

## Quantum Heterostructures

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*Quantum Heterostructures* provides a detailed description of the key physical and engineering principles of quantum semiconductor heterostructures. Blending important concepts from physics, materials science, and electrical engineering, it also explains clearly the behavior and the operating features of modern microelectronic and optoelectronic devices.

The authors begin by outlining the trends that have driven development in this field, most importantly the need for high-performance devices in computer and communications technologies. They then describe the basics of quantum nanoelectronics, including various transport mechanisms. In the latter part of the book, they cover novel microelectronic devices and optical devices based on quantum heterostructures.

The book contains many homework problems and is suitable as a textbook for undergraduate and graduate courses in electrical engineering, physics, or materials science. It will also be of great interest to those involved in research or development in microelectronic or optoelectronic devices.

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Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio

Frontmatter

[More information](#)

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Microelectronics and Optoelectronics

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# Contents

<i>Preface</i>	<i>page</i> xiii
<i>Notation</i>	xv
<b>Chapter 1</b>	
<b>Trends in Microelectronics and Optoelectronics</b>	<b>1</b>
<hr/>	
<b>Chapter 2</b>	
<b>Theoretical Basis of Nanoelectronics</b>	<b>12</b>
<hr/>	
2.1 Introduction	12
2.2 Wave–Particle Duality in Quantum Physics	13
2.3 Time and Length Scales	15
2.3.1 Electron Fundamental Lengths in Solids	15
2.3.2 Quantum and Classical Regimes of Electron Transport	20
2.3.3 Time Scales and Temporal (Frequency) Regimes	21
2.4 Schrödinger Equation	23
2.4.1 Average Values of Physical Quantities	29
2.4.2 Separation of Variables	30
2.4.3 Variational Method	32
2.4.4 Perturbation Methods	33
2.5 Many-Particle Systems	37
2.5.1 Spin and Electron Statistics	37
2.5.2 Many-Particle Schrödinger Equation: Self-Consistent Potential	40
2.6 An Electron in Crystalline Potential: Effective-Mass Approximation	44
2.6.1 Bloch Functions	45
2.6.2 Occupation of Energy Bands: Metals, Semiconductors, and Dielectrics	47
2.6.3 Effective Masses	50
2.6.4 The Envelope Function	53
2.7 Quantum Electron Transport: Landauer Formula	55
2.8 Boltzmann Transport Equation	61
2.9 Local Approximations for Electron Transport	64
2.9.1 Electron Mobility and Diffusion Coefficient	64
2.9.2 Electron Temperature (Hydrodynamic) Approximation	67
2.9.3 Drift-Diffusion Model	70

**vi Contents**

2.10 Closing Remarks	70
PROBLEMS	71
<b>Chapter 3</b>	
<b>Electrons in Quantum Structures</b>	<b>73</b>
3.1 Introduction	73
3.2 Quantum Wells	75
3.2.1 Density of States of a Two-Dimensional Electron Gas	81
3.2.2 Quantum Effects in a Continuum-Electron Spectrum	83
3.2.3 Two-Dimensional Electron Motion in a Smooth Potential	85
3.3 Quantum Wires	87
3.3.1 Wave Functions and Energy Subbands	88
3.3.2 Density of States for a One-Dimensional Electron Gas	90
3.4 Quantum Dots	91
3.4.1 Wave Functions and Energy Levels	91
3.4.2 Density of States for Zero-Dimensional Electrons	94
3.5 Coupling between Quantum Wells	96
3.6 Superlattices	99
3.6.1 Density of States	104
3.7 Excitons in Quantum Structures	106
3.7.1 Excitons	106
3.7.2 Excitons in Quantum Wells	110
3.8 Coulomb Bound States and Defects in Quantum Structures	115
3.8.1 Coulomb Bound States of Impurities	116
3.8.2 Interfacial Defects	119
3.9 Closing Remarks	123
PROBLEMS	125
<b>Chapter 4</b>	
<b>Properties of Particular Quantum Structures</b>	<b>126</b>
4.1 Introduction	126
4.2 Energy Spectra of Some Semiconductor Materials	127
4.2.1 Symmetry of Crystals and General Properties of Electron Spectra	127
4.2.2 Band Structures of Semiconductor Alloys	132
4.2.3 Electron Affinities: Energy-Band Discontinuities of Heterostructures	134
4.3 Lattice-Matched and Pseudomorphic Heterostructures	136
4.3.1 Lattice-Matched and Lattice-Mismatched Materials	138
4.3.2 Lattice-Matched Heterostructures	141
4.3.3 Strained Pseudomorphic Structures	143
4.3.4 Si/Ge Strained Heterostructures	146
4.4 Single-Heterojunction Devices: Selective Doping	151

