International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-13, Issue-4; Apr, 2026
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.134.14

Investigation of Optical Gain Characteristics in GaInP/AlGaInP Nanoscale Heterostructures for Visible Light Emitters

Jayprakash Vijay*, Divya Bhardwaj

Department of Electronics and Communication Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, Rajasthan, India
*E-Mail: jpvijay121@gmail.com

Received: 27 Mar 2026,

Received in revised form: 20 Apr 2026,

Accepted: 24 Apr 2026,

Available online: 30 Apr 2026

***Keywords*— GaInP/AlGaInP Heterostructures, Quantum Wells, Optical Gain Characteristics, Visible Light Emitters, Band Structure Engineering.**

***Abstract*—*This paper presents the design and optical gain analysis of a $Ga_{0.45}In_{0.55}P$/AlGaInP nanoscale quantum well heterostructure for visible-light-emitting applications. The proposed structure consists of a 4 nm GaInP quantum well and 10 nm AlGaInP barrier layers grown on a GaAs substrate. The electronic band structure and carrier wave functions are analyzed using the $k\cdot p$ method to investigate carrier confinement and optical transition characteristics. The results confirm the formation of a type-I heterostructure, providing efficient confinement of electrons and holes within the active region. The optical gain spectrum exhibits a peak gain of approximately 4850 cm^{-1} at 625 nm (1.985 eV), corresponding to the red region of the visible spectrum. The enhanced gain is attributed to strong quantum confinement and improved electron–hole recombination within the quantum well. The obtained results demonstrate the potential of the proposed GaInP/AlGaInP heterostructure for high-efficiency visible-light emitters, semiconductor lasers, and integrated photonic devices.*

I. INTRODUCTION

Semiconductor quantum well (QW) heterostructures have become fundamental building blocks for modern optoelectronic devices owing to their superior carrier confinement, enhanced radiative recombination efficiency, and tunable optical properties [1]–[4]. The quantum confinement effect arising from nanoscale dimensions modifies the electronic density of states and enables precise control of optical transitions, making quantum well structures highly attractive for light-emitting diodes (LEDs), laser diodes (LDs), optical sensors, and integrated photonic circuits [2], [3]. Continuous advancements in visible-light communication, high-resolution display technologies, biomedical imaging, and photonic integration have further increased the demand for efficient visible-light-emitting semiconductor materials with high optical gain and thermal stability [4], [5].

Among the various III–V semiconductor material systems, GaInP/AlGaInP heterostructures have attracted considerable research interest due to their direct bandgap nature, high internal quantum efficiency, and excellent compatibility with GaAs substrates [5], [9]–[11]. These characteristics make them particularly suitable for visible-spectrum applications, especially in the red and orange wavelength regions. The incorporation of quantum wells within GaInP/AlGaInP structures provides strong carrier confinement through conduction- and valence-band discontinuities, leading to enhanced carrier localization and increased optical gain at lower injection currents [1], [2], [9]. Furthermore, the ability to tailor the quantum well thickness and alloy composition enables precise bandgap engineering and wavelength tuning, which are essential for next-generation visible-light emitters [3], [5].

Theoretical and experimental investigations have demonstrated the significance of strain and quantum confinement effects in improving the performance of AlGaInP/GaInP-based optoelectronic devices. Summers et al. reported enhanced gain-current characteristics in strained AlGaInP quantum well lasers, demonstrating the potential of strain engineering for gain optimization [9]. Hunziker et al. analyzed spontaneous emission and optical gain spectra in strained GaInP quantum well lasers and observed substantial improvements in optical performance due to stronger carrier confinement [10]. Similarly, Yen and Lee developed a theoretical framework for strained GaInP-AlGaInP quantum well lasers and highlighted the influence of continuum states on optical gain characteristics [11]. Experimental investigations on compressively strained AlGaInP/GaInP multi-quantum-well LEDs have further revealed improvements in emission efficiency and optical output power [12], [13].

