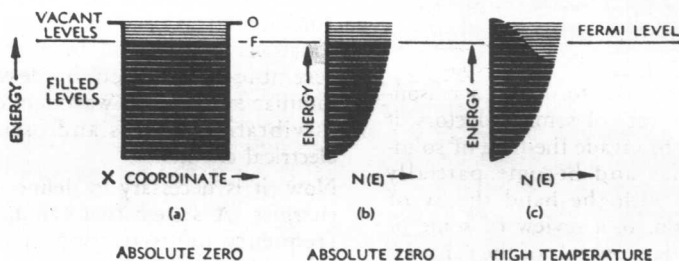
Fig. 2. (A) Schematic of electron energy levels in a metal with the potential field of Fig. 1. In (B) and (C), the number of electronic states for each energy interval shown for two different temperatures.
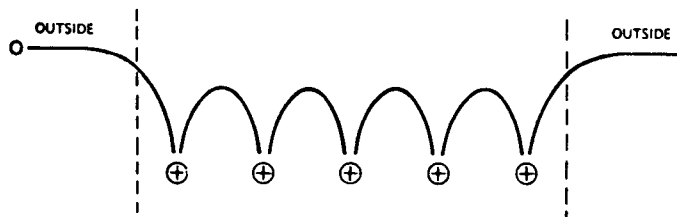
Fig. 3. Periodic potential field in a crystalline solid. The circled crosses represent atoms.

from what is known as the Pauli exclusion principle, which states that only one electron can be in a given energy state at one time. Two electrons can occupy a given energy level but they must have opposite spins.

Once an energy level is filled by a pair of electrons (with opposite spins), additional electrons must go to higher levels. The value of energy OF is called the work function of the metal, and it expresses the energy needed to liberate an electron from the metal.

If the number of allowed energy levels in each energy interval in Fig. 2(A) is plotted, the type of energy distribution shown in Figs. 2(B) and 2(C) is obtained. At absolute zero, the maximum electronic energy level is called the Fermi level; at higher temperatures, some electrons can have higher energies than the Fermi level, as shown in Fig. 2(C).

In order for an electron to conduct a current, it must be accelerated; that is, its energy must be increased. In the absence of an applied field, there is no net drift of electrons and, hence, no observable current even though some electrons are moving about with velocities as high as 250,000 miles per hour. By means of considerations such as outlined in this section, the conductivity of a metal can be expressed by an equation relating it directly to its electronic mean free path. Since the mean free path decreases as the temperature is raised (due to scattering of the electron waves by increasing lattice imperfections), the conductivity of a metal decreases with increase in temperature, as is actually observed in practice.

Band Theory of Solids

Thus far, in considering the movement of the valence electrons in a metal it was assumed that they move in a uniform electrostatic field within the crystal (Fig. 1). In effect, this is only an approximation. It is known that the atoms in a crystal are arranged in a regular array, and because of the concentration of a positive charge in the nucleus, the electric field would be expected to vary and to be strongest in the immediate vicinity of the atoms, as indicated schematically in Fig. 3.

Furthermore, inasmuch as the electrons have wave properties, the electron waves would be expected to interact with the crystal's varying electric field and to be diffracted by the lattice atoms just like X rays are diffracted. Therefore, electrons with certain critical velocities and directions would be reflected, with the result that the corresponding energy states would not exist. It will be seen shortly that these nonexistent energy states give rise to what is known as forbidden energy regions as shown in Fig. 5(B).

In the case of a free electron moving in a uniform field, the energy is given by the familiar relationship

$$E = \frac{mv^2}{2} \tag{2}$$

whence, by substitution of the value of v from equation 1

$$E = \frac{h^2}{2m\lambda^2} \tag{3}$$

If λ is replaced by a reciprocal quantity k, called the wave number, and then the relationship between E and k is plotted, the energy values fall on

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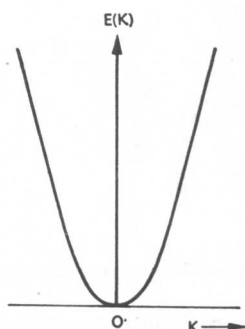
Fig. 4. *(Left)* Energy of a perfectly free electron moving in a uniformly constant force field as a function of wave number k.

a parabola, as shown in Fig. 4. This corresponds to the case of a perfectly free electron.

