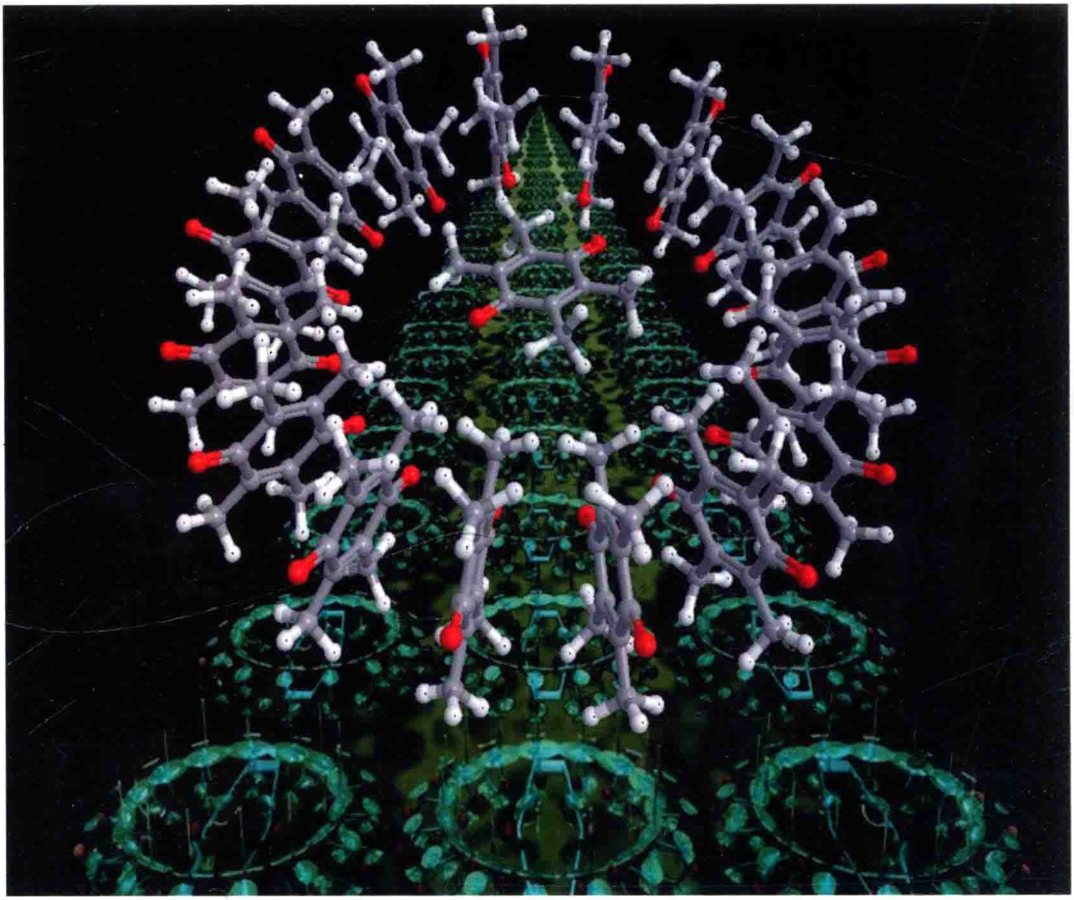
PHYSICS TEXTBOOK

Edward L. Wolf

WILEY-VCH

Quantum Nanoelectronics

An Introduction to Electronic Nanotechnology and Quantum Computing



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Dedicated to
My Family and Colleagues

Preface

The starting point for this book was my experience in designing and teaching a successful course "Physics of Nanoelectronics" to students at Polytechnic University, in Brooklyn, NY, which is now affiliated with New York University. The syllabus for the course was an outgrowth of earlier courses: "Concepts of Nanotechnology", and "Techniques and Applications of Nanotechnology". These courses were designed for upper level undergraduate and beginning graduate students in science and in engineering. The prerequisite was limited to introductory calculus-based college Physics. It is not surprising that the content of the new book has evolved beyond these topics.

The present result, Physics Text "Quantum Nanoelectronics: An Introduction to Electronic Nanotechnology and Quantum Computing", is unique in several regards. This is the only book on Nanoelectronics, *which presumes only elementary college physics* and related courses, to reach, in a quantitative fashion, the latest device aspects of nanoelectronics and nanoelectronic technology. (The disclaimer: computer architectures and advanced circuit designs are topics beyond the present scope. For these topics the reader is referred to References 6–8 in Chapter 1.)

In a second unique aspect, "Nanoelectronic Technology", based by definition on "controlled structures having at least one dimension in the range 1 to 100 nm", is extended in some cases to devices based on ions. The atomic scale workings of lithium ion batteries and similar devices are of great importance and are likely to be improved by the thinking and instrumentation normally associated with semiconductor nanoelectronics. Advancing Moore's Law has always been a multidisciplinary and interdisciplinary endeavor.

