Field Guide to

Solid State Physics

Marek S. Wartak

C. Y. Fong

SPIE Field Guides
Volume FG43

John E. Greivenkamp, Series Editor

SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Names: Wartak, Marek S., author. | Fong, C. Y. (Ching-yao), author.
Title: Field guide to solid state physics / Marek S. Wartak and Ching-Yao Fong.
Other titles: Solid state physics
Description: Bellingham, Washington : SPIE, 2019. | Series: The field guide series | Includes bibliographical references and index.
Identifiers: LCCN 2018037785 (print) | LCCN 2018053727 (ebook) | ISBN 9781510622753 (pdf) | ISBN 9781510622760 (epub) | ISBN 9781510622777 (mobi) | ISBN 9781510622746 (spiral)
Subjects: LCSH: Solid state physics.
Classification: LCC QC176 (ebook) | LCC QC176 .W345 2019 (print) | DDC 530.4/1–dc23
LC record available at https://lccn.loc.gov/2018037785

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: 360.676.3290
Fax: 360.647.1445
Email: Books@spie.org
Web: www.spie.org

Printed in the United States of America.
First printing.
For updates to this book, visit http://spie.org and type "FG43" in the search field.

Introduction to the Series

In 2004, SPIE launched a new book series, the SPIE Field Guides, focused on SPIE's core areas of Optics and Photonics. The idea of these Field Guides is to give concise presentations of the key subtopics of a subject area or discipline, typically covering each subtopic on a single page, using the figures, equations, and brief explanations that summarize the key concepts. The aim is to give readers a handy desk or portable reference that provides basic, essential information about principles, techniques, or phenomena, including definitions and descriptions, key equations, illustrations, application examples, design considerations, and additional resources.

The series has grown to an extensive collection that covers a range of topics from broad fundamental ones to more specialized areas. Community response to the SPIE Field Guides has been exceptional. The concise and easy-to-use format has made these small-format, spiral-bound books essential references for students and researchers. I have been told by some readers that they take their favorite Field Guide with them wherever they go.

We are now pleased and excited to extend the SPIE Field Guides into subjects in general Physics. Each Field Guide will be written to address a core undergraduate Physics topic, or in some cases presented at a first-year graduate level. The Field Guides are not teaching texts, but rather references that condense the textbooks and course notes into the fundamental equations and explanations needed on a routine basis. We truly hope that you enjoy using the Field Guides to Physics.

We are interested in your suggestions for new Field Guide topics as well as what could be added to an individual volume to make these Field Guides more useful to you. Please contact us at **fieldguides@SPIE.org**.

John E. Greivenkamp, *Series Editor*
College of Optical Sciences
The University of Arizona

The Field Guide Series

Look for all of the physics *SPIE Field Guides*:

Classical Mechanics
Opto-Electronics and Photonics
Quantum Mechanics
Radiation Detectors
Solid State Physics

Field Guide to Solid State Physics

Solid state physics is a branch of physics that deals primarily with the physical properties of periodic condensed matters, especially the electromagnetic, thermodynamic, and structural properties of various systems, such as semiconductors, quantum structures, and superconductors; these properties are the consequences of solids interacting with light and under external fields, etc.

The *Field Guide to Solid State Physics* provides a compact introduction of select topics within the field of condensed-matter physics. For students and engineers alike, the book facilitates an in-depth understanding of physical concepts, as well as their applications, to help them develop new ideas for innovative devices. The topics chosen were influenced by our own areas of interest: single-particle and many-body interactions in the form of quasi-particle and collective excitations. Whenever possible, simple line art illustrates the essential concepts.

Over the last few decades, we have witnessed the significant (and increasing) effect of solid state physics on everyday life. The field is essential for the development of state-of-the-art concepts because it provides effective guidance for designing circuits and new materials for electronic and spintronic devices (it contributed to both the transistor and the semiconductor chip). Over the last ten years, more than half of the Nobel Prizes in physics were awarded to topics relevant to solid state physics.

