LASERS

edited by Albert K. Levine
and Anthony J. DeMaria

VOLUME 3

LASERS

A Series of Advances

Edited by ALBERT K. LEVINE

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PREFACE

Since the earliest days of man's utilization of the electromagnetic spectrum, there has been a steady drive toward the production and use of coherent electromagnetic energy of higher frequencies. This tendency resulted mainly from the realization that an increase in transmitted information, directivity, and efficiency was available with increasing carrier frequency and from the desire to relieve the crowding and interference among existing frequency bands. Another important incentive toward generating coherent radiation of higher frequency derived from the interest in utilizing such radiation for probing the atomic domains of solids, liquids, and gases by employing techniques such as nuclear magnetic resonance, paramagnetic resonance, and cyclotron resonance. In response to these needs, active devices such as vacuum tubes, transistors, magnetrons, klystrons, traveling wave tubes, parametric amplifiers, and tunnel diodes were devised for the coherent generation of higher frequencies. These devices made available coherent radiation to approximately 100 GHz; with the use of harmonic generators this figure was extended by approximately an order of magnitude. Almost without exception, as soon as higher frequency devices became available, researchers rushed to utilize them in experiments probing the interaction of coherent radiation with matter.

The physical dimensions of the resonators used to select the oscillating frequency of conventional oscillators in the higher frequency range are of the order of the wavelength of the radiation generated. As a result, the construction of resonators to the small dimension required at submillimeter wavelengths becomes extremely difficult. In the late 1940's and early 1950's it became apparent to workers in the field that the old method of scaling down existing devices for higher frequency generation was becoming impossible to apply. In the search for alternate methods, researchers came to realize that the large supply of natural resonators in the form of atomic and molecular systems could be utilized to amplify and even generate coherent electromagnetic energy.

The operation of NH_3 beam maser by Gordon and associates in 1954 ushered in a new category of active devices falling within a rapidly expanding field called quantum electronics. In 1958 Schawlow and Townes published a classical paper suggesting the use of the maser principle (with appropriate modification) for the generation of coherent infrared, visible, and ultraviolet radiation. The realization of the ruby laser by Maiman in the latter part of 1960 made available for the first time a light beam having characteristics usually associated with radio and microwave radiation. Laser action has since been extended to solids (crystalline and noncrystalline insulators and semiconductors), organic liquids, gases, and vapors, and thousands of discrete wavelengths varying from the vacuum ultraviolet to the submillimeter portion of the infrared have been attained. The quest for new methods of generating coherent radiation, at ever higher frequencies, is still in effect, with emphasis at present on the generation of coherent radiation in the far ultraviolet and soft x-ray regions.

Few developments in science have excited the imagination of scientists as has the laser. In the ten years since its first realization in the form of pulsed coherent emission from single-crystalline ruby, the field has grown at a rate rarely experienced in science. The availability of these intense, coherent optical radiation sources made possible for the first time the experimental investigation of optically generated plasmas, optical harmonic generation, stimulated scattering effects, photon echoes, self-induced transparency, optical adiabatic inversion, picosecond optical pulses, holography, optical shocks, self-trapping of optical shocks, optical parametric amplification, optical ranging to the moon, and extremely high resolution spectroscopy. In addition to the inherent attraction of exploring, characterizing, extending, and exploiting a new physical phenomenon, research in lasers was stimulated by the early experimental verification that coherent radiation could be generated in crystalline systems different from ruby and in other optically transparent media such as gases, glasses, and liquids; thus, a large research effort in materials science was joined to the extensive phenomenological investigations.

The laser device field today encompasses numerous disciplines: solid state, molecular, and atomic physics; spectroscopy; optics; acoustics; electronics; semiconductor technology; plasma physics; vacuum technology; organic and inorganic chemistry; molecular and atomic kinetics; thin film technology; glass working technology; crystallography; and more recently fluid dynamics, aerodynamics, and combustion physics. In sum, even without considering applications, the field has grown so fast and proliferated so broadly that the tendency for scientists to specialize within it is virtually complete. As a result, today probably no individual would profess to be authoritative over the whole field of laser devices, or even knowledgeable of most of the significant literature.

Lasers is a series of critical reviews that evaluate the progress made in the field of lasers. The contributing authors are scientists who are intimately involved in expanding the research frontiers in their specialities and, therefore, write with the authority that comes from personal contribution.

The series provides the background, principles, and working information that is needed by physical and biological scientists who seek to use lasers as a tool in their research and by engineers who wish to develop the laser phenomenon for commercial and military applications. Moreover, these critical reviews are sufficiently intensive that they can be used by a specialist in one portion of the laser field to bring himself up to date authoritatively in other areas of the field.

