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Uniaxial strain induced optical properties of complex type-II InGaAs/InAs/GaAsSb nano-scale heterostructure

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ABSTRACT

Semiconducting heterostructures offer an extra degree of flexibility in terms of tuning of optical gain and transition energies or wavelengths. Modifications in the wave functions and alterations in optical transitions in binary and ternary QW (quantum well) heterostructures due to external uniaxial strain provide valuable insights on the optical characteristics of the heterostructure. In this paper, we have reported the effect of uniaxial strain along [001], [100] and [110] on the optical properties such as optical gain, and optical transition energies of W – shaped complex type-II InGaAs/InAs/GaAsSb nano-scale heterostructure consisting of two quantum wells of InAs material using the six band k.p theory. On the basis of results obtained in the work, it can be reported that the TE and TM optical gain can be enhanced by application of uniaxial strain along [110] only. It is also reported that application of strain along [001] is useful for improvement of TE optical gain while strain along [100] is useful for TM optical gain. Thus, for the type-II InGaAs/InAs/GaAsSb nano-heterostructure TE and TM gain and as well as transition energies can be controlled by the application of uniaxial strain along the choice of direction.

1. Introduction

The type-II heterostructures based optoelectronic devices have attracted a lot of interest of researchers belonging to optoelectronic community because the band alignment of these structures offers the devices operation in the mid infrared wavelength regime [1,2]. Recently, type-II nano-scale heterostructures have been very popular due to their wide applicability in the area natural sciences, environmental sciences, renewable energy, optoelectronics and telecommunication such as detection of gases, monitoring of pollution, MIR detection, photocatalysts modification and optical data transfer [3–6]. Moreover, the type-II heterostructures in form of quantum well infrared photodiodes (QWIP) have been claimed very important for free-space communication systems and heterodyne detection purpose operating in the 2–5 μm of wavelength region (MIR region) which is important for ecological monitoring, gas analysis, and medical diagnostics [7]. In Ref. [7], Konovalov et al. have fabricated type-II asymmetric heterostructure of *p*-InAs/AlSb/InAsSb/AlSb/(p, n)-GaSb material system with a three deep quantum wells (QWs) at the heterointerface and examined I–V, C-V characteristics along with photoelectric, luminescent, and magnetotransport properties. Initially, binary semiconducting materials based type-II nano-scale heterostructures were approached for study of their various characteristics and later on a group of researcher moved towards

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Table 1
Design Parameters of InGaAs/InAs/GaAsSb Nano-Heterostructure.

Role of Layer	Layers Specification	Layer Thickness (nm)	Energy Band gap (eV)	Lattice constants (Å)	Conduction band edge-offset (eV)	Valence band edge-offset (eV)
Quantum well	InAs	20	0.36	6.0583	0.36	−0.161
Barrier	$GaAs_{0.31}Sb_{0.69}$	20	0.690	5.868	0.921	−0.612
Spacer	$In_{0.25}Ga_{0.75}As$	40	1.077	5.754	0.361	–
Substrate	InP	80	1.35	5.869	–	–

ternary and quaternary compound materials based type-II structures. For example, Fuchs et al. [8] have studied Fourier-transform photoluminescence of type-II InAs/AlSb heterostructure and reported the influence of the GaSb buffer layer of PL spectra. In another example, Prevot et al. [9] have studied type-II InAs/AlSb heterostructure in superlattice mode and investigated interband and intersubband transitions experimentally as well as theoretically. Kolokolov and Ning [10] have reported that the famous type-II InAs/AlSb nano heterostructure can be converted into type-I heterostructure via doping process and hence the optical gain of the heterostructure can be improved. A group of researchers [11,12] have studied experimentally and theoretically intersubband transitions in type-II InAs/AlSb quantum well structures (QWs) under variable well widths and temperature. Ohtani et al. [13] have also reported intersubband optical absorption in *n*-doped InAs/AlSb nano heterostructures consisting of multiple quantum wells (MQWs) using k.p theory. They reported shifting of absorption peak from MIR regime to NIR regime that is from 375 meV (3.31 μm) to 627 meV (1.98 μm). Apart from InAs/AlSb heterostructure, type-II InAs/GaSb heterostructure was also reported as a cascade lasing heterostructure by Kisin et al. [14]. Recently, type-II strained InAs/GaSb heterostructure has been reported in superlattice mode showing the flexibility of varying the energy bandgap by varying the layer thickness [15]. Due to this flexibility, such heterostructures have been realized to operate in the MIR (mid infrared region), LWIR (long wave infrared region) and (VLWIR) very long wave infrared region exhibiting their superior performance over conventional PIN devices.

