



Anisotropy and optical gain improvement in type-II $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}_{0.4}\text{Sb}_{0.6}$ nano-scale heterostructure under external uniaxial strain

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ABSTRACT

Alterations in optical transitions and distortions in wave symmetry in nano-scale QW (quantum well) heterostructures are seen due to external uniaxial strain under different polarizations. This paper reports the anisotropy phenomena and optical gain improvement realized in $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}_{0.4}\text{Sb}_{0.6}$ type-II QW-heterostructure (well width = 20 Å) under uniaxial strain in the SWIR (short wave infra red) region. The detailed study of the band structure, wave functions associated with the charge carriers in the respective bands and optical gain under electromagnetic field perturbation is reported. The 6×6 diagonal $\vec{k} \cdot \vec{p}$ Hamiltonian matrix is evaluated and Luttinger-Kohn model is used for the band structure calculation. Optical gain spectrum in the QW-heterostructure under uniaxial strain along [110] for different polarizations of light is calculated. For a charge carrier injection of $5 \times 10^{12}/\text{cm}^2$ the optical gain is ~1600/cm under input z-polarization, ~14500/cm under x-polarization and ~15700/cm under y-polarization without external uniaxial strain applied. A significant improvement in optical gain is observed under uniaxial strain along [110] direction under different input polarizations. Keeping in views its utilization in optoelectronics due its very high optical gain in near-infra-red region in x- or y-polarization mode, such structure can be considered as a novel structure.

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1. Introduction

Nano-scale quantum well heterostructures, new materials and improved fabrication techniques have led to drastic improvement in the performance of optodevices such as LEDs, lasers and detectors. Lasers operating in SWIR region (0.9–1.7 μm) find applications in areas such as inspection, surveillance, process control etc. In recent years, M- and W- shaped type-II QW heterostructures have been extensively investigated for the operation in SWIR/MWIR regions. Recently, H. K. Nirmal et al. [1] have studied type-II InGaAs/GaAsSb nano-scale heterostructure and a very high optical gain have been reported in the structure in comparison to other heterostructures. In Ref. [2] it has been shown that of optical gain in type-II

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InGaAs/GaAsSb heterostructure can be tuned under high pressure. Therefore, such types of heterostructures have attracted a great attention of researchers towards their potential applications in the area of optoelectronic devices operating in SWIR and MWIR wavelength regions. InGaAs/GaAsSb ‘W’-shaped lasers fabricated on InP substrate operating in SWIR region with low threshold current has been presented in Ref. [3]. ‘M’-shaped GaAsSb/InGaAs QW lasers fabricated on InP substrate operating in MIR (mid infra red) region have been presented by Chia-Hao Chang et al. [4]. InGaAs/GaAsSb ‘W’ type quantum well lasing heterostructures for MIR laser applications has been presented in Ref. [5]. Type-II InGaAs/GaAsSb quantum well designs for MIR lasers have been modelled in Ref. [6]. Optically pumped laser with ‘W’ Type InGaAs/GaAsSb quantum wells on InP Substrate has been demonstrated by Chien-Hung Pan et al. [7]. Baile Chen et al. have shown that thickness and composition of QW can be chosen properly to get optimised wavefunction overlap and transition wavelength in InGaAs/GaAsSb type-II QW structures for MIR photodiodes [8]. In Ref. [9], GaAsSb/InGaAs and GaAsSb/InP Type- II heterostructures have been grown by metalorganic vapor phase epitaxy (MOVPE) and various optical characteristics with variation in InGaAs layer thickness have been studied. Seoung-Hwan Park et al. have investigated the Optical gain of type-II InGaAs/GaN Sb QW structure [10]. Effects of uniaxial pressure on QW-heterostructures has been studied and reported in several works recently. *p*-AlGaAs/GaAsP/*n*-AlGaAs heterostructures have been tuned under TM/TE polarizations by uniaxial compression [11]. E. V. Bogdanov et al. have studied *p*-AlGaAs/GaAsP/*n*-AlGaAs laser diode structures under uniaxial stress [12]. Electroluminescence under uniaxial stress in *p*-AlGaAs/GaAsP/*n*-AlGaAs has been reported in Refs. [13,14]. Band Structure and anisotropy phenomena in two dimensional hole Gas of GaAs/AlGaAs heterojunction is studied under uniaxial compression [15]. Minina, N. Ya et al. have studied the valence sub-bands energy spectrum and electroluminescence in *n*-AlGaAs/GaAsP/*p*-AlGaAs structures under uniaxial compression [16]. Sapna Gupta et al. have done a critical analysis of strain profile at heterointerfaces in nitride material based multilayer nano-heterostructures such as GaN/AlGaIn, InN/AlInN, and InN/GaInN [17]. In earlier, the nitride based quantum well structures have been studied in detail. For example, P. Bigenwald et al. [18] have studied Quantum Confined Stark (QCS) effect in (Al,Ga)N/GaN quantum wells due to built-in internal polarization fields and concluded that the origin of the electric field is predominantly due to spontaneous polarization effects rather than a piezoelectric effect in the well material. In their work, they have also studied temperature-dependent luminescence and reflectivity. In another similar type of work, the orientation-dependent properties of single and double (Ga,In)As-GaAs strained-layer quantum wells embedded in (pin) diodes have been studied by B. Gil et al. [19]. The existence of such properties were found mainly due to the existence of a strong internal piezoelectric field in the (Ga,In)As layers when the growth axis is polar. They have also shown that the tunnelling of the two lowest-lying heavy-hole levels can be stimulated for moderate carrier densities making such structures promissive in order to realise self electrooptic effect device (SEED) modulators.

