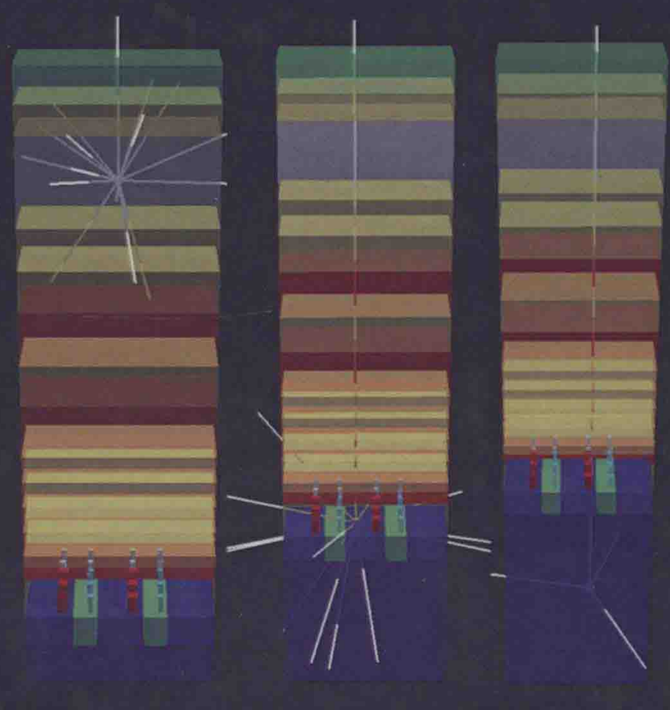
SOFT ERRORS

FROM PARTICLES TO CIRCUITS



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SOFT ERRORS

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To our beloved sons,

Alexandre and Florian.

To our families.

"Nous comprenons la Nature en lui résistant."

(We understand nature by resisting it.)

Gaston Bachelard (1884–1962)

Foreword

It is a daunting task to describe a field that is constantly in motion and that, up to now, has followed Moore's Law in the rate of its evolution, i.e., with rapid and continuous changes.

To peer into the future and outline the probable developments expected requires intimate knowledge and a deep understanding of the subject, a clear mind and a sound background, and, most of all, a critical maturity in judgment. These are the qualities of the authors of this book.

Professor Jean-Luc Autran and Dr. Daniela Munteanu have mastered the past, absorbed the present, and captured the trends of the future in one of the most important technologies of our time. Their book is the culmination of a lifelong drive to understand and contribute to the field of radiation physics and electronics.

Soft Errors: From Particles to Circuits covers all aspects of the design, use, application, performance, and testing of parts, devices, and systems and addresses every perspective from an engineering, scientific, or physical point of view.

As the authors have mentioned in their Preface, many good texts have been written on similar subjects, but none as thorough, as clear, and as complete as this volume by Professor Autran and Dr. Munteanu. Their book provides vital information to casual readers, as well as to dedicated professionals in the field, on the design and development of safe and reliable electronic systems used widely in applications in industry, engineering, and science, e.g., in automobiles, airplanes, satellites, and medical facilities and instruments.

Drawing on over 50 years of research, experiments, and testing, from the radiation physics community, from failures and successes, and from discoveries and inventions, the authors have condensed an enormous wealth of information into this outstanding book that is well organized, comprehensive, and easy to read.

This great accomplishment has resulted in an extremely useful text that has succeeded in presenting with clarity a complex reality in accessible, understandable, and helpful terms. We are grateful to our colleagues, Jean-Luc and Daniela, for their excellent work, which is highlighted in this edition, and we look forward to their ongoing research and discoveries in the exciting years to come.

Dr. Epaminondas G. Stassinopoulos
Astrophysicist, Emeritus
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Preface

This book addresses the problem of soft errors in digital integrated circuits subjected to the terrestrial natural radiation environment, one of the most important primary limits for modern digital electronic reliability. Circumscribed for several decades to the domains of space and avionics applications, and known for their severe radiation constraints, soft errors have been recognized in the last decade as a major threat for electronics at terrestrial ground level, since the miniaturization and complexity of circuits have rendered them more and more sensitive to the tenuous ground-level radiation environment.

Soft errors are a multifaceted issue at the crossroads of applied physics and engineering sciences. They are by nature a multiscale and multiphysics problem that combines not only nuclear and semiconductor physics, material sciences, circuit design, and chip architecture and operation but also cosmic-ray physics and their interaction with the earth's atmosphere, natural radioactivity issues, particle detection, and related instrumentation.

