Graduate Texts in Physics

Marius Grundmann

The Physics of Semiconductors

An Introduction including Nanophysics and Applications

Second Edition

半导体物理学 第2版

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by Marius Grundmann

To Michelle,
Sophia Charlotte
and Isabella Rose

Preface

Semiconductor electronics is commonplace in every household. Semiconductor devices have also enabled economically reasonable fiber-based optical communication, optical storage and high-frequency amplification and have recently revolutionized photography, display technology and lighting. Along with these tremendous technological developments, semiconductors have changed the way we work, communicate, entertain and think. The technological progress of semiconductor materials and devices is evolving continuously with a large worldwide effort in human and monetary capital. For students, semiconductors offer a rich, diverse and exciting field with a great tradition and a bright future.

This book introduces students to semiconductor physics and semiconductor devices. It brings them to the point where they can specialize and enter supervised laboratory research. It is based on the two semester semiconductor physics course taught at Universität Leipzig in its Master of Science physics curriculum. Since the book can be followed with little or no pre-existing knowledge in solid-state physics and quantum mechanics, it is also suitable for undergraduate students. For the interested reader some additional topics are included in the book that can be covered in subsequent, more specialized courses. The material is selected to provide a balance between aspects of solid-state and semiconductor physics, the concepts of various semiconductor devices and modern applications in electronics and photonics.

The first semester contains the fundamentals of semiconductor physics (Part I, Sects. 1–10) and selected topics from Part II (Sects. 11–19). Besides important aspects of solid-state physics such as crystal structure, lattice vibrations and band structure, semiconductor specifics such as technologically relevant materials and their properties, electronic defects, recombination, hetero- and nanostructures are discussed. Semiconductors with electric polarization and magnetization are introduced. The emphasis is put on inorganic semiconductors, but a brief introduction to organic semiconductors is given in Sect. 16. Dielectric structures (Sect. 18) serve as mirrors, cavities and microcavities and are a vital part of many semiconductor devices. Other sections give introductions to carbon-based nanostructures and transparent conductive oxides (TCOs). The third part (Part III - Sects. 20–23) is dedicated to semiconductor applications and devices that are taught in the second semester of the course. After a general and detailed discussion of various diode types, their applications in electrical circuits, photodetectors, solar cells, light-emitting diodes and lasers are treated. Finally, bipolar and field-effect transistors including thin film transistors are discussed.

In the present text of the second edition a few errors and misprints of the first edition have been corrected. Many topics have been extended and are treated in more depth, e.g. dopant diffusion, partial dislocations, etching of semiconductors, double donors/acceptors, excess charge carrier profiles, direct transitions in germanium, alloy broadening, nanowires, recombination in organic semiconductors, depletion layers beyond the abrupt approximation, Schottky diodes with inhomogeneous barrier, multi-junction solar cells, quantum dot and organic LEDs, LED degradation, strained channel transistors, MOSFET scaling, memory concepts and thin film transistors. The two chapters on carbon-based nanostructures and transparent conductive oxides have been added.

The number of references has been doubled with respect to the first edition. The references have been selected to (i) cover important historical and milestone papers, (ii) direct to reviews and topical books for further reading and (iii) give access to current literature and up-to-date research. In Fig. 1, the almost 1500 references in this book are shown by year. Roughly three phases of semiconductor physics and technology can be seen. Before the realization of the first transistor in 1947, only a few publications are noteworthy. Then an intense phase of understanding the physics of semiconductors and developing semiconductor technology and devices based on bulk semiconductors (mostly Ge, Si, GaAs) followed. At the end of the 1970s, a new era began with the advent of quantum wells and heterostructures, and later nanostructures (nanotubes, nanowires and quantum dots) and new materials (e.g. organic semiconductors, nitrides or graphene).

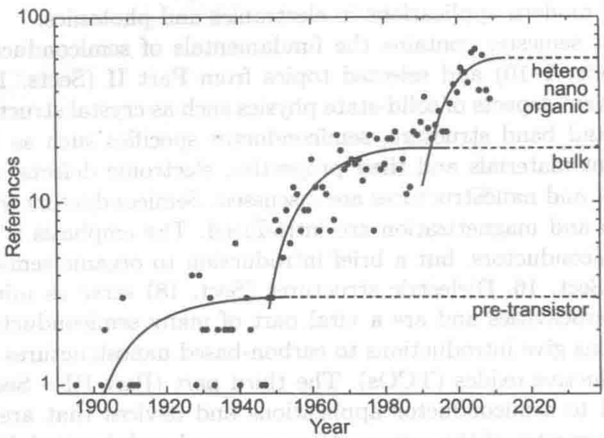

Fig. 1. Histogram of references in this book

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Leipzig, April 2010 *Marius Grundmann*

