

Eastern
Economy
Edition

FIFTH EDITION

SOLID STATE ELECTRONIC DEVICES

BEN G. STREETMAN ■ SANJAY BANERJEE



SEMICONDUCTOR PHYSICS

Electron Momentum: $p = mv = \hbar k = \frac{h}{\lambda}$

Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{p^2}{m} = \frac{\hbar^2}{2m^*}k^2$ (3-4)

Effective mass: $m^* = \frac{\hbar^2}{d^2E/dk^2}$ (3-3)

Total electron energy = P.E. + K.E. = $E_c + E(k)$

Fermi-Dirac e^- distribution: $f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \cong e^{-(E-E_F)/kT}$ for $E \gg E_F$ (3-10)

Equilibrium: $n_0 = \int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c-E_F)/kT}$ (3-15)

$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ $N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (3-16), (3-20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F-E_v)/kT}$ (3-19)

$n_i = N_c e^{-(E_c-E_i)/kT}$, $p_i = N_v e^{-(E_i-E_v)/kT}$ (3-21)

$n_i = \sqrt{N_c N_v} e^{-E_i/2kT} = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4} e^{-E_i/2kT}$ (3-23), (3-26)

Equilibrium: $n_0 = n_i e^{(E_i-E_F)/kT}$
 $p_0 = n_i e^{(E_F-E_i)/kT}$ (3-25)

$n_0 p_0 = n_i^2$ (3-24)

Steady state: $n = N_c e^{-(E_c-F_n)/kT} = n_i e^{(F_n-E_i)/kT}$
 $p = N_v e^{-(F_p-E_v)/kT} = n_i e^{(E_i-F_p)/kT}$ (4-15)

$np = n_i^2 e^{(F_n-F_p)/kT}$ (5-38)

$\mathcal{E}(x) = -\frac{dV(x)}{dx} = \frac{1}{q} \frac{dE_i}{dx}$ (4-26)

Poisson: $\frac{d^2\mathcal{E}(x)}{dx^2} = -\frac{d^2V(x)}{dx^2} = \frac{\rho(x)}{\epsilon} = \frac{q}{\epsilon} (p - n + N_d^+ - N_a^-)$ (5-14)

$\mu \equiv \frac{q\bar{v}}{m^*}$ (3-40a) Drift: $v_d \equiv \frac{\mu\mathcal{E}}{1 + \mu\mathcal{E}/v_s} \begin{cases} = \mu\mathcal{E} \text{ (low fields, ohmic)} \\ = v_s \text{ (high fields, saturated vel.)} \end{cases}$ (Fig. 6-9)

Drift current density: $\frac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathcal{E}_x = \sigma\mathcal{E}_x$ (3-43)

$$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx}$$

Conduction Current: drift diffusion (4-23)

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx}$$

$$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C \frac{dV}{dt}$$

Continuity:
$$\frac{\partial p(x, t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \quad \frac{\partial \delta n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n} \quad (4-31)$$

For steady state diffusion:
$$\frac{d^2 \delta n}{dx^2} = \frac{\delta n}{D_n \tau_n} \equiv \frac{\delta n}{L_n^2} \quad \frac{d^2 \delta p}{dx^2} = \frac{\delta p}{L_p^2} \quad (4-34)$$

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\frac{D}{\mu} = \frac{kT}{q} \quad (4-29)$

p-n JUNCTIONS

Equilibrium:
$$V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{N_a}{n_i^2/N_d} = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2} \quad (5-8)$$

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT} \quad (5-10) \quad W = \left[\frac{2\epsilon(V_0 - V)}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \quad (5-57)$$

One-sided abrupt $p^+ - n$: $x_{n0} = \frac{WN_a}{N_a + N_d} \approx W \quad (5-23) \quad V_0 = \frac{qN_d W^2}{2\epsilon}$

