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InGaAs/GaAsSb SQW Modeling for Optical Communication Applications

Jayprakash Vijay, Divya Bhardwaj

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

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***Abstract*— *This paper presents the design and simulation of an InGaAs/GaAsSb single quantum well (SQW) structure for optical communication applications at 300 K. The electronic band structure, carrier transport, and optical gain characteristics of the proposed structure are analyzed on a GaAs substrate. Simulation results show efficient carrier confinement and radiation emission at 1550 nm with a high optical gain of approximately 6500 cm^{-1}. The obtained results demonstrate the suitability of the proposed SQW structure for fiber optic communication systems, including WDM/DWDM and long-haul optical transmission applications.*

Keywords*— InGaAs/GaAsSb, Single Quantum Well (SQW), Optical Gain, Optical Fiber Communication, Carrier Transport

I. INTRODUCTION

The increasing demand for high-speed and high-capacity optical communication systems has accelerated research on semiconductor quantum well (QW) structures operating in the near-infrared region around 1550 nm. This wavelength is widely used in optical fiber communication because optical fibers exhibit minimum attenuation and dispersion losses near 1550 nm, making it highly suitable for long-distance transmission and wavelength division multiplexing (WDM/DWDM) applications [1]. Quantum well heterostructures offer enhanced carrier confinement, improved optical transition probability, and higher optical gain compared with conventional bulk semiconductor devices [2].

Among various semiconductor materials, InGaAs/GaAsSb heterostructures have gained considerable attention due to their tunable bandgap, superior carrier transport characteristics, and efficient optical emission in the telecom wavelength region [3]. The type-II band alignment in InGaAs/GaAsSb quantum wells provides effective separation and confinement of charge carriers, which enhances radiative recombination efficiency and improves device performance for photonic applications [4]. Such heterostructures are extensively used in semiconductor lasers, optical amplifiers, infrared photodetectors, and integrated photonic systems [5].

Several researchers have investigated the electronic and optical properties of InGaAs/GaAsSb quantum well structures. Bank et al. studied InGaAsN/GaAsSb type-II W-shaped quantum wells and demonstrated their suitability for long-wavelength optical communication systems operating near 1550 nm [6]. Jain et al. investigated broad gain spectrum characteristics in InGaAs/InAlGaAs quantum well lasers for optical communication applications and reported improved gain bandwidth near 1550 nm [7]. Novikov et al. experimentally analyzed strained InGaAs/InGaAlAs quantum wells and reported high modal gain with low transparency current density for near-infrared emission [8]. Recent studies have focused on improving optical gain and wavelength tunability through heterostructure engineering. Vijay et al. designed and modeled an InGaAs/GaAsSb nanoscale heterostructure on a GaAs substrate and achieved optical gain around 6220 cm^{-1} at 1550 nm [9]. Khan et al. further investigated the effect of electric field and temperature on the optical gain of InGaAs/GaAsSb/InAlAs nano-heterostructures and demonstrated controllable gain characteristics for optical communication systems [10]. Chaudhary et al. optimized type-II AlAs/AlInAs/GaAsSb heterostructures under well-width variation and obtained enhanced optical gain near 1550 nm [11]. In addition to optical communication, InGaAs-based devices have also been explored for photonic-crystal lasers, single-photon detectors, and optical modulation applications [12]. Li et al. demonstrated mid-infrared photonic-crystal surface-emitting lasers using InGaAs/GaAsSb W-type quantum wells [13]. Pellegrini et al. developed InGaAs/InP single-photon avalanche photodiodes for 1550 nm optical systems with improved detection efficiency [14]. Fang et al. further enhanced detection efficiency up to 60% for InGaAs/InP single-photon detectors operating at telecom wavelengths [15]. Despite extensive research, achieving high optical gain with efficient carrier confinement at room temperature remains a significant challenge for long-wavelength semiconductor devices. Therefore, the design and simulation of optimized InGaAs/GaAsSb single quantum well structures are important for improving the performance of next-generation optical communication systems. In this paper, an InGaAs/GaAsSb single quantum well (SQW) structure grown on a GaAs substrate is designed and analyzed at room temperature (300 K). The electronic band structure, carrier transport behavior, and optical gain characteristics are investigated in detail. The simulation results demonstrate efficient carrier confinement and high optical gain around 1550 nm, indicating the suitability of the proposed structure for optical fiber communication systems, including WDM/DWDM and long-haul transmission applications.

