time dependence as for samples in the process of change or obtaining ultracold neutrons by reflection from moving crystals. Pulsed neutron radiography is considered including "stroboscopic" radiography. A very brief Appendix 1 deals with neutron cross sections and an even briefer Appendix 2 lists symbols, units, and numerical constants and relations.

The author's extensive experience in neutron scattering at Harwell and elsewhere has provided the basis in this book for a very useful addition to the literature. The applications of the neutron scattering field are constantly expanding, and it is important to communicate the experience gained thus far to potential users of pulsed neutron techniques.

The art work in the book is superb. This, and perhaps a somewhat limited audience, may account for the rather high price. The book fills a considerable need and is a pleasure to read, and it is highly recommended as a handbook, its avowed purpose. As a text it "covers the ground," but the sketchy nature of the coverage of basic material and derivations would provide an interesting challenge to the lecturer.

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MOS (Metal Oxide Semiconductor) Physics and Technology

Authors	E. H. Nicollian and J. R. Brews
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Reviewer	A. R. Wazzan

A treatise of outstanding quality and depth, the text is addressed to the scholar in the field but contains elementary material (including both semiconductor physics and semiconductor technology) addressed to the novice or beginning student. Those who need education in this area will have some difficulty understanding the finer concepts of this treatise. The beginning student is better served by consulting standard elementary texts on solid state and semiconductor physics. However, be that as it may, the authors do a fine job of briefly introducing semiconductor physics concepts essential to understanding metal oxide semiconductor (MOS) technology.

In any given text in the physical sciences, there are those authors who stumble with the mathematics, the physical phenomena, or with the technological developments in the field—Nicollian and Brews are not among them. The authors of *MOS Physics and Technology* treat all three aspects with balance and due care. The authors relate microscopic charge behavior to macroscopic circuit characteristics and measurements. Interpretations of fundamental and far-reaching physical phenomena in terms of simple but illustrative electrical circuit concepts are not only informative, but are also refreshing. The "band-bending approximation," all too important to MOS modeling and understanding, as in many device applications and MOS capacitor measurements, is repeatedly discussed with good clarity. Ionizing radiation effects in semiconductors and MOS devices, of much interest to some readers of *Nuclear Technology*, are but briefly discussed.

The MOS capacitor, operating principles, and electrical characteristics are discussed and formulated in Chaps. 2, 3, and 4.

In Chap. 2 the depletion layer charge density, the electron and hole densities, and the band bending in the silicon substrate of the MOS capacitor are determined as functions of gate bias. Using these expressions, the one-dimensional Poisson equation is solved for potential and charge density at the silicon surface, both with and without applied bias. Only steady time-independent gate voltage (gate bias) is considered here.

Chapters 3 and 4 use solid state concepts discussed in Chap. 2 to determine the low- and high-frequency capacitance-voltage (C-V) characteristics of the simple MOS capacitor. The material through Chap. 4 develops the analysis necessary and essential for understanding many of the measurement methods using low- and high-frequency C-V characteristics.

Silicon band bending is discussed in Chap. 3. There are two ways of *directly* measuring silicon band bending as a function of gas bias: the charge density-voltage (Q-V) method and the low-frequency C-V method. An *indirect* method, the high-frequency capacitance method of determining silicon band bending uses comparison of a theoretical high-frequency capacitance-time independent band bending (C-ψ_s) curve with a measured high-frequency C-V curve. In this chapter a small alternating-current (ac) voltage is superimposed on the gate bias, and the C-V characteristics of the MOS capacitor are determined under the condition that both electron and hole distributions in the silicon respond *instantaneously* to the ac gate voltage. This chapter, along with Chap. 4, lays the groundwork for the interpretation of measurements using the MOS capacitor.

In Chaps. 4 and 5, bulk and interface traps are discussed and used to interpret the behavior of the MOS capacitor in strong and weak inversions and in the depletion mode. The role of bulk traps in the steady-state response (microscopic) of the MOS capacitor to small signals (the ac gate voltage) is analyzed.

Chapter 4 considers in greater detail the response of both majority and minority carriers to the ac gate voltage. This response determines the high-frequency C-V characteristics of the MOS capacitor in inversion. The equivalent circuit for the MOS capacitor is used throughout this chapter because it is easier to relate measured admittance to an equivalent circuit than to a complex algebraic formula. All analyses are restricted to small-signal steady-state responses and for *uniform* doping concentration only; the effect of nonuniform impurity distributions on the C-V curve is but briefly discussed.

Chapters 5 through 8 deal mainly with the small-signal steady-state methods that are well established for measuring interface trap properties.

In Chap. 5 a general equivalent circuit is derived for the MOS capacitor on the basis of capture and emission of mobile carriers by interface trap levels distributed throughout the silicon band gap. Using this circuit, the authors derive relation between the measured conductance and capacitance of the MOS capacitor and interface trap properties, capture, and emissions. The behavior in the different regions, depletion and inversion, is shown to be well described using the same basic model, thus supporting the validity of the assumptions of the model.

The admittance of the MOS capacitor, including interface traps, is derived as a function of frequency for depletion and weak and strong inversion. Using this model, the conductance method, the most accurate and sensitive of the small-signal steady-state methods, is used to extract interface trap level density, capture probability, and time-constant dispersion from the real component of the admittance. Electrical properties of interface traps are almost exclusively derived from conductance measurements. On the other hand, the small-signal steady-state capacitance methods (Chap. 3) are more suitable for rapid evaluation of interface trap level density. Because of their convenience, these methods are useful in studies of the chemical nature of interface traps, their annealing properties, etc. Errors and limitations of the conductance method are discussed, as well as the resolution with which interface trap level density is probed by any of the small-signal steady-state methods.

