This file contains excerpts from the most modern Textbook on “Characterization.” It was printed in 1998 by John Wiley and Sons.

The Preface to its 1st Edition helps explain what “Characterization” means to the Semiconductor industry.

Excerpts from Chapter 1 quote work done by my earliest Industry team (the Dave Perloff Gang) and contains references showing me as co-author.

Fred E Wahl

Thanks to Dieter Schroder.

SECOND EDITION

SEMICONDUCTOR MATERIAL AND DEVICE CHARACTERIZATION

DIETER K. SCHRODER

PREFACE TO FIRST EDITION

When I prepared to teach a course in Semiconductor Material and Device Characterization several years ago I found no suitable book for such a course. Earlier characterization books did not contain the breadth of modern characterization techniques and were out-of-print. Instead of a textbook, I used papers, review papers, chapters in books, out-of-print books still in the library, and developed my own notes. I also hold a three-day short course on this topic for which I developed related notes. I teach industrial courses from time to time and run into the same problem of lack of book and having to rely on reprints and notes. From these courses and from my industrial and academic contacts I became very much aware of the necessity of a textbook covering modern semiconductor characterization techniques. This book grew out of these notes, augmented by discussions with students and colleagues that helped to clarify points of confusion.

This book is intended to fill a gap in the semiconductor literature—Semiconductor Material and Device Characterization. There are many books on the Physics of Semiconductor Devices, there are now a number of books on Processing of Semiconductors. There are several books on Semiconductor Device and Circuit Design. There are even a few books on Modeling of Semiconductor Devices and Processes. But there are no books on Semiconductor Characterization. The earlier books *Semiconductor Measurements and Instrumentation* by W. R. Runyan and *Characterization of Semiconductor Materials* by P. F. Kane and G. B. Larrabee are out-of-print.

All semiconductor devices and materials are characterized to a greater or lesser degree. Processes are characterized through the use of test structures. Many papers, review papers, book chapters, and specialized books exist in

the field of characterization; but no one has integrated these various topics into one volume. I have attempted to do that by including the main characterization techniques of the semiconductor industry—electrical, optical, chemical, and physical—in this book.

I wrote this book with two distinct audiences in mind. One is the first or second year graduate student who is familiar with semiconductor device physics, knows and understands the basic semiconductor devices, and wishes to learn about semiconductor measurements. The second audience is the industrial researcher who also understands devices and who may be familiar with some characterization methods and who wants to learn about others or who wants to become familiar with the wide spectrum of measurement methods found in the modern semiconductor industry. The book may even be considered a sort of handbook of look for a specific characterization technique. Those readers interested in more detail may wish to consult some of the references. I have consulted and included more than 1300 references. These are the references I found most useful during the preparation of the manuscript. They are fairly comprehensive but obviously not all-inclusive. I did not exclude references deliberately; rather I chose to include those that I found to be most helpful.

I have written the book from the point of view of a semiconductor device person, who is reasonably familiar with the physics and operation of the major semiconductor devices—pn junctions, bipolar junction transistors, metal-oxide-semiconductor capacitors and transistors, solar cells, and Schottky barrier diodes. I have stressed the concepts wherever possible; in some instances I have explained the necessary material or device background for understanding certain characterization methods, but obviously there is no space to derive all device concepts and you should consult appropriate semiconductor device physics books if you are not familiar with the underlying concepts. I have used the contents of this book during the past seven years as a one-semester graduate course and most of the material is also used in an abbreviated, condensed version in a three-day short course. During the one-semester course I do not go into all the details the book contains. The material is sufficiently broad to be also suitable for a two-semester course by going into more detail.

I chose the topics by carefully considering the plethora of semiconductor characterization techniques in use and by discussions with people active in the field. I have used and am familiar with many of the methods. Electrical characterization methods are by far the most ubiquitous. Consequently I have devoted the major part of the book to them. Optical methods are for the most part more specialized, not used as frequently, but are becoming more popular. Their non-contacting nature and high sensitivity is a decided advantage. Chemical and physical characterization methods are yet more specialized. Their high spatial resolution and ability to identify elements and compounds makes them very valuable for some applications. They are usually performed by specialists or offered as services. It is very useful to be familiar with these methods to understand their applicability and their limitations.