Structural Design and Parameters

In this study, a nanoscale InGaAs/GaAsSb single quantum well heterostructure is designed and modeled to investigate its electronic band structure, carrier confinement, energy wave functions, and optical gain characteristics for optical communication applications. The analysis of lasing behavior and optical performance of the proposed heterostructure requires a comprehensive understanding of the electronic properties of the constituent bulk semiconductor materials, which form the basis for nanoscale quantum well design. The proposed structure utilizes InGaAs and GaAsSb ternary compounds due to their tunable bandgap and efficient carrier confinement capability in the near-infrared wavelength region. Figures 1 and 2 illustrate the energy band structure diagrams of the InGaAs and GaAsSb materials at room temperature (300 K). The valence band structure of these ternary semiconductors consists of three major sub-bands, namely the heavy-hole band (HHB), light-hole band (LHB), and split-off band (SOB), which are differentiated by their effective masses and energy dispersion characteristics. These sub-bands play a significant role in determining the optical transition probability, carrier dynamics, and optical gain behavior of the quantum well heterostructure. The interaction between the conduction band and valence sub-bands strongly influences the emission wavelength and lasing efficiency of the proposed nanoscale device.

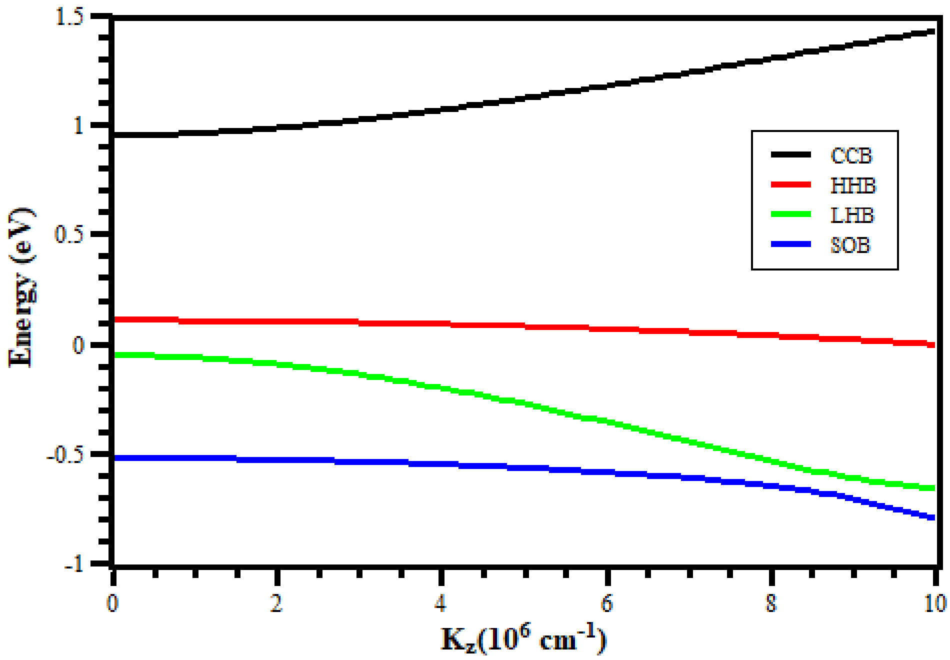

Fig.1. Band constructions of ternary compound InGaAs /GaAs

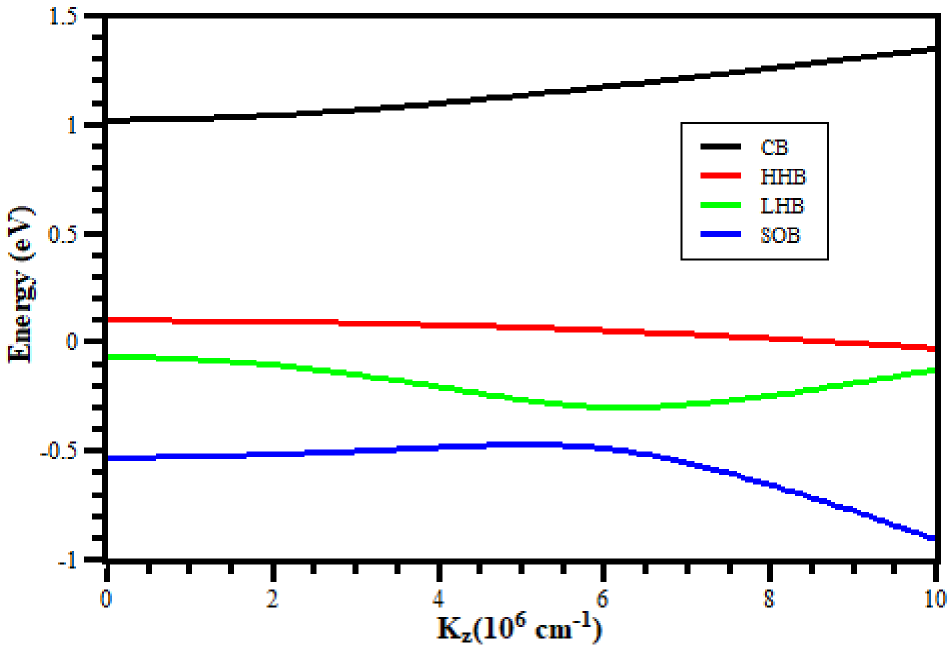

Fig. 2. Band constructions of ternary compound GaAsSb$_0$ /GaAs

The heavy-hole sub-band possesses a larger effective mass than the light-hole sub-band, whereas the light-hole band exhibits a steeper energy dispersion curve compared to the heavy-hole band. In contrast, the split-off band is located far below the conduction band and contributes minimally to the optical