April, 1971

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Chapter 1 · SEMICONDUCTOR LASERS

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I. Introduction

The p–n junction laser has followed an historical evolution familiar in other semiconductor devices. The discovery in 1962(*1–3*) was followed by studies of operating principles and comparisons between first-order theory and experiment. Finally, successive technological innovations moved the devices from the laboratory to the stage where serious systems applications were possible. This review will concentrate on the three-year period since 1967, during which important technological innovations have occurred. The fundamental aspects of laser theory as well as the earlier work on diode lasers has been extensively reviewed in the literature up to March 1967(*4–10*). In addition, the theoretical background useful in understanding laser operation may be found in various textbooks(*11*).

While diode lasers, which are of the utmost practical interest at this time, receive most of the attention in this chapter, a review of the state of the art in electron beam and optically pumped semiconductor lasers is also given. However, no attempt is made to cover these subjects exhaustively.

II. General Laser Concepts

In this section we review a few of the key concepts concerning laser action in semiconductors, without any attempt to consider the literature in detail. Extensive theoretical treatments of this subject can be found elsewhere and the objective here is to summarize the concepts needed for the subsequent description of devices.

A. DIRECT AND INDIRECT BANDGAP SEMICONDUCTORS

In direct bandgap semiconductors (the only type in which stimulated emission has been observed), both photon emission and absorption can occur without the need for a third quasi particle (a phonon) to conserve momentum. This is because the lowest conduction band minimum and highest valence band maximum are at the same wave vector ($\bar{k}$) in the Brillouin zone. Figure 1 shows the schematic diagram of electron energy vs. $\bar{k}$ in a semiconductor, such as GaAs, where the smallest bandgap energy $E_g = E_c - E_v$ is at $\bar{k} = [000]$.

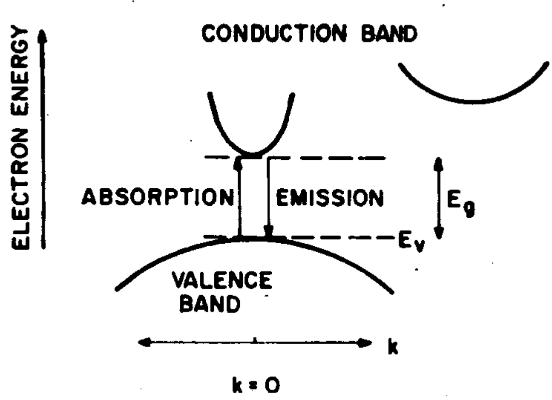

Fig. 1. Photon absorption and emission in a direct bandgap semiconductor.

In indirect bandgap semiconductors, the conduction band minimum and valence band maximum are not at the same $\bar{k}$ value. Hence, photon emission and absorption require the participation of phonons to conserve momentum. A schematic diagram of an indirect bandgap semiconductor such as GaP or AlAs is shown in Fig. 2. In these semiconductors the lowest-lying conduction band minima are along $\bar{k} =$ ⟨100⟩, of which there are 6 equivalent valleys, while the highest valence band maximum is at $\bar{k} =$ [000].

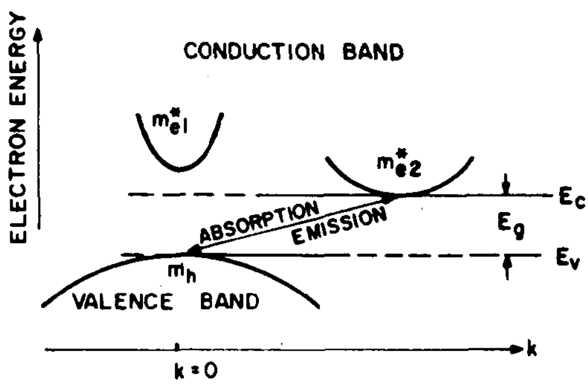

Fig. 2. Photon emission and absorption in an indirect bandgap semiconductor. The effective electron masses $m^*_{e_1}$ and $m^*_{e_2}$ refer to the two conduction band minima shown. In general, $m^*_{e_2} > m^*_{e_1}$. In the case of GaP and AlAs, the conduction band minima occur along $\bar{k} =$ ⟨100⟩. The m_h is the density-of-states effective hole mass.

By mixing different bandgap compounds, a continuous variation of the band structure is possible. For example, in $GaAs_{1-x}P_x$, the change from direct to indirect bandgap transition occurs at about $x \cong 0.45$, with $E_g \cong 1.96$ eV(*12*). Another alloy system of great technological interest is $Al_xGa_{1-x}As$ in which the crossover occurs at $x \cong 0.34$ (*13*,*14*). Figure 3 shows the variation of the bandgap energy of $Al_xGa_{1-x}As$ as a function of x. The composition at which the ⟨100⟩ and [000] conduction band minima are at the same energy marks the crossover from a direct to an indirect semiconductor ($E_g \sim 1.92$ eV).

