African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 2, Issue 4, October - December 2023, Page No: 113-121
Website: *https://aaasjournals.com/index.php/ajapas/index*
||Arab Impact factor 2022: 0.87|| SJIFactor 2023: 5.689|| ISI 2022-2023: 0.557

Characterizing the Response of Strained Layer Semiconductor Lasers Using Pressure Techniques: Review

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Received: August 29, 2023	Accepted: October 09, 2023	Published: October 18, 2023

Abstract:
The pressure technique offers a powerful approach for characterizing the response of strained layer semiconductor lasers. It allows researchers to investigate the impact of pressure-induced modifications on the band structure, lasing wavelength, optical gain, threshold current, carrier dynamics, and phase transitions. The insights gained from such studies are valuable for optimizing the design and performance of strained layer semiconductor lasers in various applications.
This research aimed to characterize the response of the stressed layer to a semiconductor laser using compression techniques by reviewing the literature related to the current research
The research concluded that understanding the various loss mechanisms in semiconductor lasers is vital for improving their efficiency, power output, and reliability. Mitigating the impact of these loss mechanisms through material optimization, device design, and advanced fabrication techniques is an ongoing area of research. By addressing and minimizing these losses, semiconductor lasers can achieve higher performance, longer lifetimes, and expanded applications in various fields.

Keywords: Characterizing, Response, Strained Layer, Semiconductor, Lasers, Pressure Techniques

Cite this article as: M. M. M. Ahmedi, “Characterizing the Response of Strained Layer Semiconductor Lasers Using Pressure Technique: Review,” *African Journal of Advanced Pure and Applied Sciences (AJAPAS)*, vol. 2, no. 3, pp. 113–121, October - December 2023.

توصيف استجابة طبقة المجهدة لليزر أشباه الموصلات باستخدام تقنيات الضغط: مراجعة

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الملخص
أدى توفر تقنية الضغط طريقة قوية لتوصيف استجابة أشعة الليزر شبه الموصلة ذات الطبقة المتوترة. فهو يسمح للباحثين بالتحقيق في تأثير التعديلات الناجمة عن الضغط على بنية النطاق، وطول موجة الليزر، والكسب البصري، وتيار العتبة، وديناميكيات الموجة الحاملة، وانتقالات الطور. تعتبر الأفكار المكتسبة من هذه الدراسات ذات قيمة لتحسين تصميم وأداء أشعة الليزر شبه الموصلة ذات الطبقة المتوترة في التطبيقات المختلفة.
هدف البحث إلى توصيف استجابة طبقة المجهدة لليزر أشباه الموصلات باستخدام تقنيات الضغط من خلال مراجعة الأدبيات ذات العلاقة بالبحث الحالي.

وخلص البحث إلى أن فهم آليات الفقد المختلفة في ليزرات أشباه الموصلات يعد أمراً حيوياً لتحسين كفاءتها وإنتاج الطاقة والموثوقية. يعد التخفيف من تأثير آليات الخسارة هذه من خلال تحسين المواد وتصميم الأجهزة وتقنيات التصنيع المتقدمة مجالاً مستمراً للبحث. ومن خلال معالجة هذه الخسائر وتقليلها إلى الحد الأدنى، يمكن لأشعة ليزر أشباه الموصلات تحقيق أداء أعلى وعمر أطول وتطبيقات موسعة في مختلف المجالات.

الكلمات المفتاحية: توصيف، استجابة، طبقة المجهدة، الليزر، أشباه الموصلات، تقنيات الضغط.

1. Introduction

Semiconductor diode lasers have indeed experienced a significant expansion in their range of applications. Their unique characteristics, such as compact size, efficiency, and wavelength tunability, make them a versatile technology with widespread utility [1]. Operating features including output wavelength, power, temperature sensitivity, astigmatism, far-field pattern, and dynamic responsiveness all affect how each one is used.