transitions because of its relatively low energy. One of the major challenges in semiconductor laser design is the large effective mass associated with the valence band carriers. This issue is commonly observed in III–V semiconductor materials due to the significant mismatch between the effective masses of electrons in the conduction band and holes in the valence band, which affects carrier transport and recombination efficiency.

The proposed heterostructure consists of a p-type InGaAs layer positioned between n-type GaAsSb barrier layers. In this configuration, the InGaAs layer acts as the quantum well because of its comparatively lower bandgap energy, while the GaAsSb layers function as potential barriers that confine charge carriers within the well region. The width of the InGaAs quantum well layer is maintained at 2 nm, whereas each GaAsSb barrier layer has a thickness of 4 nm. The complete nanoscale structure is designed and analyzed on a GaAs substrate under room temperature conditions (300 K). Figure 3 presents the energy band diagram of the proposed InGaAs/GaAsSb single quantum well heterostructure, illustrating the carrier confinement and band alignment characteristics essential for optical communication applications.

During the design of semiconductor heterostructures for targeted optoelectronic applications, the choice of materials and the thickness of individual layers play a crucial role in determining the emission wavelength and radiative energy characteristics at the nanoscale. In the present work, the layer thickness (Z-direction) is carefully optimized through iterative calculations and simulations to achieve efficient carrier confinement and improved electron–hole recombination within the quantum well region. The optimization of these structural parameters is primarily focused on maximizing the optical gain and obtaining stable emission around the 1550 nm wavelength, which is highly suitable for optical fiber communication applications.

