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Structural Design and Optoelectronic Performance Research on InP-Based Semiconductor Lasers

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Abstract. Semiconductor lasers based on indium phosphide (InP) are now crucial components of contemporary optical communication systems. Their direct wide bandgap, ability to match lattices, and compatibility with the 1.3 μm and 1.55 μm low-loss fiber communication windows are the reasons for this. The fundamentals of materials, structural design concepts, and optoelectronic performance metrics of InP-based lasers are all methodically examined in this paper. The article first examines the performance of the InP material system with alloys such as InGaAsP and InAlGaAs. It demonstrates its effectiveness in quantum dot (QD) and multi-quantum well (MQW) heterostructures. These configurations enable improved temperature stability, a larger modulation bandwidth, a higher external quantum efficiency, and a lower threshold current density. In this paper, the main structures that show significant advantages in optical confinement, mode control, and integration density are examined, such as distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers, and vertical-cavity surface-emitting lasers (VCSELs). This paper shows that InP-based semiconductor lasers are still the best way to make next-generation photonic devices, even though making them is getting harder, and managing heat is getting harder. This is shown by comparing key performance parameters like threshold current, output power, side mode suppression ratio (SMSR), and modulation bandwidth.

Keywords: InP materials, semiconductor lasers, DFB lasers, QD heterostructures.

1. Introduction

With the rapid development of optical communications, data centers, and photonic integration technology, the market demand for compact, energy-efficient, high-speed light sources is growing rapidly. InP-based semiconductor lasers have a direct bandgap of approximately 1.344 eV (corresponding to an emission wavelength of 920 nm), strong lattice matching capabilities, and compatibility with important telecommunications wavelength windows. These advantages allow them to effectively lower the fiber loss as well as the dispersion when it comes to this specific wavelength [1].

InP is a great substrate for quaternary III-V alloys like InGaAsP and InAlGaAs. This means that it is easier to control bandgap engineering and emission wavelength than it is with materials based on silicon and gallium arsenide [2]. These materials can hold multi-quantum well (MQW) and quantum dot (QD) structures, which have a lower current density, a narrower spectral linewidth, and a wider

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modulation bandwidth [3]. For example, the threshold current density of the InAs/InP quantum dot laser has been lowered to as low as 630 A/cm², and its thermal stability has been improved, which is a big step up from older quantum well designs.

With the passage of time and the continuous advancement of related technologies, InP-based lasers have evolved from simple Fabry-Perot edge-emitting lasers (EEL) to more complex and advanced lasers such as distributed feedback (DFB), distributed Bragg reflectors (DBR), and vertical cavity surface-emitting lasers (VCSEL). While their performance has been improved, these lasers have different functions that can cope with different complex environments [4]. The high contrast grating (HCG) - VCSEL and single-chip integrated InP on Si laser not only reduces the size of the laser, but also greatly improves the power and efficiency of the device. They can modulate at rates exceeding 25 GHz while maintaining a single-mode selectivity ratio (SMSR) greater than 45dB when operating in single-mode mode. InP itself has a high refractive index, excellent thermal conductivity, and relatively low surface recombination index, which ensure the performance and stability of devices based on InP. InP-based DFB lasers typically emit laser light in a single longitudinal mode with sideband suppression characteristics, allowing the laser to emit pure spectra. DBR lasers, on the other hand, use mirrors that can only reflect specific wavelengths, allowing them to exhibit narrow linewidths and excellent tuning performance, even achieving tuning ranges within a few nanometers. As a result, DBR lasers are highly suitable for dense wavelength division multiplexing systems. The combination of these performance features and the small size made possible by modern manufacturing methods makes InP-based laser architectures a flexible choice for telecommunications, data centers, and the new photonic integrated circuit (PIC) market.

This study systematically examines the material properties, essential performance indicators, and standard laser architectures, focusing on component optimization techniques for creating high-performance devices that demonstrate wavelength stability and thermal resilience to meet the demands of advanced photonic systems.