Within only a few decades, the semiconductor laser diode has evolved into a family of robust, reliable devices, with individual conversion efficiencies of better than 60 percent, continuous output powers of several kilowatts, modulation rates of several tens of gigahertz, and wavelengths from 0.4 to beyond 2 µm.

In the diode laser, the amplifying element is a forward-biased PN junction formed in a direct-bandgap semiconductor. The recombination of electrons and holes in the PN junction produces optical gain. When forward biased, electrons are injected from the N side while holes are injected from the P side; both electrons and holes are confined within a lower bandgap region where they can recombine either spontaneously or via stimulated emission when excited by an existing photon. (They also can recombine non-radiatively, a parasitic process that degrades performance) [2].

Characterizing the response of strained layer semiconductor lasers using pressure techniques involves subjecting the lasers to high-pressure conditions and analyzing their optical, electrical, and thermal properties. By applying pressure, researchers can investigate how the performance and behavior of strained layer semiconductor lasers are affected. This characterization provides valuable insights into optimizing their operation, understanding fundamental physics, and exploring potential applications in high-pressure environments.

In such research, various experimental techniques are employed to study the response of strained layer semiconductor lasers under pressure. These techniques may include high-pressure cells, diamond anvil cells, or hydrostatic pressure chambers. The lasers are typically assessed for parameters such as emission wavelength, spectral linewidth, threshold current density, output power, efficiency, and reliability [3].

By studying strained layer semiconductor lasers under pressure, researchers can gain a deeper understanding of the impact of external pressure on their performance. This knowledge aids in optimizing device design, material selection, and growth processes. It also contributes to the development of reliable and efficient strained layer semiconductor lasers for specific applications, such as deep-sea exploration, aerospace, and geothermal energy systems.

The range of the devices just stated is covered by the laser diodes under investigation in this work span the range of the devices just discussed. A wide range of experiments have been carried out in order to further understand the physical factors influencing their operation.

1.1 Importance of Laser Diodes

Laser diodes, or semiconductor diode lasers, hold great importance in various fields and applications due to their unique properties. Here are some key aspects highlighting the importance of laser diodes [4]:

1. Compactness and Efficiency: Laser diodes are small and compact, making them ideal for integration into various devices and systems. They offer high electrical-to-optical conversion efficiency, enabling energy-efficient operation.
2. Wavelength Versatility: Laser diodes cover a broad range of wavelengths, from ultraviolet (UV) to near-infrared (NIR) region, allowing for diverse applications in fields such as telecommunications, medicine, material processing, and more.
3. Precision and Control: Laser diodes provide precise and controlled beams of coherent light, which can be focused to very small spot sizes. This feature is valuable for applications requiring high precision, such as laser cutting, laser engraving, and medical procedures.
4. Speed and Modulation Capability: Laser diodes can be modulated at high frequencies, enabling their use in telecommunications for data transmission and optical networking. They are also employed in laser printers, barcode scanners, and optical storage devices.
5. Wide Range of Applications: Laser diodes find extensive use in various industries and fields, including:
    - Telecommunications: Laser diodes are crucial components in fiber-optic communication systems, enabling high-speed data transmission over long distances.

- Medicine and Biotechnology: Laser diodes are utilized in medical procedures like laser surgery, dermatology, ophthalmology, and dental treatments. They are also employed in diagnostic techniques such as fluorescence imaging and flow cytometry.
- Material Processing: Laser diodes are used for cutting, welding, marking, and surface modification in industries such as manufacturing, automotive, and electronics.
- Displays and Projection Systems: Laser diodes are employed in laser projectors, heads-up displays, and other display technologies, providing high brightness and color accuracy.
- Sensing and Metrology: Laser diodes are used in various sensing applications, including LIDAR systems, environmental monitoring, and spectroscopy for chemical analysis.
- Research and Development: Laser diodes are essential tools in scientific research and development across multiple disciplines, including physics, chemistry, biology, and engineering.
- Defense and Security: Laser diodes have applications in defense and security, such as laser range finding, target designation, and infrared illumination.

