LITERATURE REVIEW

In the 20th century, the revolution in the area of semiconductors and semiconductors based devices led to great technological and drastic social development of our society. The idea of incorporating heterostructure in the area of electronics as well as in optoelectronics was realized right from the very beginning. Most of the opto-devices such as LED, lasers, photodetectors etc. have been fabricated taking into account the concept of heterostructures. For example; first time the semiconductor LED was discovered by Losev in 1923 and since then the history of semiconductor LED began [1]. However, at that time the material technology in semiconductors aspects was not well developed, and this outstanding discovery became only history. This investigation was stimulated first by the proposal of semiconductor injection lasers by Basov, Krochin, and Popov at the Lebedev Institute (Moscow, Russia) in 1961 [2].

Because of interesting properties of III-V compound semiconducting materials, quantum well based lasing nano-heterostructure take advantage of the lower lasing threshold, better output beam confinement, higher material gain, more effective current-to-light conversion capability and the ability to attain larger color range. The theoretical estimation and experimental finding of the various properties of III–V compound semiconductors were attained separately by N. A. Goryunova in 1951, A. R. Regel in 1952, and N. H. Welker in 1953 at the Physico-technical Institute, Russia. Since then researchers in this interesting area are continuously involved in exploring various III-V material systems for various applications.

However, this chapter has been organized systematically focusing on historical review of the previously published literature related to the semiconductor heterostructures and their applications as follows:

M. B. Panish et al. [3] have seen the effects of separate optical and carrier confinement of GaAs-Al$_x$Ga$_{1-x}$As heterostructure on reduction in room temperature threshold current density. They have observed heterostructure laser with separate carrier and optical confinement can achieve as low as below 1000 A/cm$^2$ threshold current density at room temperature.
M. J. Adams et al. [4] have proposed a new approach to heterojunction theory. They have reviewed the Anderson theory of heterojunctions and then proposed alternate model and finally discussed the arguments for and against.

M. S. Wu et al. [5] have explored 1-D simulation of steady state quantum well laser diodes. They have simulated GRIN-SCH and SCH laser and found that the carriers are well confined in GRIN-SCH laser. Therefore, less recombination current density present outside the quantum well region in GRIN-SCH than in SCH. The optical confinement factor depends strongly on the waveguide structures. For a particular set of layer thickness, optical confinement is better confined in GRIN-SCH than in SCH.

T. Namegaya et al. [6] have explored the impact of quantum well number in GaInAsP/InP based GRIN-SCH strained layer quantum well lasers in the emission range of 1.3 µm. As a result, they found that the optimum well number that gives the minimum threshold current increases with operating temperature and it is limited to the degradation of crystal quality of the quantum wells because of the critical thickness.

O. Issanchou et al. [7] have theoretically compared the performance of GaInAs/GaAlInAs and GaInAs/GaInAsP based quantum well lasers. They have observed that GaInAs/GaAlInAs quantum well laser exhibits lower threshold current and higher differential gain than that of GaInAs/GaInAsP based quantum well laser.

J. R. Meyer et al. [8] have discussed the optical properties of type-II multiple quantum wells InAs/Ga\textsubscript{1-x}In\textsubscript{x}Sb/InAs/Ga\textsubscript{1-x}Al\textsubscript{x}Sb based laser structure with AlSb cladding layer. They have calculated gain at 300 K, where two different current densities are shown for both the SL and QW structures. For a given current density, QW structure achieves higher maximum gain than that of SL structure.

Toshihiko Makino [9] has presented analytical approach for computing optical gain of quantum well structures. He has interpreted that proposed analytical formulas not only provide an effective way of calculating gain but also another way of obtaining physical insights for the overall interplay of quantum well parameters.
Sandra R. Selmic et al. [10] have designed AlGaInAs-InP based multiple quantum well laser operating at 1.3 µm wavelength having application in communication systems. They have observed 12.5 mA threshold current at 25 °C with the slope efficiency of 0.43 W/A and will operate at temperature excess of 100 °C.

Sebastian Mogg et al. [11] have investigated the impact of varying barrier heights on the performance of InGaAsP/InP laser diodes at high-temperature. They have seen that improved performance achieved by reducing barrier height in the active region in terms of slope efficiency and threshold current.