However, when the field in which the electrons move varies from one point to another (Fig. 3), the results correspond somewhat to those shown in Fig. 5(A), which is drawn for the one-dimensional case of electrons traveling in the same crystallographic direction. Wave numbers can be assigned for different crystallographic directions. Because the crystal periodicity may be

different in different directions, the forbidden gaps in Fig. 5(A) may occur at different values of k. This may lead to overlapping bands as indicated in Fig. 6(B).

The significant aspect of Fig. 5(A) is that the allowed electronic energy levels lie on a parabolic curve except for certain regions (forbidden regions) where, because of diffraction effects, these energy values do not exist. Fig. 5 (B) schematically indicates how the allowed energy values of Fig. 5(A) fall into "bands" with energy gaps between them, whereas Fig. 5(C) illustrates the distribution of the energy bands within the so-called reduced zone. The quantity a is one of the dimensions of the unit cell crystal.

It must be emphasized that within the allowed bands the energy levels are so close together as to be almost continuous. Nevertheless, they are still separate (discrete) and must conform to the Pauli exclusion principle which determines how many electrons can occupy each energy state.

Band energy diagrams are very useful for they allow explanation of the
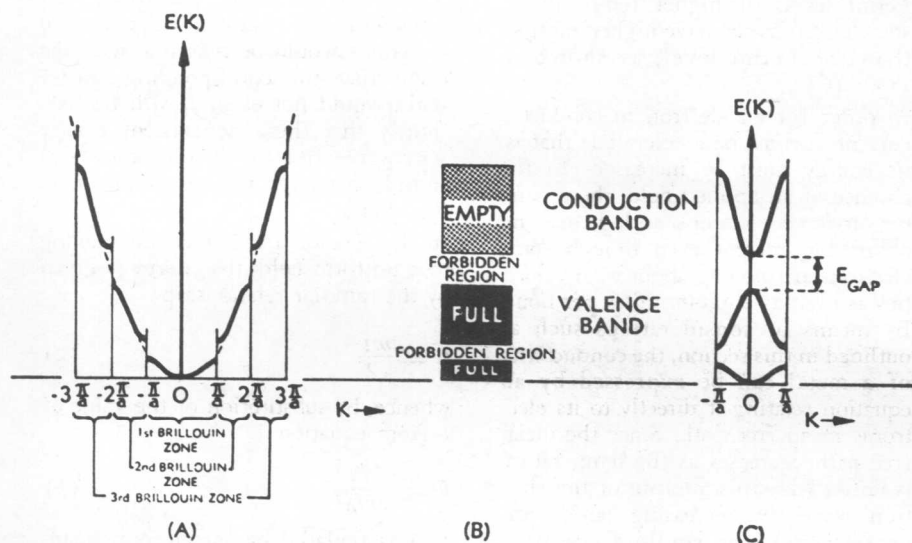
Fig. 5. *(Right)* (A) Energy of an electron as a function of wave number for the periodically varying field of Fig. 3. The gaps in the energy curve give rise to forbidden energy regions which are indicated schematically in (B). By translation of the energy curves into the first zone (C) is obtained from (A).