1.2 Types of Laser Diodes

Here are several types of laser diodes, each designed for specific applications and operating principles. Here are some common types of laser diodes [5].

1. Edge-Emitting Laser Diodes: Also known as Fabry-Perot laser diodes, these are the most common type of laser diodes. They emit laser light from the edge of the semiconductor chip. Edge-emitting laser diodes have a narrow emission linewidth and are widely used in telecommunications, optical data storage, and laser printing.
2. Vertical-Cavity Surface-Emitting Lasers (VCSELs): VCSELs emit laser light perpendicular to the surface of the semiconductor chip. They have a low divergence beam profile and can achieve high output powers. VCSELs are commonly used in optical communication, optical sensing, and facial recognition systems. Figure (1) shows the Schematics of (a) edge-emitting laser and (b) vertical cavity surface-emitting laser.

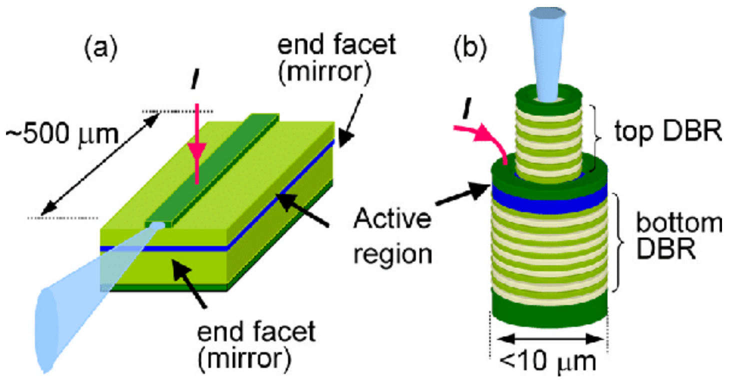

Figure 1. Schematics of (a) edge-emitting laser and (b) vertical cavity surface-emitting laser [6].

3. Distributed Feedback Laser Diodes (DFB): DFB laser diodes have a grating structure within the semiconductor material that provides feedback for lasing action. They produce a single longitudinal mode and have a narrow linewidth, making them suitable for applications such as spectroscopy, gas sensing, and optical fiber sensing.

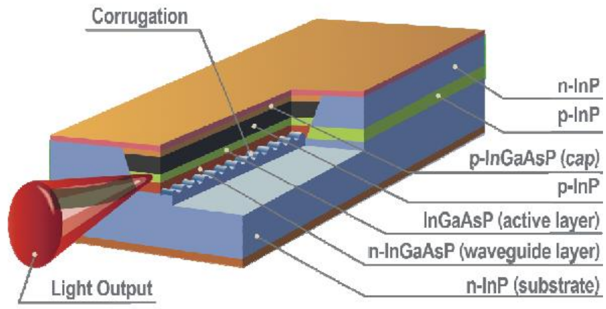

Figure 2. Distributed Feedback Laser Diodes (DFB) [7]

4. Quantum Cascade Lasers (QCLs): QCLs are semiconductor lasers that operate based on intersubband transitions in quantum wells. They emit mid-infrared or terahertz radiation and are used in applications such as trace gas analysis, chemical sensing, and security imaging.