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Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio

Frontmatter

[More information](#)

## Contents vii

4.4.1	Introduction	151
4.4.2	Metal-Oxide-Semiconductor Structures	153
4.4.3	Single Modulation-Doped Heterojunction	155
4.4.4	Basic Equations and Quantitative Results for a Single Heterostructure	156
4.4.5	Simple Analytical Estimates for a Selectively Doped Single Heterostructure	161
4.4.6	Numerical Analysis of a Modulation-Doped Single Heterojunction	163
4.4.7	Control of Charge Transfer	167
4.5	Modulation-Doped Quantum Structures	171
4.5.1	Modulation-Doped Quantum Wells	171
4.5.2	<i>n-i-p</i> Structures	176
4.5.3	Delta Doping	180
4.6	Closing Remarks	182
	PROBLEMS	184
<b>Chapter 5</b>		
<b>Lattice Vibrations in Quantum Structures</b>		<b>185</b>
5.1	Introduction	185
5.2	Vibrations of Atomic Linear Chains	186
5.2.1	Monoatomic Chain	186
5.2.2	Diatomic Chain	189
5.3	Normal Coordinates. Three-Dimensional Case	192
5.4	Phonons	196
5.5	Acoustic Vibrations in Quantum Structures	199
5.5.1	Acoustic Modes in the Long-Wavelength Limit	199
5.5.2	Acoustic-Mode Localization in Heterostructures with Quantum Wells and Wires	202
5.6	Short-Wavelength and Optical Vibrations in Quantum Structures	218
5.6.1	Qualitative Analysis of Short-Wavelength Vibrations	218
5.6.2	Optical Vibrations in Polar Crystals	223
5.7	Closing Remarks	231
	PROBLEMS	233
<b>Chapter 6</b>		
<b>Electron Scattering in Quantum Structures</b>		<b>235</b>
6.1	Introduction	235
6.2	Elastic Scattering in Two-Dimensional Electron Systems	239
6.3	Screening of a Two-Dimensional Electron Gas	242
6.4	Scattering by Remote Ionized Impurities	246
6.5	Scattering by Interface Roughness	249
6.6	Electron-Phonon Interaction	253

Cambridge University Press

978-0-521-63635-3 - Quantum Heterostructures: Microelectronics and Optoelectronics

Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio

Frontmatter

[More information](#)**viii Contents**

6.6.1	Transitions due to Electron–Phonon Interactions	253
6.6.2	Short-Range and Long-Range Electron–Phonon Interactions	255
6.6.3	The Interaction with Different Phonon Modes	256
6.7	Interaction with Acoustic Phonons	260
6.8	Interaction with Optical Phonons	267
6.9	Scattering of Electrons by Acoustic Phonons in Quantum Wells and Wires	273
6.9.1	Quantum Wells	276
6.9.2	Quantum Wires	281
6.9.3	Free-Standing Quantum Structures	281
6.10	Scattering of Electrons by Optical Phonons in Quantum Wells and Wires	284
6.10.1	Quantum Wells	284
6.10.2	Quantum Wires	288
6.11	Closing Remarks	290
	PROBLEMS	292
<b>Chapter 7</b>		
	<b>Parallel Transport in Quantum Structures</b>	<b>295</b>
7.1	Introduction	295
7.2	Linear Electron Transport	297
7.3	High-Field Electron Transport	303
7.3.1	Hot, Warm, and Cold Electrons	304
7.3.2	Velocity Saturation	307
7.3.3	Transient Overshoot Effect	311
7.3.4	Gunn Effect	312
7.3.5	Nonequilibrium Phonons	315
7.3.6	Hot-Electron Size Effect	316
7.4	Hot Electrons in Quantum Structures	317
7.4.1	Nonlinear Transport in Two-Dimensional Electron Gases	317
7.4.2	Nonlinear Electron Transport in Quantum Wires	319
7.4.3	Real-Space Transfer of Hot Electrons	324
7.4.4	Other Effects of High-Field Electron Transport in Quantum Structures	326
7.5	Closing Remarks	328
	PROBLEMS	330
<b>Chapter 8</b>		
	<b>Perpendicular Transport in Quantum Structures</b>	<b>333</b>
8.1	Introduction	333
8.2	Double-Barrier Resonant-Tunneling Structures	333
8.2.1	Coherent Tunneling	336