This book originated from different invited presentations, lectures, and short courses we have authored or coauthored in the last decade on different facets of soft-error issues. It includes a large part of our personal contributions on these subjects. Its primary ambition is to give an overview on this complex subject with comprehensive and, as far as possible, self-consistent knowledge on the complete chain of the physics of soft errors, from particles to circuits. Another objective is to address not only the fundamental aspects but also some engineering considerations and technological aspects of soft errors, with different levels of reading according to the centers of interest of the reader:

- Fundamentals and basic knowledge on the natural radiation environment, particle interactions with matter, and soft-error mechanisms
- Practical knowledge and overview of instrumentation developments in the fields of environment characterization, particle detection, and real-time and accelerated tests
- Detailed review and engineering solution analysis concerning the most recent computational developments, modeling, and simulation strategies for the soft-error-rate estimation in state-of-the-art digital circuits
- Trends for future technological nodes and emerging devices

This book should thus be read and used in different ways and by a varied public concerned with the physics of soft errors: as an introductory course for graduate students, a specialized overview for academic researchers, and a practical guide for semiconductor industry engineers or application engineers. We would like to mention that excellent books on the same subject already exist. Without trying to be exhaustive, we would like to cite *Single Event Phenomena* by Messenger and Ash; *Handbook of Radiation Effects* by Holmes-Siedle and Adams; *SER—History, Trends and Challenges* by Ziegler and Puchner; *Radiation Effects and Soft Errors in Integrated Circuits and Electronic Devices*, edited by Schrimpf and Fleetwood; *Terrestrial Neutron-Induced Soft Errors in Advanced Memory Devices* by Nakamura, Baba, Ibe, Yahagi, and Kameyama; *Architecture Design for Soft Errors* by Mukherjee; and *Soft Errors in Modern Electronic Systems*, edited by Nicolaidis. The ensemble of these books covers all aspects of soft errors, from the environment to circuit and system levels. With respect to these important contributions in the domain, our objective was to propose a book that is clearly complementary in its content and that provides a state-of-the art overview in several domains, including

- The models and computer codes used to estimate the composition and particle flux for terrestrial cosmic rays
- The detection and characterization of high-energy atmospheric neutrons using a neutron monitor and the related physics and operation of this instrument
- The metrology, modeling, and simulation of alpha-particle emissivity in microelectronics materials
- The interaction of charged particles with matter, with a special emphasis on low-energy protons and muons
- A detailed review about real-time testing, with the most recent experiments and results in the domain completed by a comparison and a simulation-based analysis with accelerated tests
- A complete survey of the different modeling and simulation approaches at both device and circuit levels, with a methodical description of transport models, emerging physical effects in scaled devices, device numerical simulations, and compact models
- An accurate presentation of a Monte Carlo radiation transport code, detailing all the computational aspects of the simulation chain, including the analytical models implemented to evaluate the response of various circuit architectures (static random-access memory and flash memories) to radiation
- A complete review of the evolving risks of single-event effects for current and future complementary-metal-oxide-semiconductor technologies, covering from bulk, silicon-on-insulator, and fin-shaped field-effect transistor circuits to multiple-gate, nanowire, and junctionless devices

Structure of the Book

This book consists of twelve chapters in four sections and is organized as follows:

Section I: Environments—Definition and Metrology

Section I focuses on the natural radiation environment and its metrology in the particular context of microelectronics.

Chapter 1 introduces the terrestrial radiation environment in the atmosphere and at ground level. It provides a short description of galactic cosmic rays and focuses on particle radiation within the earth's atmosphere and at ground level. The sea-level and mountain-altitude environments are described in terms of particle composition, absolute flux values, and flux variations as a function of time and various environmental parameters. Shielding effects of terrestrial cosmic rays are also briefly discussed. The chapter is concluded by a short review of several models and computer codes used to estimate the composition and particle flux of the atmospheric environment, from high altitude to ground level.

Chapter 2 deals with the detection and characterization of high-energy atmospheric neutrons. The chapter focuses on the neutron monitor, a ground-level instrument used to measure the atmospheric neutron flux and to characterize its real-time variations. We describe the operation of this instrument and the evaluation of its response function for the different components of the atmospheric flux. The second part of the chapter is dedicated to the Plateau de Bure Neutron Monitor, an instrument specially designed and operated to characterize the magnitude of the neutron background. We successively describe its construction, installation, and operation over more than 7 years as well as its complete modeling and simulation.

Chapter 3 details the implications for microelectronics of the natural radioactivity present in all terrestrial materials. The chapter begins with the definition of several general aspects and quantities concerning radioactive elements. Primordial, cosmogenic, and human-produced radionuclides present in nature are next described, with a special emphasis on uranium and thorium due to the presence of numerous alpha-particle emitters in their radioactive decay chains. The implications of radon gas for microelectronics are also discussed, together with several important issues concerning the radioactive contamination of advanced complementary-metal-oxide-semiconductor technologies. Finally, an analytic model of the alpha-particle emissivity from single-layer materials and multilayer stacks is presented.

