Heterostructure Lasers

Part A: Fundamental Principles

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QUANTUM ELECTRONICS

Principles and Applications

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HETEROSTRUCTURE LASERS

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To Jean Anne and Evelyn

PREFACE

The evolution of early GaAs homostructure lasers into a variety of heterostructure lasers and the present commercial implementation of these devices have required the collaboration of scientists and engineers from several areas of the physical sciences. Many diverse skills had to be brought together to achieve an understanding of the fundamental principles, the preparation, and the operating characteristics of these devices. Future work, which will extend the research to other materials and structures, will continue to require an interdisciplinary understanding of this field. This book is a tutorial research monograph with emphasis on the interdisciplinary nature of the subject. It should be noted that we have included only those topics that are sufficiently well understood to be suitable in a tutorial work. Applications are not considered.

Each major topic is introduced along with the basic laws that govern the observed phenomena. The expressions relevant to heterostructure lasers are derived from the basic laws, and realistic numerical examples are given. For example, a crystal grower may not have studied the propagation of electromagnetic radiation or gain in a laser, while a physicist interested in those subjects may not have dealt previously with phase equilibria and crystal growth. The derivations, therefore, contain definitions and considerable detail to permit the reader to study an unfamiliar subject.

Both rigorous and approximate solutions are derived. In most cases, the resulting expressions may readily be evaluated with a hand calculator or simple computer programs. The availability of a minicomputer with a hard copy graphic output permitted us to easily illustrate numerical results in graphic form. Therefore, the reader can either follow the detailed derivations or simply obtain a brief overview from the numerous illustrations. The numerical examples are based on the GaAs–$Al_xGa_{1-x}As$ heterostructure. At the present time, the $Al_xGa_{1-x}As$ system provides the only heterostructures for which there are sufficient data to evaluate numerically the derived expressions.

There are several unique difficulties encountered in the preparation of a book on a rapidly evolving interdisciplinary subject. One is the notation in which the same symbols have been used to represent different quantities. Rather than defy convention, we have attempted, where possible, to use different fonts and other minor modifications. For example, the usual symbol for electron concentration and refractive index has been n, and these two cases are distinguished by adding a bar for refractive index $\bar{n}$. To distinguish x, y, and z as spatial coordinates, script $\mathscr{x}$, $\mathscr{y}$, and $\mathscr{z}$ have been used for solid-solution compositions. In other cases, the usage should identify the symbol. The second problem is the almost daily publication of papers on heterostructure lasers. Not only do these papers provide additional data, but they often modify the interpretation of a particular concept. Chapter 4 had to be modified when the correct Γ, L, and X conduction band ordering in GaAs was established. We have attempted to be sufficiently fundamental so that continuing publications in the field will build on the principles presented here. Additional work will surely modify some of our present ideas. The third problem is the large number of publications on semiconductor lasers. Rather than attempt to include all papers, enough representative references are given to permit the interested reader to start a library search on a particular topic. Finally, the absence of students in an industrial laboratory environment prevented us from having an audience on which to try out the various presentations. However, Bell Laboratories provided access to a broad range of experts on many diverse subjects. As a result, the interdisciplinary nature of the presentation was enhanced, and topics were included that otherwise would have been omitted.

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MATERIALS AND OPERATING CHARACTERISTICS

CONTENTS

CHAPTER 1 □ INTRODUCTION

1.1 INTRODUCTORY REMARKS

The intent of this chapter is to describe some of the early studies of injection lasers and to introduce the fundamental concepts of heterostructure lasers. It should be emphasized that a major effort in Part A has been to describe the fundamentals of waveguiding (Chapter 2), gain (Chapter 3), and carrier confinement in heterostructures (Chapter 4) and to use GaAs–$Al_xGa_{1-x}As$ as a particularly well-documented example. In Part B, other possible chemical systems (Chapter 5) and epitaxial growth procedures (Chapter 6) are discussed, along with the relevant chemical thermodynamics. The fabrication and actual operating properties of GaAs–$Al_xGa_{1-x}As$ heterostructure lasers are given (Chapter 7). Broad-area lasers that confine the injected carriers and guide the radiation perpendicular to the junction plane and stripe-geometry lasers that also restrict current along the junction plane are discussed. The mechanisms that influence the operating life and the feasibility for operation in excess of 10^5 hr are discussed (Chapter 8).