	Contents ix
8.2.2 Sequential Tunneling	340
8.2.3 Comparison of Two Mechanisms of Resonant Tunneling	342
8.2.4 Negative Differential Resistance under Resonant Tunneling	343
8.3 Superlattices and Ballistic-Injection Devices	346
8.3.1 Negative Differential Resistance and Transconductance of Devices with Ballistic Superlattices	346
8.3.2 Bloch Oscillations	350
8.3.3 Wannier–Stark Energy Ladder	352
8.3.4 Negative Differential Resistance in Superlattices for Electron-Collision Regimes	355
8.3.5 Ballistic-Injection Devices	356
8.4 Single-Electron Transfer and Coulomb Blockade	357
8.5 Closing Remarks	359
PROBLEMS	361
<b>Chapter 9</b>	
<b>Electronic Devices Based on Quantum Heterostructures</b>	<b>362</b>
9.1 Introduction	362
9.2 Field-Effect Transistors	367
9.2.1 Principle of Field-Effect-Transistor Operation	367
9.2.2 Amplification and Switching	372
9.2.3 Heterostructure Field-Effect Transistors	377
9.3 Velocity-Modulation and Quantum-Interference Transistors	385
9.3.1 Velocity-Modulation Transistors	385
9.3.2 Quantum-Interference Transistors	389
9.4 Bipolar Heterostructure Transistors	394
9.4.1 $p$ - $n$ Junctions and Homostructure Bipolar Transistors	394
9.4.2 Heterostructure Bipolar Transistors	408
9.5 Si/SiGe Heterostructure Bipolar Transistors	412
9.6 Hot-Electron Transistors	416
9.6.1 Ballistic-Injection Devices	416
9.6.2 Real-Space Transfer Devices	420
9.7 Applications of the Resonant-Tunneling Effect	425
9.7.1 Resonant-Tunneling Oscillators	425
9.7.2 Resonant-Tunneling Diode as Frequency Multiplier	431
9.7.3 Resonant-Tunneling Transistors	435
9.8 Circuit Applications of Resonant-Tunneling Transistors	446
9.8.1 Multiplex Current-Voltage Characteristics and Multivalued Logic Applications	448
9.9 Closing Remarks	452
PROBLEMS	455



**x Contents**

<b>Chapter 10</b>	
<b>Optics of Quantum Structures</b>	<b>456</b>
10.1 Introduction	456
10.2 Electromagnetic Waves and Photons	457
10.2.1 Electromagnetic Fields, Modes, and Photons in Free Space	457
10.2.2 Photons in Nonuniform Dielectric Media	460
10.2.3 Optical Resonators	461
10.2.4 Photon Statistics	464
10.3 Light Interaction with Matter: Phototransitions	464
10.3.1 Photon Absorption and Emission	464
10.3.2 Calculation of Phototransition Probabilities	467
10.4 Optical Properties of Bulk Semiconductors	470
10.4.1 Interband Emission and Absorption in Bulk Semiconductors	471
10.4.2 Spectral Density of Spontaneous Emission	479
10.4.3 Phototransitions in III–V Compounds	480
10.4.4 Excitonic Effects	484
10.4.5 Refractive Index	484
10.5 Optical Properties of Quantum Structures	487
10.5.1 Electrodynamics of Heterostructures	487
10.5.2 Light Absorption by Confined Electrons	490
10.5.3 Effects of Complex Valence Bands of III–V Compounds	494
10.5.4 Other Factors Affecting the Interband Optical Spectra	496
10.5.5 Polarization Effects	499
10.6 Intraband Transitions in Quantum Structures	500
10.6.1 Intraband Absorption and Conservation Laws	500
10.6.2 Probability of Intersubband Phototransitions	502
10.6.3 Probability of Phototransitions to Extended States	508
10.7 Closing Remarks	511
PROBLEMS	512
<b>Chapter 11</b>	
<b>Electro-Optics and Nonlinear Optics</b>	<b>513</b>
11.1 Introduction	513
11.2 Electro-Optics in Semiconductors	513
11.2.1 Electro-Optical Effect in Conventional Materials	513
11.2.2 Electro-Optical Effect in Quantum Wells	518
11.2.3 Electro-Optical Effect in Superlattices	524
11.2.4 Terahertz Coherent Oscillations of Electrons in an Electric Field	529