I. Vurgaftman et al. [12] have presented a comprehensive critical review of band parameters for compound III-V wurtzite and zinc blende semiconductors such as GaP, AlP, InP, GaSb, AlSb, InSb, GaAs, AlAs, InAs, GaN, InN and AlN, together with their quaternary and ternary alloys. In order to calculate energy band structure, they have tabulated various related parameters and also studied alloy and temperature dependencies.

Yong et al. [13] have presented the theoretical study of the gain for three different active layer materials InGaAsP, AlGaInAs and InGaAsN as quantum wells. They have observed that AlGaInAs and InGaAsN active layer materials exhibits better gain performance than the frequently used InGaAsP at room temperature as well as at higher temperature.

S. Tomic et al. [14] have compared the optical gain properties of InGaAsN/GaAs and nitrogen free InGaAs/GaAs quantum well structures using realistic Hamiltonian. They have detected that differential gain and peak gain get reduced at a particular carrier concentration in dilute nitride quantum well structure as compared to nitrogen free structure.

K. I. Kolokolov et al. [15] have shown the effect of doping levels in the barrier region on band alignment of commonly known InAs/AlSb QW heterostructure. They have observed type-II to type-I transition of the band alignment and also studied interband gain of the considered quantum well structure as a function of doping concentration in barrier region within TE and TM polarization modes operating in MIR wavelength range.

D. C. Larrabee et al. [16] have carried out a systematic analysis of temperature dependency of inter-subband absorption in undoped InAs/AlSb quantum wells. They have observed a strong
red-shift of lasing wavelength with increase in temperature and found suitable application in FIR emitting range.

I. Vurgaftman et al. [17] have simulated and proposed dilute nitride based type-II ‘W’ QW InAsN/GaAsSb/InAsN lasers on InP substrate operating in MIR (3-6 µm) range. They have designed optical gains of two dilute-N ‘W’ structures and compared results with a typical antimony based ‘W’ structure InAs/GaInSb/InAs/AlSb to emit at the same operating wavelength.

Sang-Wan Ryu et al. [18] have studied the optical characteristics of a GaAsSb/InGaAs type-II (staggered) QW heterostructure grown on GaAs substrate. They have observed strong room temperature photoluminescence at 1.3 µm wavelength by doing optimization of transition wavelength and efficiency of the QW structure.

K. I. Kolokolov et al. [19] have demonstrated the transformation of an inactive interband material system InAs/AlSb into a highly efficient interband gain structure by providing proper uniform modulation doping of AlSb layers. They have realized doping induced type-II to type-I quantum well transformation of the band alignment and obtained optical gain of 4000 cm⁻¹ within TM polarization mode. And also seen the influence of doping on differential gain.

P. Adamiec et al. [20] have shown the dependence of hydrostatic pressure on lasing wavelength of type-I InGaAsSb/AlGaAsSb laser diode. They have observed emission wavelength shifting from 2.4 µm to 1.7 µm when the hydrostatic pressure increased from 0 to 19 Kbar.

Seoung-Hwan Park [21] has investigated the effects of barrier thickness on optical and electronic properties of type-II GaAsSb/GaAs/AlGaAs quantum well lasers using self-consistent method. He has found that peak gain decreases very fast with the increase in barrier thickness and starts to saturate when barrier thickness limit exceeds 100 Å. Hence careful consideration of barrier layer thickness is very much required for the design of quantum well based semiconductor laser.

J. -Y. Yeha et al. [22] have developed InGaAsN/GaAsSb type-II “W” shaped quantum well structure for long wavelength emission. They have performed design optimization of growth condition and high Sb content to achieve extended lasing wavelength. They have utilized tensile
strained GaAsP barriers to improve the luminescence properties of active region which is compressively strained and found suitable for the emission wavelength beyond 1500 nm.

**M. Debbichi et al. [23]** have proposed a new strain compensated InAsN/GaSb staggered “W” shaped QW laser structure for room temperature emission at 3.3 µm wavelength. They have obtained optical gain in the order of 1000 cm⁻¹ at injected carrier concentration of 1×10¹² cm⁻² at 300 K.

**W. Trzeciakowski et al. [24]** have well studied the temperature and pressure dependence on energy bandgap of III-V compound semiconductor and hence shifting in optical gain spectra of semiconductor laser. They have found physical limitation in pressure tuning in shorter emission wavelength i.e. in between 600 nm and 800 nm, however temperature tuning found more practical in this wavelength range.

