Chapter 1

Introduction

1.1 Historical Developments

The semiconductor optical amplifier is very similar to a semiconductor laser. The laser has a gain medium and an optical feedback mechanism. The latter is generally provided by the cleaved facets of the semiconductor itself or by a grating of suitable periodicity etched close to the gain medium. At threshold, the gain equal loss for a laser, and the gain needed for laser action is typically ∼5 to 10 dB. A traveling wave optical amplifier has only a gain medium. However, the gain is generally larger (∼20 to 25 dB) compared to that for a laser. The optical gain is caused by the recombination of electrons and holes (electrons and holes are injected by external current). Thus the semiconductor amplifier operates at a higher current density than a laser at threshold.

The concept of the laser dates back to 1958 [1]. The successful demonstration of a solid state ruby laser and He-Ne gas laser was reported in 1960 [2, 3]. Laser action in semiconductor was considered by many groups during that period [4–6]. The semiconductor injection laser was demonstrated in 1962 [7–10]. CW operation of semiconductor laser was demonstrated in 1970 [11, 12] using the concept of double heterostructure [13]. Since then the semiconductor injection laser has emerged as an important device in many optoelectronic systems such as optical recording, high-speed data transmission through fibers, optical sensors, high-speed printing, and guided wave signal processing. An important impact of semiconductor lasers is in the area of fiber optic transmission systems where the information is sent through encoded light beams propagating in glass fibers. These lightwave transmission systems, which have been installed throughout the

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world, offer a much higher transmission capacity at a lower cost than coaxial copper cable transmission systems.

The advantages of semiconductor lasers over other types of lasers, such as gas lasers, dye lasers, and solid-state lasers, lie in their considerably smaller size and lower cost and their unique ability to be modulated at gigahertz speeds simply by modulation of the injection current. These properties make the laser diode an ideal device as a source in several opto-electronic systems, especially the optical fiber transmission systems. Semiconductor laser properties are discussed in several books [14–17].

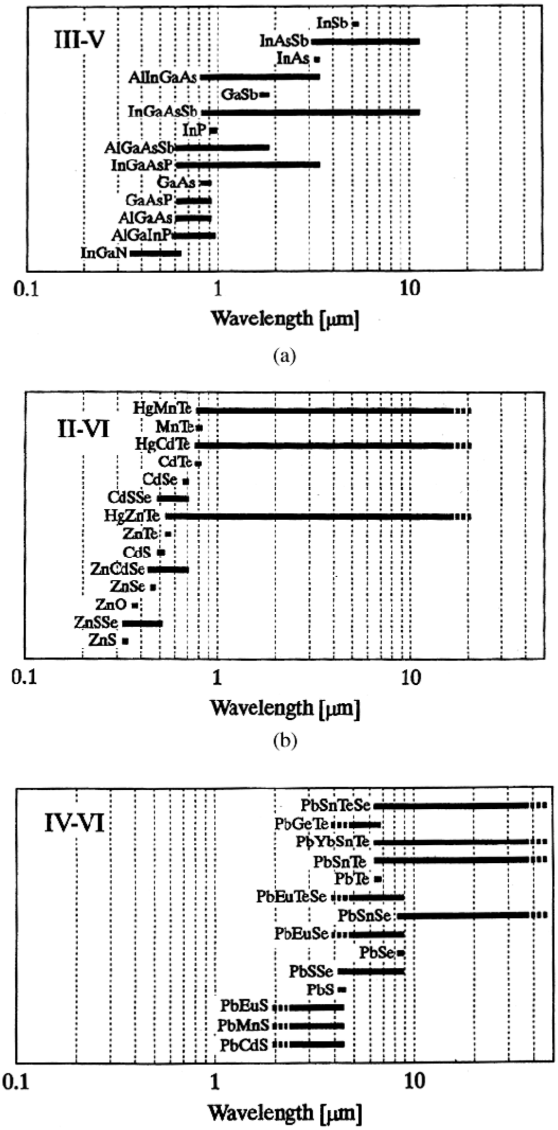
Historically, the research on optical amplifier followed that of the semiconductor laser. Early work was carried out using GaAs/AlGaAs material system [18–21]. A majority of the follow on work has been using the InGaAsP/InP material system. This material system is suitable for producing amplifiers with optical gain in the 1300 to 1600 nm wavelength range. The fiber optic transmission systems operate in this wavelength range due to the low loss of optical fibers and the commercial application of optical amplifiers are going to be driven by their need in fiber communication systems. This book provides a comprehensive and detailed account of design, fabrication, and performance of semiconductor optical amplifiers in optical networks. Earlier work is discussed in previous books [22, 23].