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Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio

Frontmatter

[More information](#)

## Contents xi

11.3	Nonlinear Optics in Heterostructures	532
11.3.1	Linear and Nonlinear Optics	532
11.3.2	Optical Nonlinearities in Quantum Wells	534
11.3.3	Virtual Field-Induced Mechanism of Nonlinear Optical Effects	535
11.3.4	Nonlinear Optical Effects due to Generation of Excitons and Electron–Hole Plasma	536
11.3.5	Nonlinear Effects Induced by Nonthermalized Electron–Hole Plasma	542
11.3.6	Optical Bistability	543
11.3.7	Applications of Nonlinear Optical Effects in Quantum Wells	548
11.4	Closing Remarks	553
	PROBLEMS	555
<b>Chapter 12</b>		
<b>Optical Devices Based on Quantum Structures</b>		<b>556</b>
12.1	Introduction	556
12.2	Light Amplification in Semiconductors	556
12.2.1	Criteria for Light Amplification	557
12.2.2	Estimates of Light Gain	560
12.2.3	Methods of Pumping	562
12.2.4	Motivations for Using Heterostructures for Light Amplifications	566
12.2.5	Light Amplification in Quantum Wells and Quantum Wires	570
12.3	Light-Emitting Diodes and Lasers	574
12.3.1	Light-Emitting Diodes	574
12.3.2	Amplification, Feedback, and Laser Oscillations	579
12.3.3	Laser Output Power and Emission Spectra	581
12.3.4	Modulation of the Laser Output	584
12.3.5	Quantum-Well Lasers	587
12.3.6	Surface-Emitting Lasers	592
12.3.7	Quantum-Wire Lasers	594
12.3.8	Blue Quantum-Well Lasers	599
12.3.9	Unipolar Intersubband Quantum-Cascade Laser	602
12.4	Self-Electro-Optic-Effect Devices	609
12.4.1	Resistor SEED	609
12.4.2	Symmetric SEED	611
12.5	Photodetectors on Intraband Phototransitions	614
12.5.1	Photoconductive Detectors	615

Cambridge University Press

978-0-521-63635-3 - Quantum Heterostructures: Microelectronics and Optoelectronics

Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroscio

Frontmatter

[More information](#)**xii Contents**

12.5.2	Intraband Phototransitions and Electron Transport in Multiple-Quantum-Well Structures	618
12.5.3	Simple Model of Multiple-Quantum-Well Photodetectors	624
12.6	Closing Remarks	631
	PROBLEMS	633
	<i>Index</i>	635

## Preface

Welcome to the world of quantum-based devices! In this book you will find the fundamental physics and engineering principles underlying quantum semiconductor heterostructures as well as new concepts in the field of quantum-based microelectronic and optoelectronic devices. We ask the readers to disregard the thickness of this volume. Just follow us from simple and basic definitions into this exciting field.

The recent and diverse trends in semiconductor and device technologies as well as in novel device concepts are driving the establishment of new subdisciplines of electronics and optoelectronics based on quantum structures, as reviewed in Chapter 1. These trends make it important for the electrical engineer, the materials engineer, the materials scientist, and the solid-state physicist alike to understand the fundamentals underlying devices based on quantum structures. Our goal in writing this book is to help you in this endeavor.