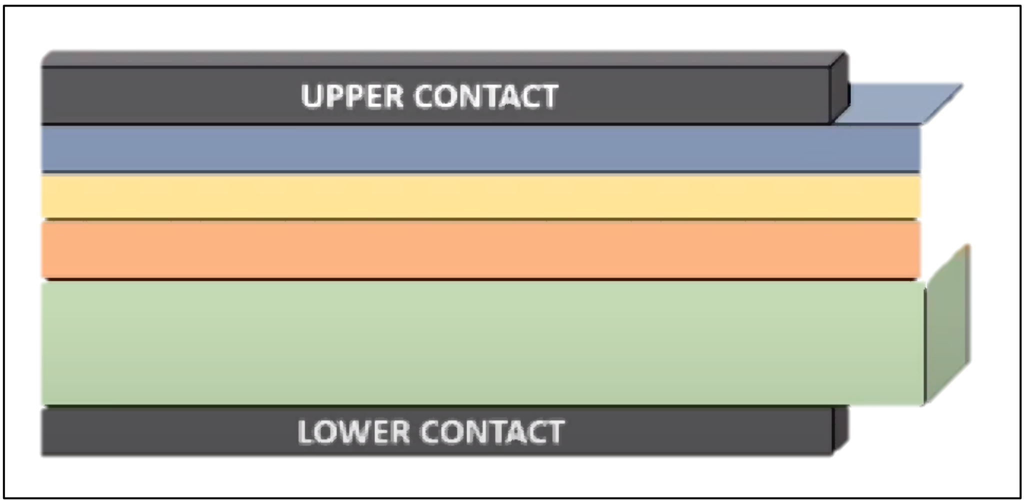

Figure 3. Quantum Cascade Lasers (QCLs) [8]

5. Quantum Dot Lasers: Quantum dot lasers utilize quantum dots as the active gain medium. They offer advantages such as low threshold current, high temperature stability, and low linewidth. Quantum dot lasers are used in optical communication, medical diagnostics, and optical coherence tomography.

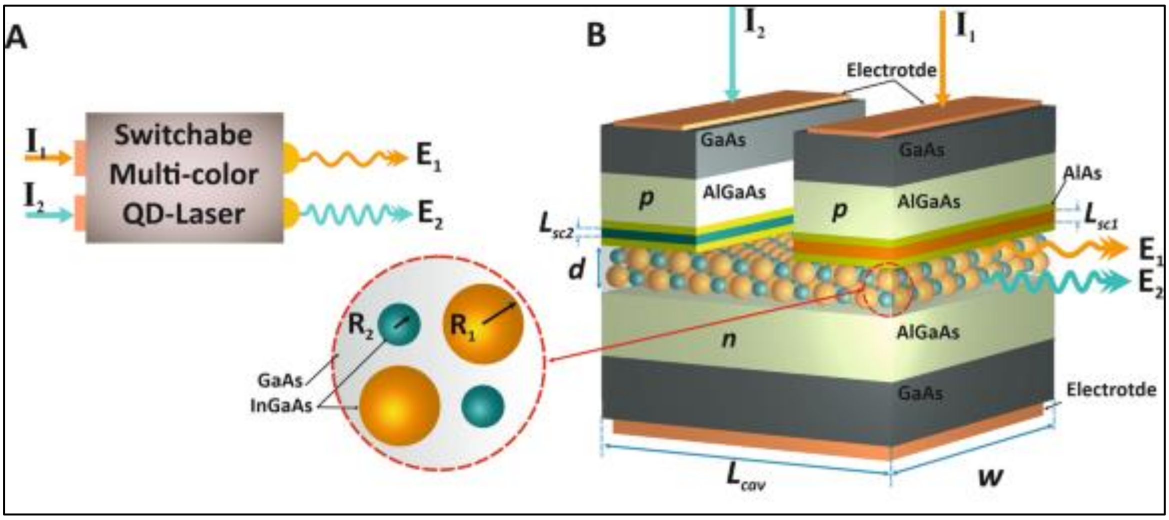

Figure 4. Quantum Dot Lasers [9]

6. External Cavity Diode Lasers (ECDLs): ECDLs consist of a laser diode chip coupled to an external cavity, which includes a diffraction grating for wavelength selection. They provide tunable and narrow linewidth output, making them suitable for spectroscopy, atomic physics, and metrology applications.