Many people have in one way or another contributed to this book by discussions, questions, comments, and reading of chapters. Students at ASU and attenders at short courses have helped clarify many concepts. I especially like to thank those who have contributed directly during the writing of this manuscript. K. J. Joardar, D. A. Johnson, S. H. Park, K. T. Shiralagi, and S. Visitserngtrakul from Arizona State University and Tom Shaffner from Texas Instruments read various chapters and made valuable corrections and suggestions. B. Hussain, Z. Mahdavi, I. G. Hwang, P. S. Ku from Arizona State University and my wife Beverley checked the many references. Many discussions with Tom Shaffner and Graydon Larrabee from Texas Instruments and Ron Roedel from ASU who have participated in presenting a short course on semiconductor characterization during the past seven years, have helped clarify numerous concepts especially in optical, chemical, and physical characterization. Several students helped with experimental data. They are acknowledged in the figure captions. My son Mark spent many hours drawing the figures and son Derek did some of the typing. Lastly I thank the Department of Electrical and Computer Engineering within the College of Engineering at Arizona State University for providing the atmosphere and one semester sabbatical leave to write this book.

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and for probes *parallel* to a *conducting boundary*,

$$F_{32} = \frac{1}{1 - \dfrac{2}{\left[1 + (2d/s)^2\right]^{1/2}} + \dfrac{1}{\left[1 + (d/s)^2\right]^{1/2}}} \tag{1.22b}$$

Equations (1.21) and (1.22) are plotted in Fig. 1.5. These correction factors apply to infinitely thick samples. It is obvious from the figures that as long as the probe distance from the wafer boundary is at least three to four probe spacings, the correction factors F_{31} to F_{34} reduce to unity. For most four-point probe measurements, this condition is easily satisfied. Correction factors F_{31} to F_{34} only become important for small samples in which the probe is, of necessity, close to the sample boundary. However, even for large samples, wafer mapping over the entire wafer requires measurements close to the wafer edge.

Other corrections must be applied when the probe is not centered even in a wafer of substantial diameter.[16] For rectangular samples it has been found that the sensitivity of the geometrical correction factor to positional error is minimized by orienting the probe with its electrodes within about 10% of the center.[11] For square arrays the error is minimized by orienting the probe array with its electrodes equidistant from the midpoints of the sides. There is also an angular dependence of the placement of a square array on the rectangular sample.[9, 11] We should mention that if the probe spacings are not exactly identical, there is a further correction.[18] This correction is small, however.

The key to high-precision four-point probe measurements, including reduced geometric effects associated with proximity of the probe to a nonconducting boundary, is the use of two measurement configurations at each probe location.[19–21] This technique is known as the "dual configuration" or the "configuration switched" method. The first configuration is usually with current into probe 1 and out of probe 4 and with the voltage sensed across probes 2 and 3. The second measurement is made with current driven through probes 1 and 3 and voltage measured across probes 2 and 4. The advantages are (1) the probe no longer needs to be in a high symmetry orientation (being perpendicular or parallel to the wafer radius of a circular wafer or to the length or width of a rectangular sample), (2) the lateral dimensions of the specimen do not have to be known since the geometric correction factor results directly from the two measurements, and (3) the two measurements self-correct for the actual probe spacings.

The sheet resistance in the dual configuration is given by[21]

$$\rho_s = -14.696 + 25.173\left(\frac{R_a}{R_b}\right) - 7.872\left(\frac{R_a}{R_b}\right)^2 \tag{1.23}$$

1.3 WAFER MAPPING

Wafer mapping, originally developed to characterize ion implantation uniformity, has become a powerful process monitoring tool. Manual wafer mapping originated in the 1970s.[33, 34] Today highly automated systems are used. During wafer mapping the sheet resistance or some other parameter proportional to implant dose is measured at many locations across a sample. The data are then converted to two-dimensional or three-dimensional contour maps. Contour maps are a more powerful display of process uniformity than displaying the same data in tabular form. A well-designed contour map gives instant information about implant uniformity, flow patterns during diffusion, epitaxial reactor nonuniformities, and so on. If desired, line scans along one line across the sample can also be displayed to show the uniformity along that line.