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1) \quad (5-29)$$

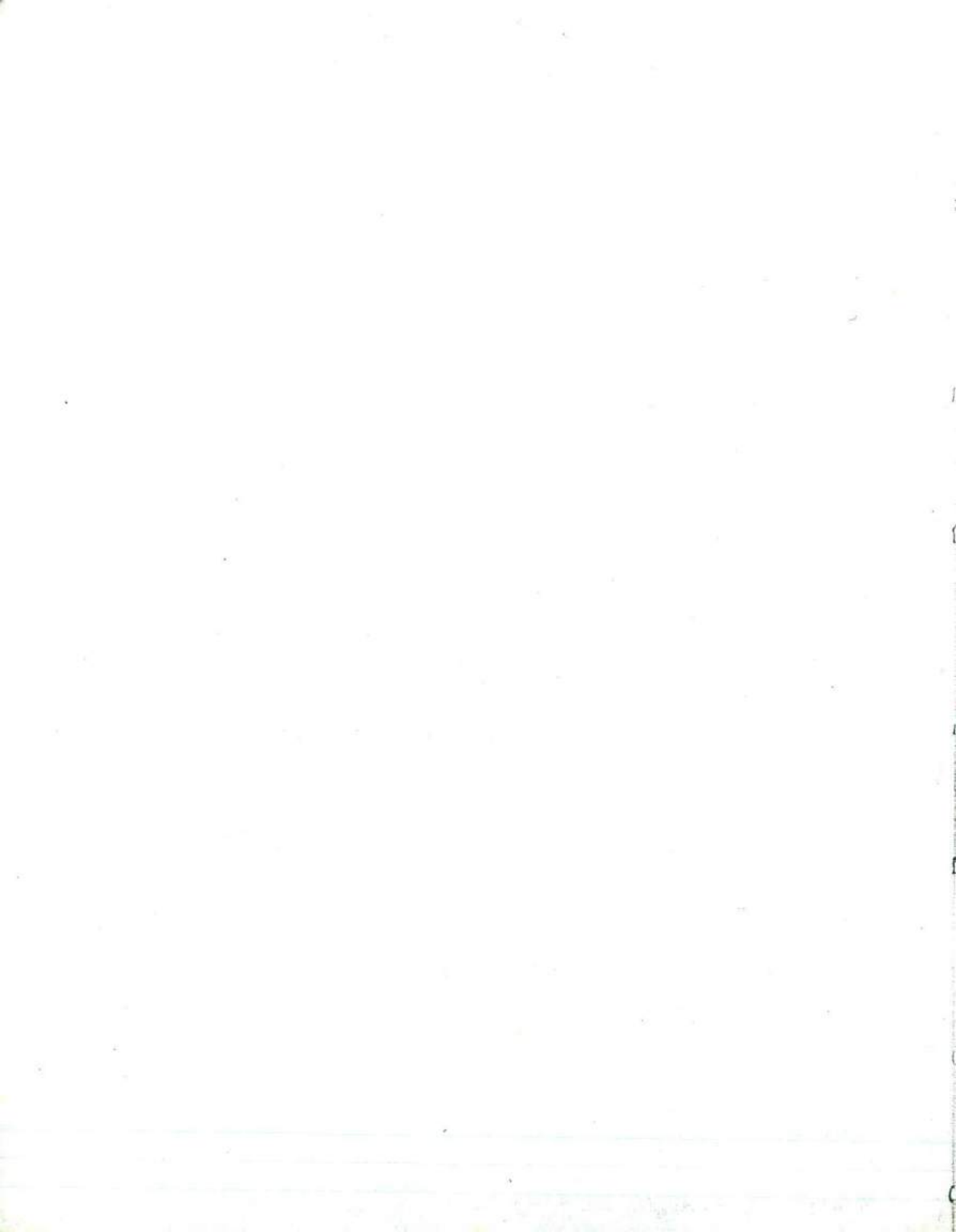
$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p} \quad (5-31b)$$

Ideal diode:
$$I = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_0 (e^{qV/kT} - 1) \quad (5-36)$$