Accurate modeling of the electronic band structure is essential for understanding carrier dynamics and optical transitions in quantum well heterostructures. The k·p perturbation theory combined with the envelope-function approximation has emerged as a powerful tool for analyzing semiconductor nanostructures [6], [7]. In particular, the 6×6 Luttinger–Kohn Hamiltonian provides an accurate representation of heavy-hole, light-hole, and split-off band interactions, enabling detailed investigation of energy eigenstates, carrier wave functions, and optical gain spectra [6], [7]. Such theoretical approaches have been widely employed for the design and optimization of high-performance quantum well lasers and visible-light emitters [8], [11].

Recent developments in semiconductor photonics have expanded the application domain of GaInP/AlGaInP heterostructures beyond conventional LEDs and laser diodes. Quantum well intermixing techniques have been explored to achieve wavelength tunability and enhanced device performance [16]. Biointegrated GaInP/AlGaInP microlasers have demonstrated significant potential for biomedical sensing and implantable photonic systems [17]. Furthermore, visible-light semiconductor lasers integrated with silicon photonic platforms have emerged as promising candidates for future optical communication and computing technologies [18]. These advancements underscore the growing importance of GaInP/AlGaInP nanoscale heterostructures in next-generation photonic devices.

Despite considerable progress in this field, several challenges remain unresolved. Most existing studies primarily focus on fabrication processes, photoluminescence analysis, and threshold current reduction, while comparatively fewer investigations address the detailed relationship between carrier wave functions, optical gain characteristics, and external environmental factors such as temperature and pressure [19-20]. Moreover, comprehensive analyses employing the coupled conduction-band and 6×6 Luttinger–Kohn Hamiltonian framework for GaInP/AlGaInP nanoscale heterostructures remain limited. The influence of external pressure on band structure modification and optical gain enhancement has also received relatively little attention in the literature. Motivated by these research gaps, the present work investigates the optical gain characteristics of a GaInP/AlGaInP nanoscale quantum well heterostructure intended for visible-light-emitting applications. The electronic band structure, confined carrier wave functions, and optical gain spectra are analyzed using a 6×6 k·p Hamiltonian model coupled with the conduction band. In addition, the effects of temperature and external pressure on the optical response are systematically examined to evaluate the tunability and operational stability of the proposed structure. The findings provide valuable insights into gain enhancement mechanisms and band-structure engineering strategies that can facilitate the development of high-efficiency visible-light emitters, semiconductor lasers, and advanced integrated photonic devices.

II. DESIGN SPECIFICATION AND SIMULATION RESULT

A GaInP/AlGaInP nanoscale quantum well heterostructure is designed and modeled to investigate its energy wave functions and optical gain characteristics. The structure consists of a GaInP quantum well and AlGaInP barrier layers grown on a GaAs substrate. To understand the optical behavior of the heterostructure, the electronic properties of the constituent bulk materials are first analyzed using the 8-band k·p Hamiltonian model with the effective mass approximation. The calculated band structures of GaInP and AlGaInP reveal three valence subbands: heavy-hole (HH), light-hole (LH), and split-off (SO) bands. At zero wave vector ($K_z = 0$), the HH band lies above the LH band in both materials; however, this ordering is influenced by strain effects arising from lattice mismatch with the GaAs substrate. Since the split-off band is energetically separated from the valence-band maximum, its contribution to electron–hole recombination is relatively small. These band structure characteristics play a crucial role in determining the carrier confinement and optical gain performance of the proposed visible-light-emitting heterostructure.