1.2 DEMONSTRATION OF STIMULATED EMISSION AND ROOM TEMPERATURE CONTINUOUS-WAVE OPERATION WITH INJECTION LASERS

Stimulated Emission with *p–n* Junctions

Since abundant treatment of the science and technology of semiconductor lasers is given in subsequent chapters, this part of Chapter 1 is intended to give the reader only a retrospective account of the early work. From 1958 through 1961,[1–4] there were suggestions that semiconductors might be used as laser materials. However, a quantitative understanding of the requirements for lasing to be achieved in a semiconductor was not available until Bernard and Duraffourg[5] stated the necessary condition for stimulated emission in a semiconductor. They showed that the separation of the quasi-Fermi levels corresponding to the nonequilibrium concentrations of electrons and holes must exceed the energy of the emitted radiation. This condition is derived in Chapter 3. They suggested, as likely semiconductors, the III–V compounds GaAs and GaSb, among others. These semiconductors had first been described as potentially useful materials for devices by Welker.[6,7]

The period around 1960 was a time when research on lasers was expanding very rapidly and when studies of *p–n* junction devices represented one of the most rapidly developing areas of electronics technology. It is not surprising that these studies converged to produce lasing action by the injection of a nonequilibrium electron population across a *p–n* junction. However, it is interesting to note that in unpublished notes made in 1953, as described by Bardeen,[8] von Neumann suggested the possibility of light amplification by the use of stimulated emission in a semiconductor pumped by injection across a *p–n* junction.

An interesting narrative account of some of the early work that led to the first series of papers reporting injection laser action has been given by Hall[9] of the General Electric laboratory in Schenectady. Before the summer of 1962, he was very skeptical about the possibility of a semiconductor laser. At the time, his reasons for skepticism seemed persuasive. Known lasers required long optical paths which seemed incompatible with the strong free carrier absorption of semiconductors. The transitions in semiconductors were over a much broader range of energies than the characteristically sharp transitions in conventional lasers, and, most important, radiative recombination in semiconductors had always been found very inefficient. Hall reported that these attitudes were modified as the concepts for stimulated emission were clarified by Bernard and Duraffourg[5] and by the demonstration of efficient radiative recombination in GaAs. At the Solid-State Device Research Conference in July 1962, Keyes and Quist[10] of Lincoln Laboratory reported that, at 77°K, close to 100% quantum efficiency could be achieved for electroluminescence in GaAs.

Meanwhile,[9] at IBM the idea of obtaining laser action in a semiconductor had been discussed in 1961 among Landauer, Lasher, Dumke, and Keyes. Lasher considered the importance of mode guiding in reducing losses due to free carriers, and Dumke[11] pointed out the importance of using a direct energy gap semiconductor. They became aware of the possibility of very efficient electroluminescence in GaAs at 77°K in March 1962, when Mayburg of GT & E visited the IBM laboratory and described his work with GaAs diodes. Mayburg reported his results in a postdeadline paper at the March 1962 American Physical Society meeting, but apparently that report went unnoticed by the scientific community. As described by Hall,[9] it was not until the IBM workers heard of the report[10] at the Solid-State Device Research Conference that there was a strong increase in their interest in using *p–n* junction diodes as semiconductor lasers.

