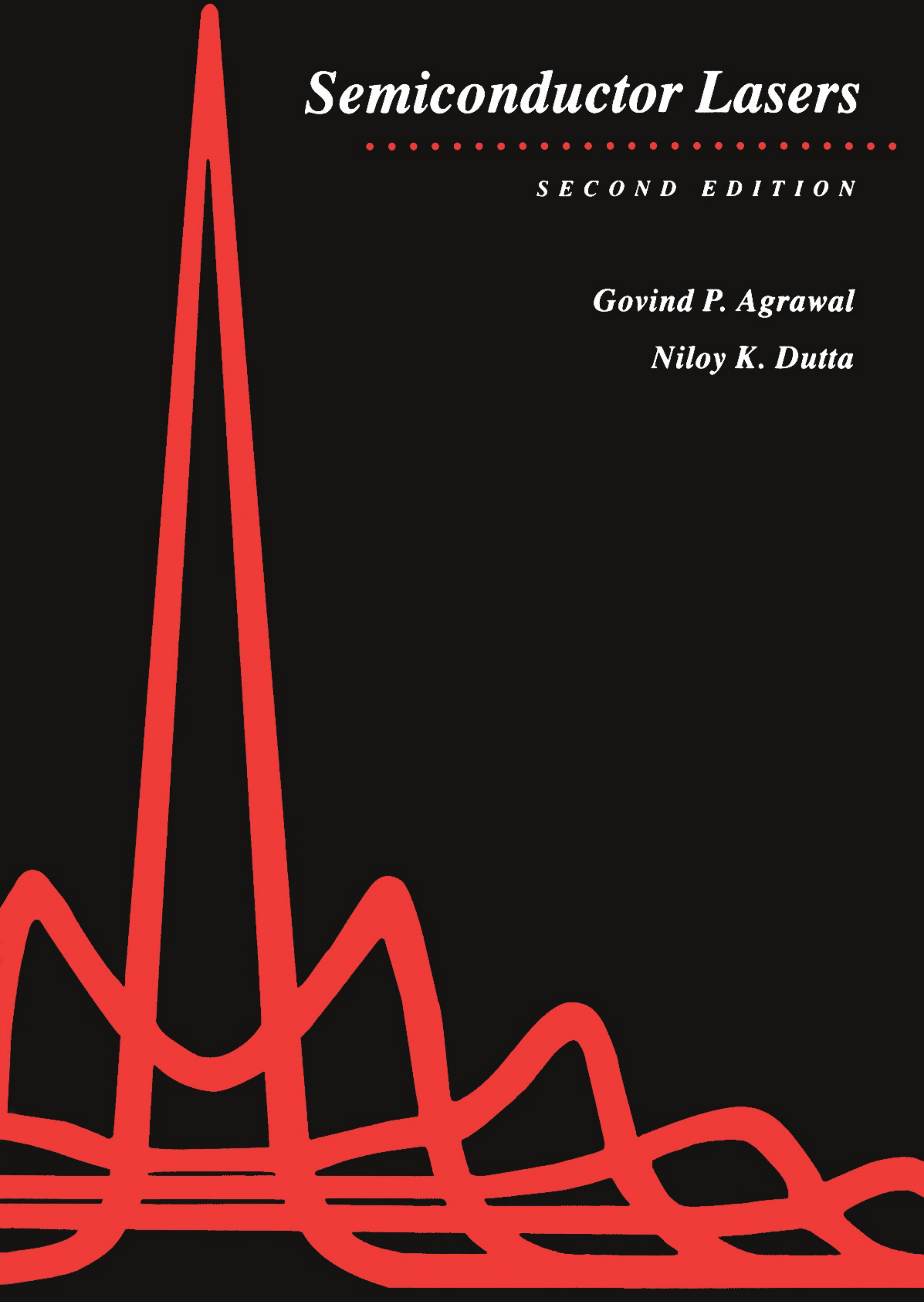
Semiconductor Lasers

SECOND EDITION

Govind P. Agrawal
Niloy K. Dutta



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PREFACE TO THE FIRST EDITION

