Physics of Semiconductor Devices

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To Rossella and Morgana

Preface

This volume originates from the lectures on Solid-State Electronics and Microelectronics that I have been giving since 1978 at the School of Engineering of the University of Bologna. Its scope is to provide the reader with a book that, starting from the elementary principles of classical mechanics and electromagnetism, introduces the concepts of quantum mechanics and solid-state theory, and describes the basic physics of semiconductors including the hierarchy of transport models, ending up with the standard mathematical model of semiconductor devices and the analysis of the behavior of basic devices. The ambition of the work has been to write a book, self contained as far as possible, that would be useful for both students and researchers; to this purpose, a strong effort has been made to elucidate physical concepts, mathematical derivations, and approximation levels, without being verbose.

The book is divided into eight parts. Part I deals with analytical mechanics and electromagnetism; purposedly, the material is not given in the form of a resumé: quantum-mechanics and solid-state theory's concepts are so richly intertwined with the classical ones that presenting the latter in an abridged form may make the reading unwieldy and the connections more difficult to establish. Part II provides the introductory concepts of statistical mechanics and quantum mechanics, followed by the description of the general methods of quantum mechanics. The problem of bridging the classical concepts with the quantum ones is first tackled using the historical perspective, covering the years from 1900 to 1926. The type of statistical description necessary for describing the experiments, and the connection with the limiting case of the same experiments involving massive bodies, is related to the properties of the doubly-stochastic matrices. Part III illustrates a number of applications of the Schrödinger equation: elementary cases, solutions by factorization, and time-dependent perturbation theory. Part IV analyzes the properties of systems of particles, with special attention to those made of identical particles, and the methods for separating the equations. The concepts above are applied in Part V to the analysis of periodic structures, with emphasis to crystals of the cubic type and to silicon in particular, which, since the late 1960s, has been and still is the most important material for the fabrication of integrated circuits. Part VI illustrates the single-electron dynamics in a periodic structure and derives the semiclassical Boltzmann Transport

Equation; from the latter, the hydrodynamic and drift-diffusion models of semiconductor devices are obtained using the moments expansion. The drift-diffusion model is used in Part VII to work out analytically the electrical characteristics for the basic devices of the bipolar and MOS type. Finally, Part VIII presents a collection of items which, although important *per se*, are not in the book's mainstream: some of the fabrication-process steps of integrated circuits (thermal diffusion, thermal oxidation, layer deposition, epitaxy), and methods for measuring the semiconductor parameters.

In the preparation of the book I have been helped by many colleagues. I wish to thank, in particular, Giorgio Baccarani, Carlo Jacoboni, and Rossella Brunetti, who gave me important suggestions about the matter's distribution in the book, read the manuscript and, with their observations, helped me to clarify and improve the text; I wish also to thank, for reading the manuscript and giving me their comments, Giovanni Betti Beneventi, Fabrizio Buscemi, Gaetano D'Emma, Antonio Gnudi, Elena Gnani, Enrico Piccinini, Susanna Reggiani, Paolo Spadini.

Last, but not least, I wish to thank the students, undergraduate, graduate, and postdocs, who for decades have accompanied my teaching and research activity with stimulating curiosity. Many comments, exercises, and complements of this book are the direct result of questions and comments that came from them.

Bologna Massimo Rudan
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Contents

Acronyms

Abbreviations

BJT	Bipolar junction transistor. A transistor whose operation is obtained by a suitable arrangement of two *p-n* junctions. The term "bipolar" is used because both electrons and holes are involved in the device functioning.
BTE	Boltzmann transport equation. The equation expressing the continuity of the distribution function in the phase space.
CVD	Chemical vapor deposition. A deposition process in which the material to be deposited is the product of a chemical reaction that takes place on the surface of the substrate or in its vicinity.
DD	Drift-diffusion. The term indicates a transport model for semiconductors made, for each band, of the balance equation for the carrier number and average velocity. Such equations contain the electric field and the magnetic induction; as a consequence, their solution must be calculated consistently with that of the Maxwell equations. Compare with the HD model.
HD	HydroDynamic. The term indicates a transport model for semiconductors made, for each band, of the balance equation for the carrier number, average velocity, average kinetic energy, and average flux of the kinetic energy. Such equations contain the electric field and the magnetic induction; as a consequence, their solution must be calculated consistently with that of the Maxwell equations. Compare with the DD model.
IC	Integrated circuit. Also called chip or microchip. An assembly of electronic circuits on the same plate of semiconductor material. The idea was proposed in the early 1950s, and demonstrated in 1958; it provided an enormous improvement, both in cost and performance, with respect to the manual assembly of circuits using discrete components.
IGFET	Insulated-gate field-effect transistor. A device architecture demonstrated in the early 1930s. Its first implementation (1960) using a thermally-oxidized silicon layer gave rise to the MOSFET architecture.
LASER	Light amplification by stimulated emission of radiation.

LOCOS	Local oxidation. The technological process consisting in depositing and patterning a layer of silicon nitride over the areas where the substrate's oxidation must be prevented.
MBE	Molecular beam epitaxy. A low-temperature epitaxial process based on evaporation.
MIS	Metal insulator semiconductor. Structure made of the superposition of a metal contact, an insulator, and a semiconductor.
MOS	Metal oxide semiconductor. Structure made of the superposition of a metal contact, an oxide that acts as an insulator, and a semiconductor.
MOSFET	Metal-oxide-semiconductor, field-effect transistor. A transistor whose active region is an MOS structure. In last-generation devices the insulator may be deposited instead of being obtained by oxidizing the semiconductor underneath. The MOSFET has been for decades, and still is, the fundamental device of the integrated-circuit architecture.
PDE	Partial-differential equation.
PVD	Physical vapor deposition. A deposition process in which the material to be deposited does not react chemically with other substances.
SGOI	Silicon-germanium-on-insulator. A technology analogous to SOI. SGOI increases the speed of the transistors by straining the material under the gate, this making the electron mobility higher.
SOI	Silicon on insulator. A technology introduced in 1998 for semiconductor manufacturing, in which the standard silicon substrate is replaced with a layered structure of the silicon-insulator-silicon type. SOI reduces the parasitic capacitances and the short-channel effect in MOS transistors.
SOS	Silicon on sapphire. A technological process that consists in growing a thin layer of silicon on a wafer made of sapphire (Al_2O_3).
VLSI	Very-large-scale integration. The process of creating an integrated circuit by placing a very large number of transistors in a single chip.

List of Tables