The reports by Pankove and Massoulie,[12] by Keyes and Quist,[10] and by Mayburg were apparently the key ingredient required to stimulate interest in injection lasers, even though those papers were concerned with noncoherent electroluminescence. Certainly a large part of the impact they generated resulted from the extensive discussions among the participants at the Solid-State Device Research Conference. One of the participants was Holonyak of the General Electric Laboratory at Syracuse. Holonyak had been studying tunneling in the crystalline solid solution GaP_xAs_{1-x} and had also observed visible light emission from forward-biased *p–n* junctions in that material at 77°K. He returned to Syracuse trying to figure out how to use an external cavity to provide feedback for an injection laser.[13]

While many of the other workers were speculating about the possibility of injection lasers, Nasledov *et al.*[14] reported early in 1962 the slight narrowing of the electroluminescent spectrum of a GaAs diode at 77°K for a current density of 1.5×10^3 A/cm^2. In that work, there was no resonant cavity, and it was not clear whether stimulated emission had occurred. Hall[9] decided to use a resonant cavity with mirrors that were polished ends of the GaAs crystal perpendicular to the plane of a diffused *p–n* junction. By September 1962, Hall *et al.*[15] had definitely observed coherent light emission from a forward-biased GaAs *p–n* junction at 77°K. The designation of stimulated emission was based on the narrowing of the emission spectrum at a wavelength of about 0.84 μm and the behavior of the farfield emission pattern. It has become common usage to refer to these lasers, comprised of a single semiconductor, as homostructure lasers. At IBM, Nathan and his co-workers looked for line narrowing in etched-mesa GaAs diodes at 77°K. As reported to Hall[9] by Nathan, the first diode they looked at had, purely by chance, a resonant cavity in which the line-narrowing characteristic of injection lasing was observed. Their paper was submitted in October.[16]

Following the Solid-State Device Research Conference, Holonyak prepared *p–n* junction diodes by diffusing Zn into *n*-type GaP_xAs_{1-x} layers on wafers that he grew by chemical–vapor deposition. He was convinced[13] by Hall to use a resonant cavity formed by the crystal itself. Holonyak and Bevacqua[17] achieved injection lasing at 77°K very shortly after Hall *et al.*[13] A particular novelty of this work was the first use of a III–V crystalline solid solution for an injection laser, and the use of a solid-solution composition that gave visible (0.71 μm) radiation. The Holonyak and Bevacqua paper was submitted in October, followed almost immediately by a paper submitted in early November by Quist and his co-workers at Lincoln Laboratory.[18] They reported lasing, as characterized by the light intensity–current behavior and spectral narrowing, at both 4.2° and 77°K.

Except for the diodes studied by Nathan *et al.*,[16] these first injection lasers were typically rectangular parallelpipeds or trapezoids made by cutting chips of GaAs (or GaP_xAs_{1-x}) and polishing two parallel ends of the chip. The material from which the chip was cut had previously had a *p–n* junction incorporated into it by the diffusion of a *p*-type dopant into *n*-type material. The plane of the *p n* junction was perpendicular to the polished ends of the parallelpiped. In this manner, a cavity corresponding to a small Fabry–Perot interferometer was formed. The cavity permits feedback as in conventional lasers because the polished ends of the crystal behave as partial mirrors. Lasing usually occurs by the selective amplification of one or more of the cavity modes.

Holonyak[13] realized that a better approach to the fabrication of the Fabry–Perot cavity might be to obtain plane-parallel mirrors by cleaving along parallel crystal planes. However, his material was difficult to cleave and he was diverted to the use of polished crystals by the rush, during the summer of 1962, to be among the first to achieve injection lasing. The earliest reported use of cleaving to form the injection laser mirrors is by Bond *et al.*[19] in 1963, and it is common now to have the junction plane parallel to a {100} face of the crystal so that the {110} natural cleavage planes are perpendicular to the junction. A homostructure laser with mirrors formed by cleaving is illustrated in Fig. 1.2-1a. The dimensions given are typical of those for homostructure and other more complex injection lasers.