Apart from binary materials based type-II heterostructures, a group of researchers belonging to optoelectronics community approached towards ternary and quaternary materials based type-II nano-heterostructures. Kim and Park [16] have studied optical properties of type-II $GaAs_{0.76}Sb_{0.24}/In_{0.26}Ga_{0.74}N_{0.6}As_{0.94}/GaAs$ quantum well (QW) heterostructure such as transition wavelength, and optical gain taking into account modulation doping effect. Moreover, Pan and Lee [17] have designed type-II "W" shaped InGaAs/GaAsSb quantum well (QW) heterostructure for MIR applications and theoretically investigated subband energies, momentum matrix elements and TE material gain of the heterostructure utilizing eight band k.p theory. More recently, Niraml et al. [18] have designed type-II "M" shaped $In_{0.70}Ga_{0.30}As/GaAs_{0.40}Sb_{0.60}$ nano-heterostructure for SWIR (short wave infrared region) applications and reported its optical gain tunability under high pressure applied externally along [110] direction by making use of six band k.p model [19].

In this paper, the "M-shaped" type-II InGaAs/GaAsSb nano-heterostructure has been modified by inserting the InAs layers between the InGaAs and GaAsSb materials. Thus the proposed heterostructure of InGaAs/InAs/GaAsSb material system consists of quantum well of InAs rather than InGaAs material. This structure can be useful in MIR (mid infra red) wavelength regime in the area of optoelectronics, environmental sciences, medical diagnostics and natural sciences. The MIR wavelength region ranging from 2 μm to 5 μm has attracted significant interest towards potential applications, such as infrared countermeasures, tunable IR spectroscopy, optical gas sensing, chemical process control, environmental pollution monitoring, non-invasive medical diagnosis, and laser based surgical operations because the region is rich in spectroscopic fingerprints of molecules, which are used to identify pollutants for medical diagnostics, for environmental, for process control, for safety, security and as well as defense applications [20]. However, for the proposed type-II heterostructure, the six band k.p model has been used to calculate the wavefunction and probability density for knowing localization of electron and holes in the entire structure. The subband energies of electrons and holes have been calculated followed by calculations of dipole matrix and momentum matrix elements and finally optical gain of the structure has been calculated with in TE and TM polarization modes. The external uniaxial pressure has been applied on the structure along [100], [001] and [110] in order to observe the strain effect on the optical properties of the heterostructure and the suitability of strain direction has been discussed in the results and discussion section.

2. Device structure and theory

The complete designed parameters of type-II InGaAs/InAs/GaAsSb nano-heterostructure are tabulated in Table 1. This is a unique "W" shaped heterostructure with the barrier's higher valence band offset value in comparison to conduction band offset value. In this structure the transition occurs between electrons of quantum well (InAs layer) and holes of barrier region (GaAsSb layer). This feature differentiates type-II heterostructure form type-I structure. For such a heterostructure, the energy band gap between conduction band edge of quantum well region and valence band edge of barrier region is minimized and therefore emitted radiations are of smaller energy and longer wavelength. Most of the type-II nano-heterostructures, based on III–V compound semiconductors materials, have been reported to emit SWIR (short wave infrared region) and MWIR (mid wave infrared region) radiations [5,18,21]. Actually, the InGaAs/InAs/GaAsSb nano-heterostructure is modified form of InGaAs/GaAsSb heterostructure with the insertion of InAs layer between the InGaAs and GaAsSb materials and thus the designed heterostructure consist of active region of InAs material (thickness ∼ 20 nm). In this structure the material InGaAs