Historical Literature Review

The concept of employing heterostructures in the field of semiconductor electronics was emerged in the very beginning. The first patent related to p-n junction transistors to attain one way injection was proposed by W. Shockley [1]. The current voltage characteristics of anisotropic and isotropic heterojunctions were theoretically analyzed by A.I Gubanov in the year 1951 [2]. However H. Kroemer carried out some significant theoretical explorations in the very beginning stage of research on heterostructures. He introduced the concept of quasi electric fields and quasi magnetic fields in a heterojunction and observed the fact that higher injection efficiencies can be attained by using heterojunctions in comparison to homojunctions [3].

L. Y. Keldysh et al. [4] formulated an analysis of the periodic potential developed on the semiconductor surface due to an ultrasonic wave of a very high intensity.

A lot of ideas employing the utilization of semiconductor heterostructures in the solar cells were evolved in the same course of time period. A very pertinent development took place after several years when Zh. I. Alferov [5] and Kroemer [6] independently expressed formulations in the concept of double heterostructure based lasers. They noticed the possibility of acquiring large carrier densities and to utilize “double” injection for attaining inversion. It was particularly noticed that it is quite difficult to achieve continuous lasing action at elevated temperature conditions. Also an additional benefit of double heterostructure based lasers was demonstrated by exploring the feasibility of extending the emission area and employing new materials to achieve emission in various regions of the gain spectra.

H. Kroemer [6] hypothesized that the carriers can be confined in the active region using double heterostructures. He also postulated that in order to attain the lasing action in many indirect band gap semiconductors a pair of heterojunction injectors could be employed effectively. During the course of period, GaAs gathered a reputed place as a substrate in semiconductor electronics. It offered an auspicious alliance of several desirable properties like wide band gap, low effective
masses, efficient radiative recombination, a pointed optical absorption edge owing to its direct band gap structure, relatively high electron mobility at the conduction band minima. The early work of H. Manasevit [7] introduced the basic concepts of MOVPE (Metal Oxide Vapor Phase Epitaxy) and it enjoyed widespread application for growing heterostructures based on III-V compounds.

The experimental investigation of superlattices began in the year 1970, when L. Esaki and R. Tsu [8] jointly analyzed the electron transport in a superlattice where a supplementary periodic potential developed by doping or by varying the composition of semiconductor materials with a period larger than the lattice constant. In this crystal, referred as “man-made crystal” by Leo-Esaki, the parabolic bands are split into minibands separated by small band gaps and also had a Brillouin zone being controlled by the period of superlattice.

Due to electron confinement in the case of double heterostructures, DH based lasers became the direct precursors of quantum well structures. In quantum well structures, there exists a narrow band gap middle layer (having thickness of the order of few angstroms) of an element having the outcome of dividing the electron levels owing to quantum well effects. Even then very high quality DHs having extremely thin layers could not be obtained till new methods were evolved for the growth of heterostructures. Molecular beam epitaxy was developed as one of the prime important technologies for growing III-V compounds based heterostructures, significantly through the colonized and innovative work of A. Y. Cho [9].

Zh. I. Alferov et al. [10] independently developed the first multi chamber device and prepared structures with GaP\(_{0.3}\)As\(_{0.7}\)/GaAs superlattice which incorporated a total of 200 layers and each layer had a thickness of 100 angstroms. The noticed features of current-voltage characteristics, the effect of temperature on them, and the photocurrent effect were attributed to splitting of the conduction band under the influence of one dimensional periodic potential in the superlattice.

R. F. Kazarinov and R. A. Suris [11, 12] carried out an analytical investigation of transmission of current in the superlattice structures, at the Physicotechnical institute in the seventies. They observed that the current flow is controlled by channelizing through potential barriers differentiating the quantum wells. In addition to it the authors also predicted and showed very
significant physical effects: effect of an electric field on carrier tunneling when the ground state of one quantum well matches with the excited state of the next quantum well and the stimulated emission occurred when the optically excited carriers channelized from the ground state of one quantum well to the excited state of the neighboring one under the effect of applied electric field. As a coincidence, at essentially the same time, L. Esaki and R. Tsu [13] inspected the resonance tunneling effects in the superlattice structures developed by vapor beam epitaxy in the system GaPₓAs₁₋ₓ/GaAs.