Abbreviations

2DEG	two-dimensional electron gas
A	atomic mass ($A = 12$ for ^{12}C)
AAAS	American Association for the Advancement of Science
AB	antibonding (position)
ac	alternating current
ACS	American Chemical Society
AFM	atomic force microscopy
AIP	American Institute of Physics
AM	air mass
APD	antiphase domain
APD	avalanche photodiode
APS	American Physical Society
AR	antireflection
ARPES	angle-resolved photoemission spectroscopy
ASE	amplified spontaneous emission
AVS	American Vacuum Society (The Science & Technology Society)
BC	bond center (position)
bc	body-centered
bcc	body-centered cubic
BD	Blu-ray^{TM}disc
BEC	Bose–Einstein condensation
BGR	band gap renormalization
CAS	calorimetric absorption spectroscopy
CCD	charge coupled device
CD	compact disc
CEO	cleaved-edge overgrowth
CIE	Commission Internationale de l'Éclairage
CIGS	$Cu(In,Ga)Se_2$ material
CIS	$CuInSe_2$ material
CL	cathodoluminescence

CMOS	complementary metal–oxide–semiconductor
CMY	cyan-magenta-yellow (color system)
CNT	carbon nanotube
COD	catastrophical optical damage
CPU	central processing unit
CRT	cathode ray tube
CSL	coincident site lattice
CVD	chemical vapor deposition
cw	continuous wave
CZ	Czochralski (growth)
DAP	donor–acceptor pair
DBR	distributed Bragg reflector
dc	direct current
DFB	distributed feedback
DH(S)	double heterostructure
DLTS	deep level transient spectroscopy
DMS	diluted magnetic semiconductor
DOS	density of states
DPSS	diode-pumped solid-state (laser)
DRAM	dynamic random access memory
DVD	digital versatile disc
EBL	electron blocking layer
EEPROM	electrically erasable programmable read-only memory
EHL	electron–hole liquid
EIL	electron injection layer
EL	electroluminescence
ELO	epitaxial lateral overgrowth
EMA	effective mass approximation
EML	emission layer
ELA	excimer laser annealing
EPR	electron paramagnetic resonance
ESR	electron spin resonance
EPROM	erasable programmable read-only memory
ESF	extrinsic stacking fault
ETL	electron transport layer
EXAFS	extended X-ray absorption fine structure
F_4-TCNQ	2,3,5,6-tetrafluoro-7,7,8,8-tetracyano-quinodimethane
fc	face-centered
fcc	face-centered cubic
FeRAM	ferroelectric random access memory
FET	field-effect transistor
FIR	far infrared

FKO	Franz–Keldysh oscillation
FLG	few layer graphene
FPA	focal plane array
FQHE	fractional quantum Hall effect
FWHM	full width at half-maximum
FZ	float-zone (growth)
Gb	Gigabit
GIZO	GaInZnO
GLAD	glancing-angle deposition
GRINSCH	graded-index separate confinement heterostructure
GSMBE	gas-source molecular beam epitaxy
GST	$Ge_2Sb_2Te_5$
HBL	hole blocking layer
HBT	heterobipolar transistor
hcp	hexagonally close packed
HCSEL	horizontal cavity surface-emitting laser
HEMT	high electron mobility transistor
HIGFET	heterojunction insulating gate FET
HIL	hole injection layer
HJFET	heterojunction FET
hh	heavy hole
HOPG	highly ordered pyrolithic graphite
HOMO	highest occupied molecular orbital
HR	high reflection
HRTEM	high-resolution transmission electron microscopy
HTL	hole transport layer
HWHM	half-width at half-maximum
IC	integrated circuit
IDB	inversion domain boundary
IEEE	Institute of Electrical and Electronics Engineers[1]
IF	intermediate frequency
IPAP	Institute of Pure and Applied Physics, Tokyo
IQHE	integral quantum Hall effect
IR	infrared
ISF	intrinsic stacking fault
ITO	indium tin oxide
JDOS	joint density of states
JFET	junction field-effect transistor
KKR	Kramers–Kronig relation

