

INTRODUCTION
TO
SOLID STATE ELECTRONICS

FRANKLIN F. Y. WANG



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1980

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM · NEW YORK · OXFORD

Printed in the U.S.A.

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ISBN 0 444 85237 9

Publishers:

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM · NEW YORK · OXFORD

Sole distributors for the U.S.A. and Canada:

ELSEVIER NORTH-HOLLAND, INC.
52 VANDERBILT AVENUE
NEW YORK, N.Y. 10017

Library of Congress Cataloging in Publication Data

Wang, Franklin F Y 1928-
Introduction to solid state electronics.

Bibliography: p.
Includes index.

1. Solid state electronics. 2. Semiconductors
I. Title.
TK7871.85.W28 G21.3815 79-188
ISBN 0-444-85237-9

PRINTED IN THE U.S.A.

FOREWORD

This book is intended as a textbook for undergraduate engineering students in their junior year. It can also be used as a supplementary text or a self-educational aid for those who use a textbook on solid state electronics. It is meant for those who did not take a course in quantum mechanics or who are studying it concurrently.

There are many textbooks which cover the topics of solid state electronics. This book covers the introductory material which can aid the readers of these textbooks. At the end of each chapter, a list of suggested references is given. Within the text, some sections overlap with these books. By these means, it is the fondest wish of this author that this textbook can live up to its title, *Introduction to Solid State Electronics*, with special emphasis on the word introduction.

This text is designed for a one-semester course. It is organized into 15 chapters of roughly equal length. Each chapter is suitable for one week's course work. This feature can be used as an indicator for self-study persons to pace their studies.

The scope of this book is restricted very narrowly to those topics which have a direct bearing on the functions of transistors and integrated circuits. Important topics, such as optical, magnetic, and dielectric properties, are omitted due to the space limitation.

In essence, this book deals with the conductivity of semiconductors. In chapter 1, a brief review of the electron and its properties according to classical electromagnetic theory, is given. Chapter 2 gives a very sketchy review of the electron and its properties, according to quantum mechanics. Chapter 3 discusses Maxwell-Boltzmann statistics, Bose-Einstein statistics, and Fermi-Dirac statistics. Chapter 4 uses the relaxation time concept to introduce the term mobility. The conductivity is obtained from the electron, its number (statistics), and its mobility. These concepts are useful to understand the measurements of resistivity and mobility.

Chapter 5 introduces wave mechanics. It covers the effect of a potential jump on an electron. It is extended to the case of a harmonic oscillator. A brief

review of the one-electron atom is given with a discussion of the elements in the periodic table to follow.

Chapter 6 deals with the periodic lattice, including the reciprocal lattices. The interrelationships between the direct lattice and its reciprocal lattice are discussed through their Fourier transforms. Bragg's diffraction condition is also introduced. Chapter 7 places the electrons in the periodic lattice. Bloch's theorem is introduced and is, generally, used throughout the text. The existence of a band gap and the concept of effective mass are shown. The counting of the number of electron states in a band is discussed. Finally, the concept of hole is introduced.

Chapter 8 extends to crystals in which the number of electrons is very large. The discussion explained is limited to demonstrations for the energy bands. The density of states is defined and the construction of Brillouin zones is explained. Chapter 9 deals with the carrier concentrations in either the conduction band or the valence band. The mathematics of the Fermi-Dirac integral is specifically shown as it is used throughout and it is also the basis from which other approximations are originated. The intrinsic semiconductor is defined. Chapter 10 introduces the various types of defect which exist in extrinsic semiconductors. Statistics of ionization equilibria and the limitations, as well as the applicabilities, of the law of mass action are discussed.

Chapter 11 introduces the concepts of phonons and lattice waves. Thermal properties, such as heat capacity and thermal conductivity, are discussed only with respect to the lattice. Chapter 12 discusses the scattering of carriers by impurities and phonons. They determine, to a large extent, the temperature dependence of mobility. Chapter 13 deals with ambipolar transport. Diffusion current, recombinations, and traps, are discussed. Measurement of drift mobility by the Haynes-Shockley experiment is shown.

Chapter 14 discusses the p-n junction. It is a topic which can be found in all other textbooks of solid state electronics. The approach here is to follow that of the classical paper by Shockley (1949).

Finally, chapter 15 discusses semiconductor surfaces. In this chapter, the application of some of the contents in this text is demonstrated. At the same time, it introduces the readers to a brief glimpse of this important topic with its tremendous implications in integrated circuits.