1.2 Semiconductor Materials

The choice of materials for semiconductor amplifiers is principally determined by the requirement that the probability of radiative recombination should be sufficiently high that there is enough gain at low current. This is usually satisfied for “direct gap” semiconductors. The various semiconductor material systems along with their range of emission wavelengths are shown in Figure 1.2.1. Many of these material systems are ternary (three-element) and quaternary (four-element) crystalline alloys that can be grown lattice-matched over a binary substrate.

Many of these materials were first used to make semiconductor lasers [7–10, 14–17]. The lines represent the range of band gaps that can be obtained by varying the composition (fraction of the constituting elements) of the material. The optical gain in amplifiers occurs at wavelengths close to the band gap. Thus a suitable set of materials must be chosen to get optical gain at the desired wavelength.

Another important criterion in selecting the semiconductor material for a specific heterostructure design is related to lattice matching, i.e. the



(a)

(b)

(c)

Figure 1.2.1 Semiconductor materials used in laser fabrication at different regions of the spectrum. The three figures refer to compound semiconductors formed using group III and group V elements (III-V), group II and group VI elements (II-VI) and group IV and group VI elements (IV-VI) of the periodic table [24]. The quantum cascade lasers are fabricated using III-V semiconductors and they operate on intraband transitions in a quantum well.

crystalline materials that form the heterostructure must have lattice constants which are equal to within ~0.01%. The binary substrates that are commonly used are GaAs and InP. They can be grown in a single crystal form from a melt. The ternary or quaternary semiconductors are epitaxially grown over the binary substrate for semiconductor laser or amplifier fabrication. In the epitaxial growth process the single crystal nature is preserved across the interface of the two materials. This leads to near absence of defect sites at the interface.

The development of epitaxial growth techniques has been of major significance for the development of semiconductor photonic devices such as lasers, amplifiers and photodetectors. The commonly used techniques for epitaxial growth are liquid phase epitaxy (LPE) [25], vapor-phase epitaxy (VPE) [26], molecular beam epitaxy (MBE) [27], and metal organic chemical vapor deposition (MOCVD) [28]. Early work on lasers and amplifiers were carried out using the LPE growth technique. The MBE technique is very useful for the growth of very thin semiconductor layers and was first used to fabricate quantum well structures [29]. The MOCVD technique and its variants are generally used for commercial production of lasers, amplifier and photodetectors. These growth techniques are described in detail in Chapter 4. In addition to growth, processing techniques of semiconductor materials for laser or amplifier fabrication was developed. The processing techniques include current confinement, low resistance contacts and etching of the semiconductor material to form specific geometries [33–35].

In the absence of lattice match the quality of the hetero-interface is poor, i.e. there are lattice defects which serve as nonradiative recombination sites. In certain instances it is possible to grow epitaxially thin layers of one semiconductor on top of another in the presence of a lattice mismatch of few percent. Such growth is called strained layer epitaxy, it is discussed in Sec. 4.4. Figure 1.2.2 shows the relationship between band gap (E_g) and lattices constant (a) of several ternary compound semiconductors. The dots correspond to the binary compounds and the lines represent the ternary compounds.

The ternary semiconductor $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ can be grown over a GaAs substrate over the entire range of Al fraction x because GaAs and AlAs have nearly the same lattice constant. However, the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ material has a direct band gap for compositions with $x < 0.45$. Semiconductors with direct band gap are needed for efficient light emission. Heterostructures using the AlGaAs/GaAs material system was the first to be studied

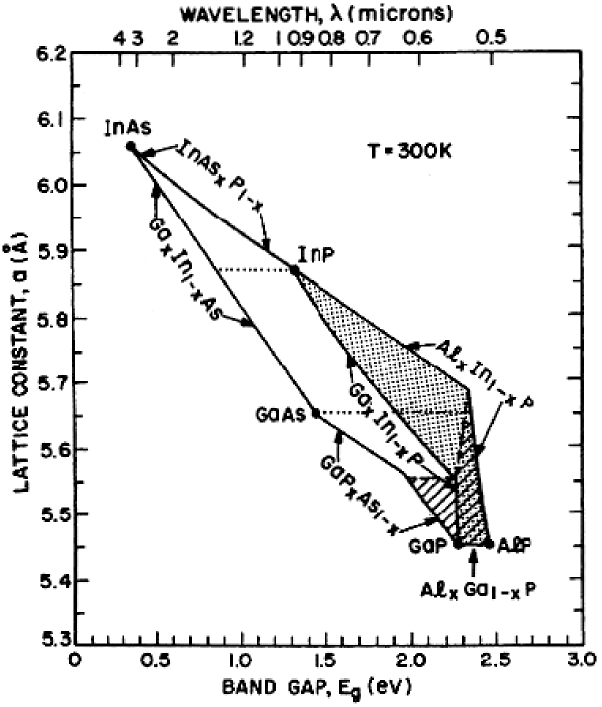


Figure 1.2.2 Band gap and lattices constants of several ternary and quaternary compounds formed from the binary compounds. For $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$ quaternary material, the clear region is the region of direct band gap [2].