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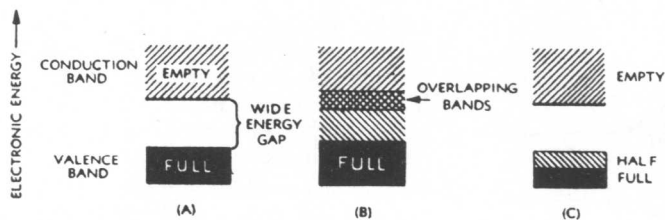
Fig. 6. Energy level diagrams for (A), an insulator; (B) and (C), metals.

difference between metals and insulators. Thus, as shown in Fig. 6(A), the energy gap between the highest (full) band and the next higher (empty) band in insulators is so large that the electrons cannot be accelerated across the forbidden region. In the case of metals, the bands either overlap as in Fig. 6(B) with essentially no forbidden regions, or else the valence band is only half filled as shown in Fig. 6(C).[1]

It should be noted that the energy contours near the center of Fig. 5(C) are circular. In a three-dimensional plot they would be spherical. In practice, however, it is found that the minimum energy states are not always spherical and do not always occur at the center of the reduced zone. Recent experimental and theoretical studies[2] for instance, indicate that the energy bands for germanium and for silicon are somewhat like that shown in Fig. 7, and it is probable that the energy band structure of many other semiconductors also is quite complicated.[4,5] The conduction bands in Fig. 7 exhibit several

minima (which are ellipsoidal rather than spherical), depending on the direction of the wave number k. The arrows VT and NVT indicate a vertical and a nonvertical transition. In the former, the wave number (momentum) remains constant; the energy gap, however, is the smallest energy distance between bands, as indicated by the nonvertical transition.

There is another way of viewing the energy band picture—when the individual atoms (with their permissible discrete energy levels) are brought together to form a solid, each allowed energy level broadens out in a series of levels, so numerous and close together that they are practically continuous within each band. This broadening is due to interaction of the atoms with each other as they come closer together. A similar situation occurs in other mechanical systems (e.g., in coupled oscillators), where the amount of interaction is related to the amount of coupling. Thus, the resonant peaks of inductively coupled tuned circuits are found to

Fig. 7. Schematic diagrams of the energy band structures at room temperature for germanium and for silicon along the 111 and 100 axes.
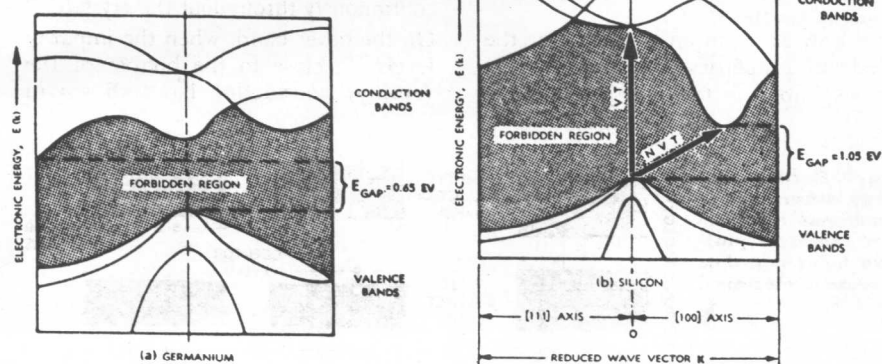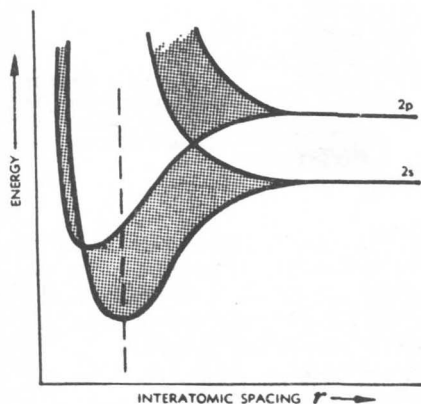
Fig. 8. Broadening of electron energy levels into bands as the atoms of carbon are brought closer together to form the crystal lattice of diamond.[7]

broaden with increased coupling, giving rise to the well-known double hump above a certain value of the coupling coefficient.[6] Fig. 8 shows how the discrete electronic energy levels (far right-hand side) broaden, overlap, and then split apart to form a low-lying band separated from higher bands by a large energy gap. Dashed line shows separation at the actual atomic spacing.[7]

For this discussion, the most important factor is the existence and magnitude of the energy gap between the valence and conduction bands. If the gap is large and the valence band is filled, conduction will not be observed. In metals, the bands usually overlap and the electrons in the valence band can easily be raised to higher, empty levels by the application of an electric field.