Since its invention in 1962, the semiconductor laser has come a long way. Advances in material purity and epitaxial growth techniques have led to a variety of semiconductor lasers covering a wide wavelength range of 0.3–100 μm. The development during the 1970s of GaAs semiconductor lasers, emitting in the near-infrared region of 0.8–0.9 μm, resulted in their use for the first generation of optical fiber communication systems. However, to take advantage of low losses in silica fibers occurring around 1.3 and 1.55 μm, the emphasis soon shifted toward long-wavelength semiconductor lasers. The material system of choice in this wavelength range has been the quaternary alloy InGaAsP. During the last five years or so, the intense development effort devoted to InGaAsP lasers has resulted in a technology mature enough that lightwave transmission systems using InGaAsP lasers are currently being deployed throughout the world.

This book is intended to provide a comprehensive account of long-wavelength semiconductor lasers. Particular attention is paid to InGaAsP lasers, although we also consider semiconductor lasers operating at longer wavelengths. The objective is to provide an up-to-date understanding of semiconductor lasers while incorporating recent research results that are not yet available in the book form. Although InGaAsP lasers are often used as an example, the basic concepts discussed in this text apply to all semiconductor lasers, irrespective of their wavelengths.

The book is aimed at researchers already engaged in or wishing to enter the field of semiconductor lasers. It should serve as a useful reference for engineers who are interested in optical fiber communications and want to know about the semiconductor-laser sources employed therein. The book can also be useful for a graduate-level course on semiconductor lasers as part of a program in optical communications. We have attempted to make the book self-contained and to provide sufficient details of the mathematical derivations. Furthermore, each chapter refers to a large number of published papers that can be consulted for further study.

The book is organized as follows. The first three chapters introduce the basic concepts and provide the mathematical derivations useful for understanding the operation of semiconductor lasers. Chapters 4 and 5 describe epitaxial techniques and various device structures employed to fabricate semiconductor lasers. The operating characteristics of these lasers are considered in Chapter 6, including static, dynamic, spectral, noise, and modulation aspects. The next two chapters are devoted to single-frequency semiconductor lasers employing the distributed-feedback and coupled-cavity schemes, while Chapter 9 considers quantum-well semiconductor lasers. The degradation mechanisms and reliability issues of semiconductor lasers are discussed in Chapter 10. Finally, Chapter 11 considers lead-salt semiconductor lasers emitting at relatively longer wavelengths in the far-infrared region 3–34 μm.

We wish to thank the members of the semiconductor laser development department and other colleagues at AT&T Bell Laboratories for numerous discussions and for providing a stimulating working environment. We are thankful to D. P. Wilt and C. H. Henry for their comments on several chapters. The support of the AT&T Bell Laboratories management for this project is gratefully acknowledged. We particularly thank R. W. Dixon, J. E. Geusic, and P. J. Anthony for their encouragement.

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N. K. Dutta

PREFACE TO THE SECOND EDITION

The field of semiconductor lasers has advanced considerably since the publication of the first edition in 1986. Among the recent advances, to name a few topics, are surface-emitting semiconductor lasers, high-power laser arrays, visible semiconductor lasers, and strained layer quantum-well lasers. The second edition is intended to bring this book up to date so that it remains a source of comprehensive coverage on semiconductor lasers. Whereas the first edition focused mainly on long-wavelength semiconductor lasers (mostly InGaAsP lasers), the scope of this edition has been widened to include all kinds of semiconductor lasers, as reflected by the change in the title of the book. Since the first edition has occasionally been used as a textbook in some graduate-level courses, we have added selective problems at the end of each chapter to help teachers and students. It is our hope that the second edition can serve as a textbook for graduate courses dealing with semiconductor lasers. Selective chapters can also be useful for other courses related to lasers, optoelectronics, and optical communications.