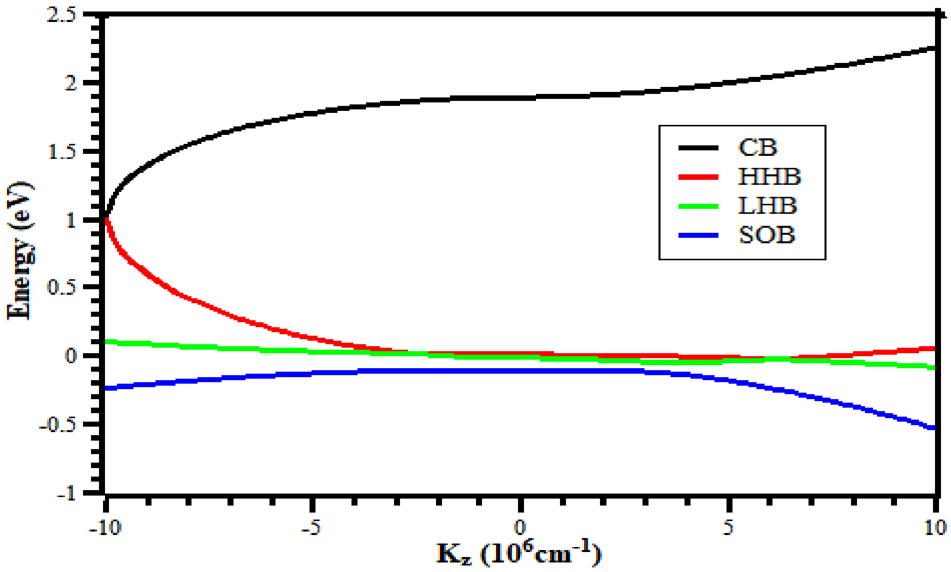

Fig.1. The band constructions of quaternary ternary compound GaInP

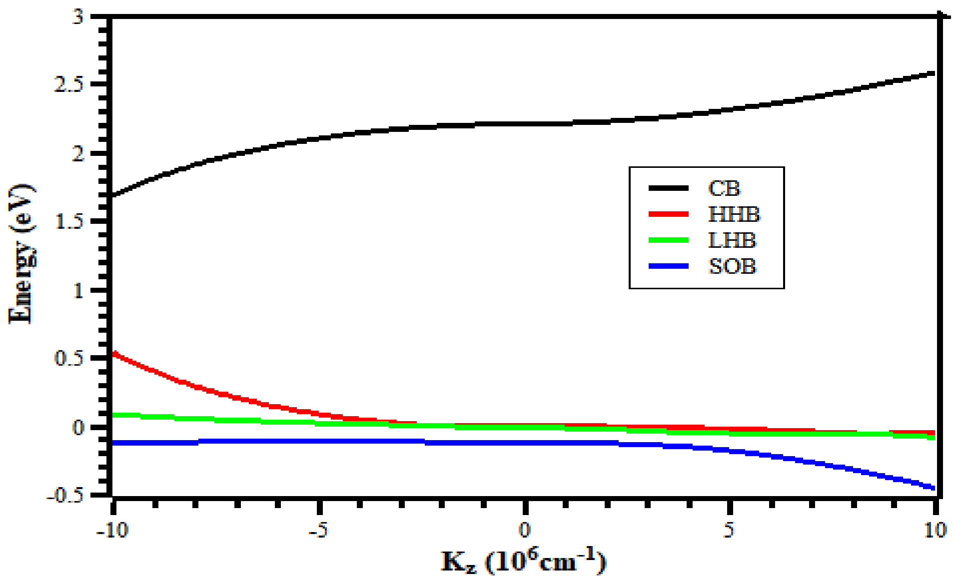

Fig.2: The band constructions of quaternary compound AlGaInP

The primary objective of this work is to design a GaInP/AlGaInP nanoscale heterostructure capable of efficient visible-light emission. In quantum well devices, the thickness of the well and barrier layers plays a crucial role in determining the electronic and optical characteristics of the structure. Accordingly, a GaInP quantum well thickness of 4 nm and an AlGaInP barrier thickness of 10 nm are selected to achieve emission within the red region of the visible spectrum (620–750 nm). The layer dimensions and material compositions are optimized to enhance carrier confinement and optical performance.

The calculated energy band diagram and carrier wave functions of the proposed heterostructure are presented in Figures 3 and 4, respectively. Analysis of the band alignment indicates the formation of a type-I heterostructure, where both electrons and holes are confined within the GaInP active region, facilitating efficient radiative recombination. The carrier wave functions provide insight into the spatial distribution and confinement of charge carriers, which directly influence the optical transition probability and gain characteristics of the device.