The period immediately following the demonstration of lasing at *p–n* junctions in homostructure lasers was one of rather intense activity. At the Solid-State Device Conference of June 1963, there was a session on diode lasers in which lasing was reported with *p–n* junctions in InAs and $Ga_xIn_{1-x}As$[20] and InP.[21] There were also papers describing efficiency[22] and threshold.[23] The effect of temperature on threshold current was estimated by Mayburg[24] and studied by Engeler and Garfinkel[25] and by Pilkuhn *et al.*[26] The experimental T^3 dependence did not agree with the predicted $T^{3/2}$ dependence. Lasing was reported in InP_xAs_{1-x} in 1964,[27] and there were nine review papers[28–36] in 1963 and 1964. Injection lasing was achieved in several new materials from 1964 through 1966 with interesting new additions such as the IV–VI compounds.[37] In addition, during this period there were numerous papers on device design, the effect of various parameters on optical properties, and on possible uses of injection lasers. This work was reviewed by Nathan.[38]

A common and discouraging feature of the homostructure injection lasers was that the usual threshold current density for lasing was very high ($\gtrsim$50,000 A/cm^2) at room temperature. Most studies were done at liquid nitrogen temperature (77°K) or lower. Room temperature continuous operation was not feasible, although with adequate heat sinking, continuous operation was achieved in 1967 by Dyment and D'Asaro[39] at temperatures up to 205°K. The injection current was limited to a narrow stripe along the length of the laser. This technique reduces the total current and facilitates heat sinking. As discussed in Chapter 7, the stripe geometry in one variation or another was later to be an important feature of almost all practical heterostructure lasers. The usual mode of operation of homostructure lasers

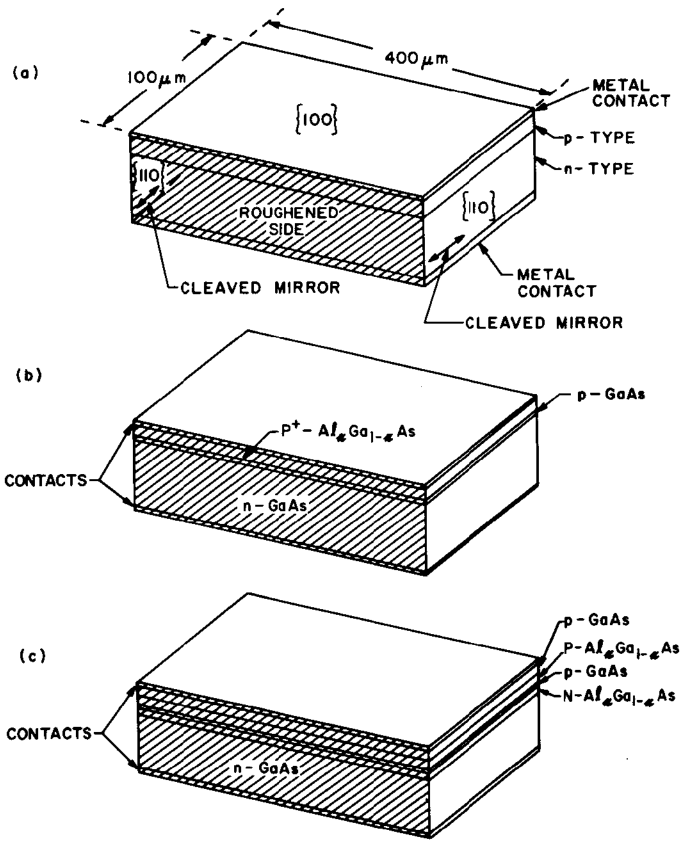

FIG. 1.2-1 (a) Homostructure laser. The cleaved ends of the semiconductor crystal act as the mirrors of a Fabry–Perot cavity. Typical values for length and width are 400 and 100 μm, respectively. (b) Single-heterostructure laser. The p–GaAs layer is ~ 2 μm thick. (c) Double-heterostructure laser. The p–GaAs active layer is usually less than 0.5 μm thick.

was with very short pulses ($\lesssim 1$ μsec) and low duty cycles ($<0.1\%$). With the benefit of hindsight, it is now realized that the very high room temperature threshold current densities were an intrinsic property of the homostructure laser.