The book grew out of our research and teaching experience in these subjects. Many of the ideas and the achievements in the field can be explained in a relatively simple setting, if the necessary underlying fundamentals are presented properly. Our book provides a unifying framework for the basic ideas needed to understand recent developments and culminates with treatments of electronic and optoelectronic devices based on quantum structures.

With this purpose in mind, we present the material on quantum-heterostructure physics and engineering in Chapters 2–6. The foundational topics covered in these early chapters set the stage for the study of a variety of important electron transport regimes in Chapters 7 and 8 and the optics of quantum structures in Chapter 10. Chapters 9, 11, and 12 are built on the preceding chapters to describe successively the subdisciplines that are emerging from the theory underlying quantum-based structures; these are electronic, electro-optical, and optical devices based on quantum structures.

The scope and the organization of this book facilitate instruction on both the undergraduate and the graduate levels. In our experience, the material can be covered in a one-semester course with sixty contacts and with a few topics from the book assigned to students for self-study. For courses that are two quarters in duration, instructors may find it convenient to present the material of Chapters 2–6 during the first quarter and that of Chapters 7–12 during the second quarter; this method of presentation separates the fundamental background from the subject matter on specific quantum structures and devices. The problems included in each chapter of this book focus on amplifying the understanding of the key concepts underlying quantum-based devices. Many of the problems

Cambridge University Press

978-0-521-63635-3 - Quantum Heterostructures: Microelectronics and Optoelectronics

Vladimir V. Mitin, Viatcheslav Kochelap and Michael A. Stroschio

Frontmatter

[More information](#)**xiv Preface**

contain extensive discussions that lead the readers to the frontiers of electronics and optoelectronics. Every chapter also has a list of recommended literature, which typically includes the most useful reviews and books on the subjects.

The authors have many professional colleagues and friends from different countries who must be acknowledged. Without their contributions and sacrifices this work would not have been completed. These people include Professors Michael P. Polis and Frank Westervelt – the former and the current Chairs of the Electrical and Computer Engineering of the Wayne State University; Professors Z. Gribnikov, S. Svechnikov, V. Sokolov, and V. Pipa of the Institute of Semiconductor Physics, Kiev, Ukraine; Professor Gerald J. Iafrate of Notre Dame University; Professors Ki Wook Kim, M. A. Littlejohn, and Mitra Dutta of the North Carolina State University; Professors Pallab K. Bhattacharya, George I. Haddad, and Jasprit Singh of the University of Michigan; Professors Karl Hess and J.-P. Leburton of the University of Illinois; and Professors H. Craig Casey and Steven Teitsworth of Duke University. The help of Dr. R. Mickevičius in preparing Chapters 5 and 6 is especially appreciated. We also thank the students who took this course with us. Their feedback helped us in the choice and presentation of the material.

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Michael Stroschio, *Raleigh, NC*

# Notation

## Symbols

Other symbols are self-evident and are given as they occur within specific analyses.

$A$	cross-sectional area
$a$	lattice constant
$a_B$	Bohr radius
$\vec{a}_i$	basic vectors of the Bravais lattice
$a_0^{\text{ex}}$	radius of bulk exciton
$a_0$	Bohr radius for an impurity atom in semiconductors
$c$	velocity of light
$c_{ij}$	elastic moduli of the crystal
$c_{\vec{q},s}$	phonon annihilation operator
$c_{\vec{q},s}^+$	phonon creation operator
$D_{ij}$	tensor of the deformation potential
$D$	diffusion coefficient
$d$	distance between wells; superlattice period
$d_{\text{sp}}$	width of spacer
$E$	photon energy; electron energy
$E_{A,D}$	ionization energy of acceptors and donors, respectively
$E_{c,v}(\vec{k})$	energy of the electron in the conduction and the valence bands, respectively
$E_{\text{el}}$	elastic energy
$E_{\text{ex}}$	exciton energy
$E_{\text{im}}$	energy associated with the misfit dislocations or misfit defects of a crystal
$E_F$	Fermi level
$E_{Fn}$	electron quasi-Fermi level
$E_{Fp}$	hole quasi-Fermi level
$E_g$	bandgap
$E_h$	energy of hole
$\mathcal{E}$	electric field of electromagnetic wave; energy functional
$F$	electric-field intensity; restoring force
$F_\alpha(\vec{r})$	envelope function
$\mathcal{F}$	finesse of resonator
$\mathcal{F}_F$	Fermi distribution function
$\mathcal{F}(\vec{k}, \vec{r}, t)$	electron distribution function
$\vec{f}$	external force applied to the surface of a crystal