The results demonstrate strong carrier confinement within the quantum well due to the bandgap discontinuities at the well–barrier interfaces. This enhanced confinement increases the carrier density in the active region, leading to improved electron–hole recombination efficiency, higher optical gain, and reduced threshold current requirements. These characteristics make the proposed GaInP/AlGaInP heterostructure a promising candidate for low-power visible-light emitters in photonic, biomedical, and optical communication applications.

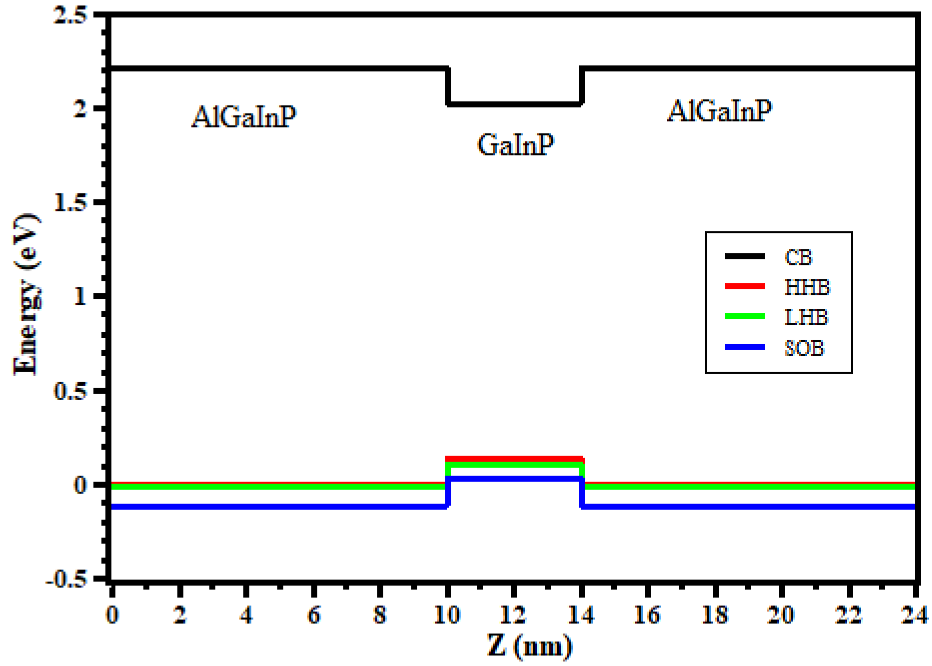

Fig.3: Energy band for GaInP/AlGaInP heterostructure

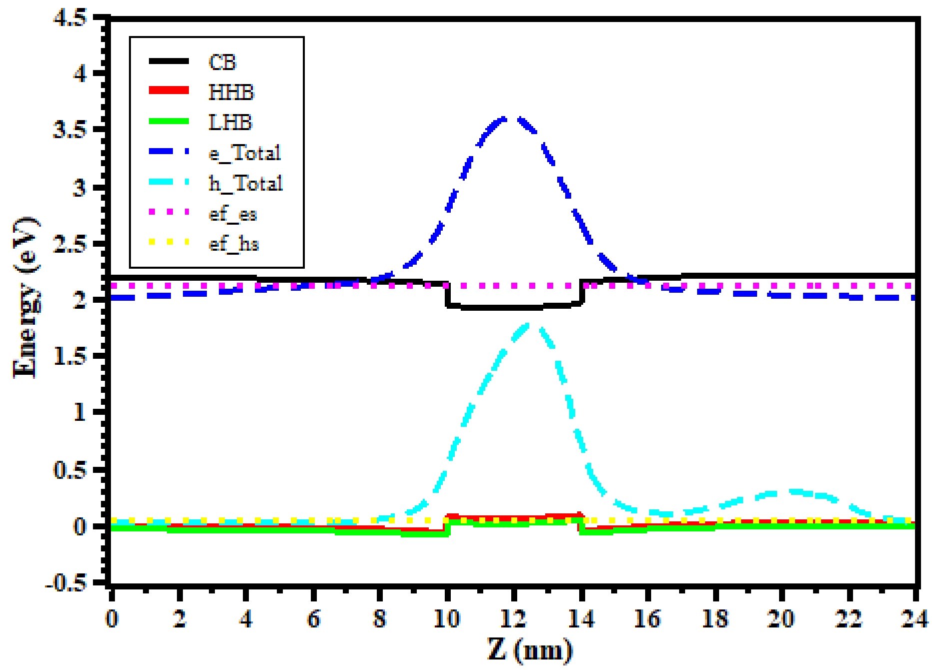

Fig.4: Energy wavefunctions for GaInP/AlGaInP heterostructure

After the analysis of the wavefunction, the optical gain is determined at room temperature 300K with the injected carrier density of $4*10^{12}/cm^2$. Figure 5 shows the computed optical gain characteristics with the emitted energy. It is observed that designed GaInP/AlGaInP heterostructure is able to emit the radiation