The list of topics that could have been included in the second edition was quite large. Size limitations forced us to make a selection. It was felt that surface-emitting semiconductor lasers, semiconductor laser amplifiers, and optoelectronic integration needed enough coverage that a new chapter was justified for each of them. The main change consists of adding three new chapters (Chapters 10, 11, and 12) and several new sections to the existing chapters. Major changes are made in Chapters 6, 7, and 9 while other chapters are updated to bring the discussion up to date. Specifically, a section on mode-locked semiconductor lasers is added to Chapter 6. The advances in the field of distributed feedback semiconductor lasers are covered by adding a section on tunable semiconductor lasers and three sections on phase-shifted, quantum-well, and gain-coupled distributed feedback lasers. Chapter 9 has a new section on strained-layer quantum-well lasers, a topic that has attracted considerable attention in recent years. Visible semiconductor lasers are included in Chapter 13. We feel that these additions have improved the text enough that it should serve the need of the scientific community during the 1990s. We would welcome suggestions and comments from the readers.

G. P. Agrawal
N. K. Dutta

Chapter 1
INTRODUCTION

1.1 HISTORICAL PERSPECTIVE

The advent of the laser dates back to 1958, the year in which the seminal paper of Schawlow and Townes[1] appeared. It was followed by the successful operation of a solid-state ruby laser[2] in May 1960 and of an He-Ne gas laser[3] in December 1960. The feasibility of stimulated emission in semiconductor lasers was considered during this period,[4–6] and in 1962 several groups[7–10] reported the lasing action in semiconductors. The device consisted of a forward-biased GaAs *p-n* junction.[7–9] Electron-hole recombination in the depletion region of the *p-n* junction provided the optical gain, and the polished facets perpendicular to the junction plane provided the optical feedback (by forming a resonant cavity)—the two necessary ingredients for any laser. Soon *p-n* junctions of other direct-band-gap semiconductor materials such as InAs, InP, GaAsP, GaInAs, and InPAs were used to obtain semiconductor lasers at different wavelengths. Practical utility of these earlier devices was, however, limited since a large value of the threshold current density ($J_{\text{th}} \gtrsim 50\ \text{kA/cm}^2$) inhibited their continuous operation at room temperature.

As early as 1963 it was suggested[11,12] that semiconductor lasers might be improved if a layer of one semiconductor material were sandwiched between two cladding layers of another semiconductor that has a relatively wider band gap. Such a device consisting of two dissimilar semiconductors is commonly referred to as a *heterostructure laser*, in contrast to the single-semiconductor devices, which are labeled as *homostructure lasers*. Both of these structures are shown schematically in Fig. 1.1, which also indicates their typical physical dimensions. Heterostructure lasers are further classified as *single-heterostructure* or *double-heterostructure* devices depending on whether the active region, where lasing occurs, is surrounded on one or both sides by a cladding layer of higher band gap. The use of a heterostructure, however, requires a careful matching of the lattice constants of the two semiconductors. It was only in 1969 that the successful room-temperature operation of a