L. L. Chang et al. [14, 15] employed molecular beam epitaxy technique to an AlGaAs based system and published the first experimental illustration of the very new physical attributes of quantum well heterostructures. The authors working on resonance tunneling measured the variation of conductivity and tunneling current as a measure of the stress being applied in a double barrier GaAs-GaAlAs heterostructure. During the same period, however, L. Esaki and L. L. Chang [16] analyzed the phenomenon of resonance tunneling having the potentially significant applications in high speed electronics attributed to the intensified preoccupation in the minds of research groups. Following it, by the end of eighties switching times of the order of picoseconds were reported for a double resonance tunneling diode. Also at room temperature, an oscillation frequency of 420 GHz was obtained in GaAs resonance tunneling diodes.

In the year 1974 R. Dingle et al. [17] further demonstrated a distinctive manifestation of the quantum well effects in the gain spectrum of GaAs-AlGaAs semiconductor heterostructure with an extremely thin layer of the active region. The authors noticed an indicative step structure in the absorption spectrum and as the thickness of active region was decreased, an orderly shift in the characteristic energies was observed. Lasing action by making the use of quantum wells was first accomplished by J. P. Vander Ziel et al. [18] but the lasing parameters fell short of double heterostructure lasers. Later on R. D. Dupis and P. D. Dapkus predicted the successful implementation for creating a room temperature injection double heterostructure laser in the AlGaAs system [19].

The term “quantum well” was first surfaced in a paper published by R. Dupuis and P. Dapkus in association with N. Holonyank [20]. The authors reported the first design of quantum well laser having matching parameters of double heterostructure lasers. The actual benefits of quantum
well lasers was expressed and manifested later by W.T. Tsang of Bell Telephone Laboratories. Incorporating some significant required improvements in the MBE (Molecular Beam Epitaxy) growth technology and the integration of an optimized structure in the form of a SCH (Separate Confinement Heterostructure) and with a uniform variation of the refractive index in the active region, that is GRINSCH (graded index separate confinement heterostructure), it was possible to achieve the value of threshold current density upto 160 A/cm².

Thereafter modulation doped superlattices were studied, which resulted in the enhancement of mobility as compared to bulk crystals. It marked the development of research in achieving microwave amplification by utilizing a 2D i.e. two dimensional electron gas with a significant mobility. Almost at the same point of time, a single modulation doped n-AlGaAs/n-GaAs heterostructure was used in designing new types of transistors in France and Japan. These acquired the nomenclature as HEMT i.e. high electron mobility transistor and TEGFET i.e. two-dimensional electron gas field effect transistor in Japan [21] and France [22] respectively.

A.E. Blakeslee et al. proposed significant advancements in the growth of very low defect density strained layer superlattices. The theoretical explorations carried out by G. Osbourn [23] at Sandia National Laboratories and the independent work of M. J. Ludowise [24] in the growth of the first high quality GaAs-In₀.₂Ga₀.₈As strained layer superlattice structures was followed by N. Holonyank who successfully utilized these structures in designing a continuous wave laser having the capability to operate at room temperature. A remarkable concept was being noticed that the presence of stress in strained layer superlattice structures establishes an additional degree of freedom and it is possible to vary continuously and independently the basic parameters like band gap width, lattice constant etc. by varying the composition and thickness of layers.