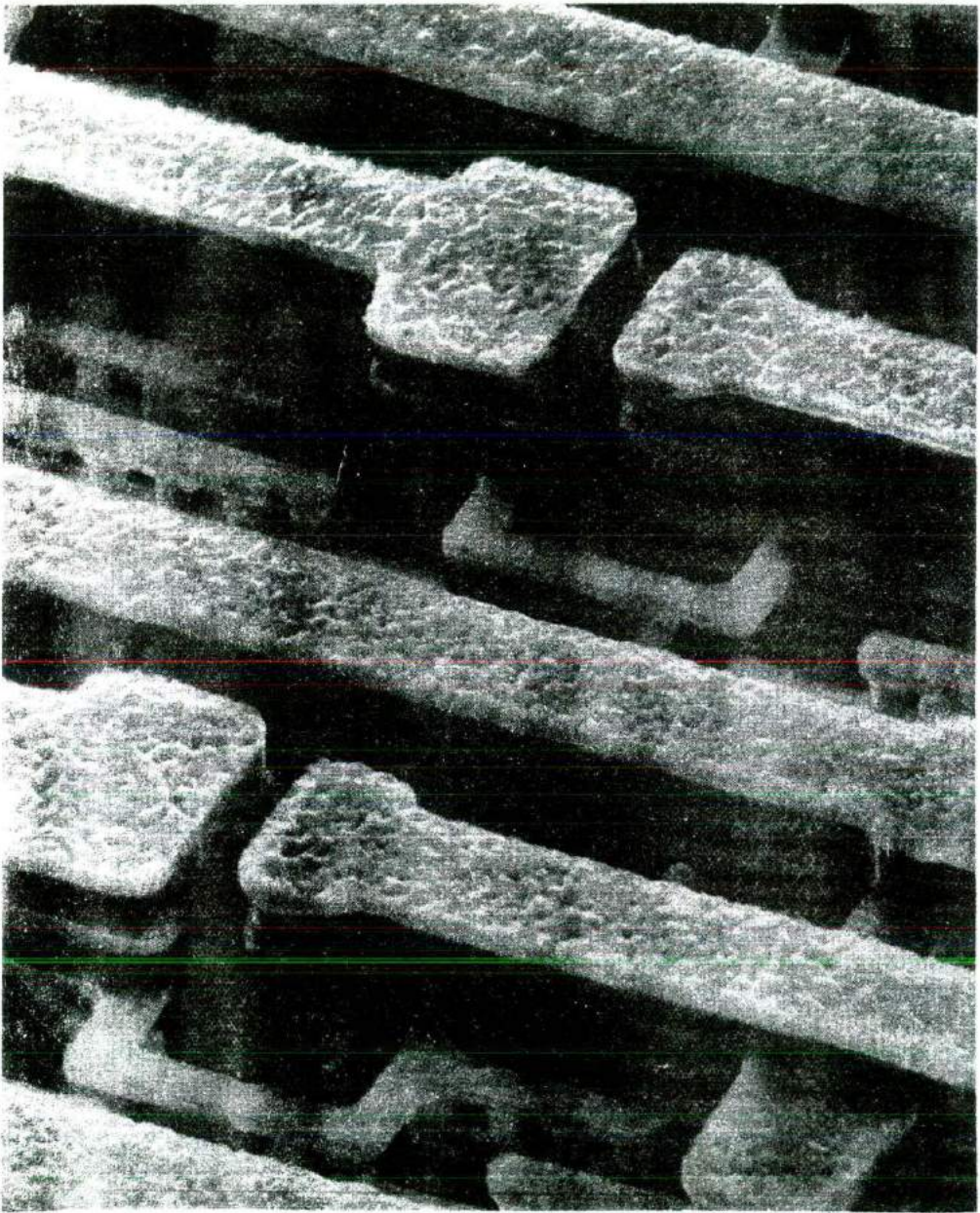
Non-ideal:
$$I = I_0 (e^{qV/mkT} - 1) \quad (5-74)$$

($m = 1$ to 2)

With light:
$$I_{\text{op}} = qA g_{\text{op}} (L_p + L_n + W) \quad (8-1)$$



Solid State Electronic Devices



Multi-level copper metallization of a complementary metal oxide semiconductor (CMOS) chip. This scanning electron micrograph (scale: 1 cm = 3.5 microns) of a CMOS integrated circuit shows six levels of copper metallization that are used to carry electrical signals on the chip. The inter-metal dielectric insulators have been chemically etched away here to reveal the copper interconnects. (Photograph courtesy of IBM.)