2. Materials and physical basis of InP-based semiconductor conductor lasers

2.1. InP-based material system

InP is a binary semiconductor composed of indium and phosphorus, InP is a binary semiconductor composed of indium and phosphorus, featuring a face-centered cubic crystal structure, as Figure 1 shows. It is an important III-V compound semiconductor material, widely used in optical communication and laser applications due to its excellent optoelectronic properties and good matching with the 1.3 μm to 1.55 μm optical communication window [4]. The direct bandgap of InP is about 1.344 eV, corresponding to an emission wavelength of about 920 nm, which precisely meets the requirements of optoelectronic devices in the near-infrared region. Therefore, devices based on InP are mostly used in this field, such as laser diodes and photodetectors [5]. Due to its high lattice matching with III-V compounds, InP is often used as a lattice-matched substrate for III-V semiconductor compounds such as InGaAs and InGaAsP. High-quality heterojunctions can be obtained between InP and these active layers through epitaxial growth techniques such as metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). By using bandgap engineering and ensuring that the lattices of indium phosphide (InP) and quaternary alloys such as InGaAs or InAlGaAs are well bonded together, very precise multi-quantum well (MQW) structures can be fabricated on InP substrates. These MQW lasers have lower fiber loss in the wavelength range of 1.3-1.55 μm compared to other lasers, making them highly suitable for optical

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communication systems operating in this range. They also have low threshold current density, narrow emission linewidth, and wide modulation bandwidth.

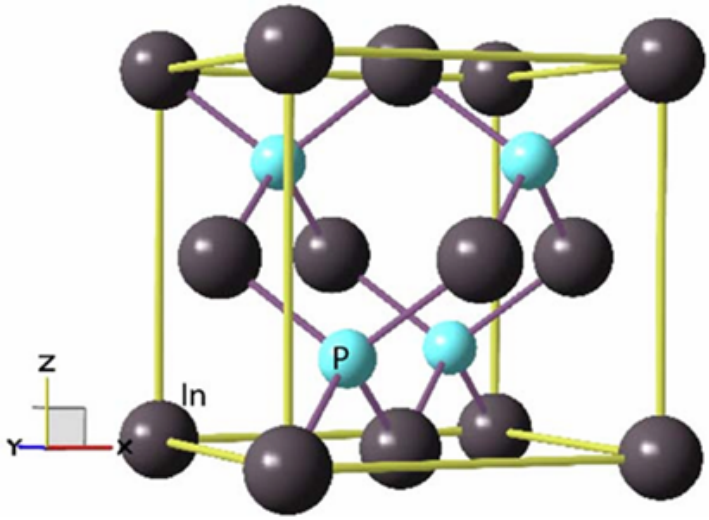

Figure 1. Crystal structure of InP [6]

InGaAsP alloy is a popular choice for the active layer in lasers. To get these lasers to emit across the infrared spectrum, you can tweak the bandgap. The energy gap between the materials' valence and conduction bands. To anywhere between 0.75 eV and 1.35 eV. This is done by adjusting the mix of arsenic and phosphorus in the alloy, which is surprisingly simple; just change the ratio of arsenic to phosphorus, and it can be achieved. One key thing about using InP as a substrate is that it helps keep devices running smoothly thanks to its thermal conductivity. This means they're more stable when things get hot and they don't degrade quickly over time [1]. To optimize the performance parameters of the laser, controllable strain control can be introduced into the InGaAs/InP heterojunction. This method can effectively improve the photoelectric conversion efficiency and dynamic response characteristics of the device through band engineering [7].

Semiconductor materials made from InP are versatile. They can be tweaked to have a bandgap; their structure matches up nicely with other materials, and they can handle heat well. This makes them a great starting point for creating efficient and reliable lasers. With these properties, it's easy to see why InP-based materials are so promising for technology. They offer a base for building high-speed, low-power power and extremely stable laser devices that could revolutionize a lot of fields.

2.2. Key performance parameters of the semiconductor laser

Lasers made from InP-based semiconductors are pretty common in speed optical communications and other areas because they work so well and are really reliable. To ensure the long-term stable operation of the laser, some key measures need to be adopted. That means tweaking the mix and thickness of the quantum as well as the length of the cavity, how much doping is used, and how heat is managed. If you can optimize all these components, you can expect top-notch performance from your laser.

