Semiconductor Laser Photonics

This modern text provides detailed coverage of the important physical processes underpinning semiconductor devices. Advanced analysis of the optical properties of semiconductors without the requirement of complex mathematical formalism allows clear physical interpretation of all obtained results. The book describes fundamental aspects of solid-state physics and the quantum mechanics of electron–photon interactions, in addition to discussing in detail the photonic properties of bulk and quantum well semiconductors. The final six chapters focus on the physical properties of several widely used photonic devices, including distributed feedback lasers, vertical cavity surface-emitting lasers, quantum dot lasers, and quantum cascade lasers. This book is ideal for graduate students in physics and electrical engineering, and a useful reference for optical scientists.

Mauro Nisoli is Professor of Physics and Photonics at Politecnico di Milano, where he leads the Attosecond Research Center. His research is focused on attosecond science and ultrafast phenomena in matter. He has published more than 200 research papers in international journals and several physics textbooks.

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Second Edition

MAURO NISOLI
Politecnico di Milano

CAMBRIDGE
UNIVERSITY PRESS

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Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

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www.cambridge.org
Information on this title: www.cambridge.org/9781009098748

DOI: 10.1017/9781009106153

First published 2023

A catalogue record for this publication is available from the British Library.

A Cataloging-in-Publication data record for this book is available from the Library of Congress

ISBN 978-1-009-09874-8 Hardback

To Margherita,
Matilde, and Kim

Contents

Preface

The term *photonics* was introduced in the late 1960s by Pierre Aigrain, who gave the following definition: "Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation and amplification and, most importantly, its utilisation for the benefit of mankind." In the last three decades impressive progress in the field of photonics has been achieved, thanks to remarkable advances in the understanding of the physical processes at the heart of light–matter interaction in photonic applications and to the introduction of crucial technological innovations. Photonics is an extremely wide field, as clearly demonstrated by the above definition, since it refers to all types of technological device and process, where photons are involved.

This book does not aim to analyze all aspects of photonics: A few excellent textbooks already exist, which present several topics relevant for photonic applications. The aim of this book is to introduce and explain important physical processes at the heart of the optical properties of semiconductor devices, such as light emitting diodes (LEDs) and semiconductor lasers. It is suitable for a half-semester (or a single-semester) course in Photonics or Optoelectronics at graduate level in engineering physics, electrical engineering, or material science. It originated from the graduate course of Photonics I have been teaching at the Politecnico di Milano since 2006. The concepts of solid-state physics and quantum mechanics, which are required to understand the subjects discussed in this book, are addressed in the introductory chapters. It is assumed that the reader has had courses on elementary quantum mechanics, solid-state physics, and electromagnetic theory at the undergraduate level.

The book presents a selection of topics, which I consider essential to understand the operation of semiconductor devices. It offers a relatively advanced analysis of the photophysics of semiconductors, trying to avoid the use of exceedingly complex formalisms. Particular attention was devoted to offer a clear physical interpretation of all the obtained results. Various worked examples are added throughout all the chapters to illustrate the application of the various formulas: The solved exercises are evidenced by the colored boxes in the text. The numerical examples are also important since they allow the reader to have a direct feeling of the order of magnitude of the parameters used in the formulas discussed in the text. The gray boxes contain concise discussions of supplementary topics or more advanced derivations of particular results reported in the main text, which may not be easily derived by the reader.

Semiconductor Laser Photonics is organized as follows. Chapter 1 focuses on the description of a few concepts of solid-state physics, which are relevant for the calculation and analysis of the band structure of semiconductors. The Bloch theorem is introduced, which describes the wavefunction of electrons in periodic structures. The tight-binding method is considered, with a few simple examples, and the $\mathbf{k} \cdot \mathbf{p}$ method, which are used to calculated the band structure of semiconductors. Chapter 2 deals with the discussion of the main properties of charged particles (electrons and holes) in intrinsic and doped semiconductors. The density of states is first calculated and the essential concepts of carrier statistics in semiconductors are discussed. Basic concepts of quantum mechanics are contained in Chapter 3. In particular, the density matrix formalism is introduced, which is used in the book for the calculation of the optical susceptibility of a semiconductor. After a very short overview of essential aspects of classical electromagnetic theory, Chapter 4 analyzes the interaction of electrons with an electromagnetic field. The expressions of the interaction Hamiltonian, which are extensively used throughout the book, are derived in this chapter. Chapters 5 and 6 build on the previous chapters. In particular, Chapter 5 deals with the optical properties of bulk semiconductors, that is, semiconductors with spatial dimensions much larger than the de Broglie wavelength of the electrons involved in the relevant physical processes. Absorption and gain coefficients are calculated and the radiative and nonradiative recombination processes in semiconductors are analyzed. Chapter 6 analyzes the principles of the photophysics in semiconductor quantum wells, that is, in semiconductor structures where the electrons are confined in one direction by a potential well, with a thickness smaller than the electron de Broglie wavelength.

In the remaining six chapters the general results obtained in the first part of the book are applied to the investigation of the main optical properties of semiconductor devices: light-emitting diodes and lasers. The general philosophy adopted in these chapters is the following: The fundamental physical processes are investigated, rather than the technological characteristics of the devices. After a short and general analysis of semiconductor lasers in Chapter 8, based on the rate equation approach, Chapter 9 is devoted to the analysis of the optical properties of quantum dots, where three-dimensional quantum confinement leads to peculiar properties, which have been used for the development of quantum dot lasers. Chapter 10 contains a detailed theoretical analysis of the distributed feedback (DFB) lasers, based on the use of the coupled-mode equations. By using a simple perturbative approach, the threshold laser conditions are obtained. Vertical cavity surface-emitting lasers (VCSELs) and Quantum cascade lasers are analyzed in the final two chapters.