J. Menendez et al. [25] made use of inelastic light scattering for determining the energy band offsets of semiconductor heterostructures. The authors obtained the conduction-band discontinuity from the spacing of energy levels metered in the electronic light scattering spectrum of photon excited quantum-well heterostructures. The strategy was applied to different heterostructures like InGaAs-GaAs, AlGaSb-GaSb and GaAs-AlGaAs. The band offsets determined from light scattering were analysed and also the observed results were compared with those being reported using other conventional techniques.
P. Saunier et al. [26] fabricated monolithic amplifiers and discrete devices using AlGaAs/InGaAs/GaAs-type heterostructures and obtained transconductance of 530 mS/mm and current density of 1 A/mm and. A 100-µm monolithic one-stage amplifier demonstrated 93 mW (0.93-W/mm power density) at 31.5 GHz with 4.2-dB gain and 29% efficiency. A record 34% efficiency was achieved with a 53.7-mW output power and 4.8-dB gain

H. K. Choi et al. [27] utilized organometallic vapor phase epitaxy to fabricate GRIN SCH heterostructure InGaAs/AlGaAs single quantum well lasers having a lasing wavelength of 1.02 µm. They reported very low values of threshold current densities ~ 65 A/cm², power conversion efficiency around 47% and approximately cent percent internal quantum efficiency for strained InGaAs/AlGaAs Single Quantum Well lasers.

M. A. McKee et al. [28] employed low pressure MOVPE (metal organic vapor phase epitaxy technique) to grow high-quality In₀.₅Ga₀.₅P and InGaAlP layers. Highly uniform films were obtained both on a single 50-mm-diameter wafer at the center of a 5-in-diameter wafer carrier and on three 50-mm-diameter GaAs wafers symmetrically placed on a 5-in-diameter carrier. The authors analyzed the effects of V/III ratio and temperature on morphology and composition and presented the initial results on InGaAlP/InGaP double heterostructure lasers.

H. Yoon et al. [29] demonstrated strained quantum well lasers and compared the characteristics as compared to unstrained structures. The reliability of device and the stability of active region are the two significant factors in utilizing strained quantum well based structures. The authors investigated the effects of strain on reliability and for InₓGa₁₋ₓAs-GaAs MQW lasers and reported the lasing characteristics of the device. The nonradiative defect densities in the GaAs-Al₀.₄Ga₀.₆As quantum wells with and without the surrounding active In₀.₂Ga₀.₈As layers were compared by measuring the photoluminescence intensity after deliberately introducing defects and enhancing their diffusion. It was observed that a significantly good value of photoluminescence intensity was achieved with pseudomorphic In₀.₂Ga₀.₈As layers which attributed to the observed reliability improvement in strained quantum well lasers.

V. Mosser et al. [30] investigated the realization of Hall Effect in the magnetic sensors based on AlGaAs/InGaAs/GaAs heterostructures resulting in a good sensitivity and very low thermal drift.
A set of test devices were observed in a well controlled environment and the physical phenomena resulting in the thermal drift of the Hall sensitivity were analyzed for optimizing the design of structure. The authors reported a sensitivity of 900 V/A/T with an ambient temperature coefficient of -160 ppm/°C.

S. Burkner et al. [31] studied the compatibility of IFID technique with the fabrication and growth of highly strained InGaAs-GaAs multiple quantum well structures which led to the concept of selectively inter-diffusing of quantum well heterostructures in designing and fabricating the integrated optoelectronic devices.

T. Toyonaka et al. [32] demonstrated and carried out a highly stable operation of strain-compensated InGaAs/InGaAsP lasing structures emitting at 0.98 µm with an observed estimated lifetime of 170 kh at 25°C. Additionally the authors revealed that the degradation rates at 90°C and 80 mW output power were four times less than those of identical lasers with GaAs barriers.

T. Egawa et al. [33] employed MOCVD technique for fabricating a reliable 877- nm InGaP-GaAs light-emitting diode (LED) on Silicon as the substrate. A conventional aluminium containing AlGaAs-GaAs LED on a Silicon substrate exhibited a rapid degradation due to dark-line defects. On the other hand the aluminium free InGaP-GaAs LED on a Silicon substrate had no significant growth of dark line defecrs which resulted in a reliable operation for more than 1500 h being attained in an InGaP-GaAs LED on a Si substrate.