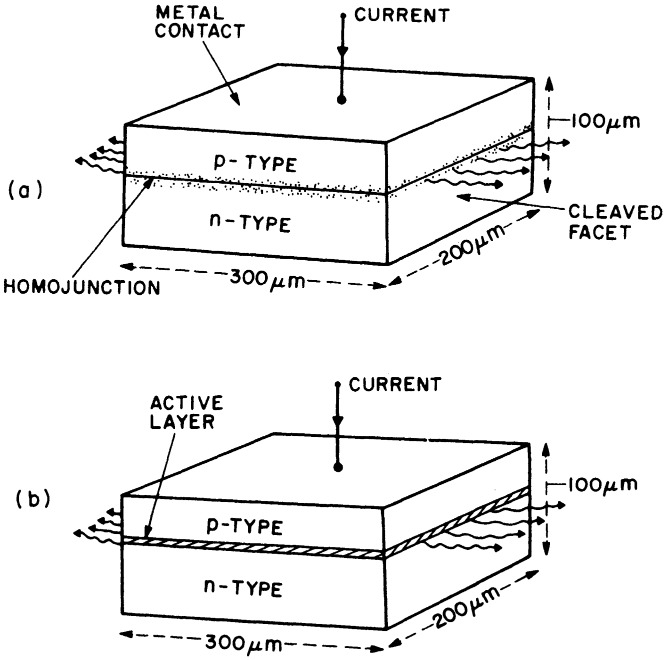

Fig. 1.1 Schematic illustration of (a) homostructure and (b) double-heterostructure semiconductor lasers with their typical physical dimensions. The dotted area represents the depletion region in the vicinity of the homojunction. The hatched area shows the thin (~0.2 μm) active layer of a semiconductor material whose band gap is slightly lower than that of the surrounding cladding layers.

heterostructure laser was demonstrated[13–15] using the liquid-phase epitaxial technique[16] for the growth of GaAs and $Al_xGa_{1-x}As$ layers. However, these lasers operated in the pulsed mode. Further work led in 1970 to heterostructure lasers operating continuously at room temperature.[17,18] Notation such as (Ga,Al)As or AlGaAs/GaAs is often used to emphasize the heterostructure nature of these GaAs lasers. However, since homostructure lasers are no longer used, we shall simplify the notation in this book, whenever no confusion is likely to arise, by denoting a heterostructure laser only by the composition of its active layer.

Already in 1969 double-heterostructure GaAs lasers with a room-temperature value of $J_{th} \cong 5$ kA/cm^2 were reported.[15] This value was reduced[17] to about 1.6 kA/cm^2 in 1970, and by 1975 AlGaAs layers with $J_{th} \cong 0.5$ kA/cm^2 were demonstrated using thin (~0.1 μm thick) active layers.[19] This was an improvement by more than two orders of magnitude over the simple homostructure lasers first made in 1962. It converted the semiconductor laser from a laboratory curiosity to a practical, compact, coherent light source useful for numerous applications.

The physical reason for the reduction in the threshold current density with the use of a heterostructure device is twofold.[11,12] The cladding layers surrounding the active layer have a higher band gap and at the same time a lower refractive index compared with those of the active layer (see Fig. 1.2). The band-gap difference helps to confine electrons and holes to the active layer, where they recombine to produce the optical gain. At the same time the refractive-index difference confines the optical mode close to the active layer, which acts as a dielectric waveguide. The optical-mode confinement significantly reduces the internal loss[13] that would otherwise occur in the absence of index guiding due to the spreading of the optical mode in the lossy regions.

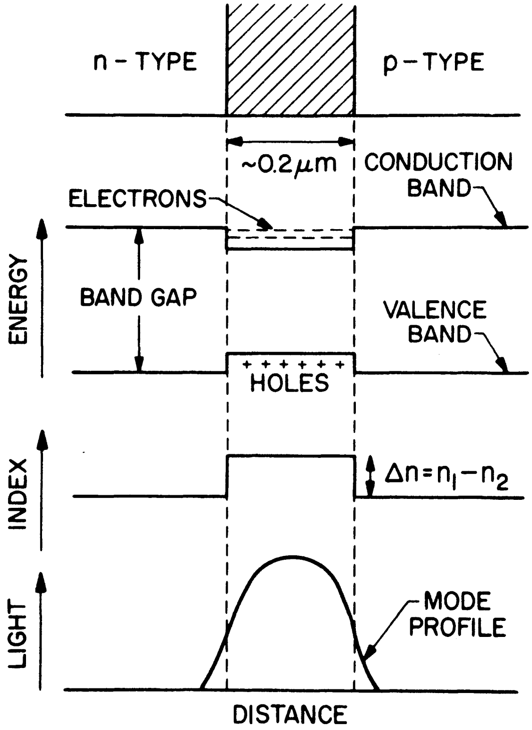

Fig. 1.2 Schematic illustration of the simultaneous confinement of the charge carriers and the optical mode to the active region occurring in a double-heterostructure semiconductor laser. The active layer has a lower band gap and a higher refractive index than those of the cladding layers. (After Ref. 24)