Impurity Levels

It is now easier to understand how the electrical properties of semiconductors are explained in terms of their energy bands. If the energy gap is small enough, as seen in Fig. 6(A), so that electrons can be excited thermally from the lower filled valence band to the upper empty conduction band, an intrinsic semiconductor exists.

Now, when an electron moves into the higher band (energetically speaking), not only can this electron carry a current, but so can the vacancy left behind in the valence band as shown in Fig. 9(A). This vacancy, which acts like a positive electronic charge, is called a defect electron, a positive hole or, more simply, a hole. The concept of conduction by holes is basic to the modern theories of semiconductors.

In most semiconductors, however, the value of the energy gap is too large for intrinsic conduction to take place at room temperature, and the observed conductivities are explained on the basis of what is known as impurity conduction. According to this view, impure (or extrinsic) semiconductors owe their conductivity to the presence of additional discrete energy levels located within the forbidden energy region. When the impurity levels lie close to the top of the (full) valence band as shown in Fig. 9(B), they are able to accept electrons from the valence band and, therefore, are called acceptor levels. In this case, the semiconductor is said to be p-type, because most of the current is carried by positive holes. The holes left behind in the valence band are free to move. The electrons that moved up into the acceptor levels do not, as a rule, conduct because these levels are localized and not distributed continuously throughout the crystal.

On the other hand, when the impurity levels lie close to the bottom of the (empty) conduction band shown in

Fig. 9. Electronic energy diagrams for semiconductors. Circles represent positive holes and dots represent electrons.
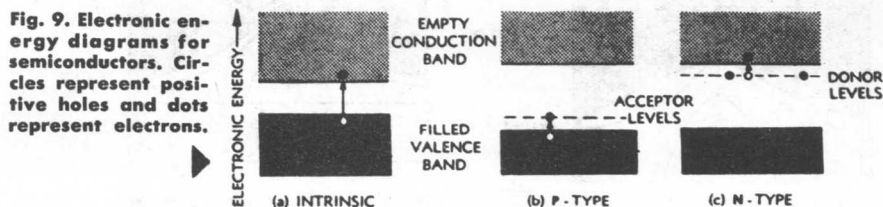
Fig. 9(C), they will donate electrons to the conduction band wherein they will be free to move. The impurity levels are here called donor levels and the semiconductor is termed n-type because most of the current is carried by negative charges.

We thus distinguish two types of semiconductors, p and n type, respectively. To illustrate how n and p type semiconductors can be prepared by suitable doping, consider germanium and silicon, two widely used elements from the fourth group of the periodic table of the elements.

These elements have a chemical valency of four due to their four valence electrons, and their atoms tend to join together by means of "covalent" bonds. In every covalent bönd, two electrons are found equally shared by the two atoms. Inasmuch as the covalent bond is very stable, the electrons are not free to conduct and, therefore, under normal conditions the electrical conductivity will be low. (As the temperature is increased, however, the conductivity increases because electrons and holes are produced in equal numbers whenever a bond breaks.)

If additional electrons are now introduced into the crystal lattice by adding elements from Group V (such as arsenic or phosphorus), the additional energy levels will be located somewhat like those shown in Fig. 9(C)

Fig. 11. Density of charge carriers versus temperatures for the same germanium samples of Fig. 10. The dashed line indicates the density of intrinsic carriers.

Greatly enhanced conductivity will be observed because the energy difference between the donor levels and the conduction band is relatively small, of the order. of 0.01 electron-volts for germanium and of 0.05 for silicon.[8] These values are small when compared with the room temperature energy gap values of approximately 0.065 for germanium and 1.08 for silicon given in Table I.

The additional electrons come from the donor atoms. Thus, when an arsenic atom is substituted for one of germanium, there is an electron left over which can contribute to the conductivity to an extent dependent on how firmly attached it is to the arsenic atom.