As illustrated in Fig. 2, the effective masses in the different non-equivalent conduction band minima are not equal and generally $m^*_{e_2} > m^*_{e_1}$. Hence, the electron mobility is lower in the indirect than in the direct composition range as was shown in Ga(AsP)(*15*).

Lasing in indirect bandgap semiconductors is improbable because the lowest-energy band-to-band transition probabilities are much smaller than in direct semiconductors. Because of the relatively long lifetime of electrons in the indirect minima, there is time for non-radiative processes to occur. Furthermore, the stimulated recombination rate is a function of the band-to-band absorption coefficient(*11*,*16*). Since this coefficient is lower for indirect than direct transitions, the potential laser gain is correspondingly reduced(*17*). Theoretical discussion of the possibilities of lasing in indirect bandgap semiconductors will be found also in Refs.(*18*,*19*).

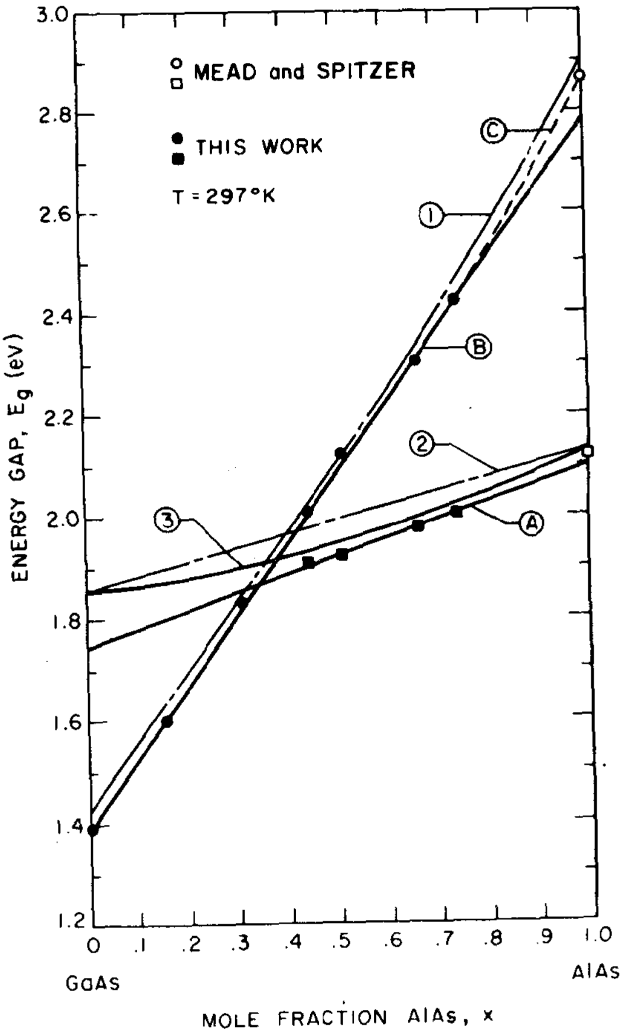

Fig. 3. The direct $\Gamma_{15} \rightarrow \Gamma_1$ and indirect $\Gamma_{15} \rightarrow X_1$ energy gaps for $Al_xGa_{1-x}As$. Line A is the straight-line fit to the photoresponse indirect energy gap values designated by the squares. Line B is the straight-line fit to the photoresponse direct energy gap values given by the circles. Line C is the direct energy gap calculated from the empirical relation [A. G. Thompson and J. C. Woolley, *Can. J. Phys.*, **45**, 255 (1967)]:

$$E_{gd}(x) = E_{gd}(\mathrm{GaAs}) + Bx + 0.3x^2/\{\tfrac{1}{2}[E_{gd}(\mathrm{GaAs}) + E_{gd}(\mathrm{AlAs})]\}^{1/2}$$

with B evaluated at $x = 1$, $E_{gd}(\mathrm{GaAs}) = 1.395$ eV, and $E_{gd}(\mathrm{AlAs}) = 2.86$ eV. Line 1 is the direct energy gap calculated from the quadratic relation with $E_{gd}(\mathrm{GaAs}) = 1.435$ eV and $E_{gd}(\mathrm{AlAs}) = 2.90$ eV. Line 2 is a straight-line approximation to the indirect energy gap with $E_{gi}(\mathrm{AlAs}) = 2.13$ eV and the difference in Γ_1 and X_1 as 0.43 eV. Line 3 is given by the quadratic relation with $E_{gi}(\mathrm{GaAs}) = E_{gd}(\mathrm{GaAs}) + 0.42 = 1.855$ eV and $E_{gi}(\mathrm{AlAs}) = 2.13$ eV. From (*14*).