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2.2.1. Threshold Current Density (TCD)

The threshold current density is the minimum amount of current required for a laser to produce stimulated emission. A lower TCD indicates higher laser efficiency and lower heat consumption. Recent InAs/InP quantum dot lasers have demonstrated TCD as low as 630 A/cm² (for a 2000 μm cavity) at room temperature. Multi-quantum-well Fabry–Perot lasers on InP-on-Si substrates have achieved a TCD of around 0.65 kA/cm² with an output power exceeding 155 mW per facet at room temperature [8].

2.2.2. External Quantum Efficiency (EQE)

External quantum efficiency (EQE) is the proportion of injected electrons that are converted into output photons. It is closely related to vertical light coupling efficiency, mirror loss, internal quantum efficiency, and non-radiative recombination processes. InP-based material systems typically have high external quantum efficiency due to their good lattice matching and low defect density [9]. Optimized InGaAs/InAlGaAs superlattice active regions have yielded internal efficiency up to 53%, with very low internal loss (~6 cm^{-1}) and transparency current density around 500 A/cm² [3].

2.2.3. Modulation Bandwidth (MB)

Modulation bandwidth is a key parameter used to measure a laser's response capability under high-speed signal modulation conditions. It is primarily limited by carrier lifetime and resonant frequency. Increasing the modulation bandwidth typically requires increasing the resonant frequency and reducing the damping coefficient. InP-based lasers can achieve bandwidths exceeding 25 or even 40 GHz by using a short cavity length design and a high-gain quantum well structure [7]. Additionally, quantum-dot mode-locked lasers have demonstrated 3-dB comb bandwidths over 2.2 THz and repetition rates up to 60 GHz—very promising for DWDM systems [10].

2.2.4. SMSR and output power

SMSR reflects the intensity difference between the main mode and the strongest side mode in the laser output spectrum. A high SMSR indicates that the laser has excellent single-mode output performance, which is crucial for wavelength division multiplexing (WDM) systems. The SMSR of InP lasers can be effectively improved by optimizing the cavity length and using distributed feedback (DFB) or distributed Bragg reflector (DBR) structures [7].

Output power reflects a laser's light output capability, while slope efficiency describes the increase in optical power per unit of injected current. InP lasers usually increase output power and slope efficiency by optimizing output end-face reflectance and reducing internal losses [11]. Also, InP-on-Si DFB lasers demonstrated robust slope characteristics with noted wall-plug efficiencies around 9% [1].

2.3. The basic structure of semiconductor lasers

InP-based semiconductor lasers typically use a heterostructure design consisting of an active region, a waveguide layer, a cladding layer, and a mirror. The active region, which uses InGaAsP or InGaAs MQW structures, facilitates electron-hole recombination to generate stimulated emission and serves as the light source. The waveguide layer confines and guides the light signal, and the cladding layer

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provides a high refractive index difference to achieve strong optical confinement. This enhances the stability of the laser mode and power efficiency. The following text will introduce these aspects from four perspectives: lateral structure, vertical structure, thermal management, electrode design, and optical output design [1].

From a structural perspective, InP-based lasers include edge-emitting lasers (EELs), such as DFBs and distributed DBRs, as well as laser amplifiers (SOAs). Most of these structures use a straight-cavity Fabry-Perot resonator with highly reflective mirrors on both ends that form standing waves through reflection, achieving laser oscillation [9].

Lasers typically employ double heterostructure (DH) or MQW structures vertically. The most common structure is the InGaAsP/InP. The DH structure restricts electron and hole diffusion, thereby improving injection efficiency, while the MQW structure provides higher gain and lower threshold current. To further improve mode control and side-mode suppression performance, DFB lasers introduce periodic gratings into the active region, achieving wavelength-selective feedback and outputting stable single-mode laser light. Compared to traditional structures, DFB lasers offer higher propagation accuracy and are widely used in optical communication systems [1] (Figure 1).

