

Physics of Submicron Devices

MICRODEVICES

Physics and Fabrication Technologies

Series Editors: Julius J. Muray† and Ivor Brodie

*SRI International
Menlo Park, California*

ELECTRON AND ION OPTICS

Miklos Szilagy

GaAs DEVICES AND CIRCUITS

Michael Shur

ORIENTED CRYSTALLIZATION ON AMORPHOUS SUBSTRATES

E. I. Givargizov

PHYSICS OF SUBMICRON DEVICES

David K. Ferry and Robert O. Grondin

SEMICONDUCTOR LITHOGRAPHY

Principles, Practices, and Materials

Wayne M. Moreau

† *Deceased.*

A Continuation Order Plan is available for this series. A continuation order will bring delivery of each new volume immediately upon publication. Volumes are billed only upon actual shipment. For further information please contact the publisher.

Physics of Submicron Devices

David K. Ferry and
Robert O. Grondin

*College of Engineering and Applied Science
Center for Solid State Electronics Research
Arizona State University
Tempe, Arizona*

Springer Science+Business Media, LLC

Library of Congress Cataloging in Publication Data

Ferry, David K.

Physics of submicron devices / David K. Ferry and Robert O. Grondin.

p. cm. — (Microdevices)

Includes bibliographical references and index.

ISBN 978-1-4613-6444-3 ISBN 978-1-4615-3284-2 (eBook)

DOI 10.1007/978-1-4615-3284-2

1. Semiconductors. 2. Solid state physics. 3. Electronics—Materials. 4. Electron transport. 5. Microstructure. I. Grondin, Robert Oscar. II. Title. III. Series.

QC611.F42 1991

91-31155

537.6'22—dc20

CIP

ISBN 978-1-4613-6444-3

© 1991 Springer Science+Business Media New York
Originally published by Plenum Press, New York in 1991

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording, or otherwise, without written permission from the Publisher

Preface

The purposes of this book are many. First, we must point out that it is not a device book, as a proper treatment of the range of important devices would require a much larger volume even without treating the important physics for submicron devices. Rather, the book is written principally to pull together and present in a single place, and in a (hopefully) uniform treatment, much of the understanding on relevant physics for submicron devices. Indeed, the understanding that we are trying to convey through this work has existed in the literature for quite some time, but has not been brought to the full attention of those whose business is the making of submicron devices.

It should be remarked that much of the important physics that is discussed here may not be found readily in devices at the $1.0\text{-}\mu\text{m}$ level, but will be found to be dominant at the $0.1\text{-}\mu\text{m}$ level. The range between these two is rapidly being covered as technology moves from the 256K RAM to the 16M RAM chips. Indeed, devices can be made much smaller, as Si MOSFETs have been made by IBM and MIT with effective gate lengths as short as 70 nm, while MESFETs and HEMTs have been made at Arizona State University and in Japan with gate lengths as short as 25 nm. Whether devices with these gate lengths will ever make it into production in VLSI chips is problematical. It is far more important to note that these devices will provide windows into the relevant physics that will set the ultimate limits on downscaling of semiconductor devices. As much as the minimum feature size (usually the gate length) on VLSI chips has shrunk, the *predicted* limit to down-scaling has shrunk, often at the same rate. Less than two decades ago, it was stated by one knowledgeable individual (whose identity shall remain unknown to the reader) that MOSFETs could never be made (in integrated circuits) with gate lengths less than $10\ \mu\text{m}$. We clearly do much better. We illustrate in Figure P1 how this predicted limit to down-scaling has progressed through the recent decades.

The current “projected” minimum feature size (indicated by the symbol next to the question mark in Figure P1) is based upon the observation in 20–25- μm HEMTs that tunneling through the depletion region prevents the devices from being “pinched off” and therefore greatly reduces the transconductance. It is not at all sure that this will be a limitation on downsizing, as clever engineers find

