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## Structural and Optical Characteristics of Nanoscale Semiconductor Lasers for Telecommunication and Biomedical Applications: A Review

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# Structural and Optical Characteristics of Nanoscale Semiconductor Lasers for Telecommunication and Biomedical Applications: A Review

Jayprakash Vijay<sup>1,2</sup>, Kulwant Singh<sup>1</sup>, Dimple Soni<sup>2</sup>, Amit Rathi<sup>1</sup>

<sup>1</sup>Department of Electronics and Communication Engineering, Manipal University Jaipur

<sup>2</sup>Department of Electronics and Communication Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur

E-Mail: [jpvijay121@gmail.com](mailto:jpvijay121@gmail.com)

[amit.rathi@jaipur.manipal.edu](mailto:amit.rathi@jaipur.manipal.edu)

**Abstract.** This paper presents the structural and optical characteristics of nanoscale semiconductor lasers for telecommunication and biomedical applications. Improved fabrication techniques, new materials and nano-scale heterostructures have led to improvement in the device performance. The material selection and their bandgap have an important role in the heterostructure to generate a lasing wavelength for particular applications. The bandgap modification can be done by the use of alloy semiconductor, quantum well structure, and strain layer epitaxy without changing the material itself. Semiconductor multilayers on the substrate are generally grown by using the metal-organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) process. Many researchers have provided different designs of heterostructures for the lasers. Generally, lasers are manufactured by using different semiconductor layers grown on GaAs, InP or GaSb substrate at the nanoscale. But controlling the thickness of the layer grown on the substrate at the nanoscale is the major problem in the fabrication. In a study, it has been found that for the proper functioning of semiconductor lasers it is beneficial to have light conduction and valence band masses. By using band structure engineering theory of quantum confinement and incorporation of strain on the active layer, this problem can be resolved. Red lasers are currently used in biomedical applications for treatment of superficial skin diseases like psoriasis, vitiligo etc. The manufacturing of red laser was earlier done by using nitrides material but they are harmful to skin and are expensive as well. An alternative for designing of red laser is manufacturing red lasers by using phosphides. The red laser is manufactured by using GaInP and AlGaInP ternary and quaternary compounds are widely used in the biomedical industry currently. This paper is the outcomes of the papers presented by many researchers in the field of optoelectronics.

**Keywords:** Double heterostructure, Laser, Quantum well, Optoelectronics.

## 1. Introduction

Nowadays in the world of science optoelectronic devices like LASER diodes, photodetectors, optical waveguides, directional couplers, and LED's are playing the major role in communication industries [1, 2]. The optoelectronics deals with the systems that detect and control the light and it is considered as a sub-field of photonics. Optoelectronic devices can be designed to be used for the shortwave infrared region, mid-wave infrared regions and near-infrared regions. The regions are selected on the basis of the wavelength at which the device is operating for an application [3]. Currently, for the treatment of tumor, cancer and superficial skin diseases, researchers are more concerned about the use of laser in telecommunication and biomedical applications in photo-dynamic therapy (PDT). A laser is a light



source which also provides the optical amplification based on the principle of stimulated emission of electromagnetic waves. Lasers are classified on the basis of material used in active medium and broadly it is classified as gas lasers, solid lasers, liquid lasers and semiconductor lasers [4, 5]. Today one of the most important laser in optical communication is semiconductor laser [6, 7]. These lasers use semiconductors as the lasing medium and are characterized by specific advantages such as the capability of direct modulation in the gigahertz region, small size and low cost [8]. Lasers can be designed by using semiconductor heterostructures also. In several applications of semiconductors emission and absorption of light which is done in the energy bandgap by electron-hole pair combination and hence generating some photoconduction which gives importance to modification of bandgap. The modification of energy bandgap can be done by using ternary and quaternary semiconductor compounds. The laser using the heterojunction was first proposed by the Herbert Kroemer, in 1963 [9]. He suggested that the population inversion can be enhanced with the use of heterostructure. Interface of two layer having different crystalline semiconductors is the main concept of a heterojunction. These semiconductor materials have unequal bandgaps unlike to homojunction. The semiconductor materials for the heterostructures are selected on the basis of wavelength and for which application it can be used [10]. The heterostructure has various solid state devices and having different applications with solar cells, semiconductor LASER, and transistors. Depending on the band alignment between the layers of heterostructure they can be categorized as, Type-I-II-III heterostructure [11]. These are widely used to design optoelectronic devices and structures (Photodetectors, Laser diodes, Quantum well and superlattice optical and optoelectronic devices), optical components (Mirrors, Waveguides) and advanced electronic devices (Resonant tunneling devices, modulation doped FET). Figure 1 shows the band alignment for these heterostructures.