[1] Pronounced Eye-triple-E

KOH	potassium hydroxide
KTP	$KTiOPO_4$ material
LA	longitudinal acoustic (phonon)
LCD	liquid crystal display
LDA	local density approximation
LEC	liquid encapsulated Czochralski (growth)
LED	light-emitting diode
lh	light hole
LO	longitudinal optical (phonon), local oscillator
LPE	liquid phase epitaxy
LPCVD	low-pressure chemical vapor deposition
LPP	longitudinal phonon plasmon (mode)
LST	Lyddane–Sachs–Teller (relation)
LT	low temperature
LUMO	lowest unoccupied molecular orbital
LVM	local vibrational mode
MBE	molecular beam epitaxy
MEMS	micro-electro-mechanical system
MESFET	metal–semiconductor field-effect transistor
MIGS	midgap (surface) states
MILC	metal-induced lateral crystallization
MIOS	metal–insulator–oxide–semiconductor
MIR	mid-infrared
MIS	metal–insulator–semiconductor
MHEMT	metamorphic HEMT
ML	monolayer
MLC	multi-level cell
MMIC	millimeter-wave integrated circuit
MO	master oscillator
MODFET	modulation-doped FET
MOMBE	metalorganic molecular beam epitaxy
MOPA	master oscillator power amplifier
MOS	metal–oxide–semiconductor
MOSFET	metal–oxide–semiconductor field-effect transistor
MOVPE	metalorganic chemical vapor deposition
MQW	multiple quantum well
MRAM	magnetic random access memory
MRS	Materials Research Society
MS	metal–semiconductor (diode)
MSA	mobility spectral analysis
MSM	metal–semiconductor–metal (diode)
MTJ	magneto-tunneling junction
MWNT	multi-walled (carbon) nanotube

NDR	negative differential resistance
NEP	noise equivalent power
NIR	near infrared
NMOS	n-channel metal–oxide–semiconductor (transistor)
NTSC	national television standard colors
OLED	organic light emitting diode
OMC	organic molecular crystals
ONO	oxide/nitride/oxide
OPSL	optically pumped semiconductor laser
PA	power amplifier
PBG	photonic band gap
pc	primitive cubic
PCM	phase change memory
PFM	piezoresponse force microscopy
PHEMT	pseudomorphic HEMT
PL	photoluminescence
PLD	pulsed laser deposition
PLE	photoluminescence excitation (spectroscopy)
PMC	programmable metallization cell
PMMA	poly-methyl methacrylate
PMOS	p-channel metal–oxide–semiconductor (transistor)
PPC	persistent photoconductivity
PPLN	periodically poled lithium niobate
PV	photovoltaic
PWM	pulsewidth modulation
PZT	$PbTi_xZr_{1-x}O_3$ material
QCL	quantum cascade laser
QCSE	quantum confined Stark effect
QD	quantum dot
QHE	quantum Hall effect
QW	quantum well
QWIP	quantum-well intersubband photodetector
QWR	quantum wire
RAM	random access memory
RAS	reflection anisotropy spectroscopy
RF	radio frequency
RFID	radio frequency identification
RGB	red-green-blue (color system)
RHEED	reflection high-energy electron diffraction
RIE	reactive ion etching

RKKY	Ruderman–Kittel–Kasuya–Yoshida (interaction)
rms	root mean square
ROM	read-only memory
RRAM	resistance random access memory
SAGB	small-angle grain boundary
SAM	separate absorption and amplification (structure)
sc	simple cubic
SCH	separate confinement heterostructure
SdH	Shubnikov-de Haas (oscillation)
SEL	surface-emitting laser
SEM	scanning electron microscopy
SET	single-electron transistor, single electron tunneling
SGDBR	sampled grating distributed Bragg reflector
SHG	second-harmonic generation
si	semi-insulating
SIA	Semiconductor Industry Association
SIMS	secondary ion mass spectrometry
SL	superlattice
SLC	single-level cell
SLG	single layer graphene
s-o	spin-orbit (or split-off)
SOA	semiconductor optical amplifier
SPD	spectral power distribution
SPIE	International Society for Optical Engineering
SPS	short-period superlattice
sRGB	standard RGB
SRH	Shockley–Read–Hall (kinetics)
SSR	side-mode suppression ratio
STM	scanning tunneling microscopy
SWNT	single-walled (carbon) nanotube
TA	transverse acoustic (phonon)
TAS	thermal admittance spectroscopy
TCO	transparent conductive oxide
TE	transverse electric (polarization)
TED	transferred electron device
TFET	transparent FET, tunneling FET
TFT	thin film transistor
TEGFET	two-dimensional electron gas FET
TEM	transmission electron microscopy
TES	two-electron satellite
TF	thermionic field emission
TFT	thin-film transistor
TM	transverse magnetic (polarization)

TMAH	tetramethyl-ammonium-hydroxide
TMR	tunnel-magnetoresistance
TO	transverse optical (phonon)
TOD	turn-on delay (time)
TPA	two-photon absorption
TSO	transparent semiconducting oxide
UHV	ultrahigh vacuum
UV	ultraviolet
VCA	virtual crystal approximation
VCO	voltage-controlled oscillator
VCSEL	vertical-cavity surface-emitting laser
VFF	valence force field
VGF	vertical gradient freeze (growth)
VIS	visible
VLSI	very large scale integration
WGM	whispering gallery mode
WKB	Wentzel–Kramer–Brillouin (approximation or method)
WS	Wigner–Seitz (cell)
YSZ	Yttria-stabilized zirconia (ZrO_2)
X	exciton
XX	biexciton
XSTM	cross-sectional STM
Z	atomic number ($Z = 2$ for helium)
ZnPc	zinc-phthalocyanine