**Wen Lei et al. [25]** have presented an overall review of the latest advancements in III-V semiconductor photodetectors and lasers working in 2-3 µm wavelength window. They have suggested antimonide based type-I QW lasers found promising for shorter MIR wavelength range (2-2.6 µm) and for longer MIR wavelength range (2.6-3 µm) antimonide based Type-II QW lasers found suitable. Also, for type-I QW infrared photodetector operating in 2-3 µm wavelength range, they have found GaN based QWs exhibit great ability. Moreover, for type-II QWIPs operating in 2-3 µm wavelength range, InAs/GaSb material system found most suitable.

**M. Debbichi et al. [26]** have numerically evaluated optical characteristics and electronic band structure of dilute-nitride InAsN/GaSb/InAsN type-II ‘W’ shaped QW based laser on InAs substrate. By doing extensive analysis using 10-bands k.p model, they have found the structure suitably operating in mid infrared region at room temperature.

**S. Ridene et al. [27]** have presented a theoretical investigation of dilute N InAsN/GaSb/InAsN and N-free InAs/GaSb/InAs laser structures in terms of energy band structure and optical gain by utilizing k.p model. They have observed improvement in optical gain performance by incorporating few percent of nitrogen in the active laser region to lase at 3.3 µm wavelength for room temperature operation.
N. Y. Minina et al. [28] have well studied EL spectra of $p$-Al$_{\text{x}}$Ga$_{1-\text{x}}$As/GaAs$_{1-\text{y}}$P$_{\text{y}}$/n-Al$_{\text{x}}$Ga$_{1-\text{x}}$As heterostructures under uniaxial compression of 400 MPa along [110] crystallographic directions at liquid nitrogen temperature. They have proposed the possibility of wavelength tuning of laser diodes by applying uniaxial compression.

B. Dong et al. [29] have evaluated energy band structure and optical gain spectra of compressively strained GaAsSbN/GaAs quantum well using 10-band k.p method for 1.3 µm lasing. They have realized that for longer emission wavelength, a thicker well width and a higher N and Sb content in the quantum well layer is very much required.

I. V. Berman et al. [30] have thoroughly studied the effect of uniaxial stress on the electroluminescence spectra in $p$- AlGaAs/GaAsP/n-AlGaAs double heterostructure. They have seen enhancement in the electroluminescence intensity under compression and also, with increasing stress, the emission spectra demonstrate a blue shift of up to 25 meV at a pressure of 4 Kbar.

J. Y. T. Huang et al. [31] have investigated strained type-II ‘W’ quantum wells InGaAs/GaAsSb on InP substrate operating in mid-IR emission. They have designed the structure having potential of emission in the range of 2-4 µm. Also, by incorporating AlAsSb as a barrier layer, the electron confinement got substantially enhanced.

R. A. Abdullah et al. [32] have numerically studied the performance of InGaN MQW based violet laser diode with quaternary AlInGaN blocking layer and compared it with the ternary AlGaN blocking layer. They have analyzed that laser with quaternary blocking layer have superior optical and electrical properties than that of ternary blocking layer in terms of power, threshold current, optical intensity and operating temperature.

M. V. Klymenko et al. [33] have theoretically analyzed the effects of bulk and digital alloyed barriers on the optical and transport properties of In$_{0.49}$Ga$_{0.51}$P/In$_{0.49}$(Ga$_{0.6}$Al$_{0.4}$)$_{0.51}$P single quantum well structure. They have seen that transport properties of the structure get effected very drastically as compare to optical properties. Careful designing of digital alloy barrier is very much needed because it has strong influence on the capture and escape times while gain and absorption spectra are nearly insensible.
P. A. Alvi et al. [34] have seen the effects of Aluminium composition in GaN/AlGaN based multilayer nano-heterostructure. The electron density is found to decrease with the increment in Al concentration in the active region while the hole density gets decreased. The bandgap energy gets reduced by the increment in Al concentration significantly as a result of less overlapping in equivalent energy wave functions.

S. H. Park et al. [35] have compared the optical gain properties of type-II InGaN/GaNSb quantum well structure with that of the conventional type-I InGaN/GaN QW structure. They have found that longer wavelength quantum well structures with a relatively lesser Indium content can be simply achieved by controlling the composition of GaNSb, compared to the standard type-I InGaN/GaN quantum well structures. And also, the optical gain and the differential gain of type-II QW structure found to be very large as compare to conventional type-I QW structure at same carrier concentrations.