**xvi Notation**

$f_T$	cutoff frequency of a field-effect transistor
$G$	conductance; total gain
$G_0 = 39.6 \mu\text{S}$	quantum of conductance
$g_m$	transconductance
$g_0$	conductance of a field-effect transistor for a completely opened channel
$\mathcal{H}$	Hamiltonian of a system
$h = 6.62 \times 10^{-34} \text{Js}$	Planck's constant
hh	heavy-hole band
lh	light-hole band
sh	split-off band
$\hbar = h/2\pi$	reduced Planck's constant
$I$	current; collision integral; total intensity of waveguide mode
$\vec{i}$	density of particle flow
$j$	electron current density
$k$	wave number, wave vector of the electron in the crystal
$\vec{k}$	wave vector
$k_{\parallel}$	parallel component of three-dimensional vector $\vec{k}$
$k_B$	Boltzmann constant
$k_F$	Fermi wave vector
$L$	length, thickness of a well
$L_E$	inelastic-scattering length
$L_R$	ambipolar length
$L_T$	thermal diffusion length
$L_i$	geometrical size of a sample in the direction $i$
$L_{n,p}$	electron $L_n$ and hole $L_p$ recombination lengths
$l$	angular-momentum quantum number
$l_e$	electron mean free path
$l_{\phi}$	coherence length
$M$	electron effective mass along the superlattice axis
$M^{\text{ex}}$	exciton effective mass
$m$	free-electron mass
$m^*$	effective mass
$(1/m^*)_{ik}$	reciprocal effective-mass tensor
$m_e$	electron effective mass
$m_h$	hole effective mass
$m_l$	longitudinal effective mass
$m_{lh}$	effective mass of the light hole
$m_{hh}$	effective mass of the heavy hole
$m_r$	reduced mass of the electron-hole pair
$m_t$	transverse effective mass
$N$	total number of phonons, electrons, atoms
$\vec{N}$	vector perpendicular to the surface of a crystal

$N_{A,D}$	concentration per unit volume of ionized acceptors and donors, respectively
$N_{c,v}$	effective density of states for electrons and holes
$\mathcal{N}$	number of atoms per primitive crystal cell; total number of photons
$n$	electron concentration per unit volume; principal quantum number; refractive index
$n_e$	electron concentration per unit volume; area of length
$n_i$	intrinsic electron concentration
$n_s$	surface concentration of electrons
$n_{3D}$	electron concentration per unit volume
$n_{2D}$	electron concentration per unit area
$n_{1D}$	electron concentration per unit length
$P_{i \rightarrow f}$	probability of electron transition from state $i$ to state $f$
$\vec{p}$	operator of momentum; macroscopic polarization vector
$P_b$	probability of finding the electron in the barrier layer
$\vec{p}$	momentum vector
$p_i$	intrinsic hole concentration
$q$	wave vector
$R$	reflection coefficient
$R_y$	Rydberg constant; ionization energy of the hydrogen atom
$R_y^{\text{ex}}$	ionization energy of bulk exciton
$R_y^*$	effective Rydberg constant
$r$	space coordinate; amplitude of a reflected wave
$S$	cross-sectional area
$s$	spin number; sound velocity
$T$	temperature; transmission coefficient
$T_e$	electron temperature
$T_t$	tunneling matrix element
$\mathcal{T}_{\vec{d}}$	translational operator
$t$	amplitude of a transmitted wave; time
$t_{lw}$	characteristic time for changes in the light-wave amplitude
$t_{tr}$	transit time
$U$	elastic energy per unit volume; power gain
$\vec{u}(\vec{r})$	vector of relative displacement of point $\vec{r}$
$u_{ij}$	strain tensor
$u_{\vec{k}}(\vec{r})$	Bloch function
$V$	potential energy, volume of the system
$V_{\text{FB}}$	voltage on the metal required for reaching the flat-band condition in a metal-oxide-semiconductor structure
$V_b$	depth of a potential well; potential-barrier height
$V_0$	volume of the primitive cell
$v$	electron velocity; group velocity
$v_p$	phase velocity