L. J. Mawst et al. [34] reported the use of the broad-waveguide concept to quantify the continuous wave output power for optimizing the InGaAs/InGaAsP/InGaP strained-layer quantum well heterostructures. The authors made use of low pressure metal oxide vapour deposition technique for fabricating aluminium free double quantum well laser structures. It was indicated that the material of quantum well that is strained-layer InGaAs rather than the cladding layer material that is the prime factor responsible for the COMD value.

A. M. Jones et al. [35] successfully fabricated a broad area single quantum well lasing structures n-type InGaAs substrates without incorporating aluminum-containing alloys. The authors employed atmospheric pressure MOCVD technique for fabricating strained-layer InGaP-GaAs-InGaAs heterostructures.
A. Al-Muhanna et al. [36] reported a record value for quasi continuous wave output power, 14.3 W for 100 µm-wide stripe, 0.97 µm-emitting aluminium free InGaAsP-InGaP-GaAs quantum well lasers. Additionally very low internal losses ($\alpha=1$ cm$^{-1}$) and high differential quantum efficiency (86% for 2 mm-long lasers) was observed. Long cavity, large-stripe devices exhibited relatively small spectral broadening with increased output power.

M. R. Gokhale et al. [37] formulated the experimental results for 0.98 µm-aluminum-free SCH-MQW InGaAsP/InGaP/GaAs lasers. The decreased overlap of the optical mode with the highly doped cladding regions resulted in lesser free carrier absorption which led to decrease in the internal losses with an increase in the width of the waveguide layer. The authors reported a record low internal loss of 2.2 cm$^{-1}$ and highest CW output power of 6.8 W for a InGaP/GaAs lasers as well as the highest quasi-continuous output power of 13.3 W measured for a single 100 µm aperture, 0.8-0.98 µm aluminum free laser diode, grown by either Molecular Beam Epitaxy or Metal Organic Chemical Vapor Deposition.

Q. Yang et al. [38] analyzed the effect of group V switching times on the formation of interfacial layers in InGaP/GaAs heterostructures grown by LP-MOCVD using low temperature photoluminescence (PL), double crystal X-ray diffraction (DCXRD) and high resolution transmission electron microscopy (HRTEM). By improving the switching conditions, the interfacial layers could be minimized to one monolayer (ML) of In$_{0.5}$Ga$_{0.5}$As at the GaAs-to-InGaP interface and 1 monolayer of In$_{0.65}$Ga$_{0.15}$P$_{0.15}$As$_{0.85}$ at the InGaP-to-GaAs interface. Heterojunction bipolar transistors (HBTs) grown by making use of this switching scheme exhibited wonderful etch selectivity and dc characteristics.

J. J. Russell-Harriott et al. [39] investigated the behavior of oval defects using cathodoluminescence (CL) and wavelength dispersive X-ray spectroscopy (WDS) in MBE-grown strained InGaAs/GaAs heterostructures.

S. Sassen et al. [40] hypothesized the barrier height engineering of n-GaAs-based millimeter-wave Schottky diodes using lattice mismatched InGaAs/GaAs and InGaP/GaAs heterostructures and a highly doped surface layer. The Schottky barrier height was varied between $\Phi_{fb}=0.52$ eV and $\Phi_{fb}=1.0$ eV. Schottky barrier height was effectively reduced by employing a pseudomorphic
thin and highly doped InGaAs layer. The theoretical results were in good agreement with the experimental results.

R. Absin et al. [41] studied the interfacial coherence effects in low-strained $\text{In}_x\text{Ga}_{1-x}\text{As}$ layers grown on GaAs substrates and observed the values of the critical strains corresponding to increasing layer thickness.

A. I. Klimovskaya et al. [42] employed Photoluminescence study to characterize $\text{In}_x\text{Ga}_{1-x}\text{As}$ quantum well layers grown on GaAs substrate matrix. The authors presented the relation between the Photoluminescence parameters and ambiguity of the lattice parameters of matrix and active layer. Several Photoluminescent bands were noticed in highly strained layers rather than single band. This was attributed to varying the content of Indium in highly strained active layers.