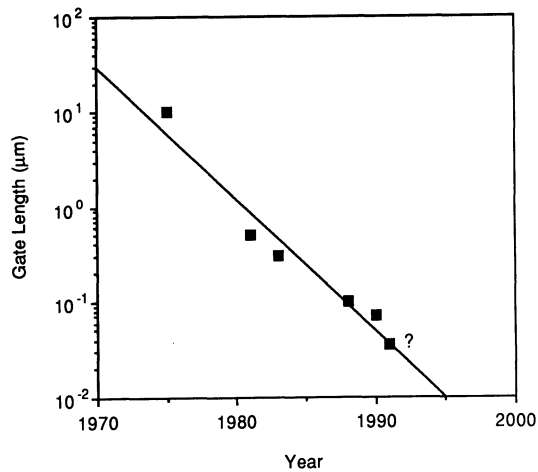


FIGURE P1. Projected minimum feature size.

other ways to introduce devices. However, the downsizing arguments point out the need to understand much physics, which has been ignored as "... second- and third-order effects, ..." in current devices. If for no other reason, it is important to understand the physics that becomes important in submicron (and ultrasubmicron) devices just as it is important to understand the circuit interaction effects.

In the process above, we try to provide a good summary of a widely scattered literature. The focus is generally on physics instead of devices, but even then the physics is not usually discussed in a conventional solid-state or semiconductor physics book. Here, rather than greatly worry over band structure and phonon spectra calculations, we instead employ the physical pictures produced by such calculations in a detailed study of electric current flow in submicron systems.

Chapter 1 reviews the material usually found in a conventional solid-state physics book, but we try to illustrate certain critical assumptions (e.g., treating scattering processes as being independent) and the weakness of certain commonly discussed ideas (e.g., tunneling times). Chapter 2, on the other hand, reviews a number of important technological processes involved in the preparation of submicron structures. Then in Chapter 3 the important properties of interfaces, whether heterojunctions between semiconductors or between an insulator and a semiconductor, are discussed. We also introduce simple models of the operation of the common devices.

Chapter 4 begins, and Chapter 5 finishes, a detailed tutorial overview of semiclassical transport theory. All commonly used, and some rarely used, schemes are discussed and their interrelationship explored. The central theme that develops is that the ensemble Monte Carlo technique is for a variety of good reasons the workhorse technique of hot-carrier transport calculations. What may not be as obvious is that many of the supposedly computationally simpler approaches may

not be computationally simpler. These approaches often look simple, but when one starts asking about performing calculations in two or three spatial dimensions one finds that the equation sets grow rapidly in complexity. Such an extension, however, is basically quite trivial for Monte Carlo models. The boundary conditions also are not simplified when compared to Monte Carlo cases, and in small devices this can be quite important. Last, and often overlooked, since people usually do not publish numerical methods that fail, is the issue of numerical stability. While the Monte Carlo approach is inherently stable, the coupled sets of nonlinear partial differential equations produced in other approaches often pose formidable problems in a numerical implementation.

Chapter 5 concludes with a review of numerous attempts at experimentally seeing the effects of transient hot-carrier transport effects. The holy grail is to somehow see a velocity overshoot. We hope that this review will illustrate that while it seems clear from a variety of experiments that a velocity overshoot is occurring, a quantitative experimental observation has not yet been produced.

Chapter 6 discusses the important materials area of alloys between different semiconductors. These are both useful and interesting, but it is important to know that some “warts” appear in the simple theories that have been formulated. Then, in Chapter 7 the important electron–electron interaction and the screening effects introduced by this process are discussed. This is followed in Chapter 8 by a discussion of the relatively new area of surface superlattices.

We end the book in Chapters 9 and 10 with a discussion of quantum transport and of noise in submicron devices. These are areas in which very few experiments have been performed and relatively few calculations done. Perhaps the most important observation there is that some of the guesses that one is tempted to make about the spatial and temporal correlations seen in hot-carrier transport are not only wrong but in some cases predict trends opposite to the correct ones. We suspect that a detailed understanding of the noise limits faced in submillimeter-wave systems still lies outside the limits of our theories.

It is assumed that the reader has a basic understanding of solid state physics and electronics, at least to the level of a text such as Kittel’s or Ashcroft and Mermin’s. This also assumes that the reader has had an introductory course in quantum mechanics, although such important topics as tunneling and time-dependent perturbation theory are reviewed in Chapter 9, where they are important for very small devices and very high electric fields.