Third, the evolving forms of photovoltaic solar cells, of increasing timely importance, are covered in a comprehensive and completely up-to-date fashion. Recent advances include multi-junction "tandem" cells of record 42.8% conversion efficiency, and production of a full Gigawatt of capacity from a revolutionary nano-ink printing-press process. This high volume process may well produce electricity at cost below the present market.

As a fourth unique aspect, *Quantum computing* is covered with emphasis on experimental solid state devices, and, in particular, on the *Adiabatic Quantum*

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Computing approach. The treatment certainly makes clear the huge potential benefit of quantum computing in a time of rapidly rising computational energy costs, with greenhouse gas emissions already attributed to cloud computing. The rapid single flux quantum superconducting technology is covered, preceded by appropriate preparatory material.

Other remarkable recent nanoelectronic advances fully explained to the motivated reader include a sixteen-bit molecular computing device of overall diameter 2.5 nm (see cover illustration), highly efficient multi-junction organic white-light-emitting diodes, a photonic-crystal injection laser emitting in the blue-violet, and single crystal magnetotunneling junctions exhibiting 300% magnetoresistance at room temperature.

A final unique aspect is that a more entrepreneurial approach has been taken, including economic and market aspects, mostly with respect to the perceived energy technology opportunities for nanoelectronic technology.

The theme "Innovation, Invention, and Entrepeneurship", which relates to The Polytechnic Institute in its nascent role in New York University, and which historically has led the advance of Moore's Law, is embraced in this book. After all, "the traitorous eight" had to leave the established firm to actually get integrated circuits into production.

Polytechnic students in various majors, enthusiastic members of the several classes, have influenced this book. I particularly note stimulating interactions with Samir Ajmera, Aung Thant, Chris LoBello, Juanpablo Borja, Lily Kuo, Eric Laird, Richard Stern and Pavel Borodulin.

I also thank Dr. Anirban Bandyopadhyay for providing access to his most recent unpublished works, which have contributed to the Cover, and to sections in Chapter 3 and Chapter 9. Thanks are also due to Prof. S. Hughes, University of. Kingston, Ontario, Canada, Prof. Randall M. Feenstra, Carnegie-Mellon Univ., and Prof. Thomas Furtak, Colorado School of Mines, for helpful communications.

The new book has also followed from my previous rewarding experiences with Editors at Wiley-VCH, in writing and publishing *Nanophysics and Nanotechnogy*, 1st and 2nd Editions, in 2004 and 2006, respectively. The present book, as the earlier books, has greatly benefited from the competent advice and assistance of Ulrike Werner, Vera Palmer and their associates at Wiley-VCH, and also from the encouragement of Ed Immergut, Consulting Editor.

The project has benefited from competent cheerful assistance of DeShane Lyew in the Physics Department, and from grant of a sabbatical leave from Polytechnic University. I am grateful particularly to Prof. Locan Folan and Dr. Erich Kunhardt for helping me arrange this sabbatical.

My wife Carol has been a constant source of help and encouragement with these projects.

Brooklyn, NY
July 6, 2008

Edward Wolf

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Introduction and Review of Electronic Technology

Electronic devices are central to modern technology. Silicon chips are everywhere, including cars and appliances, and have transformed computation, information processing, and communications, culminating in the modern Internet. The silicon revolution started with the transistor, leading to the integrated circuit, and to the Pentium chip. A related semiconductor device, the solid-state junction laser, in conjunction with the optical fiber, has led to cheap, reliable virtually instantaneous worldwide communication. Outsourcing, globalization, and the "flat world" have been enabled by these technical advances.

The assumption of this book is that this revolution is not over, but rather is entering a new phase. The era of microelectronics is opening to a future of nanoelectronic technology.

The central feature of the silicon revolution has been the miniaturization of transistors and their grouping into integrated circuits, which now contain billions of identical transistor elements. In very large scale integration (VLSI), a whole computer can exist on a square centimeter of silicon. Smaller transistors are cheaper, more are available on a single chip, and operate more quickly, now as fast as 3 billion steps per second. Gordon Moore, a founder of the Intel Corporation, noted long ago that the number of transistors per chip, roughly one square centimeter, tended to double every 18 months or so as the technology improved and larger markets appeared. "Moore's law" has seen the transistor count increase from hundreds to hundreds of millions! Chips containing 0.8 billion transistors on roughly one square centimeter are being produced as described in Chapter 7 [1].

The key to this advance has been the "scaling" to smaller size of the active cells, containing field effect transistors (FETs) and other devices. Scaling has taken silicon electronics into the nanometer domain, where it now is approaching its limit, set by the size of atoms. The smallest dimension in the FET has been the thickness of the thermally grown silicon dioxide insulator for the gate electrode. It has long been recognized that scaling will work only down to thicknesses large compared to the silicon and oxygen atomic radii in the SiO_2, needed to preserve the desired insulating property. Intel Corporation [1] has abandoned the scaled silicon dioxide to insulate the gate electrode, in favor of deposited "high dielectric constant" oxides based on the heavy metals hafnium and zirconium. Literally, the thermally grown silica, forced

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