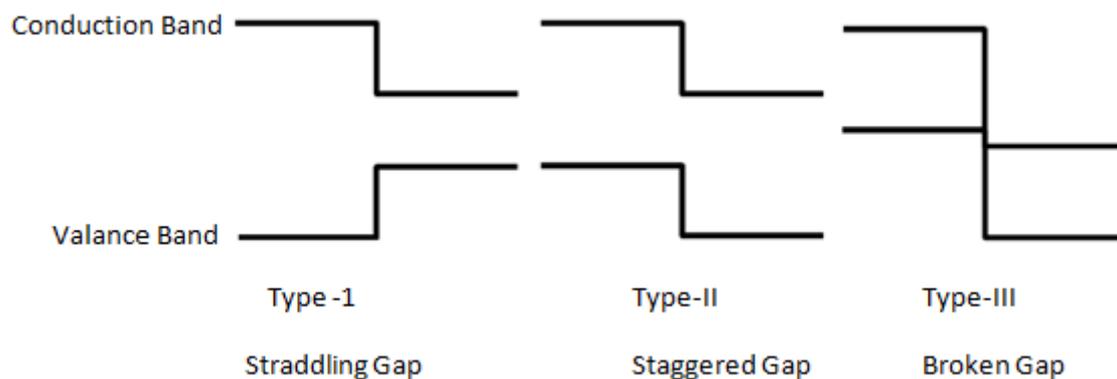


Figure 1 Band alignment types of heterostructure

A LASER is used in the field of medicine also. There are several techniques based on optical radiation which can be used for the diagnosis as well as for the treatment of the disease because of their non-invasive nature and high resolution [12, 13]. The major application in medical is fighting against cancer. The treatment of cancer can be done with different techniques. One of these techniques is photodynamic therapy which involves the use of chromophore that works as a catalyst for intermolecular energy transfer. PDT involves the injection of a photosensitizer which can collect within the tumor once exposed to the particular wavelength (630 nm-689 nm) which kills the cancer cells. Red LASER is preferred in PDT due to its short wavelength and low absorption of light by chromophore [14, 15].

## 2. Quantumwell LASER

In heterostructure one type is quantum well which has one thin “well” layer which is surrounded by two “barrier” layers. The layer in which these holes and electrons are confined is very thin, so we consider the electron and holes are both waves in the well. By using two techniques MBE (Molecular beam epitaxy) and MOCVD (Metal organic chemical vapor deposition) can be used for growing Quantum well structure [16]. We can use these techniques to make quantum well structure but the basic requirement is to keep Lattice constant of layers to be identical. Unidentical Lattice constants can lead to “Dangling bonds” which will create difficulty in retaining a well-defined crystal structure throughout

the layers. A partial list of material used for the quantum well includes III-V group materials GaAs/GaAlAs on GaAs Type-I, GaSb/GaAlSb on GaSb Type-I, InAs/GaSb Type-II structures. II-VI group materials HgCdTe/CdTe, ZnSe/ZnMnSe [3, 10]. Quantum well lasers are laser diodes with a narrow active region which leads to quantum confinement. The determination of wavelength is just not dependent on energy bandgap of materials used but the thickness of the active region also plays an important role. The benefit of Quantum well laser is it can achieve much shorter wavelength than the conventional lasers. In Quantum well lasers the carrier motion is restricted in a particular direction normal to the well, which results in the set of discrete energy levels and density of states that can be modified. Modifications in the density of states provide us with improvement in laser characteristics such as lower threshold current, higher efficiency, and higher modulation bandwidth and dynamic spectral width. They are preferred over conventional lasers because they require fewer electrons and holes to reach the threshold. For higher quantum efficiencies in optical absorption, quantum well lasers are beneficial [17-19].

### 2.1 Band Structure of heterostructures

Band structure engineering involves the incorporation of strain, quantum confinement and superlattices [20]. This technology contains a conjunction of both quantum and strain confinement which is used in valence band that leads to more propitious energy dispersion in the laser as compared to the natural crystal. Recently it has been studied that lowered valence band effective mass is beneficial for semiconductor lasers. Heavy valence band mass is the main problem in semiconductor lasers [21]. Regrettably, this problem is common in III-V semiconductors heavy valence band mass and very light conduction band mass due to asymmetry. For proper functioning of the laser, these masses should be light as possible and density of states should be low. [22-23].

