Eastern
Economy
Edition

Electrical Engineering Materials

A.J. Dekker

PHI

Electrical Engineering Materials

PRENTICE-HALL ELECTRICAL ENGINEERING SERIES

W. L. EVERITT, Ph.D., *Editor*

ANNER *Elements of Television Systems*
BALABANIAN *Network Synthesis*
BENEDICT *Introduction to Industrial Electronics*
DAVIS AND WEED *Industrial Electronic Engineering*
DEKKER *Electrical Engineering Materials*
EVANS *Experiments in Electronics*
FETT *Feedback Control Systems*
FICH *Transient Analysis in Electrical Engineering*
FICH AND POTTER *Theory of A-C Circuits*
GOLDMAN *Information Theory*
GOLDMAN *Transformation Calculus and Electrical Transients*
HERSHBERGER *Principles of Communication Systems*
JORDAN *Electromagnetic Waves and Radiating Systems*
LO, ENDERS, ZAWELS, WALDHAUER, AND CHENG *Transistor Electronics*
MARTIN *Electronic Circuits*
MARTIN *Physical Basis for Electrical Engineering*
MARTIN *Ultrahigh Frequency Engineering*
MOSKOWITZ AND RACKER *Pulse Techniques*
NIXON *Handbook of Laplace Transformation: Tables and Examples*
NIXON *Principles of Automatic Controls*
PARTRIDGE *Principles of Electronic Instruments*
PUMPHREY *Electrical Engineering*, 2d ed.
PUMPHREY *Fundamentals of Electrical Engineering*, 2d ed.
REED *Electric Network Synthesis*
RIDEOUT *Active Networks*
RYDER *Electronic Engineering Principles*, 3d ed.
RYDER *Electronic Fundamentals and Applications*, 2d ed.
RYDER *Networks, Lines, and Fields*, 2d ed.
SHEDD *Fundamentals of Electromagnetic Waves*
SKRODER AND HELM *Circuit Analysis by Laboratory Methods*, 2d ed.
SOOHOO *Theory and Application of Ferrites*
STOUT *Basic Electrical Measurements*, 2d ed.
THOMSON *Laplace Transformation*, 2d ed.
VAIL *Circuits in Electrical Engineering*
VAN DER ZIEL *Noise*
VAN DER ZIEL *Solid State Physical Electronics*
VAN VALKENBURG *Network Analysis*
VON TERSCH AND SWAGO *Recurrent Electrical Transients*
WARD *Introduction to Electrical Engineering*, 3d ed.
WARFIELD *Introduction to Electronic Analog Computers*
WEED AND DAVIS *Fundamentals of Electron Devices and Circuits*

ELECTRICAL ENGINEERING MATERIALS

ADRIANUS J. DEKKER

PROFESSOR, DEPARTMENT OF ELECTRICAL ENGINEERING
INSTITUTE OF TECHNOLOGY
UNIVERSITY OF MINNESOTA

Prentice-Hall of India Private Limited
New Delhi - 110 001

This Twentieth Indian Reprint—Rs. 120.00
(Original U.S. Edition—Rs. 655.00)

ELECTRICAL ENGINEERING MATERIALS
by A.J. Dekker

ISBN-81-203-0080-7

Twentieth Printing 2008

Published by Asoke K. Ghosh, Prentice-Hall of India Private Limited, M-97, Connaught Circus, New Delhi-110001 and Printed by Tarun Offset Printers, New Delhi-110064.

Preface

It might be said justifiably that the curriculum offered in most electrical engineering departments has changed a good deal during the last five or ten years. In our own department, for example, there has been an increasing emphasis on the teaching of fundamental concepts rather than more specialized subjects. This is true particularly of the first four years of our five-year undergraduate curriculum, the fifth year being reserved for the discussion of the specialized areas. Running parallel with this tendency there has been an increasing emphasis on a sound background in physics and mathematics.

Another aspect of the changes in the curriculum involves the increasing importance of the science of materials, which has led to a number of new devices used in present-day electrical engineering, and which will probably become even more important in the future. In our own department this has resulted in a gradual filtering-down of subjects such as electron physics and "molecular engineering" from the graduate level to the undergraduate level. Thus, a few years ago an elective course in the fifth year of the undergraduate program was introduced in which the operation of solid state devices is discussed along the lines of A. van der Ziel's book *Solid State Physical Electronics* (Prentice-Hall, Inc., 1957).