In Chap. 6, emphasis is on the way that interfacial charge nonuniformities [those caused by the localized nature of interface traps and oxide-fixed charge, gross nonuniformities (e.g., edge effects and decoration of large defects that collect or nucleate clusters of ions), and chemical inhomogeneity (stretched, bent or broken bonds, and oxide compositional variations)] affect the interpretation of small-signal steady-state MOS capacitor measurements and how they can be detected. First, the effects of large-scale nonuniformities on MOS capacitance measurements are evaluated. Next, the three-dimensional randomly distributed microscopic interfacial charge nonuniformities are treated and its effects on the band bending evaluated; the equivalent circuit for the MOS capacitor is obtained and used in extracting interface trap properties (Chaps. 5 and 8) from the measured admittance of the MOS capacitor. In effect, Chap. 6 discusses the extraction of interface trap properties using the conductance method, making certain assumptions about the structure of the interface that are justified, however, with data presented in Chap. 7.

In Chap. 8 the authors develop methods of extracting, from the capacitive component of the admittance measured as a function of frequency (very high and very low) and gate bias, the interface trap level density as a function of gate bias, then determine interface trap level density as a function of energy in the silicon bandgap. This incomplete characterization of the interface (only trap density) is sufficient for studies into the effects of stress or annealing on interface trap level density during integrated circuit fabrication. The errors involved in this method of computing trap level density are discussed.

Chapter 9 discusses how the conductivity type (*n* or *p* type), the deep depletion condition, the most accurate way of determining the doping profile near the silicon surface, and the lifetime can be determined from the MOS capacitor C-V measurements. These properties are useful in characterizing starting materials for device applications in integrated circuits (MOSFET, bipolar, transistor, and CCD) and give a baseline for accepting or rejecting the material.

In Chap. 11 the authors discuss the properties of bulk oxide traps that are associated with SiO_2 defects, e.g., impurities and broken bonds. Bulk oxide traps are important in nonvolatile memory applications and to device stability. Bulk oxide traps, normally not charged, become charged when electrons and holes are introduced into the oxide, e.g., as a result of ionizing radiation. The chapter discusses hole and electron injection (by means of internal photoemission, avalanche injection, Fowler-Nordheim tunneling, direct tunneling, etc.).

Chapter 12 is dedicated to preparing the reader to make measurements (of properties described in Chaps. 3 through 11) for production, monitoring, developmental studies, or research, using mostly commercially available instrumentation. The material sets the stage for the reader to be able to digitalize the measured data and feed it into a computer. The computer can be programmed to operate the instrumentation and acquire and process the data to obtain the desired end results, e.g., a doping profile.

Oxide layers play a variety of important functions in silicon integrated circuit technology. These functions [a diffusion mask, passivation for a silicon device (e.g., bipolar transistor), isolating one device from another, etc.] require oxide layers of differing characteristics, e.g., purity, thickness, etc. To obtain such oxides, different methods of oxide preparation have been developed. Several of these methods are discussed in detail in Chap. 13; particular emphasis is given to the thermal oxidation of silicon. It gives current state-of-the-art understanding of the oxidation of silicon, including oxidation techniques as well as the interaction between device characteristics and the chemical and electrical properties of the oxide layer. The chapter also discusses growth mechanisms, the structure of thermally grown oxide, and the phenomenological kinetics of oxidation.

Chapter 14 discusses oxide film technology, including preparation, thickness measurements, and the effects of thermal oxidation on silicon bulk. These changes are accompanied with modifications of the electrical properties (e.g., reduced minority carrier injection efficiency and a change in the C-V characteristics of an MOS capacitor). Thermal oxidation, for example, disturbs the silicon structure by introducing stacking faults, the redistribution of ionized impurities at the surface, and the production of strain in both the oxide and the silicon.

In Chap. 15 the junction diode, the bipolar transistor, the MOSFET, and the gate-controlled diode are used to discuss the ways that interface traps, oxide fixed charges, oxide traps, and a mobile sodium ion affect device performance and stability. Optimal device performance and stability are maintained through control during fabrication of the oxide and interfacial properties and by keeping these properties stable during device operation. Ionizing radiation is briefly discussed.

In Chap. 16 electrical measurements of the MOS system provide for substantial, but not complete understanding of device behavior, aging, and reliability studies of integrated circuits, etc. Supplementary information is needed to construct a chemical and structural picture of the Si-SiO_2 interface. Recently, transmission electron microscopy has been used to study the morphology structure, while a host of other techniques, including ellipsometry, electron spin resonance, and x-ray photoelectron spectroscopy, are used to study the chemical composition of the Si-SiO_2 interface. Despite major recent advances in these techniques, measurements remain difficult to interpret and the results are quite tentative. The authors bring their penetrating understanding of the field to bear on this subject and give a brilliant synthesis of recent measurements leading to a speculative picture of the Si-SiO_2 interface.

A. R. Wazzan, who received a BS in chemical engineering in 1959, an MS in aeronautical engineering in 1961, and a PhD in engineering science in 1963, all from the University of California, Berkeley, has been a professor in the Department of Chemical Engineering at the University of California, Los Angeles (UCLA) since 1962. He is the author of many review and research articles on the physics of fluids, physics of solids, modeling of fission gas behavior in irradiated oxide and carbide fuels, and most recently he is a coauthor with a team from Electricité de France of a series of articles in Nuclear Engineering and Design *on the thermal-hydraulic characteristics of pressurized water reactors during commercial operation. In July 1986 he was appointed acting dean of the School of Engineering and Applied Science at UCLA.*