extensively. Semiconductor lasers, amplifiers, bipolar transistors and field effect transistors have been made using this material system.

In the 1970's considerable resources were devoted for lasers and photodetector fabrication using the quaternary $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$/InP material system. This material system is particularly suitable for lasers in the 1.3 μm, 1.55 μm wavelength range which is the region of low dispersion and low optical loss for silica optical fibers. $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$ can be grown lattice matched over a InP single crystalline substrate for $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$ compositions for which $x \sim 0.45y$. Lasers and detectors based on this material system are widely used in current fiber optic communication systems. Semiconductor amplifiers are important for all optical networks which operate near 1.55 μm wavelength range. Thus much of the developments on optical amplifiers in the 1990's and continuing on has been using the $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$/InP material system.

1.3 Operating Principles

Semiconductor optical amplifier is very similar to a laser except it has no reflecting facets [36, 37]. A typical amplifier chip is ∼0.6 to 2 mm long. It has a p-cladding layer, a n-cladding layer and a gain region all of which are epitaxially grown over a binary substrate.

The schematic of a semiconductor optical amplifier (SOA) chip is shown in Figure 1.3.1. The amplifier chips have cleaved facets with anti-reflection coating (and possibly other modifications) which reduces its reflectivity to nearly zero. Just like the laser, the amplifier has a p-n junction which is forward biased during operation. The injected current produces gain in the gain region.

The majority carries are holes in the p-cladding layer and they are electrons in the n-cladding layers. The electrons and holes are injected into the gain region which is made of a lower band gap semiconductor than the cladding layers. The co-located electrons and holes recombine. This results in spontaneous emission of light and optical gain for light propagating in the gain region. It is a fortunate coincidence that semiconductors with lower band gap also has a higher index than semiconductors with higher band gap. The small index difference produces a waveguide for the propagating signal light. The signal is guided in this waveguide and it experiences amplification (gain) until it emerges from the output facet of the amplifier. Thus the double heterostructure material with n-type and p-type high band gap semiconductors around a low band gap semiconductor is instrumental in simultaneous confinement of the charge carriers (electrons and holes) and the optical signal. This is illustrated in Figure 1.3.2.

The electrons are located in the conduction band and holes are present in the valence band. In the gain region, the electrons and holes recombine

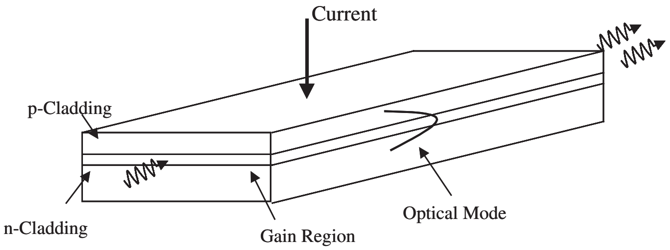


Figure 1.3.1 Schematic of a semiconductor optical amplifier with no waveguide in the lateral (along the plane of p-n junction) direction.

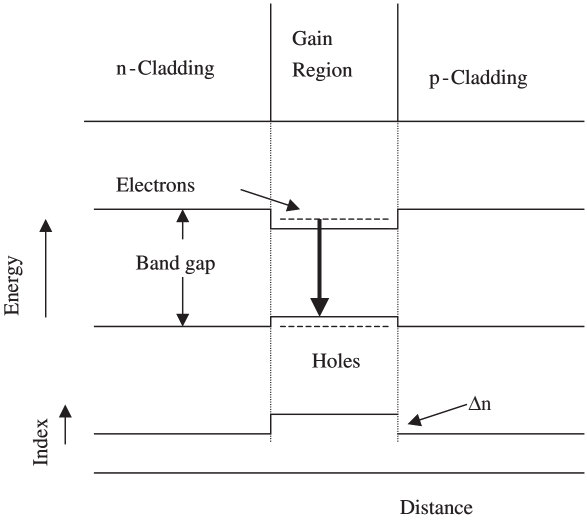


Figure 1.3.2 Schematic illustration of confinement of the electrons and holes and also simultaneous confinement of optical mode in a double heterostructure.