David K. Ferry
Robert O. Grondin

Tempe, Arizona

Contents

CHAPTER 1. An Introductory Review	
1.1. General Introduction	1
1.2. Constitutive Relations	3
1.3. Surfaces, Interfaces, and Boundary Conditions	5
1.4. States, Bands, Zones, and Lattices	8
1.5. Ballistic Electron Dynamics in Lattices	16
1.6. Tunneling	18
1.7. Phonons and Carrier Scattering	21
1.8. Some Scattering Related Times, Paths, and Rates	26
1.9. Hot-Carrier Effects	29
1.10. Summary	38
A.1. Electron Scattering in GaAs and Si	40
A.2. Hole Scattering in GaAs and Si	45
References	48
CHAPTER 2. Fabrication Techniques for Submicron Devices	
2.1. Lithography	52
2.1.1. Patterning Considerations	53
2.1.2. Time	54
2.1.3. Resist Materials	54
2.1.3.1. Exposure	55
2.1.3.2. Resolution Limits	57
2.1.3.3. Multilevel Resists	59
2.1.3.4. Dry Processing	60
2.1.4. Optical Patterning	61
2.1.4.1. Proximity Printing	61
2.1.4.2. Projection Patterning	62
2.1.5. X-ray Lithography	63
2.1.6. Electron-Beam Lithography	65
2.1.7. Ion-Beam Lithography	68

2.2. Dry Processing	71
2.2.1. Reactive Ion Etching Mechanisms	73
2.2.2. Etching Rate and Control	73
2.3. Epitaxial Growth	75
2.3.1. Vapor-Phase Epitaxy	75
2.3.2. Metal-Organic Chemical Vapor Deposition	76
2.3.3. Molecular-Beam Epitaxy	77
2.3.4. Heterostructures	78
2.4. Metallization	78
2.5. Contacts and Schottky Barriers	79
2.5.1. The Potential Interface	80
2.5.2. The Space-Charge Region	84
2.5.3. Current Flow	85
2.5.4. Contacts	87
References	88
CHAPTER 3. Heterojunctions and Interfaces	
3.1. Modulation Doping	92
3.1.1. Carrier Density	94
3.1.2. Band Discontinuity	99
3.2. Semiconductor-Insulator Interfaces	100
3.3. Two-Dimensional Quantization	102
3.3.1. Surface Subbands	103
3.3.2. Approximate Solutions	106
3.3.3. Effects of Nonparabolicity	109
3.4. Interface Scattering Mechanisms	109
3.4.1. Coulomb Scattering	110
3.4.2. Surface-Roughness Scattering	112
3.5. The MOS Device	116
3.5.1. The Gradual-Channel Approximation	118
3.5.2. Field-Dependent Mobility	121
3.5.3. Short-Channel Effects	123
3.6. The High-Electron-Mobility Transistor	125
3.6.1. Charge Control by the Gate	126
3.6.2. The Current-Voltage Relation	129
3.6.3. A Two-Dimensional Result	133
3.7. Real-Space Transfer	133
References	136
CHAPTER 4. Semiclassical Carrier Transport Models	
4.1. Carrier Transport	137
4.2. Drift-Diffusion Laws and Brownian Motion	138

4.3. Distribution Functions and Their Use	143
4.4. The Boltzmann Transport Equation	145
4.5. Linearizing the Boltzmann Transport Equation	147
4.6. Linear Transport Theory in the Relaxation-Time Regime.....	149
4.7. Nonlinear Energy-Momentum-Conserving Models	151
4.8. The Monte Carlo Technique	159
4.9. Brownian Dynamics	165
4.10. Retarded Langevin Equations	167
References	170
CHAPTER 5. Transient Hot-Carrier Transport	
5.1. Ensemble Monte Carlo Techniques	173
5.1.1. Direct Comparison with Retarded Langevin Equations	173
5.2. Projection Operators and Transport Equations.....	176
5.3. Path Integral Solutions to General Transport Equations	179
5.4. Nonequivalence of Boltzmann Theory and Ensemble Monte Carlo	181
5.5. Extraction of Moment Equations	186
5.6. Application to a Degenerate System.....	188
5.7. Drive and Frequency Dependence of the Complex Mobility...	191
5.7.1. Analyses of Undepleted Epitaxial Material	191
5.7.2. Monte Carlo Studies of the Admittance of a Semiconductor	192
5.8. Iterative Solution to the Boltzmann Equation.....	195
5.9. Transient Dynamic Response Experiments: Frequency- and Time-Domain Studies	198
5.9.1. Introduction	198
5.9.2. Frequency-Domain Studies	201
5.9.3. Time-Domain Studies.....	204
5.9.4. Monte Carlo Studies of Transient Photoconductivity....	211
5.9.5. Circuit Effects in Transient Photoconductivity	217
5.10. DC Studies in Submicron Structures	223
5.11. High-Excitation Effects	225
5.12. Ballistic Transport in Small Structures	236
References	238
CHAPTER 6. Alloys and Superlattices	
6.1. The Semiempirical Tight-Binding Method.....	246
6.2. The Dielectric Theory of Band Structures	250
6.2.1. Silicon	254
6.2.2. The III-V Compounds	255
6.2.3. Some II-VI Compounds	256