The main objective of this work is to design a nanoscale heterostructure capable of generating radiation at the 1550 nm wavelength with enhanced optical gain, which is essential for improving the output power and performance of optical communication devices. The evaluation of optical gain requires a detailed analysis of carrier confinement and carrier distribution within the quantum well region. To investigate the localization behavior of charge carriers, the electronic wavefunctions of conduction band electrons and valence band holes are calculated and analyzed. Figure 4 presents the computed wavefunctions for electrons (e_total) and holes (h_total), together with the corresponding electron Fermi energy levels, demonstrating the carrier confinement characteristics of the proposed heterostructure.

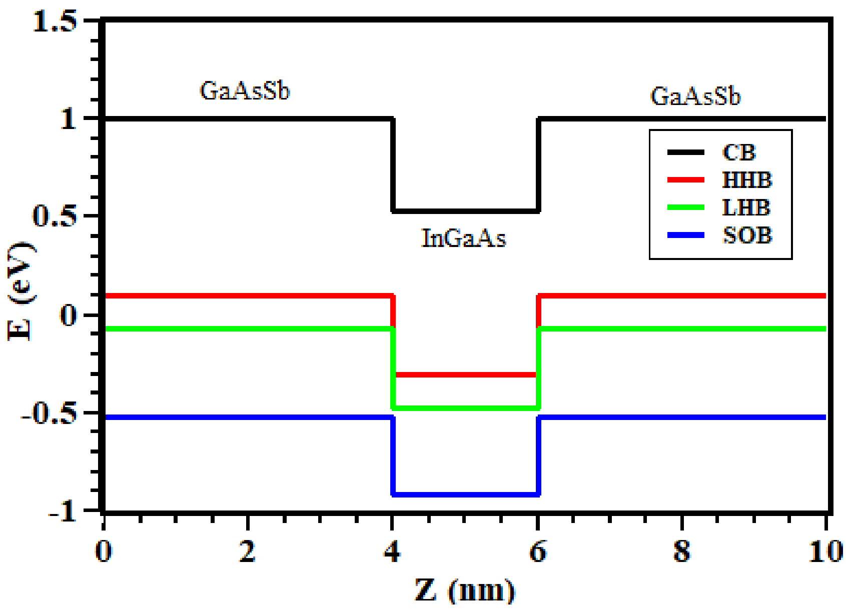

Fig. 3. Energy band diagram of the designed heterostructure

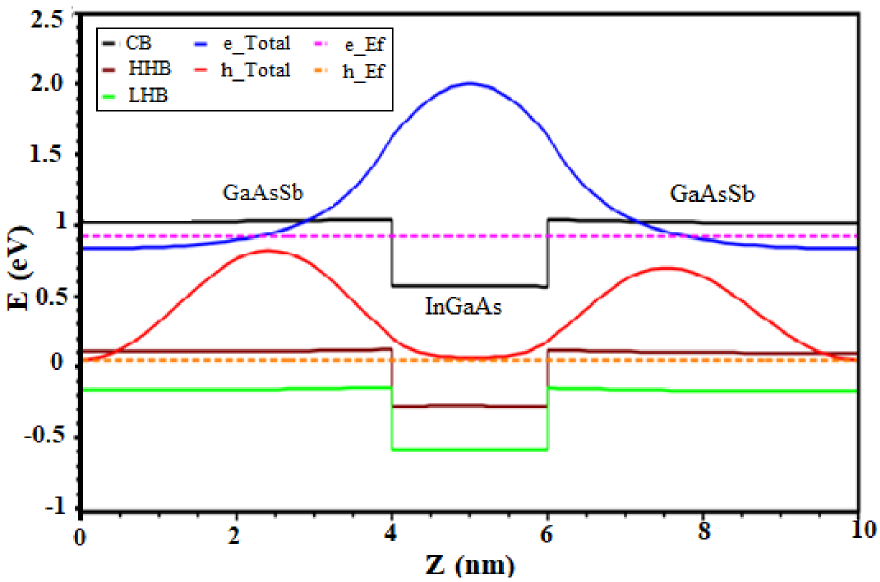

Fig 4. The energy wave function of the designed heterostructure

To analyze charge carrier confinement in the quantum well and barrier regions, a 6 × 6 Luttinger–Kohn Hamiltonian based on the effective mass approximation is employed. This model considers the heavy-hole, light-hole, and split-off bands along with their spin states. Figure 4 shows that electrons are strongly confined within the quantum well region, while holes remain localized near the barrier layers, leading to enhanced carrier recombination and higher optical gain.