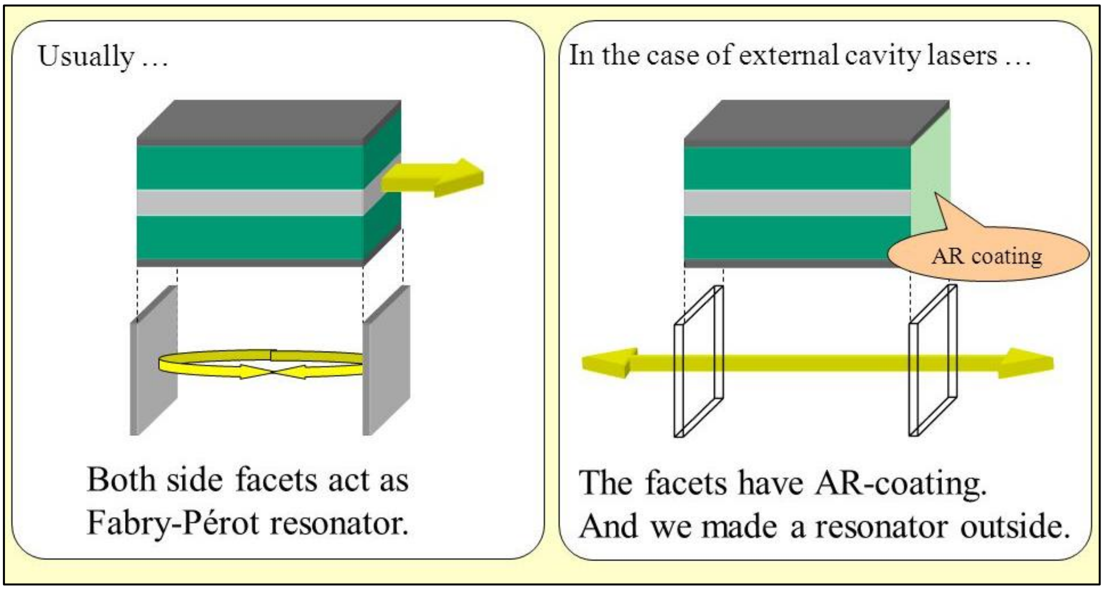

Figure 5. External Cavity Diode Lasers (ECDLs) [10]

7. Super luminescent Diodes (SLDs): SLDs produce broad-spectrum, low-coherence light similar to light-emitting diodes (LEDs) but with higher optical power. They are used in optical coherence tomography (OCT), fibre optic gyroscopes, and biomedical imaging.

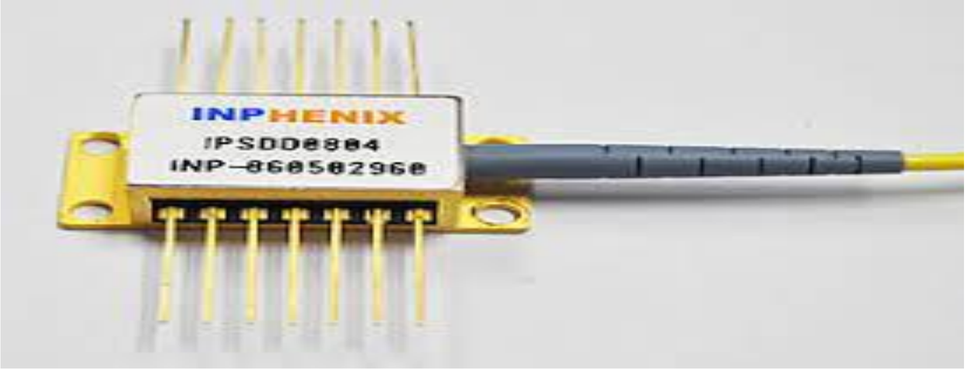

Figure 6. Superluminescent Diodes (SLDs) [11]

2.literature Review

To produce optical gain, semiconductor lasers are essentially p-n junctions operated in forward bias (thus, they are frequently referred to as diode lasers). The cleaved ends of the semiconductor function as partially reflecting mirrors and provide the feedback necessary to maintain lasing action. The reader is advised to consult references [12] for a thorough discussion of the fundamental characteristics of semiconductor lasers. The current significance of semiconductor lasers is entirely dependent on current technical developments. These accomplishments were made feasible by solving the puzzles surrounding their operation and developing a solid theoretical knowledge of their underlying nature. The techniques used in this thesis to increase our understanding of semiconductor lasers rely on a number of significant elements of known theory. This chapter outlines [13].