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STREETMAN AND SANJAY BANERJEE

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CONTENTS

PREFACE XV

ABOUT THE AUTHORS XIX

1 CRYSTAL PROPERTIES AND GROWTH OF SEMICONDUCTORS 1

- 1.1 Semiconductor Materials 1
 - 1.2.1 Periodic Structures 3
- 1.2 Crystal Lattices 3
 - 1.2.2 Cubic Lattices 5
 - 1.2.3 Planes and Directions 7
 - 1.2.4 The Diamond Lattice 9
- 1.3 Bulk Crystal Growth 12
 - 1.3.1 Starting Materials 12
 - 1.3.2 Growth of Single Crystal Ingots 13
 - 1.3.3 Wafers 14
 - 1.3.4 Doping 16
- 1.4 Epitaxial Growth 17
 - 1.4.1 Lattice Matching in Epitaxial Growth 18
 - 1.4.2 Vapor-Phase Epitaxy 21
 - 1.4.3 Molecular Beam Epitaxy 23

2 ATOMS AND ELECTRONS 28

- 2.1 Introduction to Physical Models 28
- 2.2 Experimental Observations 30
 - 2.2.1 The Photoelectric Effect 30
 - 2.2.2 Atomic Spectra 31
- 2.3 The Bohr Model 33
- 2.4 Quantum Mechanics 36
 - 2.4.1 Probability and the Uncertainty Principle 36
 - 2.4.2 The Schrödinger Wave Equation 38
 - 2.4.3 Potential Well Problem 40
 - 2.4.4 Tunneling 42
- 2.5 Atomic Structure and the Periodic Table 43
 - 2.5.1 The Hydrogen Atom 43
 - 2.5.2 The Periodic Table 46

3

ENERGY BANDS AND CHARGE
CARRIERS IN SEMICONDUCTORS 55

- 3.1 Bonding Forces and Energy Bands in Solids 55
 - 3.1.1 Bonding Forces in Solids 55
 - 3.1.2 Energy Bands 58
 - 3.1.3 Metals, Semiconductors, and Insulators 61
 - 3.1.4 Direct and Indirect Semiconductors 62
 - 3.1.5 Variation of Energy Bands with Alloy Composition 64
- 3.2 Charge Carriers in Semiconductors 66
 - 3.2.1 Electrons and Holes 67
 - 3.2.2 Effective Mass 70
 - 3.2.3 Intrinsic Material 74
 - 3.2.4 Extrinsic Material 75
 - 3.2.5 Electrons and Holes in Quantum Wells 79
- 3.3 Carrier Concentrations 80
 - 3.3.1 The Fermi Level 80
 - 3.3.2 Electron and Hole Concentrations at Equilibrium 83
 - 3.3.3 Temperature Dependence of Carrier Concentrations 88
 - 3.3.4 Compensation and Space Charge Neutrality 90
- 3.4 Drift of Carriers in Electric and Magnetic Fields 92
 - 3.4.1 Conductivity and Mobility 92
 - 3.4.2 Drift and Resistance 96
 - 3.4.3 Effects of Temperature and Doping on Mobility 97
 - 3.4.4 High-Field Effects 99
 - 3.4.5 The Hall Effect 100
- 3.5 Invariance of the Fermi Level at Equilibrium 102

4

EXCESS CARRIERS IN SEMICONDUCTORS 108

- 4.1 Optical Absorption 108
- 4.2 Luminescence 111
 - 4.2.1 Photoluminescence 111
 - 4.2.2 Electroluminescence 114
- 4.3 Carrier Lifetime and Photoconductivity 114
 - 4.3.1 Direct Recombination of Electrons and Holes 115
 - 4.3.2 Indirect Recombination; Trapping 117
 - 4.3.3 Steady State Carrier Generation; Quasi-Fermi Levels 120
 - 4.3.4 Photoconductive Devices 123
- 4.4 Diffusion of Carriers 124
 - 4.4.1 Diffusion Processes 124
 - 4.4.2 Diffusion and Drift of Carriers; Built-in Fields 127

- 4.4.3 Diffusion and Recombination; The Continuity Equation 130
- 4.4.4 Steady State Carrier Injection; Diffusion Length 132
- 4.4.5 The Haynes-Shockley Experiment 134
- 4.4.6 Gradients in the Quasi-Fermi Levels 137