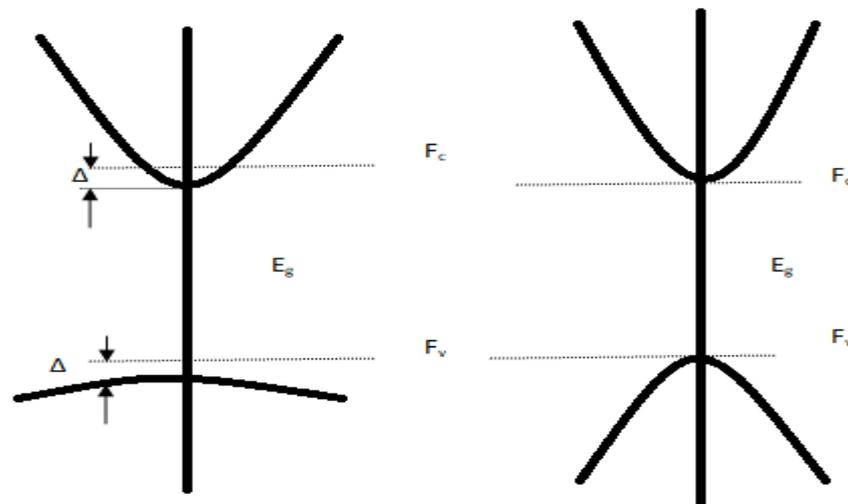


Figure 2. Actual and Ideal band structure of a typical III-V semiconductor [22]

In figure 2, the right image shows the ideal band structure for which lasing can be easily met. For this structure, both the holes and electron masses are light to achieve Bernard-Duraffourg Condition [24]. This condition is used to provide certain benefits to the laser-like threshold current, nonradiative recombination. In the laser, we have a threshold condition for gain that is given by

$$(F_c - F_v) > \hbar\omega \geq E_g \quad 1$$

This equation denotes that for a better gain separation in LASER Quasi Fermi Levels ( $F_c - F_v$ ) should be greater than the energy band gap. By achieving this condition valence band mass reduction takes place which leads to change in valence band structure. Hereby varying the valence band structure in order to lessen mass and population of heavy can lead to the solution of three troublesome aspects of semiconductor lasers a.) Asymmetry of conduction and valence band mass, b.) Intervalence band optical absorption and c.) The Auger recombination. Here intervalence band optical absorption is explained as a possible cause of temperature sensitivity of threshold currents in greater wavelength semiconductor lasers and in Auger recombination, two holes and one electron collide and recombine leaving only one

hole and some heat behind. Due to this Auger recombination laser threshold conditions and even nonradiative recombination is affected. So there is the need to reduce this rate of the combination. Some researchers reported that if we combine strain and quantum confinement in valence band this can provide us with more favorable energy dispersions for laser actions than in natural semiconductor crystal. This leads to band structure engineering in which laser threshold current and intervalence band absorption can be significantly diminished [17, 18, 25, 26]

## 2.2 Strain and electric field effects on heterostructure Lasers

In general when we talk about the stress we consider uniaxial stress i.e. force exerted along a particular direction divided by cross section of that surface. When a strain is applied, a degeneracy generated in original symmetry of semiconductor which leads to band splitting. The applied strain changes the band structure by reducing the crystal symmetry [25, 26]. Uniaxial stress results in degeneracy lifting and mixing of heavy holes and light holes bands which warps the bands and that is the reason for anti-crossing in quantum well valence band structure. Hence strain applied to change the wavefunctions and hence optical gain and bandgap energies are affected. Bandgap shifts directly affect the wavelength of ternary and quaternary compounds. It provides us extra flexibility in designing a semiconductor laser with more optimized parameters. Due to strain, change in density of state (DOS) affects the absorption efficiency of the quantum well laser [27-29]. There is a reduction in density of state for valence band which reduces the threshold current and increases gain. Strained quantum well lasers are investigated nowadays because of their potential to be used in laser printers and high power pump lasers. The Strained quantum well lasers are showing better results as compared to unstrained lasers in term of high optical gain. Chih-Sheng Chang et.al [18] has shown the effect of strain on the reliability of  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$  multiple quantum well lasers. The results clearly show that reliability improves with increment in strain in the quantum well. In order to understand the strain induced reliability improvement, the study of the propagation of defects in semiconductor heterostructure and the theory of elasticity is required [29]. Different types of strain like the tensile and compressive strain that depends on lattice mismatching between substrate and bulk semiconductor are reported by the researchers [30, 34]. Jianfeng Chen [19] reported the  $\text{InGaAsSb}/\text{AlGaAsSb}$  quantum well diode structure, which is grown over GaSb by molecular beam epitaxy technique with the compressive strain of both 1% and 1.5% respectively. By observing the results it was concluded that use of  $\text{InGaAsSb}$  quantum well with compressively strain above 1% can be used for the reduction in threshold current density. For heavily strained structure threshold current density is nearly half ( $120\text{A}/\text{cm}^2$ ) than that of moderately strained structure ( $230\text{A}/\text{cm}^2$ ). E.V. Bogdanovet. al. [30] reported the effect of tensile strained on p- $\text{AlGaAs}/\text{GaAsP}/\text{n-AlGaAs}$  quantum well and results are obtained for the external application of uniaxial stress. Uniaxial stress is used for wavelength tuning of laser diodes. The statement is concluded with the help of research work is done by I.V. Berman [35], who presented the effect of uniaxial stress on heavy and light holes mixing, optical gain in laser diodes and electron band. There is also an increment in gain under uniaxial compression for TE mode whereas in TM mode gain is decreased under uniaxial compression. So it was concluded that optical gain can be enhanced for tensile strained laser diode under uniaxial stress in TE mode more preferably than in TM mode. Under the effect of electric field on quantum well structure, there are variations in wavefunctions of both conduction and valence bands. Conduction bands electrons move opposite to the direction of electric field whereas valence band heavy holes move towards the direction of the electric field which changes their energy levels and hence emission wavelength is changed. The result is obtained for different values of the electric field applied and it was concluded that for high electric field optical gain is reduced but emission wavelength increases under electric field [33]. The effect of electric field on the optical gain of different semiconductor compounds with different compositions is studied in order to obtain laser operating at different wavelengths. The effect of electric field on the optical gain in  $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}/\text{GaAs}_{0.8}\text{P}_{0.2}$  type-I nanoscale heterostructure is reported [36]. The designed heterostructure is suitable for a wavelength ranging from (708nm to 826nm). Thus a wide range of tuning is available with the effect of electric field. Type-I heterostructure can be used for shorter wavelength and can be tuned by using the external electric field and strain [37-39]. Type-II heterostructure is advantageous because of their high interband transitions that lead to larger wavelength as compared to fundamental bandgap energies and widely used in optical fiber communication. It is found that  $\text{GaAsSb}/\text{InGaAs}$  heterostructure over GaAs substrate can be good material for the designing of  $1.3\mu\text{m}$  wavelength the design is a 'W' type structure in which optical transitions are strongly dependent on conduction band offset. A design of type-II QW