2.1 The effect of hydrostatic pressure on tetrahedral semiconductors

Tetrahedral semiconductors, such as diamond (C), silicon (Si), germanium (Ge), and some III-V compounds (e.g., GaAs), possess a unique crystal structure characterized by a tetrahedral arrangement of atoms. These materials exhibit remarkable electronic, optical, and mechanical properties, making them essential for various technological applications. One intriguing aspect of tetrahedral semiconductors is their response to hydrostatic pressure. The application of pressure can significantly influence their structural, electrical, and optical properties. In this article, we will explore the effect of hydrostatic pressure on tetrahedral semiconductors and its implications in different fields [14].

Effects on Band Structure:
Hydrostatic pressure can modify the band structure of tetrahedral semiconductors, leading to changes in their electronic properties. By compressing the crystal lattice, the interatomic distances decrease, resulting in an increase in the bandgap energy. This phenomenon, known as the pressure-induced bandgap widening, has profound implications for optoelectronic devices, such as solar cells and light-emitting diodes (LEDs), as it affects the absorption and emission characteristics of the materials.
Transport: Properties:
The application of hydrostatic pressure alters the transport properties of tetrahedral semiconductors. For instance, pressure can modify the carrier mobility, resistivity, and carrier concentration. These changes can be attributed to variations in the effective mass of charge carriers, phonon scattering, and modifications in the density of states. Understanding the pressure-dependent transport behavior is vital for designing high-performance electronic devices, including transistors and sensors.
Phase. Transitions:
Hydrostatic pressure can induce phase transitions in tetrahedral semiconductors. Depending on the magnitude of pressure, different crystal structures may emerge. For example, diamond can transform into a metallic phase known as BC8 structure under high pressure. These pressure-induced phase transitions can lead to the emergence of new properties, such as superconductivity or enhanced mechanical hardness. Investigating and controlling such phase transitions can open up new avenues for material design and synthesis [13].
Optical Properties:
Hydrostatic pressure influences the optical properties of tetrahedral semiconductors by modifying their refractive index, absorption coefficient, and photoluminescence characteristics. The changes in the band structure, as mentioned earlier, directly impact the optical response of these materials. Understanding the pressure-dependent optical properties is crucial for developing advanced photonic devices, including lasers, photodetectors, and optical switches [12].
Applications:
The effect of hydrostatic pressure on tetrahedral semiconductors has significant implications across various disciplines. In high-pressure research, these materials serve as important pressure-transmitting media due to their exceptional mechanical properties. Additionally, the tunability of their electronic and optical properties under pressure makes them promising candidates for pressure sensors, high-pressure optoelectronic devices, and quantum technologies. Furthermore, the study of pressure-induced phase transitions in tetrahedral semiconductors offers insights into materials science, solid-state physics, and the fundamental behavior of condensed matter under extreme conditions.
Hydrostatic pressure not only affects the bandgaps of semiconductors but also the dispersion of the bands, especially at the I' conduction band minimum and light hole band maximum. According to Adams et al. [14], the direct bandgap, which is 0.7%/kbar for GaAs, is roughly proportionate to the relative increase in effective mass.