The author owes his gratitude to many. First, he owes many constructive criticisms from his colleagues, past and present. He is particularly indebted to Professors Robert J. Maurer, Donald H. Lyons, Robert W. Kedzie, and Herbert R. Carleton, from whom he learned a great deal. Any mistakes which remain in the text are, however, the sole responsibility of this author. Second, he wishes to thank his former students at the State University of New York at

Stony Brook. Their inquisitive questions improved this text greatly. The author claims sole responsibility for any remaining ambiguities. Third, he wishes to thank Connie Hof, Peggy McCarthy, Marie Hughes, and Mary Faith Healey for their assistance in typing the manuscript. Fourth, he thanks Kee-Chang Yoo for his drafting and Chuck Webber for his photographs. Finally, he expresses his love and gratitude to his wife Katharine, his daughter Jennifer, and his son Alexander. Without their understanding and forbearance, this textbook would not have been possible.

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ELECTRONS AS PARTICLES

1.1 Resistivity and conductivity

Solid state electronics is a field which blossomed with the discovery of the transistor by John Bardeen, Walter Brattain, and William Shockley in 1946. Since then, its progress has reached far and wide; it encompasses many devices and employs many different effects. As a first step toward understanding solid state electronics, an understanding of the bulk properties of semiconductor materials is essential. Foremost among their bulk properties, electronic conduction in semiconductors is the source from which all solid state electronic devices derive their unique properties.

When a voltage V (in volts) is placed across a resistance R (in ohms), an electrical current I (in amperes) results; according to Ohm's law

$$V = IR. \quad (1.1.1)$$

The interrelationships between V , I , and R describe the electrical behavior of the material which makes up the resistor in the circuit. The resistance R , which depends on the physical dimensions of the resistor, such as its cross-sectional area A m² and its length l m between the electrodes, is given by the relation

$$R = \rho l/A. \quad (1.1.2)$$

The proportional constant in eq. (1.1.2), called the resistivity ρ (in Ω m), is a property of the material. The inverse of the resistivity ρ is the conductivity σ (Ω m)⁻¹.

$$\sigma = 1/\rho. \quad (1.1.3)$$

Traditionally, different categories of materials are classified according to their resistivities at room temperature. Those with high conductivities are called conductors (usually $\sigma > 10^{-2}$ (Ω m)⁻¹). Those with high resistivities are

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called insulators (usually $\rho > 10^4 \Omega \text{ m}$). Those with ρ or σ between these limits are called semiconductors. The resistivities of materials are strongly dependent on temperature, as shown in figs. 1.2.1 through 1.2.4. In some cases, the resistivity of a material, such as in fig. 1.2.3, can span many orders of magnitude. The classification of materials according to their ρ values at room temperature is an obsolete idea, but the terminology in metal, insulator, and semiconductor classification continues to be generally used. In the following pages, the governing principles of electronic conduction in materials will be introduced and examined. Then, an understanding of solid state electronics can begin with a firm foundation.

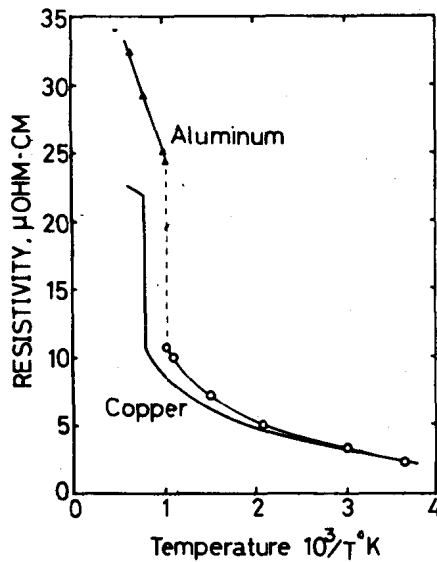


Fig. 1.2.1 Resistivities of pure aluminum and copper as functions of temperature. Data on copper were taken by Dies (1967) and data on aluminum are from Roll and Motz (1957).

1.2 Temperature dependence of resistivity

The resistivities of materials change with temperature in many different ways. Some, such as aluminum (Al) in fig. 1.2.1, have a linear temperature

dependence as a first approximation. It can be expressed as

$$\rho(T) = \rho_0 + A_1 T \quad (1.2.1)$$

where T is the temperature in K , ρ_0 is the intrinsic residue resistivity, and A_1 is the temperature coefficient of resistivity in $\Omega m/K$. Within a sufficiently narrow temperature region, eq. (1.2.1) can be used for all materials. Indeed this is done in industrial practice. Those with $A_1 > 0$ are called materials with positive temperature coefficients of resistivity. Those with $A_1 < 0$ are called materials with negative temperature coefficients of resistivity. Some, such as those in fig. 1.2.2, show both types in different temperature regions. In some cases, such as V_2O_3 in fig. 1.2.3, the temperature coefficients can approach infinity. These abrupt changes represent phase transitions, either crystallographic or electronic.