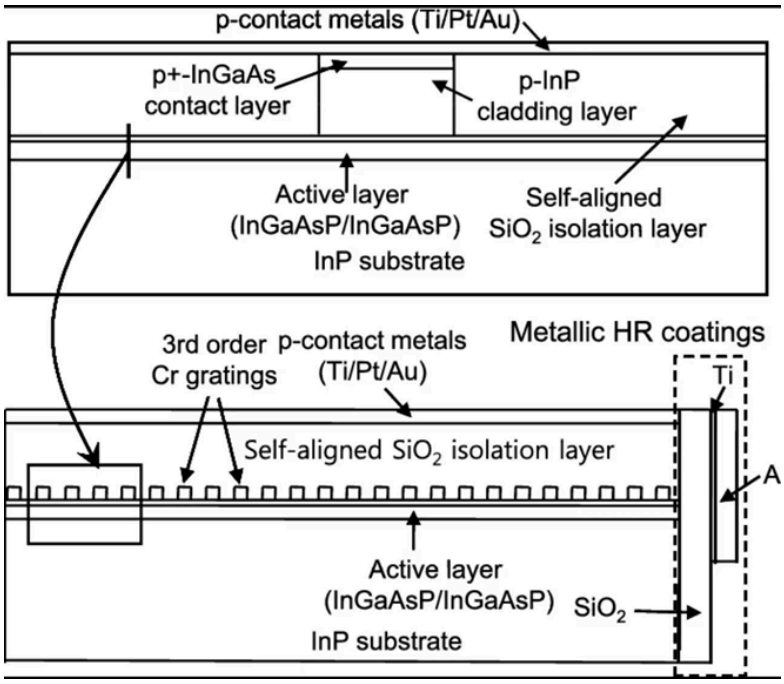

Figure 2. Laterally coupled InGaAsP MQW SCH DFB laser with surface gratings [1]

InP materials have a certain degree of thermal conductivity, so even under high-power operating conditions, they still require efficient heat dissipation structures to prevent wavelength drift and thermal degradation of efficiency caused by heat accumulation. Common structural designs include metal heat sinks and top metal heat spreaders. Good heat dissipation design is crucial for improving the life and stability of lasers [9]. Light output is usually emitted from the cavity end face, either vertically or horizontally. For EELs, however, the light-emitting surface is the lateral end face, which makes them suitable for integration into fiber optic communications. While vertical emission structures are not commonly used in indium phosphide (InP) systems, they are valuable for specific wavelength tuning and integrated photonic devices.

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3. Application of InP semiconductor lasers

3.1. VCSELs

VCSELs are a type of semiconductor laser that, unlike traditional edge-emitting lasers (EELs), emit laser beams vertically. This structure allows for two-dimensional array integration, reduces costs, and is ideal for large-scale optical interconnects, optical communications, and sensor systems [12].

VCSELs were initially developed using GaAs-based materials with operating wavelengths centered at 850 nm; however, researchers are now exploring InP-based VCSELs to cover the 1.3 μm and 1.55 μm optical communication windows [13]. However, fabricating high-reflectivity Bragg reflectors (DBRs) in InP-based structures remains a significant challenge. Due to the low refractive index contrast of InP-based materials, other oxide or nitride materials are often introduced to enhance reflectivity. This imposes higher requirements on production technology.

A typical InP-based VCSEL design employs an InGaAsP multi-quantum well structure in the active region paired with DBR mirrors featuring high refractive index contrast. To further improve device performance, high-contrast grating (HCG) mirrors have been introduced, which enable single-mode operation with side-mode suppression ratios (SMSR) exceeding 45 dB at 1550 nm, though they require precise nanofabrication such as electron-beam lithography [14].

3.2. Quantum Dot Laser (QDL)

QDLs, which are based on the three-dimensional quantum confinement effect, offer advantages such as low threshold current, good temperature stability, and narrow spectral linewidth. Compared to traditional quantum well lasers, QDLs have become a key area of development in optical and quantum communications and high-speed optical interconnects within the InP material system [15].

The most commonly used quantum dot materials on the InP platform are InAs or InAsP nanodots, grown on InP or InGaAsP substrates via epitaxial growth techniques. These quantum dots form deep energy level traps that effectively confine charge carriers. This significantly reduces the threshold current density required for stimulated emission and enhances the device's temperature stability [16].