5 JUNCTIONS 142

- 5.1 Fabrication of p-n Junctions 142
 - 5.1.1 Thermal Oxidation 142
 - 5.1.2 Diffusion 144
 - 5.1.3 Rapid Thermal Processing 146
 - 5.1.4 Ion Implantation 147
 - 5.1.5 Chemical Vapor Deposition (CVD) 150
 - 5.1.6 Photolithography 151
 - 5.1.7 Etching 155
 - 5.1.8 Metallization 156
- 5.2 Equilibrium Conditions 157
 - 5.2.1 The Contact Potential 159
 - 5.2.2 Equilibrium Fermi Levels 163
 - 5.2.3 Space Charge at a Junction 164
- 5.3 Forward- and Reverse-Biased Junctions; Steady State Conditions 169
 - 5.3.1 Qualitative Description of Current Flow at a Junction 169
 - 5.3.2 Carrier Injection 174
 - 5.3.3 Reverse Bias 183
- 5.4 Reverse-Bias Breakdown 185
 - 5.4.1 Zener Breakdown 186
 - 5.4.2 Avalanche Breakdown 188
 - 5.4.3 Rectifiers 190
 - 5.4.4 The Breakdown Diode 193
- 5.5 Transient and A-C Conditions 194
 - 5.5.1 Time Variation of Stored Charge 195
 - 5.5.2 Reverse Recovery Transient 198
 - 5.5.3 Switching Diodes 201
 - 5.5.4 Capacitance of p-n Junctions 202
 - 5.5.5 The Varactor Diode 210
- 5.6 Deviations from the Simple Theory 211
 - 5.6.1 Effects of Contact Potential on Carrier Injection 212
 - 5.6.2 Recombination and Generation in the Transition Region 214
 - 5.6.3 Ohmic Losses 217
 - 5.6.4 Graded Junctions 218
- 5.7 Metal-Semiconductor Junctions 220
 - 5.7.1 Schottky Barriers 220

- 5.7.2 Rectifying Contacts 222
- 5.7.3 Ohmic Contacts 224
- 5.7.4 Typical Schottky Barriers 226
- 5.8 Heterojunctions 227

6

FIELD-EFFECT TRANSISTORS 241

- 6.1 Transistor Operation 242
 - 6.1.1 The Load Line 242
 - 6.1.2 Amplification and Switching 244
- 6.2 The Junction FET 244
 - 6.2.1 Pinch-off and Saturation 245
 - 6.2.2 Gate Control 247
 - 6.2.3 Current-Voltage Characteristics 249
- 6.3 The Metal-Semiconductor FET 251
 - 6.3.1 The GaAs MESFET 251
 - 6.3.2 The High Electron Mobility Transistor (HEMT) 252
 - 6.3.3 Short Channel Effects 254
- 6.4 The Metal-Insulator-Semiconductor FET 255
 - 6.4.1 Basic Operation and Fabrication 256
 - 6.4.2 The Ideal MOS Capacitor 260
 - 6.4.3 Effects of Real Surfaces 272
 - 6.4.4 Threshold Voltage 275
 - 6.4.5 MOS Capacitance-Voltage Analysis 277
 - 6.4.6 Time-dependent Capacitance Measurements 280
 - 6.4.7 Current-Voltage Characteristics of MOS Gate Oxides 283
- 6.5 The MOS Field-Effect Transistor 286
 - 6.5.1 Output Characteristics 286
 - 6.5.2 Transfer Characteristics 288
 - 6.5.3 Mobility Models 290
 - 6.5.4 Short Channel MOSFET I-V Characteristics 293
 - 6.5.5 Control of Threshold Voltage 293
 - 6.5.6 Substrate Bias Effects 300
 - 6.5.7 Subthreshold Characteristics 301
 - 6.5.8 Equivalent Circuit for the MOSFET 304
 - 6.5.9 MOSFET Scaling and Hot Electron Effects 307
 - 6.5.10 Drain-Induced Barrier Lowering 311
 - 6.5.11 Short Channel and Narrow Width Effect 313
 - 6.5.12 Gate-Induced Drain Leakage 315