N. N. Grigor'ev et al. [43] carried out PL study of $\text{In}_x\text{Ga}_{1-x}\text{As}$ SQWs (single quantum wells) fabricated on GaAs substrate with Indium composition varying from 0.16 to 0.35. The thickness ($d$) of quantum well layers was comparable to or larger than the critical thickness ($d_c$). The heterostructures with quantum well thickness $d$ lesser than the critical thickness $d_c$, resulted in almost defect free homogeneously elastically strained heterostructures. The authors explained theoretically the energy levels in quantum wells and PL bands.

J. J. Coleman [44] reviewed the characteristics of lattice mismatched InGaAs/GaAs quantum well heterostructure lasers.

Hyejin Kim et al. [45] employed transmission electron microscopy (TEM) technique to examine the dimensional properties like thickness of active region, interface quality etc. in context with semiconductor heterostructures. The authors proposed the use of a simple wet etching technique to cross-section a heterostructure (InGaAs/GaAs multiple quantum well) at a very shallow angle.

M. Kanskar et al. [46] presented the study of aluminum-free diode lasers demonstrating high power conversion efficiency at 970 nm. Aluminum free active diode lasers like InGaAs (P)/InGaP/GaAs had far better power-conversion efficiency as compared to conventional Aluminum containing devices because of their higher thermal conductivity and low differential series resistance.
Michal Szymanski [47] analyzed calculations for semiconductor heterostructures, InGaAs SQW surrounded by GaAs waveguide layers and AlGaAs cladding layers. The authors used finite difference method for solving Schrodinger equation. Temperature of the laser active region was also measured and taken into account. The laser mirror was investigated by using thermoreflectance mapping which a modulation technique is being employed to obtain a 2 D map of temperature of resolution up to several microns.

M. Arai et al. [48] realized a lattice mismatched InGaP graded buffer layer grown by MOVPE (Metal Organic Vapor Phase Epitaxy) on GaAs as substrate that resulted in a lasing wavelength of 1.3 µm. The authors confirmed that the proposed InGaP metamorphic buffer was more efficient in improving the crystal quality than conventional InGaAs buffer realized using PL and TEM (Transmission Electron Microscope) measurements.

P. Moser et al. [49] investigated the behavior of optical properties and gain spectrum of InGaAs/GaAs quantum wells under the effect of the changing orientation of the substrate. The experimental data for the transition energies as obtained by photoluminescence (PL) and selective photoluminescence excitation spectroscopy (PLE) were in good agreement with the theoretical results.

D. P. Sapkota et al. [50] studied the effects of compressive and tensile strain of single quantum well lasers on differential gain, transparency carrier’s density and threshold current density. Aluminum composition was adjusted at 0.07 and 0.09 for compressive and tensile strain respectively. In both compressive and tensile strain quantum well, the minimum threshold current density was achieved at 1.5% strain as 110 Acm$^{-2}$ and 125 Acm$^{-2}$ respectively, with a cavity length of 400 µm.

C. Grasse et al. [51] reported a composition-dependent empirical interpolation formula for the refractive index of AlGaInAs epilayers lattice matched to InP substrate by using a reflection spectroscopy technique. They have also claimed that the resulting expression will be very useful for designing optoelectronic devices like VCSELs.

Shudong Wu et al. [52] investigated the optical gain and radiative injection current density of the InGaNAs/GaAs/AlGaAs separate confinement heterostructure quantum well laser operating at
the lasing wavelength of 1300 nm. The effect of hole filling has the strong impact on the optical gain and the radiative injection current density but the electron filling may be occurred negligible. The effect of hole occupation in the waveguide layer has decreased the optical gain, and increased the radiative injection current densities and the threshold current densities of the laser.