C. H. Pan et al. [36] have evaluated emission characteristics of “W” shaped type-II InGaAs/GaAsSb/InAlGaAs/InAlAs QWs on InP substrate. Emission wavelength in the range of 2-3 μm within IR region have been achieved at room temperature by incorporating ‘W’ quantum well structure of InGaAs/GaAsSb material system.

S. Ben Rejeb et al. [37] have demonstrated the applicability of the k.p method to model the InAs/GaSb/InSb short pulse super-lattice and the utility of the junction design as a tool in band gap engineering to describe MWIR short pulse super-lattice structures.

E. V. Bogdanov et al. [38] have analyzed that with increasing pressure, the electroluminescence spectra of $n$-Al$_x$Ga$_{1-x}$As/GaAs$_y$P$_{1-y}$/$p$-Al$_x$Ga$_{1-x}$As hetero-structures based diode shift to little shorter wavelengths under uniaxial compression along the [110] and [110] crystallographic orientations and exhibit 2-3 times increase in the intensity.

L. V. Asryan et al. [39] have discussed band-edge engineering of quantum well laser. They have considered two asymmetric barrier layers (on both the side of QW) and found prevention of bipolar population in the optical confinement layer and thus, suppression in electron-hole recombination. Because of this, the threshold current density of a band-edged QW laser gets considerably reduced and characteristic temperature $T_o$ get enhanced as compare to conventional quantum well lasers.
Gregory Belenky et al. [40] have analyzed the role of carrier confinement in obtaining room temperature CW high power operation of GaSb based type-I QW laser working above 3 µm. They have made use of compressive strain and quaternary barrier materials resulting in improvement of hole confinement in active QWs to improve overall laser performance.

E. V. Bogdanov et al. [41] have calculated light hole and heavy hole energy states under uniaxial compression along [110] crystallographic orientation of $p$-Al$_x$Ga$_{1-x}$As/GaAs$_{1-y}$P$_y$/n-Al$_x$Ga$_{1-x}$As at $y=0.16$ and found blue shifts of lasing wavelength along with 2-3 times increase in the electroluminescence intensity.

Stephan Sprengel et al. [42] have demonstrated light emission properties of type-II QW InGaAs/GaAsSb based laser on InP substrate at room temperature lasing up to 3 µm. They have compared standard superlattice and so called “W” shaped quantum well structure and found drastic reduction in emission line-width necessary for low threshold operation by utilizing “W” shaped quantum well as compare to standard superlattice.

E. V. Bogdanov et al. [43] have numerically calculated the energy band structure, size quantized levels, energy wave functions, matrix elements of the electron–photon interaction operator, and optical gain under uniaxial compression indicates that the nonlinear growth of the optical gap is decided by the character of the motion of the size quantized levels in the quantum well of the valence band and the gain in the intensity is obtained by the strong mixing of the states of heavy and light holes in a broad range of pressures.

P. Lal et al. [44] have thoroughly evaluated the optical response of AlGaAs/GaAs based lasing nano-heterostructure. They have calculated photon energy as well as wavelength dependent optical gain and modal gain. Therefore, found a useful application in near infra-red regime.

P. A. Alvi et al. [45] have evaluated simple and GRIN separate confinement InGaAlAs/InP based nano-heterostructures. The maximum optical gain for the considered nano-heterostructures have been obtained at wavelength of 1.55 µm and 1.38 µm respectively for simple and GRINSCH structures in TE mode. However, for the case TM polarization mode, lasing wavelength at peak optical gain are found to be 1.34 µm for both the structures.
E. V. Bogdanov et al. [46] have shown that the optical properties and the energy spectrum of low-dimensional semiconductor devices like the experimentally examined $p$-Al$_x$Ga$_{1-x}$As/GaAs$_{1-y}$P$_y/n$-Al$_x$Ga$_{1-x}$As laser diode are very much sensitive to even small uniaxial stress. They have reported a reasonable tuning of the electroluminescence photon energy up to 27 meV and, also seen the chance of a noticeable modification in the intensity relation between TM and TE modes by doing numerical calculations.