in the red spectrum with the maximum gain of 4850 /cm at the 625 nm with narrow spectral width, which is widely used for biomedical application in photo dynamic therapy (PDT) for the treatment of superficial skin disease. So the designed heterostructure can be fabricated and utilized as the source in the PDT.

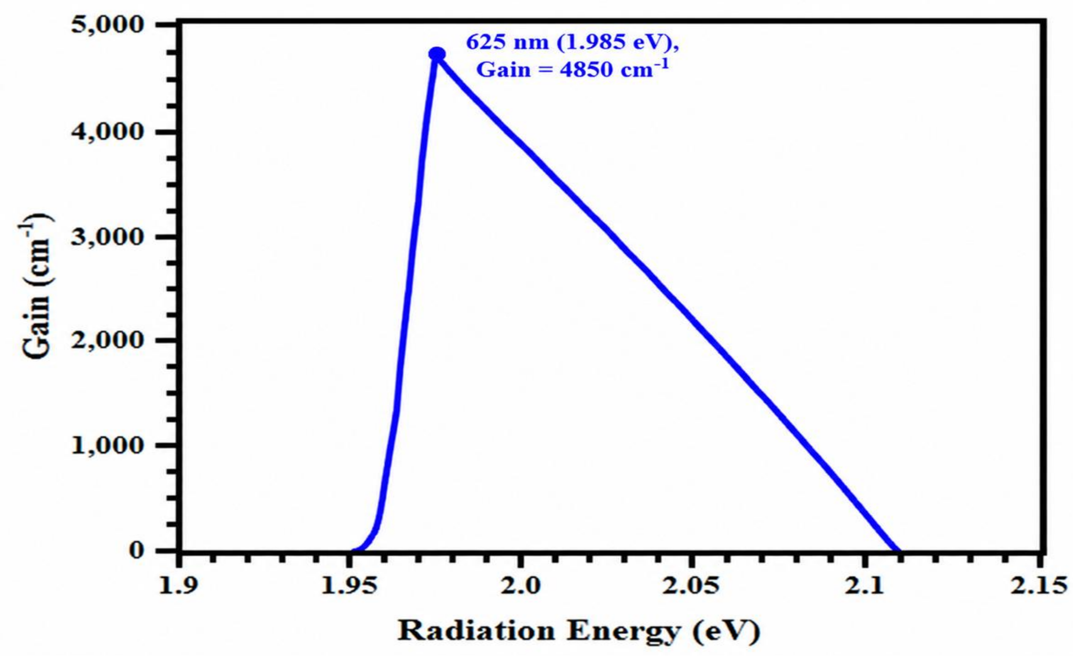

Fig.5: Optical gain characteristic for GaInP/AlGaInP heterostructure

III. CONCLUSION

A GaInP/AlGaInP nanoscale quantum well heterostructure was designed and analyzed for visible-light emission. The proposed type-I heterostructure exhibited strong carrier confinement, resulting in enhanced radiative recombination and optical gain. The optical gain spectrum showed a maximum gain of approximately 4850 cm^{-1} at 625 nm (1.985 eV) in the red region of the visible spectrum. The results demonstrate that the optimized GaInP/AlGaInP structure is a promising candidate for high-efficiency visible-light emitters, semiconductor lasers, and photonic devices requiring high gain and low-threshold operation.