To assess the amplification performance of the proposed heterostructure, the optical gain characteristics are analyzed. Figure 5 presents the variation of optical gain with emitted photon energy. At room temperature (300 K), the designed structure exhibits a maximum optical gain of nearly 6500 cm^{-1} at an emission energy of approximately 0.8 eV, corresponding to a wavelength of 1550 nm. The obtained results indicate that the proposed heterostructure provides enhanced optical gain performance compared to several recently reported nanoscale heterostructures for optical communication applications.

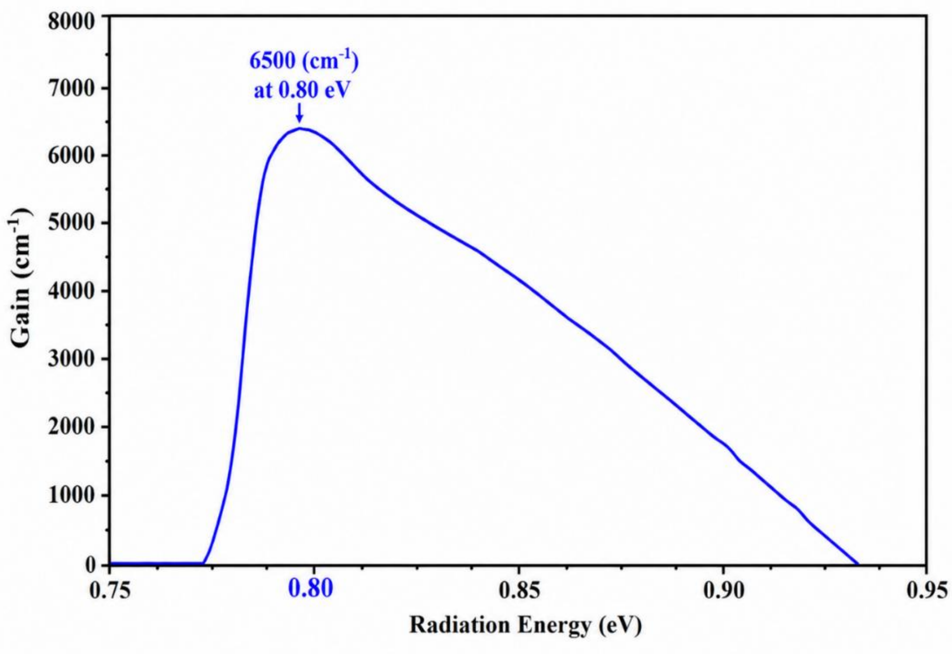

Fig 5: Optical gain characteristics of designed heterostructure

II. RESULTS AND CONCLUSION

This study presents the design and analysis of an InGaAs/GaAsSb nanoscale heterostructure for optical communication applications at 1550 nm. The electronic band structure, carrier confinement, and optical gain characteristics are investigated using a 6 × 6 Luttinger–Kohn Hamiltonian model. The results show strong electron confinement within the quantum well region, leading to enhanced carrier recombination and improved optical performance. The proposed heterostructure achieves a high optical gain of approximately 6500 cm^{-1} at room temperature (300 K), demonstrating its suitability for WDM/DWDM systems and long-haul optical fiber communication applications.

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