Similar consideration applies to the preparation of p-type germanium or silicon by doping with Group III elements, such as boron or aluminum. These atoms, which have only three valence electrons, will create holes (lack of electrons) in the valence band, introduc-

Fig. 10. Variation of mobility with temperature for two samples of germanium.

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ing acceptor levels within the forbidden region, as indicated in Fig. 9(B).

When the concentration of impurities in the semiconductor becomes very large, we find the semiconductor becoming metallic in character. It is then said to be degenerate. Under such conditions, the number of charge carriers is practically independent of temperature as indicated in Fig. 11.

Recombination, Lifetime and Minority Carriers

As discussed in connection with Fig. 9, carriers are created by either intrinsic or extrinsic excitation. But at the same time that carriers are being generated (through absorption of radiation or by injection through a suitable contact, as in a transistor), they also are being destroyed through recombination. Under conditions of equilibrium, the rates of generation and of recombination are equal, and the number of charge carriers will be given in equation 5.

TEMPERATURE IN DEGREES K
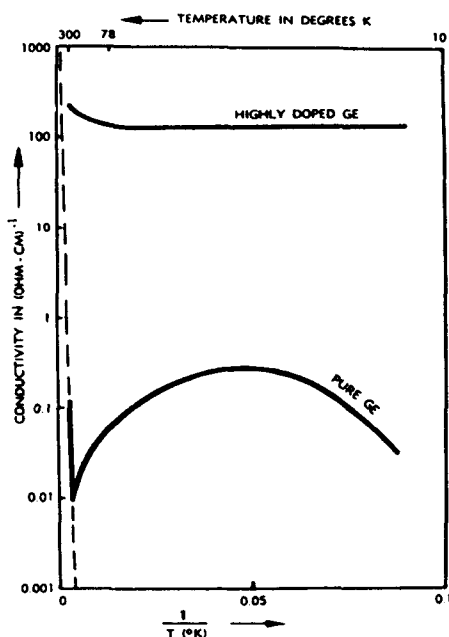
Fig. 12. Conductivity versus temperature for the same two germanium samples of Figs. 10 and 11.

It has been found that these generation and recombination rates are related to the so-called mean lifetime of the minority carriers. For our purpose, the latter can be considered as the average length of time that the minority carrier exists between generation and recombination. Lifetimes in semiconductors depend on the state of perfection and of the purity of the crystal. Values as high as 0.001 to 0.01 seconds have been obtained in high purity germanium; the values in silicon and in other semiconductors are lower.

Although direct recombination of holes and electrons has been observed in germanium and in silicon, the most important recombinations processes in most semiconductors appear to be those occurring at the surface and in the bulk by means of recombination centers, or energy levels within the forbidden region. These centers may consist of lattice imperfections, vacant lattice sites, interstitial atoms, and impurities. In many cases, a carrier that has dropped into such an intermediate energy level will be thermally re-excited and released before it recombines with a carrier of opposite sign. In such cases, the recombination center is often called a trap.

Conductivity, Mobility, and Concentration

The electrical conductivity of a semiconductor is determined both by the number of mobile charge carriers and the facility with which these carriers move under an applied field. The latter property is called the mobility and is defined as the drift velocity per unit field.

The actual expression for conductivity, σ, is given by

$$\sigma = \sigma_n + \sigma_p = ne\mu_n + pe\mu_p \qquad (4)$$

where n and p are the electron and hole concentrations, e is the electronic charge, and μ_n and μ_p are the electron and hole mobilities, respectively.

From equation 4 one can see that in order for the conductivity to increase with temperature, the product of concentration and mobility must increase.

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In practice, it is found that the conductivity at first tends to increase with rise in temperature, and then at higher temperatures it tends to decrease (illustrated by the sample labelled "pure" in Fig. 12).