Reduction of Threshold Current Density at Room Temperature

The work on homostructure lasers that had started so enthusiastically in 1962 had begun to diminish after 1965, as little or no reduction in the threshold current density was achieved. In 1963, Kroemer[40] suggested that improved junction lasers could be achieved with a structure in which a layer of a semiconductor with a relatively narrow energy gap is sandwiched between two layers of a wider energy gap semiconductor. A junction of two such dissimilar semiconductors is called a heterojunction. It was intended that efficient radiative recombination occur in the narrow energy gap material. Kroemer's paper apparently went unnoticed by the people who were fabricating injection lasers, and a similar suggestion by Alferov and Kazarinov[41] in 1963 was actually never published and was thus unavailable to the scientific community.

At the time of these initial suggestions for the use of heterojunctions for injection lasers, sufficient knowledge had not been attained to permit selection of a suitable set of semiconductors from which to prepare the heterojunction. Kroemer suggested, among other combinations, that the wide energy gap regions be GaAs and that the narrow energy gap material be Ge. Alferov[42,43] suggested GaAs–GaP_xAs_{1-x} heterojunctions and undertook a series of studies, but low-threshold lasers were not achieved by those efforts. The principal difficulty in the latter studies appears to have been poor crystal quality that resulted from lattice mismatch between the two different semiconductors at the heterojunction. Unfortunately, the GaP_xAs_{1-x} system provides a poor lattice match to GaAs at phosphorus concentrations high enough to provide a useful wide energy gap.

In June 1967, Woodall and co-workers[44] at IBM reported on the growth of $Al_xGa_{1-x}As$ on GaAs by liquid-phase epitaxy (LPE). This growth process had first been reported for GaAs on GaAs by Nelson[45] of RCA and was destined to become technologically quite important. Since the energy gap of $Al_xGa_{1-x}As$ increases with AlAs mole fraction x, $Al_xGa_{1-x}As$ light-emitting diodes (LEDs) yield radiation at somewhat shorter wavelengths than can be achieved with GaAs. Because of the near identity of the lattice parameters of GaAs and AlAs, high-quality epitaxial layers can be obtained. This work was published by Rupprecht *et al.*[46] some months later, just before the November 1967 IEEE Conference on Semiconductor Lasers. None of the papers that were presented at that conference was primarily concerned with reducing the threshold current density. However, Rupprecht *et al.*[47] presented a paper that extended their earlier $Al_xGa_{1-x}As$ LED work to $Al_xGa_{1-x}As$ homostructure lasers.

Although the presentation of the $Al_xGa_{1-x}As$ work at the two conferences did not stimulate the fruitful discussions that occurred for the electroluminescence papers of 1962, the efforts of the IBM group did not go unnoticed. Panish and Hayashi of Bell Laboratories were present at the laser conference. Both were rather new to semiconductor work. Panish came from a background in chemical thermodynamics, and Hayashi came from a background in nuclear instrumentation. Panish had been studying the behavior of impurities in solution-grown GaAs and with co-workers[48] in

1966 had reported on the relatively efficient photoluminescence of LPE-grown GaAs as compared to melt-grown material. Hayashi and Panish had recently decided to collaborate on work on injection lasers with the objective of reducing the room temperature threshold current density J_{th} (300°K). This collaboration had been instigated by J. K. Galt, who was director of the Solid State Electronics Research Laboratory at Bell Laboratories. Sufficient reduction of J_{th} (300°K) would permit continuous operation at room temperature, and Galt strongly believed that such an achievement would have significant implications for the possibility of a practical large-scale optical communication system.

A few weeks before the 1967 Semiconductor Laser Conference, Hayashi had considered what advantages might be gained from the use of heterojunctions to confine carriers in injection lasers. Several III–V combinations were noted,[49] but it was not appreciated that GaAs and $Al_xGa_{1-x}As$ had virtually the same lattice parameter. Hayashi had also studied the effect of bandtail shapes on the injected carrier distribution in GaAs.[50] The main thrust that Hayashi and Panish were considering for reducing the room temperature threshold current density was to use dopants to adjust the bandtail shapes.

