Microwave Electronics

Measurement and Materials Characterization

L. F. Chen, C. K. Ong and C. P. Neo
National University of Singapore

V. V. Varadan and V. K. Varadan
Pennsylvania State University, USA

John Wiley & Sons, Ltd

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John Wiley & Sons, Ltd

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John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

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British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-470-84492-2

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

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Preface

Microwave materials have been widely used in a variety of applications ranging from communication devices to military satellite services, and the study of materials properties at microwave frequencies and the development of functional microwave materials have always been among the most active areas in solid-state physics, materials science, and electrical and electronic engineering. In recent years, the increasing requirements for the development of high-speed, high-frequency circuits and systems require complete understanding of the properties of materials functioning at microwave frequencies. All these aspects make the characterization of materials properties an important field in microwave electronics.

Characterization of materials properties at microwave frequencies has a long history, dating from the early 1950s. In past decades, dramatic advances have been made in this field, and a great deal of new measurement methods and techniques have been developed and applied. There is a clear need to have a practical reference text to assist practicing professionals in research and industry. However, we realize the lack of good reference books dealing with this field. Though some chapters, reviews, and books have been published in the past, these materials usually deal with only one or several topics in this field, and a book containing a comprehensive coverage of up-to-date measurement methodologies is not available. Therefore, most of the research and development activities in this field are based primarily on the information scattered throughout numerous reports and journals, and it always takes a great deal of time and effort to collect the information related to on-going projects from the voluminous literature. Furthermore, because of the paucity of comprehensive textbooks, the training in this field is usually not systematic, and this is undesirable for further progress and development in this field.

This book deals with the microwave methods applied to materials property characterization, and it provides an in-depth coverage of both established and emerging techniques in materials characterization. It also represents the most comprehensive treatment of microwave methods for materials property characterization that has appeared in book form to date. Although this book is expected to be most useful to those engineers actively engaged in designing materials property–characterization methods, it should also be of considerable value to engineers in other disciplines, such as industrial engineers, bioengineers, and materials scientists, who wish to understand the capabilities and limitations of microwave measurement methods that they use. Meanwhile, this book also satisfies the requirement for up-to-date texts at graduate and senior undergraduate levels on the subjects in materials characterization.

Among this book's most outstanding features is its comprehensive coverage. This book discusses almost all aspects of the microwave theory and techniques for the characterization of the electromagnetic properties of materials at microwave frequencies. In this book, the materials under characterization may be dielectrics, semiconductors, conductors, magnetic materials, and artificial materials; the electromagnetic properties to be characterized mainly include permittivity, permeability, chirality, mobility, and surface impedance.

The two introductory chapters, Chapter 1 and Chapter 2, are intended to acquaint the readers with the basis for the research and engineering of electromagnetic materials from the materials and microwave fundamentals respectively. As general knowledge of electromagnetic properties of materials is helpful for understanding measurement results and correcting possible errors, Chapter 1 introduces the general properties of various electromagnetic materials and their underlying physics. After making a brief review on the methods for materials properties characterization, Chapter 2 provides a summary of the basic microwave theory and techniques, based on which the methods for materials characterization are developed. This summary is mainly intended for reference rather than for tutorial purposes, although some of the important aspects of microwave theory are treated at a greater length. References are cited to permit readers to further study the topics they are interested in.

Chapters 3 to 8 deal with the measurements of the permittivity and permeability of low-conductivity materials and the surface impedance of high-conductivity materials. Two types of nonresonant methods, reflection method and transmission/reflection method, are discussed in Chapters 3 and 4 respectively; two types of resonant methods, resonator method and resonant-perturbation method, are discussed in Chapters 5 and 6 respectively. In the methods discussed in Chapters 3 to 6, the transmission lines used are mainly coaxial-line, waveguide, and free-space, while Chapter 7 is concerned with the measurement methods developed from planar transmission lines, including stripline, microstrip-, and coplanar line. The methods discussed in Chapters 3 to 7 are suitable for isotropic materials, which have scalar or complex permittivity and permeability. The permittivity of anisotropic dielectric materials is a tensor parameter, and magnetic materials usually have tensor permeability under an external dc magnetic field. Chapter 8 deals with the measurement of permittivity and permeability tensors.

Ferroelectric materials are a special category of dielectric materials often used in microwave electronics for developing electrically tunable devices. Chapter 9 discusses the characterization of ferroelectric materials, and the topics covered include the techniques for studying the temperature dependence and electric field dependence of dielectric properties.

In recent years, the research on artificial materials has been active. Chapter 10 deals with a special type of artificial materials: chiral materials. After introducing the concept and basic characteristics of chiral materials, the methods for chirality measurements and the possible applications of chiral materials are discussed.