Sayid et al. [53] investigated the temperature dependent threshold current and slope efficiency of the multiple quantum well based InGaAlAs/InP buried heterostructure lasers (BHLs) operating at the lasing wavelength of 1550 nm as a function of radiative-currents, non-radiative-currents, internal differential quantum efficiency and internal optical losses.

T. Czyszkanowski [54] carried out the physical self-consistent comprehensive analysis of the room-temperature characteristics for the InGaAlAs/InP quaternary material system based photonic crystal tunnel junction (PCTJ) vertical cavity surface emitting lasing sources (VCSELSs) performed at the lasing wavelength of 1300 nm.

Wang et al. [55] fabricated the InGaAlAs/InP quaternary semiconducting material system based micro cylinder laser sources (MCLSs) with an output waveguide by using the planar technology (PT) at the room temperature continuous wave operation.

Yong et al. [56, 57] reported the separate confinement heterostructure (SCH) based InGaAlAs/InP multiple quantum well (MQW) lasers operating at the lasing wavelength of 1500 nm. The theoretical calculations have shown a drastic increment on the threshold current and slope efficiency from the step index separate confinement heterostructure (STIN-SCH) to the graded index separate confinement heterostructure (GRIN-SCH).

Z. D. Kaftroudi et al. [58] studied the optical performance of the InGaAlAs /InP MQW based vertical cavity surface emitting laser operating at lasing wavelength of 1305 nm. They have also studied the peak optical gain–carrier density characteristics and optical output power-current characteristics for the linear graded index separate confinement heterostructures based InGaAlAs /InP multiple quantum well laser. The carrier density dependent behavior of material gain with lasing wavelength in the TE mode at 293K, and the temperature dependent behavior of peak material gain in terms of carrier density have also been studied for the multiple quantum wells.
Wang et al. [59] fabricated the InGaAlAs/InP quaternary material system based long rectangle resonator lasers with three sides surrounded by SiO$_2$ with the operation at lasing wavelength of 1550 nm using conventional photolithography and the inductively coupled plasma (ICP) etching method. The continuous wave operation and electrically injected operations have also been realized for the lasing sources with the length of 53-micron and the width of 2-micron at room temperature.

Pyare Lal et al. [60] analyzed the gain spectrum of AlGaAs/GaAs SQW lasing nano heterostructure. Several other important parameters like differential gain, peak material gain as a function of carrier density, anti-guiding factor, and gain compression were also analyzed and simulated. They have been able to achieve maximum optical gain at an approximate lasing wavelength of 830 nm.

A. Keshavarz et al. [61] calculated the optical gain in symmetric double semi-parabolic Al$_x$Ga$_{1-x}$As/GaAs quantum well laser. The authors carried out numerical analysis using Schrodinger equation to get an insight into the energy levels and the wave functions of electrons and holes in proposed double semi-parabolic quantum well. The optical gain spectrum of the proposed structure was thoroughly studied. The effects of material parameters quantum well width, barrier thickness, composition of aluminum, carrier densities, pressure and temperature on the gain spectrum were investigated. The results obtained revealed that optical gain increases by increasing of carrier concentrations, quantum well width and reducing the barrier thickness, temperature and pressure values.

P. A. Alvi et al. [62] proposed and analyzed In$_{0.71}$Ga$_{0.21}$Al$_{0.08}$As/InP SQW lasing nano heterostructure by studying the energy band structure, quasi-Fermi levels in both the conduction and valence bands. In addition to this they have simulated the material gain of the proposed structure as a function of lasing wavelength under the effect of different polarization modes i.e. TE mode and TM mode.

Meha Sharma et al. [63] reported the lasing characteristics of SCH based InGaP/GaAs nanoheterostructure like anti-guiding factor, material gain, mode gain, and carrier induced refractive index change. The theoretical results achieved revealed that maximum gain of 2921.535 /cm was
achieved at a lasing wavelength 0.625 µm and the corresponding photonic energy is 1.98 eV. In addition to it the analysis also showed that the proposed nano heterostructure provided better optical gain in Transverse Electric polarization mode than Transverse Magnetic polarization mode.