A history of wafer mapping techniques is shown in Fig. 1.13.[35] The most common techniques are four-point probe sheet resistance, four-point probe double implant, spreading resistance, modulated photoreflectance, and optical densitometry. Of these, the configuration-switched four-point probe method is most frequently used. It allows for rapid comparison between samples and has been used for ion implantation, diffusion, poly-Si films, and metal uniformity characterization.[36, 37] Example wafer maps are shown in Fig. 1.14.

1.3.1 Double Implant

The sheet resistance of low-dose, high resistance implanted layers is difficult to measure by the conventional four-point probe technique. Such layers are important because they are used to control the threshold voltage of

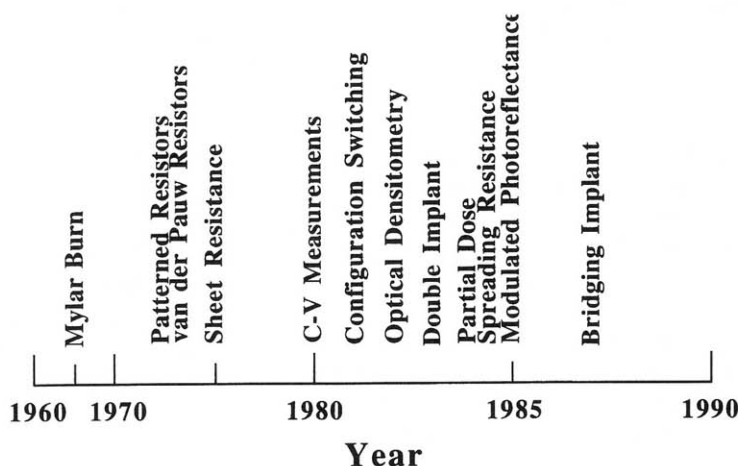

Fig. 1.13 A history of wafer mapping techniques.

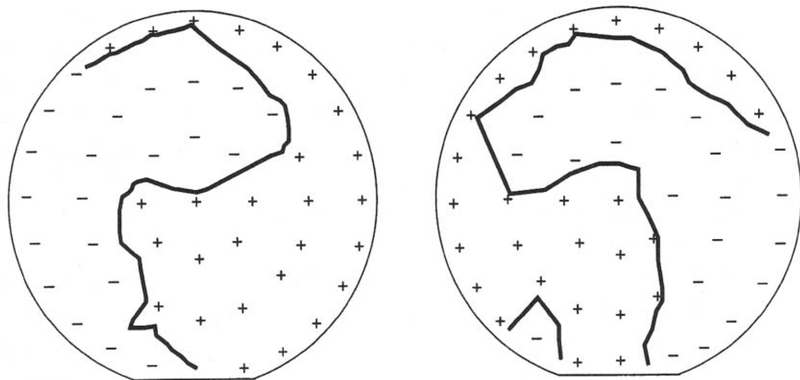

Fig. 1.14 Four-point probe contour maps; (a) boron, 10^{15} cm^{-2}, 40 keV, ρ_s(average) = 98.5 ohms/square; (a) arsenic, 10^{15} cm^{-2}, 80 keV, ρ_s(average) = 98.7 ohms/square; 1% intervals. 200 mm diameter Si wafers. Data courtesy of Marylou Meloni, Varian Ion Implant Systems.

MOSFETs. The reasons for the measurement difficulties are (1) it is difficult to make good electrical contact from the probe to the semiconductor; (2) low doses give low carrier densities and therefore poor conductivity; and (3) the surface leakage current can be comparable to the measurement current. The conventional four-point probe method can be used provided the starting wafers are of high resistivity and they are oxidized before the implant to

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