Apart from the experimental work, the theoretical work has also been carried out on nitride based quantum well structures. P. Bigenwald et al. [20] have adopted the self-consistent procedure of solving both the Schrödinger and Poisson equations for electron and hole wave functions combined with the variational calculation of exciton states in strained GaN/Al_xGa_{1-x}N quantum wells. The entire calculations revealed an interesting interplay between the screening of the polarization fields, which leads to the increase of the electron-hole overlap, and the screening of the electron-hole interaction, which affects the exciton Bohr radius. In addition, the evolution of exciton binding energies in GaN/AlGaIn quantum structures that are photo-pumped have been studied theoretically with the help of variational approach by P. Bigenwald et al. [21]. In this work, the excitation intensity leading to the bleaching of the electron–hole interaction has been shown to depend strongly on the well width and on the lattice temperature.

A-M Vasson et al. [22] have used a non-conventional technique of thermally detected optical adsorption (TD-OA) to study a strained InAs/InP quantum well of thickness between two and three monolayers. Experimental arrangement along with the spectrometer, TD cell and TD-OA spectra have been described in their work. Moreover, L. Aigouy et al. [23] have reported a detailed optical study of ZnSe-based graded index separate confinement (GISC) heterostructures. These structures were grown by metalorganic vapor phase epitaxy and were composed of either one or two Zn_{0.79}Cd_{0.21}Se central well(s) embedded between two ZnCdSe barriers which cadmium composition varies linearly from 5% near the wells to 0% at the end of the barriers. T. Cloitre et al. [24] have shown the cancelation of excitonic effects in type-II ZnSe–ZnTe superlattices by injection of photo carriers. They have also reported that the strong confinements of electrons and holes by large bands offsets lead to important values of Rydberg energies; and thus, important energy-shifts of some 20 meV are measured when exciton screening is produced in such superlattices.

The aim of this paper is to report the anisotropy and optical gain improvement in In_{0.3}Ga_{0.7}As/GaAs_{0.4}Sb_{0.6} type-II quantum well heterostructure under uniaxial strain for SWIR applications. The theoretical gain spectrum in the QW-heterostructure under external uniaxial strain along [110] for different polarizations of light is calculated. In the next section, design and theory of the In_{0.3}Ga_{0.7}As/GaAs_{0.4}Sb_{0.6} type-II heterostructure is presented following which the simulation results are discussed. Finally a conclusion on the work is made.

2. Heterostructure design specifications and theory

The type-II quantum well heterostructure under consideration consists of an *n*-type In_{0.3}Ga_{0.7}As material in between two *p*-types GaAs_{0.4}Sb_{0.6} layers. The *n*-type In_{0.3}Ga_{0.7}As and *p*-type GaAs_{0.4}Sb_{0.6} layers are taken of equal width (2 nm). The energy band diagram of the entire heterostructure showing band offsets is shown in Fig. 1. The interesting feature of this structure is that the conduction band of *n*-type In_{0.3}Ga_{0.7}As QW material lies below the conduction band of *p*-type GaAs_{0.4}Sb_{0.6} barrier material. Also, the valence band of *n*-type In_{0.3}Ga_{0.7}As QW material lies below the valence band of *p*-type GaAs_{0.4}Sb_{0.6} barrier

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