Pyare Lal et al. [64] studied the effect of strain on InGaAlAs/InP lasing nano heterostructure. It has been observed that material gain as a function of current density varies slowly under the effect of tensile strain and rapidly under the effect of compressive strain. The value of required transparent current density is more in the case of tensile strain than compressive strain. The proposed structure exhibited maximum optical gain at a wavelength of 1.55 µm and 1.77 µm under compressive and tensile strain, respectively. It was assessed that the proposed structure is of better optoelectronics use under compressive strain.

Pyare Lal et al. [65] proposed a step SCH based Al$_{0.10}$Ga$_{0.90}$As/GaAs nano heterostructure. They have analyzed gain spectrum of proposed structure in terms of material gain and mode gain. Moreover the effect of polarization modes on the gain spectrum has also been taken into consideration.

V. I. Kozlovsky et al. [66] fabricated InGaAs/GaAs MQW structure by employing MBE (Molecular Beam Epitaxy) and high-reflective AlGaAs/GaAs distributed Bragg reflector. The authors have reported an electron beam pumped VCSEL (Vertical External Cavity Surface Emitting Laser) with a pulse peak power of 9 W and emitting at a wavelength of 1035 nm. Maximum laser efficiency of about 15% was obtained at the corresponding electron energy of 22-23 keV. In the Continuous Wave mode, average output power of 23 mW was achieved near the wavelength of 1026 nm.

Pyare Lal et al. [67] studied the gain spectrum of graded index based InGaAlAs/InP lasing nano heterostructures. They have analyzed the behavior of modal gain with respect to current density for single and multiple quantum wells. The proposed structure has been shown to give better gain characteristics in TE mode as compared to TM mode.

Rashmi Yadav et al. [68] investigated the behavior of modal gain spectrum of step SCH based InGaAlAs/InP based nano heterostructure single and multiple quantum wells. It has been
observed that modal gain increases with current density. Also the threshold current density required for lasing action was less in single quantum well based structure than multiple quantum well based structure.

P. A. Alvi et al. [69] reported the gain spectrum of graded index based InGaAlAs/InP nano-heterostructure. The behavior of modal gain, transparent current density, saturated modal gain and optical losses in the structure have also been accounted. Moreover, the effect of temperature and grin steps on the modal gain characteristics of structure has been reported. The effect of different polarization modes on the gain spectrum of structure has also been investigated thoroughly.

Pyare Lal et al. [70] reported gain spectrum of InGaAlAs/InP lasing nano heterostructure. Also several other parameters of interest like anti-guiding factor, carrier induced refractive index change have been reported and studied. Authors have calculated that maximum material gain of proposed structure can be achieved at a lasing wavelength of 1.55 µm at an optimum carrier concentration of \(2 \times 10^{18}/\text{cm}^3\).

Rashmi Yadav et al. [71] analyzed the gain spectra of a SQW step SCH based \(\text{In}_{0.90}\text{Ga}_{0.10}\text{As}_{0.59}\text{P}_{0.41}/\text{InP}\) lasing heterostructure in both TE and TM modes. In addition, the lasing characteristics like anti-guiding factor, refractive index change with carrier density and differential gain, quasi Fermi levels in the conduction and valence bands have also been investigated and reported.

Meha Sharma et al. [72] theoretically investigated lasing characteristics and gain spectrum of \(\text{In}_{0.45}\text{Ga}_{0.55}\text{P}/\text{GaAs}\) nano-heterostructure. Also differential gain, anti-guiding factor being responsible for material gain associated with the structure and refractive index change with respect to carrier density have been reported in context with the structure proposed.

A. R. Adams et al. [73] proposed a new design and demonstrated the operation of a MQW laser structure which can overcome the intrinsic temperature sensitivity of the laser.