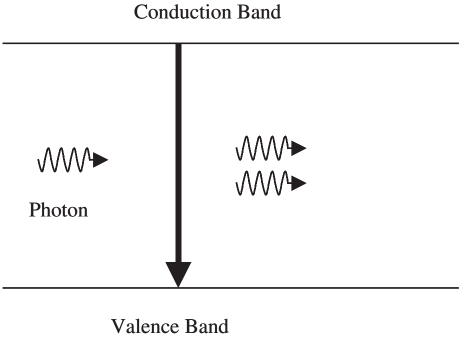


Figure 1.3.3 Schematic illustration of gain (or amplification). An electron-hole pair recombines to generate a photon. This photon is emitted in the same direction as the incident photon. The process is known as stimulated emission.

to produce photons through both spontaneous and stimulated emission process (Figure 1.3.3). The optical gain of the input signal is due to the stimulated emission process. In the absence of current (electrons and holes), the semiconductor would absorb the incident photons. A certain minimum number density of electrons (and holes) are needed to achieve net optical gain or amplification.

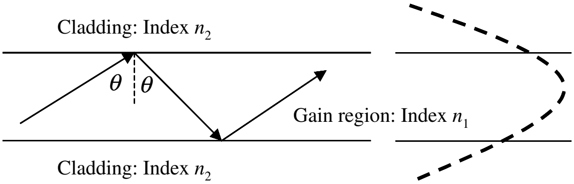


Figure 1.3.4 Waveguiding in a double heterostructure. The gain region of index n_1 has cladding layers of index n_2 on both sides. The index $n_1 > n_2$. The above figure shows the total internal reflection of a ray incident at an angle θ (with $\sin\theta > (n_2/n_1)$) propagating in the gain region. An alternate view is that a confined optical mode with intensity profile (shown dashed in the figure) propagates in the waveguide.

Low current operation of an amplifier or laser requires that the optical signal remain confined in the vicinity of the gain region. In the double heterostructure this is accomplished by slightly higher index of the gain material compared to that for the cladding materials. These three layers form a waveguide. The optical mode propagation in a three layer waveguide using the ray approach is shown in Figure 1.3.4. The rays incident at an angle θ, with $\sin\theta > (n_2/n_1)$, undergoes total internal reflection at the interface of the cladding and active region. Thus rays with these sets of angle of incidence continue to propagate through the amplifier and gets amplified. Other rays escape from the gain region. An alternative view is an optical mode with a certain profile determined by the thickness of the gain region and the indices can propagate through the amplifier without any diffraction loss. The intensity profile of a propagating mode is also sketched in Figure 1.3.4. A fraction of the incident optical signal can, in general, be coupled to the propagating mode. The remaining fraction is lost. When an amplifier is viewed as an optical element in a larger optical system, this lost optical signal is viewed as a coupling loss, typically ~50% per facet (~3 dB). Various schemes exist to reduce the coupling losses. So far the optical waveguiding normal to the p-n junction has been discussed. Optical waveguiding in the lateral direction (along the plane of the p-n junction) is also important for fabrication of high performance (low noise) amplifiers that have high gain at low current. Various schemes for lateral optical guiding and current confinement have been developed. These are described in detail in Chapter 4.

1.4 Applications

Semiconductor optical amplifier (SOA) as the name implies could be used as an amplifier in a fiber optic communication system or other types of optical amplifier applications. Although many studies on applications of SOA in optical fiber systems have been reported, in these applications a limitation is a relatively low saturation power of the SOA ($\sim$10 to 100 mW).

However, the SOA have found many novel applications in all-optical networks. This includes wavelength conversion where data on a signal at wavelength λ_1 is converted to data at another wavelength λ_2. Optical demultiplexing where a very high speed (>100 Gb/s) optical data is converted to several tributaries of low speed ($\sim$10 to 20 Gb/s) data for information retrieval using conventional electronic means. Optical clock recovery where a clock signal (timing signal which determines the positions of the 1's and 0's) are generated from the high speed optical data signal. SOA is also suitable for many all optical processing such as label swapping, optical header recognition and optical switching.