REFERENCES

[1] G. Bastard, Wave Mechanics Applied to Semiconductor Heterostructures. Paris, France: Les Editions de Physique, 1988.
[2] S. L. Chuang, Physics of Photonic Devices, 2nd ed. Hoboken, NJ, USA: Wiley, 2009.
[3] P. Harrison, Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures, 4th ed. Hoboken, NJ, USA: Wiley, 2016.
[4] P. Y. Yu and M. Cardona, Fundamentals of Semiconductors: Physics and Materials Properties, 4th ed. Berlin, Germany: Springer, 2010.
[5] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, "Band parameters for III–V compound semiconductors and their alloys," J. Appl. Phys., vol. 89, no. 11, pp. 5815–5875, 2001.
[6] J. M. Luttinger and W. Kohn, "Motion of electrons and holes in perturbed periodic fields," Phys. Rev., vol. 97, no. 4, pp. 869–883, 1955.
[7] D. Ahn, S. L. Chuang, and Y. C. Chang, "Theory of optical gain in strained-layer quantum wells within the 6×6 Luttinger–Kohn model," IEEE J. Quantum Electron., vol. 28, no. 10, pp. 2196–2214, 1992.
[8] A. Girndt, S. W. Koch, and W. W. Chow, "Microscopic theory of laser gain in semiconductor quantum wells," Appl. Phys. A, vol. 66, no. 1, pp. 1–12, 1998.
[9] H. D. Summers, P. Blood, and P. Rees, "Gain-current characteristics of strained AlGaInP quantum well lasers," Appl. Phys. Lett., vol. 63, no. 20, pp. 2792–2794, 1993.
[10] G. Hunziker, H. Melchior, and R. Germann, "Gain, refractive index, and linewidth enhancement factor from spontaneous emission of strained GaInP quantum-well lasers," IEEE J. Quantum Electron., vol. 31, no. 5, pp. 791–798, 1995.
[11] S. T. Yen and C. P. Lee, "Theoretical analysis of 630-nm-band GaInP-AlGaInP strained quantum-well lasers considering continuum states," IEEE J. Quantum Electron., vol. 33, no. 3, pp. 443–456, 1997.
[12] S. J. Chang and C. S. Chang, "650 nm AlGaInP/GaInP compressively strained multi-quantum-well light-emitting diodes," Jpn. J. Appl. Phys., vol. 39, pp. 1758–1761, 2000.
[13] C. Y. Tsai, Y. K. Kuo, and M. C. Lee, "The influence of window layers on the performance of 650 nm AlGaInP/GaInP multi-quantum-well light-emitting diodes," J. Cryst. Growth, vol. 200, pp. 382–390, 1999.

[14] A. Twardowski, M. Kamińska, and P. Wisniewski, "Photoluminescence from GaInP layers and GaInP/AlGaInP quantum wells grown by molecular beam epitaxy," J. Cryst. Growth, vol. 265, pp. 410–419, 2004.
[15] I. Nomura, Research on GaInP/AlInP Strained Quantum Well Lasers Grown by Gas Source Molecular Beam Epitaxy, Sophia University, Tokyo, Japan, 1994.
[16] T. He, Y. Zhang, and H. Liu, "Research on quantum well intermixing of 680 nm AlGaInP/GaInP semiconductor lasers," J. Semicond., vol. 43, no. 8, 2022.
[17] M. Schubert et al., "Red-shifted excitation and two-photon pumping of biointegrated GaInP/AlGaInP quantum well microlasers," ACS Photonics, vol. 9, no. 2, pp. 456–464, 2022.
[18] P. Dhingra et al., "Low-threshold InP quantum dot and InGaP quantum well visible lasers on silicon," arXiv preprint arXiv:2106.xxxxx, 2021.
[19] D. V. Ushakov et al., "Phosphides-based terahertz quantum-cascade laser," arXiv preprint arXiv:2301.xxxxx, 2023.
[20] R. Sharma, A. Kumar, and S. Singh, "Optical gain analysis of GaInP/AlGaInP nanoscale heterostructure for applications in visible light emission," Materials Today: Proceedings, vol. 66, pp. 3493–3497, 2022.