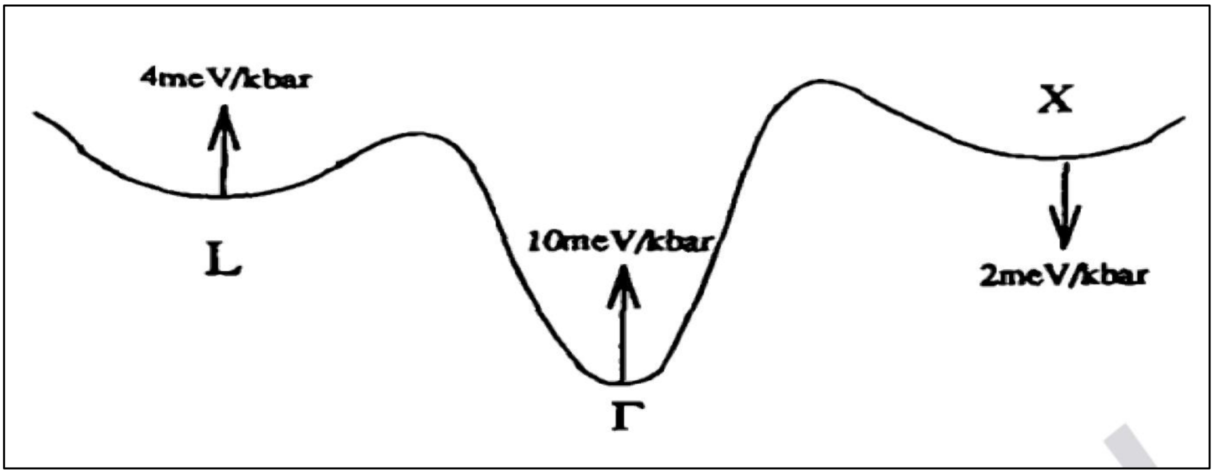

Figure 7. The effect of hydrostatic pressure on the bandgaps of a III-V semiconductor

2.2 The effect of pressure on Quantum wells

Quantum wells are nanostructures that play a crucial role in modern optoelectronic devices. These structures consist of thin semiconductor layers with a lower bandgap sandwiched between wider-bandgap materials. Quantum wells exhibit unique electronic and optical properties due to quantum confinement effects. In recent years, the influence of pressure on quantum wells has garnered significant attention. This article explores the effect of pressure on quantum wells and its implications for device performance and material properties [15].

1. Pressure-Induced Band Structure Engineering:
   Hydrostatic pressure applied to quantum wells can modify their electronic band structure. The change in lattice parameters affects the wavefunctions and energy levels of confined electrons and holes. Pressure-induced band structure engineering enables tailoring the bandgap and energy levels, influencing the optical and electrical properties of quantum wells. This effect finds applications in the design of laser diodes, photodetectors, and modulators with enhanced performance.
2. Shifts in Optical Transitions:
   Pressure alters the energy levels and spacing between electronic states in quantum wells. Consequently, the absorption and emission wavelengths of optical transitions shift. This effect is useful in tuning the emission wavelength of quantum well-based devices such as light-emitting diodes (LEDs) and semiconductor lasers. Pressure-induced spectral tuning provides a means to achieve wavelength selectivity and optimize device characteristics for specific applications.
3. Carrier Dynamics and Transport Properties:
   Pressure modifies the carrier dynamics and transport properties in quantum wells. Pressure-induced changes in the band structure affect the effective masses of carriers and their scattering mechanisms. The carrier lifetime, mobility, and diffusion coefficients can be altered, impacting the device performance. Understanding the pressure-dependent carrier dynamics is crucial for optimizing the design of quantum well devices, including high-speed transistors and solar cells.
4. Strain Effects and Lattice Distortion:
   Pressure-induced strain in quantum wells can cause lattice distortion, affecting the crystal symmetry and electronic properties. Strain alters the band structure, carrier confinement, and exciton binding energies. The interplay between strain and quantum confinement effects provides opportunities for strain engineering and the creation of novel device functionalities. Precise control of strain through pressure allows tailoring the electronic and optical properties of quantum wells.
5. Pressure-Induced Phase Transitions:
   Extreme pressure conditions may induce phase transitions in quantum wells, leading to structural changes and alterations in their properties. For example, pressure-induced transitions from a direct to an indirect bandgap can occur, affecting the optical absorption and emission characteristics. Understanding and controlling these pressure-driven phase transitions can offer new avenues for developing advanced quantum well devices and exploring fundamental phenomena in condensed matter physics [16].

