Quantum Heterostructures

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
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Microelectronics and Optoelectronics

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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

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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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VK is deeply thankful to all his family members who have waited for him during long periods of lecturing and working on this book in Detroit; these include his father and mother, wife and daughter, and, finally, granddaughter Asya.

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Vladimir Mitin, *Detroit, MI*
Viatcheslav Kochelap, *Detroit, MI; Kiev, Ukraine*
Michael Stroscio, *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^{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_{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_{el}	elastic energy
E_{ex}	exciton energy
E_{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

f_T	cutoff frequency of a field-effect transistor
G	conductance; total gain
$G_0 = 39.6\ \mu\mathrm{S}$	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
$h = 6.62 \times 10^{-34}\,\mathrm{Js}$	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_ϕ	coherence length
M	electron effective mass along the superlattice axis
M^{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
$P_{i\to f}$	probability of electron transition from state i to state f
$\vec{\mathcal{P}}$	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^{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_{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

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
α	Frölich coupling constant
β	quasi-elastic force coefficient
Δ_{so}	spin-orbital splitting of valence bands
∇	dell operator
$\delta(x)$	Dirac delta function
δ_{ij}	Kronecker delta
ϵ	energy of a transverse motion of an electron in a well or a wire
$\Theta(x)$	Heaviside step function
θ	angle in spherical coordinates
κ	dielectric permitivity of the medium
κ_{el}	dielectric permitivity of an electron gas
λ	wave vector; de Broglie wavelength; elastic modulus
μ	electron mobility
ν	frequency
$\vec{\xi}$	vector of polarization of electromagnetic wave
ρ	linear density of the string; density of a semiconductor; density of states
$\vec{\rho}$	two-dimensional vector of space coordinate
σ_{ij}	stress tensor
τ_E	mean time between two inelastic collisions; energy-relaxation time
τ_R	lifetime of a charge carrier
τ_T	thermal diffusion spreading time
τ_e	mean time between two elastic-scattering events; mean free time
τ_{ee}	time of electron–electron interaction
τ_{ep}	time of electron interaction with lattice
$\tau_{n,p}$	electron–hole recombination time for p-type material τ_n, and n-type material τ_p
τ_p	momentum-relaxation time
τ_s	duration of scattering
Υ	total photon flux
Υ_0	photon flux in steady state
Φ	voltage applied to a device; many-electron time-dependent wave function
Φ_p	internal pinch-off voltage
ϕ	wave phase

$\phi(\vec{r})$	electrostatic potential
$\phi(z)$	electrostatic potential
φ	many-electron time-independent wave function
χ	electron wave function; electric susceptibility
$\Psi(\vec{r}, t)$	one-electron time-dependent wave function
Ψ_{tr}	true wave function
$\psi(\vec{r}, t)$	one-electron time-dependent wave function
Ω	angular frequency of the de Broglie wave
ω	angular frequency of a wave
ω_{IF}	frequency of interface modes
ω_{LO}	frequency of longitudinal-optical modes
ω_{TO}	frequency of transverse-optical modes

ACRONYMS

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	*n*-channel MOSFET
PMOS	*p*-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