The electrical transport properties at microwave frequencies are important for the development of high-speed electronic circuits. Chapter 11 discusses the microwave Hall effect techniques for the measurement of the electrical transport properties of low-conductivity, high-conductivity, and magnetic materials.

The measurement of materials properties at high temperatures is often required in industry, scientific research, and biological and medical applications. In principle, most of the methods discussed in this book can be extended to high-temperature measurements. Chapter 12 concentrates on the measurement of the dielectric properties of materials at high temperatures, and the techniques for solving the problems in high-temperature measurements can also be applied for the measurement of other materials property parameters at high temperatures.

In this book, each chapter is written as a self-contained unit, so that readers can quickly get comprehensive information related to their research interests or on-going projects. To provide a broad treatment of various topics, we condensed mountains of literature into readable accounts within a text of reasonable size. Many references have been included for the benefit of the readers who wish to pursue a given topic in greater depth or refer to the original papers.

It is clear that the principle of a method for materials characterization is more important than the techniques required for implementing this method. If we understand the fundamental principle underlying a measurement method, we can always find a suitable way to realize this method. Although the advances in technology may significantly change the techniques for implementing a measurement method, they cannot greatly influence the measurement principle. In writing this book, we tried to present the fundamental principles behind various designs so that readers can understand the process of applying fundamental concepts to arrive at actual designs using different techniques and approaches. We believe that an engineer with a sound knowledge of the basic concepts and fundamental principles for materials property characterization and the ability apply to his knowledge toward design objectives, is the engineer who is most likely to make full use of the existing methods, and develop original methods to fulfill ever-rising measurement requirements.

We would like to indicate that this text is a compilation of the work of many people. We cannot be held responsible for the designs described that are still under patent. It is also difficult to always give proper credits to those who are the originators of new concepts and the inventors of new methods. The names we give to some measurement methods may not fit the intentions of the inventors or may not accurately reflect the most characteristic features of these methods. We hope that there are not too many such errors and will appreciate it if the readers could bring the errors they discover to our attention.

There are many people to whom we owe many thanks for helping us prepare this book. However, space dictates that only a few of them can receive formal acknowledgements. But this should not be taken as a disparagement of those whose contributions remain anonymous. Our foremost appreciation goes to Mr. Quek Gim Pew, Deputy Chief Executive (Technology), Singapore Defence Science & Technology Agency, Mr. Quek Tong Boon, Chief Executive Officer, Singapore DSO National Laboratories, and Professor Lim Hock, Director, Temasek Laboratories, National University of Singapore, for their encouragement and support along the way. We are grateful to Pennsylvania State University and HVS Technologies for giving us permission to include the HVS Free Space Unit and the data in this book. We really appreciate the valuable help and cooperation from Dr. Li Zheng-Wen, Dr. Rao Xuesong, and Mr. Tan Chin Yaw. We are very grateful to the staff of John Wiley & Sons for their helpful efforts and cheerful professionalism during this project.

L. F. Chen
C. K. Ong
C. P. Neo
V. V. Varadan
V. K. Varadan

1

Electromagnetic Properties of Materials

This chapter starts with the introduction of the materials research and engineering at microwave frequencies, with emphasis laid on the significance and applications of the study of the electromagnetic properties of materials. The fundamental physics that governs the interactions between materials and electromagnetic fields is then discussed at both microscopic and macroscopic scales. Subsequently, we analyze the general properties of typical electromagnetic materials, including dielectric materials, semiconductors, conductors, magnetic materials, and artificial materials. Afterward, we discuss the intrinsic properties and extrinsic performances of electromagnetic materials.

1.1 MATERIALS RESEARCH AND ENGINEERING AT MICROWAVE FREQUENCIES

While technology decides how electromagnetic materials can be utilized, science attempts to decipher why materials behave as they do. The responses of materials to electromagnetic fields are closely determined by the displacement of their free and bounded electrons by electric fields and the orientation of their atomic moments by magnetic fields. The deep understanding and full utilization of electromagnetic materials have come from decoding the interactions between materials and electromagnetic fields by using both theoretical and experimental strategies.

This book mainly deals with the methodology for the characterization of electromagnetic materials for microwave electronics, and also discusses the applications of techniques for materials property characterization in various fields of sciences and engineering. The importance of the research on the electromagnetic properties of materials at microwave frequencies can be understood in the aspects that follow.