7

BIPOLAR JUNCTION TRANSISTORS 322

- 7.1 Fundamentals of BJT Operation 322
- 7.2 Amplification with BJTs 325

- 7.3 BJT Fabrication 329
- 7.4 Minority Carrier Distributions and Terminal Currents 332
 - 7.4.1 Solution of the Diffusion Equation in the Base Region 333
 - 7.4.2 Evaluation of the Terminal Currents 334
 - 7.4.3 Approximations of the Terminal Currents 337
 - 7.4.4 Current Transfer Ratio 339
- 7.5 Generalized Biasing 340
 - 7.5.1 The Coupled-Diode Model 340
 - 7.5.2 Charge Control Analysis 344
- 7.6 Switching 346
 - 7.6.1 Cutoff 347
 - 7.6.2 Saturation 348
 - 7.6.3 The Switching Cycle 349
 - 7.6.4 Specifications for Switching Transistors 350
- 7.7 Other Important Effects 351
 - 7.7.1 Drift in the Base Region 352
 - 7.7.2 Base Narrowing 353
 - 7.7.3 Avalanche Breakdown 354
 - 7.7.4 Injection Level; Thermal Effects 356
 - 7.7.5 Base Resistance and Emitter Crowding 357
 - 7.7.6 Gummel-Poon Model 359
 - 7.7.7 Kirk Effect 363
- 7.8 Frequency Limitations of Transistors 365
 - 7.8.1 Capacitance and Charging Times 365
 - 7.8.2 Transit Time Effects 368
 - 7.8.3 Webster Effect 369
 - 7.8.4 High-Frequency Transistors 369
- 7.9 Heterojunction Bipolar Transistors 371

8

OPTOELECTRONIC DEVICES 379

- 8.1 Photodiodes 379
 - 8.1.1 Current and Voltage in an Illuminated Junction 379
 - 8.1.2 Solar Cells 382
 - 8.1.3 Photodetectors 384
 - 8.1.4 Noise and Bandwidth of Photodetectors 386
- 8.2 Light-Emitting Diodes 390
 - 8.2.1 Light-Emitting Materials 390
 - 8.2.2 Fiber Optic Communications 392
 - 8.2.3 Multilayer Heterojunctions for LEDs 395
- 8.3 Lasers 396

- 8.4 Semiconductor Lasers 400
 - 8.4.1 Population Inversion at a Junction 400
 - 8.4.2 Emission Spectra for p-n Junction Lasers 403
 - 8.4.3 The Basic Semiconductor Laser 404
 - 8.4.4 Heterojunction Lasers 405
 - 8.4.5 Materials for Semiconductor Lasers 408

9

INTEGRATED CIRCUITS 415

- 9.1 Background 415
 - 9.1.1 Advantages of Integration 416
 - 9.1.2 Types of Integrated Circuits 418
 - 9.1.3 Monolithic and Hybrid Circuits 418
- 9.2 Evolution of Integrated Circuits 420
- 9.3 Monolithic Device Elements 423
 - 9.3.1 CMOS Process Integration 423
 - 9.3.2 Silicon-on-Insulator (SOI) 437
 - 9.3.3 Integration of Other Circuit Elements 439
- 9.4 Charge Transfer Devices 444
 - 9.4.1 Dynamic Effects in MOS Capacitors 444
 - 9.4.2 The Basic CCD 446
 - 9.4.3 Improvements on the Basic Structure 447
 - 9.4.4 Applications of CCDs 448
- 9.5 Ultra Large-Scale Integration (ULSI) 449
 - 9.5.1 Logic Devices 452
 - 9.5.2 Semiconductor Memories 461
- 9.6 Testing, Bonding, and Packaging 474
 - 9.6.1 Testing 474
 - 9.6.2 Wire Bonding 476
 - 9.6.3 Flip-Chip Techniques 478
 - 9.6.4 Packaging 479

10

NEGATIVE CONDUCTANCE MICROWAVE DEVICES 486

- 10.1 Tunnel Diodes 486
 - 10.1.1 Degenerate Semiconductors 487
 - 10.1.2 Tunnel Diode Operation 487
 - 10.1.3 Circuit Applications 490
- 10.2 The IMPATT Diode 490
- 10.3 The Gunn Diode 494
 - 10.3.1 The Transferred Electron Mechanism 494
 - 10.3.2 Formation and Drift of Space Charge Domains 496
 - 10.3.3 Fabrication 499

11 POWER DEVICES 504

- 11.1 The p-n-p-n Diode 504**
 - 11.1.1 Basic Structure 505
 - 11.1.2 The Two-Transistor Analogy 506
 - 11.1.3 Variation of α with Injection 507
 - 11.1.4 Forward-Blocking State 507
 - 11.1.5 Conducting State 508
 - 11.1.6 Triggering Mechanisms 509
- 11.2 The Semiconductor Controlled Rectifier 511**
 - 11.2.1 Gate Control 511
 - 11.2.2 Turning off the SCR 512
 - 11.2.3 Bilateral Devices 513
 - 11.2.4 Fabrication and Applications 514
- 11.3 Insulated Gate Bipolar Transistor 515**