It is obvious that eq. (1.2.1) is inadequate to represent the temperature dependence of resistivity. The range of temperatures for which eq. (1.2.1) is

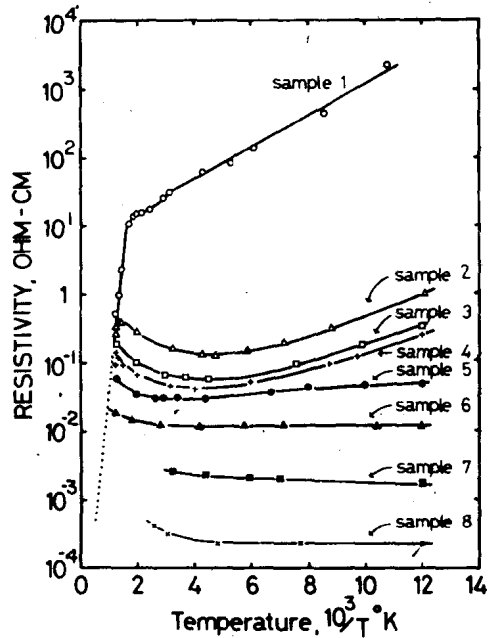


Fig. 1.2.2 Resistivities of silicon samples doped with boron as functions of temperature. Sample 1 was high-purity Si. The B contents in samples 2 through 8 were 6.7×10^{17} , 1.3×10^{18} , 2.7×10^{18} , 6.7×10^{18} , 1.3×10^{19} , 1.3×10^{20} , and $1.3 \times 10^{21} \text{ cm}^{-3}$, respectively. Results are from Pearson and Bardeen (1949).

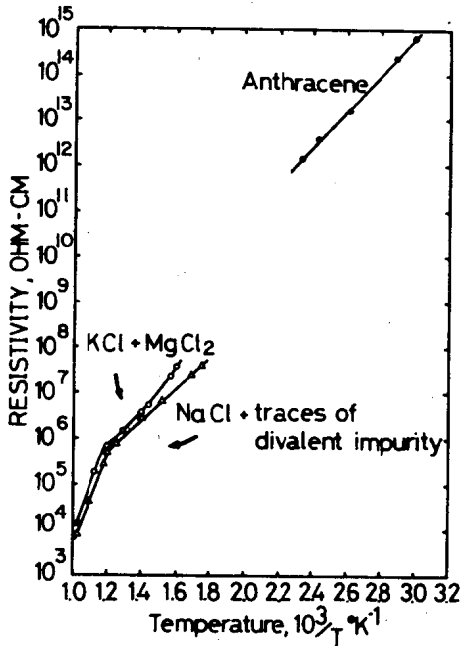


Fig. 1.2.3 Resistivities of Ag_2S crystal (Busch and Junod, (1958), V_2O_3 crystal (McWhan and Remeika, 1970), and Fe_3O_4 (100) crystal (Tannhauser, 1962), as functions of temperature.

applicable is usually too small to be meaningful. Other expressions can better represent the experimental data; however, caution must be exercised. It is insufficient, though necessary, that the experimental results match a specific theoretical expression for the temperature dependence of resistivity. Other conditions must also be confirmed in order to ascertain the correct application of the theoretical expression. When the correct expression is applied to fit the experimental results, the constants can be determined. They are useful in the characterization of the material. Since the resistivity measurement is one of the easier measurements that can be made as a function of temperature, it is often used to characterize the material as to its electron conduction behavior.

Two types of expression are useful in describing the temperature dependence of resistivity over a range of temperatures. One type is the polynomial approximation where

$$\rho(T) = \rho_0 + A_1 T + A_2 T^2 + A_3 T^3 + \dots + A_r T^r + \dots \quad (1.2.2)$$

Eq. (1.2.2) can be reduced to eq. (1.2.1) when $A_r = 0$ for $r \geq 2$. Eq. (1.2.2) can also be reduced to another empirical formula, namely

$$\rho(T) = \rho_0 + A_2 T^2. \quad (1.2.3)$$

Another type of expression is the exponential form, where

$$\rho(T) = \rho_0 \exp(A/T) \quad (1.2.4)$$

and the pre-exponential term ρ_0 is the resistivity at $T = 0$ K and the constant in the exponential term is A with the unit of K. Eq. (1.2.4) can also be expressed in logarithmic form so that

$$\ln \rho = \ln \rho_0 + (A/T). \quad (1.2.5)$$

Eq. (1.2.5) represents a straight line when $\ln \rho$ is plotted versus $(1/T)$, such as fig. 1.2.4. The intercept of the line, extrapolated to $T = 0$, is $\ln \rho_0$ and the slope of the line is A . If expressed in base 10 logarithmic terms, eq. (1.2.5) becomes