Firstly, though it is an old field in physics, the study of electromagnetic properties of materials at microwave frequencies is full of academic importance (Solymar and Walsh 1998; Kittel 1997; Von Hippel 1995a,b; Jiles 1994; Robert 1988), especially for magnetic materials (Jiles 1998; Smit 1971) and superconductors (Tinkham 1996) and ferroelectrics (Lines and Glass 1977). The knowledge gained from microwave measurements contributes to our information about both the macroscopic and the microscopic properties of materials, so microwave techniques have been important for materials property research. Though magnetic materials are widely used in various fields, the research of magnetic materials lags far behind their applications, and this, to some extent, hinders us from making full application of magnetic materials. Until now, the electromagnetic properties of magnetic properties at microwave frequencies have not been fully investigated yet, and this is one of the main obstacles for the development of microwave magnetoelectrics. Besides, one of the most promising applications of superconductors is microwave electronics. A lot of effort has been put in the study of the microwave properties of superconductors, while many areas are yet to be explored. Meanwhile, as ferroelectric materials have great application potential in developing smart electromagnetic materials, structures, and

Microwave Electronics: Measurement and Materials Characterization L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan and V. K. Varadan
 ISBN: 0-470-84492-2

devices in recent years, microwave ferroelectricity is under intensive investigation.

Secondly, microwave communications are playing more and more important roles in military, industrial, and civilian life, and microwave engineering requires precise knowledge of the electromagnetic properties of materials at microwave frequencies (Ramo *et al.* 1994). Since World War II, a lot of resources have been put into electromagnetic signature control, and microwave absorbers are widely used in reducing the radar cross sections (RCSs) of vehicles. The study of electromagnetic properties of materials and the ability of tailoring the electromagnetic properties of composite materials are very important for the design and development of radar absorbing materials and other functional electromagnetic materials and structures (Knott *et al.* 1993).

Thirdly, as the clock speeds of electronic devices are approaching microwave frequencies, it becomes indispensable to study the microwave electronic properties of materials used in electronic components, circuits, and packaging. The development of electronic components working at microwave frequencies needs the electrical transport properties at microwave frequencies, such as Hall mobility and carrier density; and the development of electronic circuits working at microwave frequencies requires accurate constitutive properties of materials, such as permittivity and permeability. Meanwhile, the electromagnetic interference (EMI) should be taken into serious consideration in the design of circuit and packaging, and special materials are needed to ensure electromagnetic compatibility (EMC) (Montrose 1999).

Fourthly, the study of electromagnetic properties of materials is important for various fields of science and technology. The principle of microwave remote sensing is based on the reflection and scattering of different objects to microwave signals, and the reflection and scattering properties of an object are mainly determined by the electromagnetic properties of the object. Besides, the conclusions of the research of electromagnetic materials are helpful for agriculture, food engineering, medical treatments, and bioengineering (Thuery and Grant 1992).

Finally, as the electromagnetic properties of materials are related to other macroscopic or microscopic properties of the materials, we can obtain information about the microscopic or macroscopic properties we are interested in from the electromagnetic properties of the materials. In materials research and engineering, microwave techniques for the characterization of materials properties are widely used in monitoring the fabrication procedure and nondestructive testing of samples and products (Zoughi 2000; Nyfors and Vainikainen 1989).

This chapter aims to provide basic knowledge for understanding the results from microwave measurements. We will give a general introduction on electromagnetic materials at microscopic and macroscopic scales and will discuss the parameters describing the electromagnetic properties of materials, the classification of electromagnetic materials, and general properties of typical electromagnetic materials. Further discussions on various topics can be found in later chapters or the references cited.

1.2 PHYSICS FOR ELECTROMAGNETIC MATERIALS

In physics and materials sciences, electromagnetic materials are studied at both the microscopic and the macroscopic scale (Von Hippel 1995a,b). At the microscopic scale, the energy bands for electrons and magnetic moments of the atoms and molecules in materials are investigated, while at the macroscopic level, we study the overall responses of macroscopic materials to external electromagnetic fields.

1.2.1 Microscopic scale

In the microscopic scale, the electrical properties of a material are mainly determined by the electron energy bands of the material. According to the energy gap between the valence band and the conduction band, materials can be classified into insulators, semiconductors, and conductors. Owing to its electron spin and electron orbits around the nucleus, an atom has a magnetic moment. According to the responses of magnetic moments to magnetic field, materials can be generally classified into diamagnetic materials, paramagnetic materials, and ordered magnetic materials.

1.2.1.1 Electron energy bands

According to Bohr's model, an atom is characterized by its discrete energy levels. When atoms are brought together to constitute a solid, the discrete levels combine to form energy bands and the occupancy of electrons in a band is dictated by Fermi-dirac statistics. Figure 1.1 shows the relationship between energy bands and atomic separation. When the atoms get closer, the energy bands broaden, and usually the outer band broadens more than the inner one. For some elements, for example lithium, when the atomic separation is reduced, the bands may broaden sufficiently for neighboring bands to merge, forming a broader band. While for some elements, for example carbon, the merged broadband may further split into separate bands at closer atomic separation.

[Image not available in this electronic edition.]