Chapter 4 introduces the alpha-particle detection techniques used as standard tools in microelectronics to detect, quantify, and identify the ultratraces of alpha emitters present in circuit materials. After introducing the basic definitions and important notions concerning alpha-radiation detection, the chapter focuses on the description of an ultralow-background alpha-particle counter recently introduced as a new standard of measurement at wafer level. The design, operation, modeling, and simulation of this metrology tool are illustrated from different contributions and recent works. Other detection techniques are briefly described in the last part of the chapter.

Section II: Soft Errors—Mechanisms and Characterization

The second section of the book deals with the soft-error mechanisms in semiconductor devices and the different experimental methods used to estimate the soft-error rate at circuit level.

Chapter 5 describes the interactions of both alpha and atmospheric particles with matter and their impact on the production of soft errors in semiconductor circuits. The interactions of neutrons and charged particles with matter are addressed, and different phenomena or quantities of interest are introduced. Interactions of protons, pions, and muons with matter are also detailed. The second part of the chapter introduces the basic mechanisms of creation of single-event effects and their impact on the operation of microelectronic devices. Finally, single-event upsets in advanced static random-access memory and single-event-effect mechanisms in logic circuits are considered. The production and propagation of digital single-event transients in sequential and combinational logic are also addressed.

Chapter 6 constitutes a short introduction to accelerated-soft-error-rate tests. We detail several types of accelerated-soft-error-rate experiments using intense beams of different types and flavors of particles: high-energy neutrons, thermal neutrons, monoenergetic protons, and muons. Accelerated tests using alpha-particle solid sources are also presented. The last part of the chapter details a recent simulation study that analyzes in-depth the differences between several artificial broad-spectrum sources of atmospheric-like neutrons in terms of recoils produced in the interactions of neutrons with silicon.

Chapter 7 gives an overview of recent real-time soft-error rate experiments, conducted at altitude, underground, or both, and investigating modern complementary-metal-oxide-semiconductor logic technologies down to the 40 nm technological node. The overview also includes several contributions by the authors, conducted during the last decade to characterize soft-error mechanisms in advanced static random-access memory. Finally, the chapter discusses the specific advantages and limitations of this approach as well as its comparison with accelerated tests using intense particle beams or sources.

Section III: Soft Errors—Modeling and Simulation Issues

The third section of this book overviews the crucial issues of soft-error modeling and simulation at both device and circuit levels.

Chapter 8 presents the different approaches of modeling and simulation of single-event effects in microelectronic devices and integrated circuits. The interest of simulating radiation effects is discussed in the first section, and a brief overview of the simulation at device and circuit levels is presented and illustrated. Device-level simulation is addressed next, including a detailed description of transport models, emerging physical effects in scaled devices, device numerical simulations, and compact models. Finally, circuit-level simulation is introduced, with a particular emphasis on the advantages and drawbacks of various approaches that can be used to simulate single-event effects at circuit level.

Chapter 9 gives an overview of different Monte Carlo computational methods applied to the analysis of single-event effects in semiconductor devices. In the first part, this chapter provides a brief inventory of Monte Carlo-based radiation transport tools to simulate a variety of effects that result from particle interactions with matter. We also provide a short description of a few recent simulation codes specially designed to support the analysis of single-event effects in semiconductor devices. In the second part of the chapter, we describe in more detail a complete general-purpose simulation platform we have developed in recent years for the numerical evaluation of the sensitivity of digital circuits subjected to natural radiation at ground level. Applications of this simulation platform are illustrated through different case studies.

Section IV: Soft Errors in Emerging Devices and Circuits

Finally, the fourth section of the book explores the important consequences of the evolution of microelectronics for the single-event susceptibility of current and future devices and circuits.

Chapter 10 discusses the major consequences of the scaling down of complementary metal-oxide semiconductors for the single-event susceptibility of devices and circuits. Several factors impacting their soft-error rate are surveyed, notably the reduction of device geometry, the increase of operation frequency, and the reduction of the critical charge/energy deposition necessary to cause a single event. The combination of these factors and their consequences for transistor/circuit operation are carefully examined. The impact of all these factors on the soft error rate is also explained and illustrated for sub-45 nm bulk and silicon-on-insulator complementary-metal-oxide-semiconductor technologies.

Chapter 11 addresses an important reliability issue concerning the sensitivity of non-volatile flash memories to the terrestrial radiation environment. We report a recent study based on a new type of experiment conducted at wafer level that combined characterization