A. J. Ghazai et al. [47] have investigated the quantum well number effect and as well as built-in polarization effect on quaternary AlInGaN MQW laser performance operating in UV range. They have seen that optimized number of quantum wells for low threshold current, high slope efficiency and output power is 4. For the same number of quantum wells, optical gain and intensity were found to be maximum. Electron blocking layer was employed to improve the laser performance by enhancing the optical confinement factor in the wells.

B. Chen et al. [48] have proposed the model of various type-II InGaAs/GaAsSb QW designs for MIR laser diodes using six band k.p method. They have seen the effects of different quantum well parameters such as material composition and thickness and also different cladding layers on gain performance. Also, observed that for the injected carrier concentration of $5\times10^{12}$ /cm$^2$, highest optical gain in the order of 1000 /cm achieved at the 2.6-2.7 µm wavelength infrared range at room temperature.

Stephan Sprengel et al. [49] have realized a novel InP based GaInAs/GaAsSb type-II W-shaped active region with AlAsSb electron and AlGaInAs hole blocking layers laser operating in pulse mode up to 42 °C. They have expected further design improvements for extension in operating wavelength up to 3 µm.

Robert P. Sarzala et al. [50] have made an attempt to design InP-based GaInNAs laser for long wavelength (> 2 µm) operation having application in distant air monitoring, laser spectroscopy, medical diagnostics, thermo-vision measurements, and wireless optical communication by using comprehensive computer simulation. They have observed that for compressively strained InP-based Ga$_{0.12}$In$_{0.88}$N$_{0.02}$As$_{0.98}$/Ga$_{0.275}$In$_{0.725}$As$_{0.6}$P$_{0.4}$ quantum Well structure with 10 nm QW thickness and at the carrier density of $5\times10^{18}$ cm$^{-3}$, the maximal optical gain of about 2150 cm$^{-1}$ was achieved at 2815 nm wavelength for room temperature operation.
G. Alahyarizadeh et al. [51] have compared the performance of green InGaN single quantum well laser diodes with quaternary (AlInGaN) and ternary (AlGaN) electron blocking layer (EBL). They have analyzed that laser with quaternary (AlInGaN) electron blocking layer were exhibiting lower threshold current, higher output power and differential quantum efficiency as compared to laser with conventional ternary (AlGaN) electron blocking layer.

N. Y. Minina et al. [52] have seen the effects of external uniaxial compression on valence subbands energy spectrum and electroluminescence intensity in strained $p$-$Al_{x}Ga_{1-x}As/GaAs_{1-y}P_{y}/n$-$Al_{x}Ga_{1-x}As$ (y=1.6) quantum well lasing structure along [110] direction. They have minutely observed nonlinear behavior of photon energy shift and increase in electroluminescence intensity because of strong LH1-HH1 mixing carried out at the pressure of about 4 Kbar.

R. A. Abdullah et al. [53] have revealed the quantum confined stark effect and well thickness effect on the optical characteristics of double quantum well based violet InGaN laser diodes. They have detected that compensation of insufficient overlapping of electrons and holes inside the QW has been carried out by optimizing the QW thickness. In the range of 2.5 nm and 3 nm quantum well thicknesses the best optical properties of the laser diode have seen and also, minimum blue shift of wavelength has been found by reducing QCSE.

B. Chen et al. [54] have theoretically studied the optical properties of InP based InGaAs(N)/GaAsSb type-II quantum well laser having “W” structure. They have observed a shift of peak gain to longer wavelengths by incorporating more nitrogen content in the InGaAsN layer and hence emission wavelength of 2 to 4 µm can be achieved by increasing the nitrogen content from 0 % to 3 % and therefore suited for MIR region laser applications.

C. H. Pan et al. [55] have theoretically explored InGaAs/GaAsSb/InAlAs type-II quantum well laser for MIR range utilizing 8 band k.p method. They have optimized that the structures with thinner InGaAs and GaAsSb layers and also, with higher antimonide content in proper compressively strained GaAsSb to get material gain of 1000 cm$^{-1}$ at carrier concentration of $3 \times 10^{12}/cm^2$.

Gerhard Boehm et al. [56] have proposed different approaches for the design of active regions for InP and GaSb based devices to emit light in the range from 2 to 4 µm for gas sensing applications. They have observed that InP based type-I rectangular and triangular shaped QWs
found suitable for emission up to 2.3 µm, beyond this range up to 4 µm GaSb based type-I active regions found promising.