APPENDICES

- I. Definitions of Commonly Used Symbols 519
- II. Physical Constants and Conversion Factors 523
- III. Properties of Semiconductor Materials 524
- IV. Derivation of the Density of States in the Conduction Band 525
- V. Derivation of Fermi-Dirac Statistics 530
- VI. Dry and Wet Thermal Oxide Thickness as a Function of Time and Temperature 534
- VII. Solid Solubilities of Impurities in Si 536
- VIII. Diffusivities of Dopants in Si and SiO₂ 538
- IX. Projected Range and Straggle as a Function of Implant Energy in Si 540

INDEX 543



PREFACE

This book is an introduction to semiconductor devices for undergraduate electrical engineers, other interested students, and practicing engineers and scientists whose understanding of modern electronics needs updating. The book is organized to bring students with a background in sophomore physics to a level of understanding which will allow them to read much of the current literature on new devices and applications.

An undergraduate course in electronic devices has two basic purposes: (1) to provide students with a sound understanding of existing devices, so that their studies of electronic circuits and systems will be meaningful; and (2) to develop the basic tools with which they can later learn about newly developed devices and applications. Perhaps the second of these objectives is the more important in the long run; it is clear that engineers and scientists who deal with electronics will continually be called upon to learn about new devices and processes in the future. For this reason, we have tried to incorporate the basics of semiconductor materials and conduction processes in solids, which arise repeatedly in the literature when new devices are explained. Some of these concepts are often omitted in introductory courses, with the view that they are unnecessary for understanding the fundamentals of junctions and transistors. We believe this view neglects the important goal of equipping students for the task of understanding a new device by reading the current literature. Therefore, in this text most of the commonly used semiconductor terms and concepts are introduced and related to a broad range of devices.

GOALS

As a further aid in developing techniques for independent study, the reading list at the end of each chapter includes a few articles which students can read comfortably as they study this book. Some of these articles have been selected from periodicals such as *Scientific American* and *Physics Today*, which specialize in introductory presentations. Other articles chosen from books and the professional literature provide a more quantitative treatment of the material. We do not expect that students will read all articles recommended in the reading lists; nevertheless, some exposure to periodicals is useful in laying the foundation for a career of constant updating and self-education.

READING LISTS

One of the keys to success in understanding this material is to work problems that exercise the concepts. The problems at the end of each chapter are designed to

PROBLEMS

facilitate learning the material. Very few are simple "plug-in" problems. Instead, they are chosen to reinforce or extend the material presented in the chapter.

UNITS In keeping with the goals described above, examples and problems are stated in terms of units commonly used in the semiconductor literature. The basic system of units is rationalized MKS, although cm is often used as a convenient unit of length. Similarly, electron volts (eV) are often used rather than joules (J) to measure the energy of electrons. Units for various quantities are given in Appendices I and II.

PRESENTATION In presenting this material at the undergraduate level, one must anticipate a few instances which call for a phrase such as "It can be shown . . ." This is always disappointing; on the other hand, the alternative is to delay study of solid state devices until the graduate level, where statistical mechanics, quantum theory, and other advanced background can be freely invoked. Such a delay would result in a more elegant treatment of certain subjects, but it would prevent undergraduate students from enjoying the study of some very exciting devices.

The discussion includes both silicon and compound semiconductors, to reflect the continuing growth in importance for compounds in optoelectronic and high-speed device applications. Topics such as heterojunctions, lattice matching using ternary and quaternary alloys, variation of band gap with alloy composition, and properties of quantum wells add up to the breadth of the discussion. Not to be outdone by the compounds, silicon-based devices have continued their dramatic record of advancement. The discussion of FET structures and Si integrated circuits reflects these advancements. Our objective is not to cover all the latest devices, which can only be done in the journal and conference literature. Instead, we have chosen devices to discuss which are broadly illustrative of important principles.