More recently, the faculty of our department decided to go one step further in this direction by offering a new course to be taken by all electrical engineering students in their fourth year. The course was to run for only one quarter, at least to begin with, and its purpose was to introduce the students to the physical interpretation of the dielectric, magnetic, and conductive properties of materials without entering into the actual applications. This book is a modest attempt to provide material for a course of this kind. It is limited in scope, but the subjects discussed would seem particularly suitable for a course aimed at giving the students some idea of the methods and models employed in the study of materials of interest to the electrical engineer. Also, I believe that it is more useful for a student to have absorbed a certain amount of knowledge about a limited number of subjects than to have been exposed to a great variety in a hurry.

Since most undergraduate electrical engineers have no working knowledge of wave mechanics, no attempt has been made to introduce quantum mechanical concepts, except in a passing manner. This may disappoint some of my colleagues, who will point out that one can introduce wave mechanics by qualitative arguments. However, I am not convinced that the students will benefit greatly from such arguments at this level unless they have acquired a certain degree of maturity in handling classical problems. Thus, the models used in this book are essentially classical or semiclassical. I feel that the lack of rigor implied by these models is outweighed by their usefulness in providing the student with a reasonable amount of insight into the physical mechanisms which underlie the properties of materials. I have also found that these models provide good exercise for the student, to which he can apply his knowledge of elementary field theory.

Although it is not necessary to adhere to the order in which the subjects are discussed in this book, it would seem desirable to have dielectrics precede magnetics; on the other hand, one may well discuss all or part of the last three chapters on conduction in metals and semiconductors before one deals with dielectric and magnetic properties.

A list of general references is given at the beginning of this book, whereas references to specialized topics can be found at the end of each chapter. In general, I have limited the references to representative books or review articles. A set of problems has been given at the end of each chapter. In a number of cases these problems are intended to supplement the text. I have refrained from giving many problems which merely require application of the slide rule. However, a number of numerical problems have been included to give the student a feeling for the order of magnitude of the quantities which enter into the discussion. Answers to the problems are provided at the end of the book; a table of frequently occurring physical constants may be found at the beginning. Throughout this book, the mks system of units has been used.

I wish to express my appreciation to Dr. W. G. Shepherd for his encouragement before and during the preparation of the manuscript, and to Dr. K. M. van Vliet for valuable discussions and for reading a large part of the manuscript.

A. J. Dekker

Contents

4. Magnetic Properties of Materials 79

Part I. Preparatory Discussion

Part II. Atomic Interpretation of Magnetic Properties of Materials

5. The Conductivity of Metals 124

6. The Mechanism of Conduction in Semiconductors 151

General References

A. J. Dekker, *Solid State Physics*, Prentice-Hall, Englewood Cliffs, N. J., 1957.

C. Kittel, *Introduction to Solid State Physics*, Wiley, New York, 2nd ed., 1956.

T. L. Martin, Jr., *Physical Basis for Electrical Engineering*, Prentice-Hall, Englewood Cliffs, N. J., 1957.

D. C. Peaslee and H. Mueller, *Elements of Atomic Physics*, Prentice-Hall, Englewood Cliffs, N. J., 1955.

M. J. Sinnott, *The Solid State for Engineers*, Wiley, New York, 1958.

A. van der Ziel, *Solid State Physical Electronics*, Prentice-Hall, Englewood Cliffs, New Jersey, 1957.

C. Zwikker, *Physical Properties of Solid Materials*, Interscience, New York, 1954.

J. E. Goldman, ed., *The Science of Engineering Materials*, Wiley, New York, 1957.

Approximate Values of Physical Constants

Avogadro's number	6.0254×10^{23} per gram molecule
Boltzmann's constant, k	1.380×10^{-23} joule degree^{-1}
Electric conversion factor, ϵ_0	8.854×10^{-12} farad meter^{-1}
Electronic charge, e	-1.601×10^{-19} coulomb
Electron rest mass, m	9.107×10^{-31} kilogram
Loschmidt's number	2.687×10^{25} meter^{-3}
Magnetic conversion factor, μ_0	$4\pi \times 10^{-7} = 1.257 \times 10^{-6}$ henry meter^{-1}
Planck's constant, h	6.624×10^{-34} joule second
Proton rest mass	1.672×10^{-27} kilogram
Velocity of light, c	2.998×10^{8} meter second^{-1}
1 Bohr Magneton, $\beta = eh/4\pi m$	9.27×10^{-24} ampere meter^{2}
1 Debye unit	3.33×10^{-30} coulomb meter