**Stephan Sprengel et al. [57]** have demonstrated InP based type-II QW LEDs having spontaneous emission even up to 3.3 µm with electrically pumped resonant cavity LED and up to 3.9 µm with optically pumped structures and while electrically pumped InP based type-II devices with GaInAs/GaAsSb active regions laser lased at 2.6 µm in pulse mode.

**E. L. Albuquerque et al. [58]** have evaluated optical properties of unstrained graded GaAs/Al$_x$Ga$_{1-x}$As single quantum well laser. They have analyzed that peak optical gain found sensitive to the quantum well width and graded profile of the junctions.

**Tawsif Ibne Alam et al. [59]** have studied the impact of variation of quantum well number on the device performance of GaInP based multiple quantum well SCH laser operating at 635 nm. They have optimized 3 QW number in the active region for better device performance in terms of threshold current, output power, resonance frequency and modulation bandwidth.

**A. Ben Ahmed et al. [60]** have theoretically investigated optical properties for various growth directions [h h l] of dilute-nitride InAs$_{1-x}$N$_x$/GaSb with a ‘W’ and ‘M’ QW laser structure. They have observed that for the type-II ‘W’ structure, peak optical gain of 770 cm$^{-1}$ achieved for [111] direction at a typical injected carrier density of N$_{2D} = 1.5 \times 10^{12}$ cm$^{-2}$. However, this value is only 550 cm$^{-1}$ for the [001] direction. Similarly, for ‘M’ structure, gain values increase about 1.26% and 1.4%, respectively at nitrogen content, $x=0.02$.

**Pyare Lal et al. [61]** have seen the influence of carrier density on material and mode gain characteristics of InGaAlAs/InP based SQW lasing nano-heterostructure. They have suggested that maximum material gain exists at the wavelength of 1.55 µm for the carrier density of 2.0×10$^{18}$/cm$^3$.

**P. Lal et al. [62]** have investigated optical characteristics of InGaAlAs/InP nano-heterostructure for various quantum well width under TE polarization mode. They have suggested 6nm quantum well width more suitable for lasing action at the wavelength of 1.55 µm because of minimum optical loss within the waveguide.
Lukasz Piskorski et al. [63] have minutely investigated the material parameters of amorphous and antimonide materials for modeling the semiconductor laser working in MIR range. By doing analysis on experimental data of several dozen related publications they have observed that inclusion of material compositions, temperature, carrier density and wavelength dependencies are very much needed in thermal, electrical and optical models.

Chia-Hao Chang et al. [64] have experimentally demonstrated optically pumped GaAs$_{0.3}$Sb$_{0.7}$/In$_{0.53}$Ga$_{0.47}$As/GaAs$_{0.3}$Sb$_{0.7}$ “M” type-II QW laser operating at 2.41 µm wavelength at room temperature. They have observed that the threshold power density per quantum well was 234 W/cm$^2$ and the extracted internal loss was 20.5 cm$^{-1}$.

Rashmi Yadav et al. [65] have theoretically analyzed the impact of quantum well thickness on lasing wavelength and optical gain of InGaAsP/InP nano-heterostructure. They have observed maximum optical gain of ~ 8000 /cm can be obtained at wavelength of 1.35 µm for the case of 2 nm quantum well thickness at room temperature.

Vibha Kumari et al. [66] have demonstrated the effects of different barriers, claddings and substrates on lasing wavelength and optical gain spectra of InGaAlAs Quantum well of 6nm thickness under TE and TM polarization modes.

H. K. Nirmal et al. [67] have done optimization of high optical gain in M-shaped type-II InGaAs/GaAsSb symmetric lasing nano-heterostructure by utilizing the six band k.p method. They have obtained the optimized optical gain of ~9000 /cm at ~1.95 µm wavelength within TE polarization mode at 5×10$^{12}$ /cm$^2$ injected carrier density. Thus, it was found suitable for the application in SWIR wavelength region.

S. Jha et al. [68] have analyzed a theoretical insight into the different characteristics of a strained Al$_{0.15}$In$_{0.22}$Ga$_{0.63}$As/GaAs graded index separate confinement lasing nano-heterostructure under two polarization modes and observed maximum optical gain of 5557.18 /cm at lasing wavelength of ~ 0.90 µm in TE mode while in TM mode, maximum optical gain of 2760.70 /cm at lasing wavelength of 0.78 µm.