Rashmi Yadav et al. [74] investigated the dependence of material gain as a measure of lasing wavelength on the width of quantum well for InGaAsP/InP lasing nano-heterostructure. It has
been observed that gain spectrum of the structure can be monitored by changing the width of the quantum well.

Meha Sharma et al. [75] theoretically investigated the modal gain characteristics of step SCH InGaAs/GaAs lasing nano-heterostructures. The response of modal gain as a function of current density has been reported. Additionally, the effect of increasing the number of wells in the structure, varying the temperature and changing polarization mode on modal gain characteristics has been studied.

Rashmi Yadav et al. [76] carried out temperature dependent study of material gain of step SCH based InGaAsP/InP lasing nano-heterostructure with in TE mode. Material gain for the structure had been simulated for below and above the room temperatures. Different behaviors of the material gain for both ranges of the temperature have been reported in this paper. The results obtained show that only the shift in maximum gain takes place that appears at the lasing wavelength ~ 1.40 µm.

Rashmi Yadav et al. [77] reported the effects of quantum well width on material gain and lasing wavelength of step SCH based InGaAsP/InP lasing nano-heterostructure. The effect of varying quantum well width on the lasing characteristics such as material gain, differential gain, anti-guiding factor and refractive index change with carrier density has been simulated. It has been observed that both the material gain and lasing wavelength can be controlled by changing width of the quantum well sandwiched between the barriers followed by claddings in the nano-structure. The maximum material gain has been achieved at wavelength of 1.35 µm for minimum quantum well width (2 nm) with in TE mode.

Rashmi Yadav et al. [78] investigated the modal gain characteristics of InGaAsP/InP lasing nano-heterostructure. The behavior of optical losses, saturated modal gain and transparent current density has also been simulated and reported. The effect of temperature and number of grin steps on modal gain characteristics has also been studied. It has been concluded that maximum gain is achieved in the near infra red region at wavelengths ~ 1.40 µm and ~1.25 µm in TE mode and TM mode, respectively.
P. A. Alvi [79] analysed strain-induced non-linear optical properties of straddling-type indium gallium aluminum arsenic/indium phosphide nanoscale-heterostructures.

N. V. Dikareva et al. [80] reported experimentally nonlinear harmonic mixing in an InGaAs/InGaP/GaAs laser fabricated on a Ge substrate. They have observed the generation on the second and sum harmonics in the composite cavity laser, thereby confirming the possibility of efficient difference-harmonic generation.

Li Xiang et al. [81] fabricated 0.808 µm GaAs-based laser diodes by utilizing the wet chemical etching technique.

References


30. V. Mosser, S. Contreras, S. Aboulhouda, P. Lorenzini, F. Kobbi, J. L. Robert, K. Zekentes, "Physics of AlGaAs/InGaAs/GaAs heterostructures for high performance


52. Shudong Wu, Yongge Cao, Stanko Tomić, and Fumitaro Ishikawa “The optical gain and radiative current density of GaInNAs/GaAs/AlGaAs separate confinement heterostructure quantum well lasers”, Journal of Applied Physics, 107, 013107 (2010).


62. P. A. Alvi, Pyare Lal, S. Dalela and M. J. Siddiqui “An extensive study on simple and GRIN-SCH-based In_{0.71}Ga_{0.21}Al_{0.08}As/InP lasing heterostructures” Phys. Scr. 85, 035402 (2012).

63. Pyare Lal, Shobhna Dixit, S. Dalela, F. Rahman, P. A. Alvi “Gain simulation of lasing nano-heterostructure Al_{0.10}Ga_{0.90}As/GaAs” Physica E: Low-dimensional Systems and Nanostructures 46, 224 (2012).


71. Rashmi Yadav, Pyare Lal, F. Rahman, S. Dalela, P. A. Alvi, “Investigation of material gain of In_{0.90}Ga_{0.10}As_{0.59}P_{0.41}/InP lasing nano-heterostructure” International Journal of Modern Physics B, Vol. 28, No. 10, 1450068 (2014).