Compared with other lasers, QDL has a higher differential gain and compression coefficient in high-speed modulation. Therefore, under the condition of the same modulation rate as other lasers, QDL has a purer laser spectrum [17]. Quantum dot mode-locked lasers have currently achieved repetition rates as high as 60 GHz and optical bandwidths exceeding 2.2 THz [8], giving them a unique advantage in high-speed, short-distance data transmission and making them an ideal choice for data centers used for data transmission.

In addition, InP-based quantum dot lasers can tune their wavelength range over a wide range by controlling the size and composition of the quantum dots, covering a continuous wavelength range from 1.3 μm to 1.6 μm. However, due to the current manufacturing process not being fully developed, there are still some defects, such as uneven dot distribution and inconsistent emission wavelengths. However, with the continuous advancement of production technology, these issues will be resolved in the future.

3.3. Distributed Bragg Reflector Laser (DBRL)

A DBR laser is basically made up of three parts: the active region, the phase control region, and the reflective grating region. This design lets it separate the feedback from the wavelength selection, which is pretty unique. What really sets DBR lasers apart is that they can have a grating on either

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side of the active region. This design gives them a couple of advantages; they can be tuned to different wavelengths, and they produce really pure laser spectra. It's a clever setup [1].

The material used in the region of InP-based DBR lasers is typically indium gallium arsenide phosphide. This type of laser usually operates at two wavelengths: 1.3 μm and 1.55 μm. These wavelengths are perfect for communication applications that require infrared. The Bragg reflectors in these lasers are made by creating a pattern of lines with varying indices. This pattern acts like a mirror reflecting a narrow range of light frequencies. The result is a selective reflection that's useful in many applications. These structures have gotten incredibly sharp with linewidths as low as 100 kHz. They also have a strong signal with a signal-to-noise ratio higher than 50 dB. What this means is that lasers made from indium phosphide, specifically the kind with distributed Bragg reflectors, can be used much more effectively in high-speed communications that rely on coherent signals. This is a deal, especially when you think about how fast data needs to be sent these days [4].

DBR lasers have a trick up their sleeve. For one, their wavelength can be tweaked independently, which is a deal. To adjust it you just need to fiddle with the injection current or temperature in the spots. The reflection zone and phase control zone. This lets you fine-tune the output wavelength without messing up the laser's efficiency. That flexibility makes DBR lasers a great fit for lasers that need to be tweaked on the fly, like those used in optical networks or tunable optical transceiver modules [18]. Additionally, the DBR structure is relatively simple and does not require particularly complex manufacturing processes, especially since precise grating etching in the active region is unnecessary. As a result, it has lower costs and higher stability compared to other lasers.

4. Conclusion

With the advancement of technology, InP-based semiconductor lasers have become a core technology in the field of optoelectronics. Leveraging the direct bandgap properties of indium phosphide and its excellent lattice matching with ternary and quaternary III-V alloy compounds (such as GaAsP and InAlGaAs), especially its compatibility with the 1.3–1.55 μm low-loss optical communication wavelength band, it is widely used in high-speed optical communication, data center interconnection, and integrated photonic systems, playing a crucial role in these fields. The use of MQW and QD active regions allows InP-based lasers to operate with low threshold current densities, high external quantum efficiency, and broad modulation bandwidths. Furthermore, design approaches such as DFB, DBR, and VCSEL structures enable these devices to be tailored for different applications. In particular, VCSELs based on high-contrast gratings (HCG) and monolithic integrated InP-on-Si solutions enable lasers to evolve toward scalable, low-power photonic integration. However, there are still many challenges ahead. The fabrication of Bragg reflectors in InP systems remains complex, requiring optimization of production steps to improve yield rates. Additionally, thermal degradation issues arise during high-power operation. Future research should focus on improving nanofabrication techniques, enhancing control over epitaxial growth, and expanding integration compatibility with silicon photonics platforms.

In summary, gallium arsenide (GaAs)-based semiconductor lasers are a mature technology that is continuously evolving. Their flexible and versatile structure, tunable optoelectronic characteristics, and enhanced integration potential make them key components in meeting the growing global demand for faster, more efficient, and smaller photonic systems.

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