G. Alahyarizadeh et al. [69] have extensively examined the performance characteristics of InGaN MQW lasers operating in the deep violet regime for various quantum well thicknesses.
and numbers. They have seen that the lowest threshold currents for InGaN laser diode operating at 390nm and 409 nm achieves at when the number of quantum wells is two and best performance occurs at 2.5 nm quantum well thickness.

R. Yadav et al. [70] have simulated the modal gain characteristics as well as optical losses in GRIN separate confinement based InGaAsP/InP nano-heterostructure for different number of quantum wells in the active region. The maximum gain was observed at wavelengths of ~1.40 µm and ~1.25µm respectively in TE and TM polarization modes. Hence, aforementioned nano-heterostructures are found very useful as a light source of wavelengths in near infrared region.

Chia-Hao Chang et al. [71] have evaluated InP substrate based InGaAs/GaAsSb “W” QWs semiconductor laser. They have reported a low threshold current density at infinite cavity length of 83 A/cm² per QW for the semiconductor laser under study operating at 2.35 µm wavelength (SWIR).

C. Berger et al. [72] have designed and experimentally analyzed a staggered type “W” shaped MQW heterostructure for the emission in the range of 1.2 µm. They have obtained peak gain of 500 /cm at a carrier concentration of 3×10¹² /cm² and found the values in the same order of magnitude as that of the typical type-I structure for laser applications.

P. A. Alvi et al. [73] have presented the impact of different states of strain on lasing wavelength and optical gain of InGaAlAs/InP nano-scale heterostructure. They have compared the optical gain characteristics for InGaAlAs/InP based lasing nano-heterostructure under compressive and tensile strain with unstrained structure. Therefore, found the compressive and un-strained heterostructure suitable for 1.33 µm and 1.55 µm wavelengths in the optical fiber based communication system.

K. I. Kolkolov et al. [74] have experimentally performed as well as numerically calculated polarization mode switching and tuning in p-AlGaAs/GaAsP/n-AlGaAs heterostructures under uniaxial stress. They have observed that with 14nm quantum well width and phosphor fraction of 0.16, the ratio of optical gain g_{TM} / g_{TE} in TM and TE modes at zero compression is equal to 8. However, under compression of 5.1 Kbar, g_{TM}/g_{TE} ratio drops to 1.6 which has good agreement with the experimental result by about 5% variance.
E. V. Bogdanov et al. [75] have shown how TE and TM polarization modes tuning and switching is possible in GaAsP QWs based lasing structure under external uniaxial stress. They have found that this tensile strained heterostructure with low phosphorus content and narrow QW widths compressed in-plane along [110] and [100] direction is best suited for TM to TE switching.

G. Alahyarizadeh et al. [76] have explored the effects of thickness and material composition in barrier layers and well layers on output emission wavelength and deep violet InGaN/GaN double quantum well laser diode performance. They have seen that by increasing thickness of the barrier increases strain and piezoelectric field in wells and this result causes threshold current to increase and slope efficiency, output power and differential quantum efficiency to decrease.

H. K. Nirmal et al. [77] have reported the optical gain tunability in M-shaped type-II In$_{0.70}$Ga$_{0.30}$As/GaAs$_{0.40}$Sb$_{0.60}$ lasing nano-heterostructure under the high pressure using six band k.p method. They have observed that for the carrier density of $5\times10^{12}$/cm$^2$, the optimized value of optical gain is found to be $\sim$9000/cm at 1.95 $\mu$m wavelength within TE polarization mode for SWIR wavelength region operation. Externally applied pressure of 2, 5 and 8 GPa on the structure under study along [110] orientation demonstrates increment in optical gain and lasing wavelength to the higher values within SWIR region.

Lukasz Piskorski et al. [78] have thoroughly reported the impact of quantum well material compositions and strain on maximal gain of the heterostructure for MIR wavelength window operation. They have studied the arsenide based (GaInNAs/AlGaInAs) and antimonide based (GaInAsSb/AlGaAsSb) active regions for MIR wavelength window emission.

R. Ben Dhafer et al. [79] have explored the optical properties of the active laser region by considering quantum well (2D) and bulk (3D) semiconductors in terms of optical gain behavior. They have evaluated some bulk materials like InAs, GaSb, GaAs and quantum well (2D) of InAsN/GaSb as an active region in the laser structure at room temperature. They have observed optical gain sensitive to QW thickness and temperature. Finally, they have found best optical performance in the case of QW active region.