6.3. Pseudobinary Alloys	257
6.4. Alloy Ordering	263
6.5. Alloy Scattering	269
6.6. Quantum Well Superlattices	271
6.6.1. The Schrödinger Equation	272
6.6.2. Strained-Layer Superlattices	274
References	276
CHAPTER 7. The Electron–Electron Interaction	
7.1. The Random-Phase-Approximation Dielectric Function	280
7.1.1. The Lindhard Potential	281
7.1.2. The Optical Dielectric Constant	282
7.2. Plasmons and Phonons	283
7.2.1. Plasmon-Phonon Coupling	284
7.2.2. Scattering Strengths	286
7.3. Screening of Scattering Potentials	287
7.3.1. The Debye Screening Limit	288
7.3.2. Momentum-Dependent Screening	289
7.4. Plasmon Scattering	290
7.5. Descreening of a Potential	292
References	296
CHAPTER 8. Lateral Surface Superlattices	
8.1. Lateral Superlattices	298
8.2. GaAs Structures	304
8.3. Transport Effects	307
8.3.1. Steady Transport	307
8.3.2. High-Frequency Response	309
References	312
CHAPTER 9. Quantum Transport in Small Structures	
9.1. The General Problem	316
9.1.1. Fermi Golden Rule	317
9.1.2. Initial-State Decay	319
9.1.3. Field Interactions	321
9.2. Transport in Silicon Dioxide	324
9.3. Resonant Tunneling	326
9.3.1. Tunneling Probabilities	327
9.3.2. Pseudodevice Calculations	336

9.4. Linear Response Theory	342
9.4.1. The Langevin Equation	344
9.4.2. Relaxation and Green's Functions	345
9.4.3. Extension to Two-Time Functions	347
9.5. The Density Matrix Equation of Motion	350
9.6. The Wigner Transform and Equation of Motion	355
References	361
CHAPTER 10. Noise in Submicron Devices	
10.1. Introduction	363
10.2. Velocity Fluctuation Noise Sources	364
10.2.1. Velocity Fluctuation Noise Sources	364
10.2.2. Velocity Fluctuations and Diffusion	365
10.2.3. Connection with Thermal Noise	366
10.2.4. Diffusion Noise in Nonequivalent Valleys	366
10.3. The Spectral Density Functions	368
10.3.1. Physical Background	368
10.3.2. Mathematical Background	370
10.3.3. Statistical Procedures	371
10.3.3.1. Background to Time Series Analysis	371
10.3.3.2. Window Function Properties	374
10.3.3.3. Choice of Time Series Length and Sampling Rate	375
10.3.4. Discussion of Monte Carlo Results for Velocity Fluctuation Spectra	376
10.3.5. The Quantum Correction Factor	379
10.3.6. Effective Noise Temperatures	379
10.4. Spatial Correlations and Nonstationary Transport	381
10.4.1. Energy and Velocity Fluctuation Correlation Functions	381
10.4.2. Nonstationary Transport of Average Values	384
10.5. Shot Noise	385
10.5.1. Transit-Time Effects in Shot Noise	385
10.5.2. Barrier Transit-Time Diffusion Case	387
10.5.3. Noise Sideband Correlation in Time-Periodic Systems	387
10.5.4. Mathematical Introduction	388
10.5.5. Origin of the Noise Correlation	388
10.6. Poisson Point Process Model of Carrier Injection	391
10.6.1. Poisson Point Processes	391
10.6.2. Connection with Deterministic Models	393
10.6.3. Correlated Velocity Fluctuation Noise	393
10.7. Noise in Ballistic Diodes	394
References	395
Index	397