The first four chapters of the book provide background on the nature of semiconductors and conduction processes in solids. Included is a brief introduction to quantum concepts (Chapter 2) for those students who do not already have this background from other courses. Chapter 5 describes the p-n junction and some of its applications. Chapters 6 and 7 deal with the principles of transistor operation. Chapter 8 covers optoelectronics and Chapter 9 discusses integrated circuits. Chapters 10 and 11 apply the theory of junctions and conduction processes to microwave and power devices. All of the devices covered are important in today's electronics; furthermore, learning about these devices should be an enjoyable and rewarding experience. We hope this book provides that kind of experience for its readers.

The fifth edition benefits greatly from comments and suggestions provided by students and teachers of the first four editions. The book's readers have generously provided comments which have been invaluable in developing the present version. We remain indebted to those persons mentioned in the Preface of the first four editions, who contributed so much to the development of the book. In particular, Nick Holonyak has been a source of continuing information and inspiration for all five editions. Additional thanks go to our colleagues at UT-Austin who have provided special assistance, particularly Joe Campbell, Ray Chen, Dennis Deppe, Russ Dupuis, Archie Holmes, Dim-Lee Kwong, Jack Lee, Christine Maziar, Dean Neikirk, and Al Tasch. Kay Shores and Qingyou Lu provided useful assistance with the typing. We thank the many companies and organizations cited in the figure captions for generously providing photographs and illustrations of devices and fabrication processes. Kobi Benzvi and Pradipto Mukherjee at Motorola, Shubneesh Batra and Mary Miller at Micron, and Tom Way at IBM deserve special mention. Finally, we recall with gratitude many years of association with the late Greg Stillman, a valued colleague and friend.

*Ben G. Streetman
Sanjay Banerjee*

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ABOUT THE AUTHORS



Ben G. Streetman is Dean of the College of Engineering at The University of Texas at Austin and holds the Dula D. Cockrell Centennial Chair in Engineering. He is a Professor of Electrical and Computer Engineering and was the founding Director of the Microelectronics Research Center (1984–96). His teaching and research interests involve semiconductor materials and devices. After receiving a Ph.D. from The University of Texas at Austin (1966) he was on the faculty (1966–1982) of the University of Illinois at Urbana-Champaign. He returned to The University of Texas at Austin in 1982. His honors include the Education Medal of the Institute of Electrical and Electronics Engineers (IEEE), the Frederick Emmons Terman Medal of the American Society for Engineering Education (ASEE), and the Heinrich Welker Medal from the International Conference on Compound Semiconductors. He is a member of the National Academy of Engineering. He is a Fellow of the IEEE and the Electrochemical Society. He has been honored as a Distinguished Alumnus of The University of Texas at Austin and as a Distinguished Graduate of the UT College of Engineering. He has received the General Dynamics Award for Excellence in Engineering Teaching, and was honored by the Parents' Association as a Teaching Fellow for outstanding teaching of undergraduates. He has served on numerous panels and committees in industry and government, and several corporate boards. He has published more than 270 articles in the technical literature. Thirty-three students of Electrical Engineering, Materials Science, and Physics have received their Ph.D.s under his direction.



Sanjay Kumar Banerjee is Professor of Electrical and Computer Engineering, and Director of the Microelectronics Research Center at The University of Texas at Austin, where he currently holds the Cullen Trust Endowed Professorship in Engineering No. 1 as well as being a Fellow of the Cockrell Family Regent's Chair. His research interests include silicon-based heterostructure devices, device modeling and ultra-large-scale IC technology. He received his B.Tech from the Indian Institute of Technology, Kharagpur, and his M.S. and Ph.D. from the University of Illinois at Urbana-Champaign in 1979, 1981 and 1983, respectively, all in electrical engineering. At Texas Instruments from 1983–1987, he worked on polysilicon transistors and dynamic random access memory cells used in the world's first 4Megabit DRAM, for which he was the co-recipient of the Best Paper Award at the 1986 IEEE International Solid State Circuits Conference. His honors include the NSF Presidential Young Investigator Award (1988), Engineering Foundation Advisory Council Haliburton Award (1991) for teaching excellence, and the Texas Atomic Energy Centennial Fellowship (1990–1997). He has more than 225 archival referred publications, has presented over 200 talks at conferences, and has 12 U.S. patents. He has supervised 18 Ph.D. and 35 MS students. He is a Distinguished National Lecturer for the IEEE Electron Devices Society (1997–), and Fellow of the IEEE (1996).