2.3 Loss mechanisms in semiconductor lasers

Semiconductor lasers are essential devices in various applications, including telecommunications, optical data storage, and laser-based sensing. However, they are subject to several loss mechanisms that can hamper their efficiency and performance. Understanding these loss mechanisms is crucial for optimizing the design and operation of semiconductor lasers. This article provides an overview of the key loss mechanisms encountered in semiconductor lasers and their impact on device performance [17].

a. Optical Losses:

- Free Carrier Absorption: In semiconductor lasers, free carriers (electrons and holes) can absorb photons, leading to optical losses. This phenomenon is more pronounced in heavily doped or high-current operation conditions. Free carrier absorption reduces the net gain and increases the threshold current of the laser, limiting its efficiency.
- Auger Recombination: Auger recombination is a nonradiative recombination process where the energy of an electron is transferred to another carrier, resulting in the generation of a high-energy electron or hole. This process competes with radiative recombination, reducing the efficiency of the laser. Auger recombination becomes more significant at high carrier densities and can be a limiting factor in high-power semiconductor lasers.
- Residual Reflectivity: Imperfections in the facet coatings or the laser cavity can cause residual reflectivity, leading to optical feedback. This feedback can result in mode competition, reduced output power, and increased noise in the laser output. Minimizing residual reflectivity is crucial for achieving stable and efficient laser operation [18].

b. Electrical Losses:

Series Resistance: Semiconductor lasers have inherent series resistance due to the carrier injection process. The H;series resistance reduces the electrical-to-optical conversion efficiency and increases the threshold current. Minimizing series resistance is important for improving the performance of semiconductor lasers.

- Leakage Currents: Leakage currents, such as surface and bulk leakage currents, can occur in semiconductor lasers. These currents bypass the active region and result in wasted electrical power without contributing to lasing. Leakage currents increase the overall power consumption and reduce the efficiency of the laser.

Optical Waveguide Losses:

Waveguide Scattering Losses: Scattering due to imperfections, such as sidewall roughness or material impurities, can cause optical losses in the waveguide structure of semiconductor lasers. These losses reduce the overall output power and efficiency of the laser.

- Waveguide Absorption: In some cases, the waveguide material itself can exhibit absorption at the lasing wavelength, resulting in additional optical losses. This absorption can be due to impurities or defects in the waveguide material.

Thermal Losses:

Temperature Rise: Semiconductor lasers generate heat during operation, and excessive temperature rise can degrade their performance. Increased temperature affects the refractive index, carrier lifetime, and threshold current, leading to reduced output power and increased threshold current density.

(Thermal Resistance: The thermal resistance between the laser diode and its heat sink can limit heat dissipation. High thermal resistance can result in increased junction temperature and reduced laser performance.

3. Conclusions:

Hydrostatic pressure plays a crucial role in modifying the structural, electrical, and optical properties of tetrahedral semiconductors. The pressure-induced changes in their band structure, transport properties, phase transitions, and optical response have significant implications for various technological applications. Further research into the effect of hydrostatic pressure on tetrahedral semiconductors will not only enhance our understanding of their behavior but also pave the way for innovative materials, devices, and technologies with tailored properties. The effect of hydrostatic pressure on the bandgaps of a III-V semiconductor results in some perturbation of the bandgap. Electrons thermalise to the lowest available states before recombining with holes and thus 'see' a lower optical bandgap. Temperature also has a large influence on the loss mechanisms of a semiconductor laser, these are discussed later.

The effect of pressure on quantum wells presents a fascinating avenue for tailoring their electronic and optical properties. Pressure-induced band structure modifications, shifts in optical transitions, changes in carrier dynamics, strain effects, and pressure-driven phase transitions all contribute to the overall response of quantum wells. This knowledge enables the optimization and design of quantum well-based devices with enhanced performance and functionality. Future research in this field will continue to explore the potential of pressure engineering for advanced optoelectronic devices and provide insights into the fundamental behavior of quantum nanostructures under extreme conditions.

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