As a result of the Panish *et al.*[48] studies of 1966, Hayashi and Panish were thinking of using LPE. When they left for the laser conference they were unaware of Kroemer's 1963 publication and Rupprecht's just-published paper. Rupprecht, in his talk at the conference, stressed the shorter wavelength available with the $Al_xGa_{1-x}As$ homostructure laser. However, he also pointed out the excellent lattice match between GaAs and $Al_xGa_{1-x}As$. Rupprecht's talk caused Hayashi and Panish to modify their approach to the reduction of laser threshold current density. They were familiar with LPE and had already given some thought to possible advantages that might be provided by heterojunctions. The lattice-matched GaAs–$Al_xGa_{1-x}As$ heterojunction might reasonably be expected to provide an effective barrier to electron diffusion. Hayashi's considerations of injected carrier diffusion and energy distribution suggested that carrier confinement might help reduce the laser threshold.

The immediate results of attendance at the laser conference were studies by Panish and Sumski[51] to understand the equilibrium relationships between the Al–Ga–As liquid and the $Al_xGa_{1-x}As$ solid and to apply those relationships to the growth of $Al_xGa_{1-x}As$ epitaxial layers on GaAs. The result of the Hayashi–Panish collaboration was a laser with a much-improved room temperature threshold current density of 8.6×10^3 A/cm^2.[52,53] This laser structure is illustrated in Fig. 1.2-lb. It consisted of a layer of *p*-type $Al_xGa_{1-x}As$ heavily doped with Zn that was grown onto an *n*–GaAs substrate. During growth or a subsequent anneal, Zn diffused into the GaAs substrate to form a p–n junction displaced about 2 μm from the heterojunction. As described in much greater detail in subsequent chapters, the heterojunction provides a potential barrier that confines injected electrons to the p-layer of the GaAs p–n junction. Lower room temperature thresholds than with homostructure lasers were achieved in mid-1968, and by the end of the year Hayashi and Panish felt they had gone as far as they could to reduce the threshold current density with the Zn diffusion technique and the available substrate material. They submitted their papers in January 1969 with confidence that they were the first to conceive or produce a heterostructure laser. That confidence was badly shaken: first by a reviewer who pointed out the omission of reference to the 1963 Kroemer paper, and second by publication in the March issue of the *RCA Review* of a paper by Kressel and Nelson[54] describing an essentially identical laser. The Hayashi–Panish papers[52,53] appeared in April 1969 and in a subsequent, more detailed paper in 1970.[55] In anticipation of the more complex structures to follow, they suggested that such lasers be termed single-heterostructure (SH) lasers.[55]

While the efforts of Panish and Hayashi and of Kressel and Nelson were on the SH laser, Alferov and his co-workers at the Ioffe Institute in Leningrad were also working on GaAs–$Al_xGa_{1-x}As$. They reported[56] studies of injection across GaAs–$Al_xGa_{1-x}As$ p–n heterojunctions in 1968, and in a paper published in September 1969,[57] they reported threshold current densities of about 4×10^3 to 13×10^3 A/cm^2 at 300°K. The laser structure they studied is illustrated in Fig. 1.2-1c. It consisted of a sandwich of p–GaAs between n– and p–$Al_xGa_{1-x}As$ layers grown onto a GaAs substrate. This structure provides confinement of both light and carriers to the narrow GaAs region in the sandwich.

During the final phases of their work on the SH lasers in 1968, Hayashi and Panish had independently begun work on multilayered structures such as those of Fig. 1.2-1c. They called the lasers double-heterostructure (DH) lasers. By early 1970, they had reduced the threshold current density to 2.3×10^3 A/cm^2 at 300°K.[58] By the spring of 1970, they had reduced the threshold to about 1.6×10^3 A/cm^2 at 300°K and by heat sinking had achieved continuous-wave (cw) lasing with the heat sink temperatures as high as 311°K. Considerable effort was put into obtaining spectra– and current–light intensity plots that clearly demonstrated the achievement of cw stimulated emission at room temperature. This work was first described[59] to the outside world at the Device Research Conference at Seattle, Washington, in June 1970 by Hayashi. The paper[60] reporting the studies was submitted to *Applied Physics Letters* in early June and appeared in the August 1 issue. Hayashi and Panish were again convinced they had achieved a first. However, the September 1970 issue of *Fizika i Tekhnika Poluprovodnikov* contained a