All-optical signal processing is expected to become increasingly important in future ultrahigh capacity telecommunication networks. The development of all optical logic technology is important for a wide range of applications in all optical networks, including high speed all optical packet routing, and optical encryption. An important step in the development of this technology is a demonstration of optical logic elements and circuits, which can also operate at high speeds. These logic elements include the traditional Boolean logic functions such as XOR, OR, AND, INVERT, etc., and circuits such as parity checker, all-optical adder and shift register. SOA based devices such as Mach-Zehnder interferometers are being investigated for the development of all-optical logic circuits.

1.5 Book Overview

The fundamental operating principles of semiconductor optical amplifiers are derived in Chapter 2. The optical gain spectrum, saturation of gain at high powers and the mechanism for gain is discussed. The minimum carrier density needed for amplification is given. The propagation of optical mode through the dielectric waveguide and mode confinement is discussed. The need for p-n junction is discussed. Various amplifier gain region designs such as the multi-quantum-well and the design for specific performance are described.

Chapter 3 describes radiative and nonradiative recombination mechanism of electrons and holes in semiconductors. Expressions for optical gain, spontaneous recombination rate as a function of carrier density for various temperatures is obtained and their dependence on band structure parameters is discussed. Optical gain in quantum well, quantum wire and quantum dot amplifiers are described.

Epitaxial growth of amplifier materials are described in Chapter 4. Various growth processes and amplifier fabrication methods are described. Index guided amplifier structures and their fabrication is described. Strained layer gain region important for polarization independent gain is described. Growth of quantum dot materials is described.

In an ideal traveling wave (TW) amplifier the optical beam should not experience any reflectivity at the facets. However, in practice the facets with antireflection (AR) coating exhibit some residual reflectivity. This residual reflectivity results in the formation of an optical cavity which has resonance at the longitudinal modes. This causes a variation in gain as a function of wavelength of a traveling wave semiconductor amplifier. Various schemes for ultra low reflectivity facets are discussed in Chapter 5.

The rate equations for pulse propagation in semiconductor optical amplifiers are developed in Chapter 6. The effect of multiple pulses on the gain and phase changes, and the multiwavelength operation are discussed. Various factors for optical noise in amplifiers such as the spontaneous-spontaneous beat noise and signal-spontaneous beat noise are described.

There have been a significant number of developments in the technology of integration of semiconductor lasers, amplifiers and other related devices on the same chip. These chips allow higher levels of functionality than that achieved using single devices. The name photonic integrated circuit (PIC) is generally used when all the integrated components are photonic devices, e.g., lasers, detectors, amplifiers, modulators, and couplers. The design and performance of several photonic integrated circuits with amplifiers are described in Chapter 7.

The commercial use of semiconductor optical amplifiers are projected to be in the form of functional devices in all-optical networks. Such functional applications include, wavelength conversion, transparent switch networks, optical demultiplexing, optical clock recovery and others. Many of these applications utilize gain saturation phenomenon (which results in cross gain/cross phase modulation) or nonlinear four wave mixing in optical amplifiers. Both the mechanisms needed for the functional performance and the viability of the amplifier in such applications and discussed in Chapter 8.

A class of photonic integrated circuits (PIC's) which use amplifiers are being investigated for photonic logic systems. The design and performance of these PIC's are described in Chapters 9 and 10. Optical logic circuits are discussed in Chapter 10.

1.6 Future Challenges

Tremendous advances in InP based semiconductor optical amplifier (SOA) technology have been achieved in the last decade. Advances in research and many technological innovations have improved the designs of semiconductor amplifiers. Although most lightwave systems use optical fiber amplifiers for signal amplification, SOA's can be suitably used for integration and as functional devices. The functional properties such as wavelength conversion, optical demultiplexing, and optical logic elements make them attractive for all-optical network and optical time division multiplexed systems.

The demand for higher capacity is continuing to encourage research in wavelength division multiplexed (WDM) based and optical time division multiplexing (OTDM) based transmissions, which requires optical demultiplexer and high power tunable lasers. An important research area would be the development of semiconductor amplifiers for the Mach-Zehnder or Michelsen interferometers and as the low power amplifiers in integrated devices.

Improving SOA performance at high temperature is an important area of investigation. The InGaAsN based system is a promising candidate for making gain regions near 1.3 μm with good high temperature performance. Strained quantum well structures provide ways of making polarization independent amplifiers. Amplifiers using quantum dot active region possess the fast gain and phase recovery times which makes them useful for fast optical systems.

Finally, many of the advances in the SOA would not have been possible without the development in materials processing technology. The challenges of most current research in SOA are closely related to the challenges in materials growth which include not only the investigation of new material systems but improvements in existing technologies, such as quantum dots, for making them more reproducible and predictable systems.

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