Special thanks to Scott McNeill (SPIE Press) for a very careful reading of the manuscript and introducing a significant number of improvements.

Marek S. Wartak
Wilfrid Laurier University

C. Y. Fong
University of California, Davis

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Glossary of Symbols

0D	Zero-dimensional
1D	One-dimensional
2D	Two dimensional
3D	Three-dimensional
$\mathbf{A}$	Vector potential
$\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$	Vectors defining unit cell
$\mathbf{B}$	Magnetic field
$\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$	Vectors defining reciprocal lattice
bcc	Body-centered cubic
BCS	Bardeen–Cooper–Schrieffer
BJT	Bipolar junction transistor
BL	Bravais lattice
BZ	Brillouin zone
CB	Conduction band
CB	Coulomb blockade
CBM	Conduction band minimum
c_V	Specific heat at constant volume
D_n	Diffusion coefficient
DFT	Density functional theory
dHvA	de Haas–van Alphen
DOS	Density of states
$\mathbf{E}$	Electric field
E_c	Charging energy
E_F	Fermi energy
E_g	Bandgap energy
F	Free energy
$f_{FD}(\varepsilon)$	Fermi-Dirac distribution function
fcc	Face-centered cubic
FD	Fermi–Dirac
FQHE	Fractional quantum Hall effect
FS	Fermi surface
GaAs	Galium arsenide
Ge	Germanium
GL	Ginzburg–Landau
H	Hamiltonian
hcp	Hexagonal close-packed
HRs	Hund's rules
$I[f]$	Collision integral
$\mathbf{J}$	Total angular momentum

Glossary of Symbols

$\mathbf{k}$	Wavevector
$\mathbf{K}$	Reciprocal lattice vector
KS	Kohn–Sham
$\mathbf{L}$	Total orbital momentum
LDA	Local density approximation
LED	Light-emitting diode
$\mathbf{M}$	Magnetization
m^*	Effective mass
MBE	Molecular beam epitaxy
MOS	Metal–oxide–semiconductor
MOSFET	Metal–oxide–semiconductor field effect transistor
MRI	Magnetic resonance imaging
n	Density of electrons
N_A	Concentrations of acceptors
N_D	Concentrations of donors
n_i	Intrinsic concentration
$n_{\mathbf{q}}(\mathbf{r},t)$	Local density of phonons
NMR	Nuclear magnetic resonance
NN	Nearest neighbor
p_F	Fermi momentum
R_H	Hall coefficient
rf-SQUID	Radio-frequency superconducting quantum interference device
RKKY	Ruderman–Kittel–Kasuya–Yosida
RL	Reciprocal lattice
$\mathbf{S}$	Spin angular momentum operator
SET	Single-electron transistor
Si	Silicon
SOI	Silicon-on-isolator
T	Absolute temperature
T_1	Longitudinal relaxation time
T_2	Transverse relaxation time
T_C	Critical temperature
TB	Tight binding
$u_{\mathbf{k},n}(\mathbf{r})$	Periodic part of the Bloch function
$V(\mathbf{r})$	Periodic potential
(h,k,l)	Miller indices
$\hbar$	Dirac constant

Glossary of Symbols

Δ	Order parameter
$\varepsilon(\omega)$	Electrical permittivity
λ	Wavelength
$\boldsymbol{\mu}$	Magnetic moment
μ_B	Bohr magneton
μ_n	Mobility
$\rho(E)$	Density of states
σ	Electrical conductivity
τ	Average time between collisions
ϕ_0	Flux quantum
Φ	Magnetic flux
χ	Magnetic susceptibility
ψ	Wave function
$\psi_{\mathbf{k},n}(\mathbf{r})$	Bloch function
ω	Frequency
ω_c	Cyclotron frequency
ω_p	Plasma frequency
Ω	Volume of unit cell in real space
$\Omega_{\mathbf{K}}$	Volume of the primitive cell in the reciprocal lattice
QD	Quantum dot
QPC	Quantum point contact
VB	Valence band
VBM	Valence band maximum
VLSI	Very-large-scale integration
WS	Wigner–Seitz