**xviii Notation**

$v_g$	group velocity
$W(\vec{r})$	crystalline potential
$W(\vec{k}', \vec{k})$	probability of transition from an initial state $\vec{k}'$ to a final state $\vec{k}$
$W_{km}$	probability of transition from an initial state $k$ to a final state $m$ per unit time
$Y_{l,m}(\theta, \varphi)$	spherical functions
$\alpha$	Frölich coupling constant
$\beta$	quasi-elastic force coefficient
$\Delta_{so}$	spin-orbital splitting of valence bands
$\nabla$	del operator
$\delta(x)$	Dirac delta function
$\delta_{ij}$	Kronecker delta
$\epsilon$	energy of a transverse motion of an electron in a well or a wire
$\Theta(x)$	Heaviside step function
$\theta$	angle in spherical coordinates
$\kappa$	dielectric permittivity of the medium
$\kappa_{el}$	dielectric permittivity of an electron gas
$\lambda$	wave vector; de Broglie wavelength; elastic modulus
$\mu$	electron mobility
$\nu$	frequency
$\vec{\xi}$	vector of polarization of electromagnetic wave
$\rho$	linear density of the string; density of a semiconductor; density of states
$\vec{\rho}$	two-dimensional vector of space coordinate
$\sigma_{ij}$	stress tensor
$\tau_E$	mean time between two inelastic collisions; energy-relaxation time
$\tau_R$	lifetime of a charge carrier
$\tau_T$	thermal diffusion spreading time
$\tau_e$	mean time between two elastic-scattering events; mean free time
$\tau_{ee}$	time of electron–electron interaction
$\tau_{ep}$	time of electron interaction with lattice
$\tau_{n,p}$	electron–hole recombination time for $p$ -type material $\tau_n$ , and $n$ -type material $\tau_p$
$\tau_p$	momentum-relaxation time
$\tau_s$	duration of scattering
$\Upsilon$	total photon flux
$\Upsilon_0$	photon flux in steady state
$\Phi$	voltage applied to a device; many-electron time-dependent wave function
$\Phi_p$	internal pinch-off voltage
$\phi$	wave phase

$\phi(\vec{r})$	electrostatic potential
$\phi(z)$	electrostatic potential
$\varphi$	many-electron time-independent wave function
$\chi$	electron wave function; electric susceptibility
$\Psi(\vec{r}, t)$	one-electron time-dependent wave function
$\Psi_{\text{tr}}$	true wave function
$\psi(\vec{r}, t)$	one-electron time-dependent wave function
$\Omega$	angular frequency of the de Broglie wave
$\omega$	angular frequency of a wave
$\omega_{\text{IF}}$	frequency of interface modes
$\omega_{\text{LO}}$	frequency of longitudinal-optical modes
$\omega_{\text{TO}}$	frequency of transverse-optical modes

**ACRONYMS**


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BT	bipolar transistor
CHINT	charge-injection transistor
CMOS	complementary MOS, i.e., NMOS and PMOS on the same chip
FET	field-effect transistor
JBT	homojunction BT
JFET	junction FET
HBT	heterojunction BT
HEMT	high-electron-mobility transistor
HFET	heterostructure FET
MES	metal-semiconductor
MESFET	metal-semiconductor FET
MODFET	modulation-doped FET
MOS	metal-oxide-semiconductor
MOSFET	metal-oxide-semiconductor FET
NERFET	negative-resistance FET
NMOS	<i>n</i> -channel MOSFET
PMOS	<i>p</i> -channel MOSFET
QUIT	quantum-interference transistor
RHET	resonant hot-electron transistor
RST	real-space transfer
VMT	velocity-modulation transistor
SEED	self-electro-optic-effect device