$$\log_{10} \rho = \log_{10} \rho_0 + (A/2.303T). \quad (1.2.6)$$

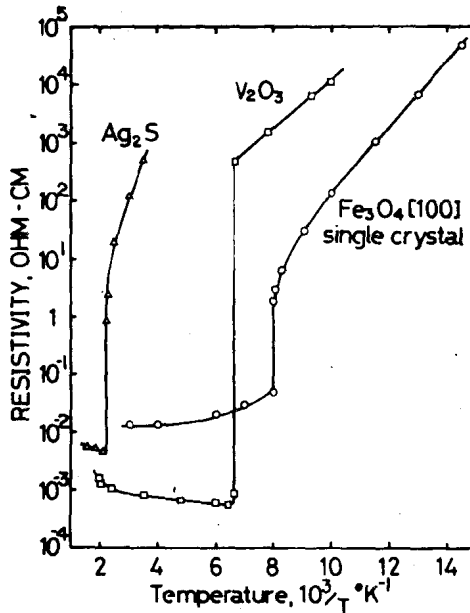


Fig. 1.2.4 Resistivities of anthracene (Okamoto et., 1962), KCl crystal containing $MgCl_2$ (Zückler, 1949), and NaCl crystal with divalent impurity (Etzel and Maurer, 1950), as functions of temperature.

The product of kT , where k is Boltzmann's constant, represents thermal energy. At a room temperature of 27°C , or 300 K , the thermal energy kT term is $4.14078 \times 10^{-21}\text{ J}$, or $2.58498 \times 10^{-2}\text{ eV}$. The slope of the line, as expressed by eq. (1.2.6), is

$$\text{slope} = \frac{A}{2.303} = \frac{Ak}{2.303k} = \frac{E}{2.303k} \quad (1.2.7)$$

Eq. (1.2.7) shows that the constant A is related to an energy term E , the physical meaning of which will be discussed in later chapters.

It is important to bear in mind that these expressions, such as eqs. (1.2.2), (1.2.4) and others, are used to represent experimental results. Confirmation of other conditions should also be satisfied before the theoretical expression can be considered applicable. In order to understand these concurrent conditions, one must first understand electrostatics.

1.3 Current and current density

A current I A is the result of the flow of electrical charge carriers. The nature of the electrical charge carrier determines many important electrical characteristics of the materials. The simplest form of electrical charge carrier is that of an electron. Each electron carries a charge e of $(1.601852 \pm 0.000024) \times 10^{-19}\text{ C}$.

The basic postulates, which are in agreement with experiments on electric charges, are as follows:

(1) There are two kinds of electric charge. One is the positive charge and the other is the negative charge.

(2) Electric charge is conserved, which means that the algebraic sum of all charges is constant in any isolated system. Whenever any positive charge appears an equal negative charge also appears, and vice versa.

(3) All charges are integral multiples of the electronic charge $|e|$. (Evidence of the existence of quarks, which have fractional electronic charges, has been reported but requires further experimental confirmation.)

The current I A is the number of charges crossing a specified surface per unit time

$$I = dq/dt \quad (1.3.1)$$

where the charge q is expressed in coulombs (C) and the time t in seconds (s). The direction of the current is defined as the direction of flow of a positive charge. Although we assign a direction to the current I , it is a regional scalar quantity. This is because I represents the total current with respect to a specific

surface. A vector quantity \mathbf{J} , which is called current density, describes the current at any location in more detail. \mathbf{J} is defined as

$$\mathbf{J} = n \frac{dI}{dS_n} \quad (1.3.2)$$

where dS_n is an infinitesimal element of area perpendicular to the direction of its surface normal \mathbf{n} . It can also be defined by its relation to I using the surface integral

$$I = \int_S \mathbf{J} \cdot d\mathbf{S} = \int_S \mathbf{J} \cdot \mathbf{n} dS_n \quad (1.3.3)$$

where the symbol S under the integral sign represents integration over the whole surface. The angle between \mathbf{J} and \mathbf{n} is θ ; eq. (1.3.3) becomes

$$I = \int_S |\mathbf{J}| \cos\theta dS_n \quad (1.3.4)$$

The unit for current density $|\mathbf{J}|$ is A/m. The direction of \mathbf{J} is, by convention, the direction in which positive charges move and thus opposite to the direction in which negative charges move.

1.4 Equation of continuity

One of the most fundamental laws of physics is the law of conservation of electrical charge. It states that no net electric charge can ever be created or destroyed. In a steady state, the current density \mathbf{J} may vary in both magnitude and direction from point to point in a medium, but it does not vary with time. This produces a static field even though there is a movement of electrical charge.

The law of conservation of electric charge leads to a very important relationship, i.e. the equation of continuity. This can be expressed in the case of direct current (dc) as

$$\oint_{\text{closed surface}} \mathbf{J} \cdot d\mathbf{S} = \oint_{\text{closed surface}} \mathbf{J} \cdot \mathbf{n} dS_n = 0. \quad (1.4.1)$$