B. POPULATION INVERSION AND LASING CRITERIA

Optical gain is possible when population inversion has been achieved; i.e., the probability of photon emission with energy $h\nu$ is greater than the inverse process of absorption at the same photon energy. Analysis of laser action in semiconductors is greatly complicated by the fact that the density-of-states distribution affects the theoretically predicted behavior. These matters will be considered below. We begin with the basic requirements for laser action.

1. In thermodynamic equilibrium, the probability of an electron occupying a state with energy E is given by the Fermi–Dirac distribution function

$$f = \left(1 + \exp\frac{E-F}{kT}\right)^{-1} \tag{1}$$

where F is the Fermi level and T the temperature.

When minority carriers are injected into a semiconductor (for example, electrons into p-type material), the condition of thermodynamic equilibrium no longer holds. However, a steady state distribution of carriers in the conduction and valence bands, independently, can be assumed to occur. Hence, a quasi-Fermi level for electrons, F_c, and for holes, F_v, is defined, where

$$f_c = \left(1 + \exp\frac{E-F_c}{kT}\right)^{-1} \tag{2}$$

Similarly, for the valence band, the probability for a state at a given energy to be empty (containing a hole) is

$$1 - f_v = 1 - \left(1 + \exp\frac{E-F_v}{kT}\right)^{-1} \tag{3}$$

It was shown by Bernard and Duraffourg (*20*) that the condition for net gain at a photon energy $h\nu$ is

$$F_c - F_v > h\nu \tag{4}$$

The carrier distribution must be degenerate for this condition to be satisfied. In order to obtain lasing in degenerate p-type material, for example, it is therefore necessary to inject a sufficient density of electrons to fill states in the conduction band until the quasi-Fermi level F_c has been raised (and F_v lowered) sufficiently for condition (4) to be satisfied. If the density-of-states variation dN/dE in the conduction band valley is large, this may require a very high injection level (high threshold current density). As will be discussed later (Section

II.C), the addition of a high density of donors to the *p*-type material (i.e., compensation) adds a *tail* of states below the conduction band which lowers dN/dE. The density-of-state variation in the tail is generally approximated by

$$\rho \propto \exp \frac{E}{E_0} \tag{5}$$

instead of the parabolic distribution $\rho \propto E^{1/2}$ of the unperturbed conduction band. If the constant E_0 is sufficiently large, the density-of-states variation with energy is much smaller in the band tail than in the conduction band. Hence, degeneracy, particularly at high temperatures, is achieved with a smaller density of injected electrons.

The lasing criterion (4) applies, of course, to both homogeneous samples (electron-beam or optically pumped) and p–n junctions. In a p–n junction, the density-of-states distribution as a function of distance is shown in Fig. 4. We assume that both the *n* and *p* sides of the junction are degenerate, with the applied voltage V sufficient to nearly

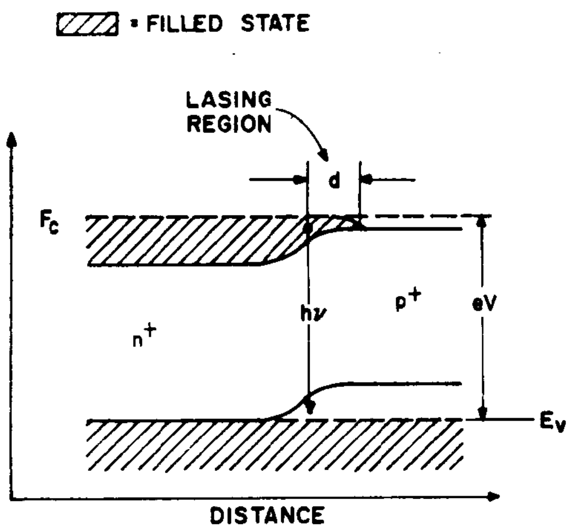

Fig. 4. Energy bands in a p–n junction under very high forward bias voltage V. Both the *n* and *p* sides of the junction were initially degenerate. As shown, a high density of electrons is injected into the *p* side, with negligible hole injection into the *n* side. Both the electron and hole populations are substantially degenerate over the active region *d* where the condition $F_c - F_v > h\nu$ is satisfied.

eliminate the barrier at the p–n junction. The injected electrons are distributed over a distance *d* (a few microns) in which, if the injection level is high enough, the population is inverted. Hole injection into the *n* side is small in such diodes, partly because the bandgap in the *p* side