The variation in mobility with temperature for two samples of n-type germanium is shown in Fig. 10, while the temperature variation of the carrier concentration for the same two samples is shown in Fig. 11. The sample marked "pure" contained less than 10^{13} charge carriers per cm³ at room temperature, or about one conduction electron for every 5½ billion germanium atoms! The other sample was highly doped with arsenic[9,10] to about 8 x 10^{18} carriers per cm.³

Fig. 12 illustrates how the conductivity varies with temperature, for the same two samples of Figs. 10 and 11. Because the number of carriers and the mobility are relatively constant for the impure sample, the conductivity is also a constant as a function of temperature.

With respect to the concentration of electrons and holes at any given temperature, equation 5 states that the product of these two quantities is a constant, regardless of the purity of the semiconductor:

$$pn = n_i^2 = \text{constant } T^3 \left[\exp \left(\frac{-E_g}{kT} \right) \right]$$

(5)

TABLE I. ENERGY GAPS AND MOBILITIES IN SEMICONDUCTORS AT ROOM TEMPERATURE

	E electron volts	μ_n, cm² per volt-second	μ_p, cm² per volt-second
Si	1.08	1200	500
Ge	0.65	3900	1900
Grey Sn	0.09	~ 2000•	~1000•
Boron	~1.1	—	—
Hexagonal Se	~1.7	—	< 10
Te	0.32	830	540
Black P	0.33	220	350
Grey As	1.20	—	—
Iodine	~1.3	—	—
CdS	2.4	210	—
CdSe	1.7	~ 100	—
CdTe	1.5	600	50
Cd₃As₂	0.6	—	—
PbS	0.30	600	~ 250
PbSe	0.22	1175	868
PbTe	0.27	1200	475
ZnS	3.60	—	—
ZnSe	2.58	—	—
ZnTe	2.2	—	—
ZnSb	0.55	—	—
Mg₂Si	0.77†	—	—
Mg₂Ge	0.74†	530	106
Mg₂Sn	0.33†	320	260
Mg₃Sb₂	0.8	—	—
InP	1.25	3400	650
InAs	0.35	30000	~ 200
InSb	0.18	77000	~1250
GaP	2.3	—	—
GaAs	1.3	4000	> 250
GaSb	0.7	4000	850
AlSb	1.6	1200	200
CuInS₂	1.2	—	—
AgInSe₂	1.18	—	—
CuInSe₂	0.92	300	26
AgInTe₂	0.96	—	—
CuInTe₂	0.95	—	—
CuFeS₂	0.53	—	—

• At 0 degrees centigrade
† At 0 degrees Kelvin

where p and n are the hole and electron concentrations, n_i the intrinsic concentration, T the absolute temperature, k Boltzmann's constant, and E_g the thermal energy gap of the forbidden region. The cubed term indicates why the number of carriers increases so rapidly with temperature.

The conductivity of a semiconductor is given in equation 4. By means of separate measurements of the conductivity and of the mobilities one obtains values for the concentrations n and p. In most semiconductors, the electron mobility is greater than the hole mobility. Some typical values for a number of semiconductors are given in Table I. The very high electron mobility of indium antimonide, in particular, leads to pronounced magnetic effects and a number of technological applications have already been proposed for this material.[11,12]

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This article originally appeared in ELECTRICAL ENGINEERING

Periodic Table of the Chemical Elements Wall Chart Available

Printed in full-color on durable stock metal edged at top and bottom, this authoritative table measuring 18" x 28" is an arrangement of the chemical elements, in order of increasing atomic number, placed in Horizontal Rows (Periods) and vertical Columns (Periodic Groups or Families). Produced and copyrighted by International Rectifier Corp., this chart gives the name, symbol, atomic number, crystal diagram, valences, and the melting and boiling point of 102 elements. Atomic and Nuclear Structure, Equivalence of Mass and Energy Isotopes, etc. are discussed. Because of the limited number available, a nominal cost of $1.00 each (includes cost of handling and postage) has been set to assure availability to those with a vital interest in this subject. Address your remittance to: "Handbook-Periodic Table", International Rectifier Corp., El Segundo, California.