Figure 1.1 The relationships between energy bands and atomic separation. (a) Energy bands of lithium and (b) energy bands of carbon. (Bolton 1992) Source: Bolton, W. (1992), *Electrical and Magnetic Properties of Materials*, Longman Scientific & Technical, Harlow

The highest energy band containing occupied energy levels at 0 K in a solid is called the *valence band*. The valence band may be completely filled or only partially filled with electrons. The electrons in the valence band are bonded to their nuclei. The conduction band is the energy band above the valence energy band, and contains vacant energy levels at 0 K. The electrons in the conduction band are called *free electrons*, which are free to move. Usually, there is a forbidden gap between the valence band and the conduction band, and the availability of free electrons in the conduction band mainly depends on the forbidden gap energy. If the forbidden gap is large, it is possible that no free electrons are available, and such a material is called an *insulator*. For a material with a small forbidden energy gap, the availability of free electron in the conduction band permits some electron conduction, and such a material is a semiconductor. In a conductor, the conduction and valence bands may overlap, permitting abundant free electrons to be available at any ambient temperature, thus giving high electrical conductivity. The energy bands for insulator, semiconductor, and good conductor are shown schematically in Figure 1.2.

Insulators

For most of the insulators, the forbidden gap between their valence and conduction energy bands

[Image not available in this electronic edition.]

Figure 1.2 Energy bands for different types of materials. (a) Insulator, (b) semiconductor, and (c) good conductor. (Bolton 1992). Modified from Bolton, W. (1992), *Electrical and Magnetic Properties of Materials*, Longman Scientific & Technical, Harlow is larger than 5 eV. Usually, we assume that an insulate is nonmagnetic, and under this assumption, insulators are called *dielectrics*. Diamond, a form of carbon, is a typical example of a dielectric. Carbon has two electrons in the 1s shell, two in the 2s shell, and two in the 2p shell. In a diamond, the bonding between carbon atoms is achieved by covalent bonds with electrons shared between neighboring atoms, and each atom has a share in eight 2p electrons (Bolton 1992). So all the electrons are tightly held between the atoms by this covalent bonding. As shown in Figure 1.1(b), the consequence of this bonding is that diamond has a full valence band with a substantial forbidden gap between the valence band and the conduction band. But it should be noted that, graphite, another form of carbon, is not a dielectric, but a conductor. This is because all the electrons in the graphite structure are not locked up in covalent bonds and some of them are available for conduction. So the energy bands are related to not only the atom structures but also the ways in which atoms are combined.

Semiconductors

The energy gap between the valence and conduction bands of a semiconductor is about 1 eV. Germanium and silicon are typical examples of semiconductors. Each germanium or silicon atom has four valence electrons, and the atoms are held together by covalent bonds. Each atom shares electrons with each of four neighbors, so all the electrons are locked up in bonds. So there is a gap between a full valence band and the conduction band. However, unlike insulators, the gap is relatively small. At room temperature, some of the valence electrons can break free from the bonds and have sufficient energy to jump over the forbidden gap, arriving at the conduction band. The density of the free electrons for most of the semiconductors is in the range of 10^{16} to 10^{19} per m^3.

Conductors

For a conductor, there is no energy gap between the valence gap and conduction band. For a good conductor, the density of free electrons is on the order of 10^{28} m^3. Lithium is a typical example of a conductor. It has two electrons in the 1s shell and one in the 2s shell. The energy bands of such elements are of the form shown in Figure 1.1(a). The 2s and 2p bands merge, forming a large band that is only partially occupied, and under an electric field, electrons can easily move into vacant energy levels.

In the category of conductors, superconductors have attracted much research interest. In a normal conductor, individual electrons are scattered by impurities and phonons. However, for superconductors, the electrons are paired with those of opposite spins and opposite wave vectors, forming Cooper pairs, which are bonded together by exchanging phonons. In the Bardeen–Cooper–Schrieffer (BCS) theory, these Cooper pairs are not scattered by the normal mechanisms. A superconducting gap is found in superconductors and the size of the gap is in the microwave frequency range, so study of superconductors at microwave frequencies is important for the understanding of superconductivity and application of superconductors.

1.2.1.2 Magnetic moments

An electron orbiting a nucleus is equivalent to a current in a single-turn coil, so an atom has a magnetic dipole moment. Meanwhile, an electron also spins. By considering the electron to be a small charged sphere, the rotation of the charge on the surface of the sphere is also like a single-turn current loop and also produces a magnetic moment (Bolton 1992). The magnetic properties of a material are mainly determined by its magnetic moments that result from the orbiting and spinning of electrons. According to the responses of the magnetic moments of the atoms in a material to an external magnetic field, materials can be generally classified into diamagnetic, paramagnetic, and ordered magnetic materials.

Diamagnetic materials

The electrons in a diamagnetic material are all paired up with spins antiparallel, so there is no net magnetic