Igor P. Marko et al. [80] have presented experimental analysis of optical gain, absorption and spontaneous emission spectra of GaAsBi/GaAs quantum well laser structure for the near IR
device application. In support of their experimental analysis, they have also presented theoretical analysis using 12-band k.p Hamiltonian model for GaAsBi alloys and found excellent agreement with the experimental data.

**P. A. Alvi et al. [81]** have studied the transformation from type-II to type-I nano-heterostructure by introducing proper doping in a particular region. They have seen that by doing proper doping, optically inactive type-II InAs/AlSb nano-heterostructure transforms to very efficient optically active type-I nano-heterostructure useful in mid infrared wavelength region.

**B. Chen [82]** has theoretically explored the optical and electronic properties of InP based dilute bismide InGaAs/GaAsSbBi type-II quantum well structures. He has analyzed the proposed structure using 14-band k.p model. He has seen a shift of peak gain to longer wavelengths by incorporating more bismuth content in GaAsSb QW layer and therefore, emission wavelengths of up to 3.26 µm achieved with 5 % Bi content in GaAsSb QW layer and hence found suitable for MIR region laser applications.

**V. K. Singh [83]** has discussed the optical gain characteristics of Type-I InGaN/GaN and Type-II InGaAs/GaAsSb heterostructure within two polarization modes TE and TM using six band k.p method. Therefore suggested Type-I heterostructure has higher optical gain than that of Type-II heterostructure.

**Indranil Mal et al. [84]** have investigated energy band structure and gain characteristics of GaSbBi/GaAs type-II QWs by utilizing 14-band k.p technique. They have shown the dependence of optical gain on quantum well width and found shifting of lasing wavelengths corresponding to the peak of the gain spectra with the decrease in the quantum well width.

**Amira Ben Ahmed et al. [85]** have well studied the hydrostatic pressure dependence on gain spectra and energy band structure of Type-II InAsN/GaSb Strained QW laser. They have been confirmed that by the application of hydrostatic pressure in the range of 0-30 Kbar, electronic band structure got changed which results decrease in optical gain with the pressure by about 50% and 80% for [001] and [111] growth orientations, respectively for TE polarization mode.

**Evgeny V. Bogdanov et al. [86]** have numerically investigated TE and TM polarization modes optical gains in \( p-Al_xGa_{1-x}As/GaAs_{1-y}P_{y}/n-Al_xGa_{1-x}As \) (y=1.6) laser structure under uniaxial
compression of about 10 kbar along normal and in-plane heterostructure directions at the temperature range 77-300 K. They have realized almost no change in $g_{TM}/g_{TE}$ gain ratio with the increase in temperature however found several times decrease in gain ratio under in-plane compression and certainly no change under compression normal to the heterostructure directions.

Christopher A. Broderick et al. [87] have theoretically and experimentally demonstrated the ability of GaAs$_{1-x}$Bi$_x$/GaN$_y$As$_{1-y}$ type-II quantum wells on GaAs substrate. They have shown that this approach exhibits optical emission and absorption up to ~3 µm wavelength range at room temperature by utilizing strain balance heterostructure. They have also try to show that this structure has the ability to extend the emission wavelength further into NIR and MIR via pseudomorphic growth on conventional GaAs substrate for various communication and sensing applications.

Nisha Yadav et al. [88] have done theoretical study on a system of two quantum wells having W-shaped heterostructure based on type-II band alignment. This heterostructure was based on InGaAs/InAs/GaAsSb material system. In their study, they have optimized high optical gain of the order of ~4500 cm$^{-1}$ in the mid-infrared wavelength (~3.2 µm) region.

Singh et al. [89] have simulated type-I band alignment based heterostructure consisting of AlGaAs/GaAsP material system. For the heterostructure, they have calculated wavefunctions associated with the conduction and valence band of the heterostructure and optimized optical gain with the help of k.p theory.

G. Bhardwaj et al. [90] have studied uniaxial strain induced optical properties of complex type-II InGaAs/InAs/GaAsSb nano-scale heterostructure. They have optimized optical gain and optical transition wavelengths under the effect of uniaxial strain applied along [001], [100], and [110].
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