heterostructure that is suitable for the mid-wave infrared region. MWIR photodiodes find their applications in gas monitoring, chemical sensing and medical diagnostics. H.K. Nirmal et al [40] presented InGaAs/GaAsSb quantum well heterostructure and the behavior of optical gain under applied pressure is investigated. By applying variable pressure (2, 5 and 8 GPa) on the structure in [110] direction shows that optical gain and lasing wavelength both approaches higher value. The designed heterostructure can be tuned externally for the application of pressure and hence can be used for various applications in the SWIR region. The optical gain seems to improve up to a value of  $\sim 9000$  /cm under pressure at a wavelength of  $1.95\mu\text{m}$ . This shows that a high optical gain value can be obtained under a uniaxial pressure application. A.K. Singh et al [41] presented the effect of uniaxial strain on type-II heterostructure. The results show that under x-polarization the gain is  $\sim 14500$ /cm and under y-polarization, the gain is  $\sim 15700$ /cm without strain after applying strain the envelope wavefunctions are modified valence subbands are moved to different positions which improve the gain. So, it is presented that the optical gain can be tuned by applying uniaxial strain and high gain can be achieved along [110] direction [39-41]. J.Y.T. Huang et al [42], presented in his work that  $3\mu\text{m}$  wavelength can be achieved without strain relaxation. The design is type-II 'W' quantum well structure on InP substrate along with  $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}/\text{GaAs}_{0.35}\text{Sb}_{0.65}$  quantum wells separated by InP barrier layers. In his work, it is reported that the higher band offset of AlAsSb over GaInP is preferred for improved carrier confinement. So it is concluded that the tuning of wavelength is possible with the help of external strain without changing the material itself.

Heterostructures can be categorized on the basis of confinement structures also such as simple separate confinement heterostructure (SCH) and graded index separate confinement structure (GRIN-SCH). P. A. Alvi et al [43], intensive study of a graded index (GRIN) SCH type heterostructure is done, which can be used for the generation of  $1.55\mu\text{m}$  wavelength, which is mostly used silica made optical fiber wavelength. Here both simple and GRIN structure is examined and results show that the designed structure has the high optical gain at  $1.55\mu\text{m}$  and  $1.38\mu\text{m}$  in TE and TM polarizations respectively. The conclusions are made that simple structure is better than GRIN structure.

### 3. Quantum dot Laser

Brief research and study are also made on quantum dot lasers which are also important in optical communication for new technology and for the requirement of high optical gain. Firstly the concept of quantum dots for semiconductor lasers was proposed by Arakawa and Sakaki in 1982 with a prediction for lesser threshold current density [44]. They are preferred as they are less temperature dependent compared to conventional semiconductor lasers. The advantages of Quantum dot lasers can be summarised as temperature independent, emission wavelength depending on energy levels of dots rather than bandgap energy, has the maximum material gain at least 2-3 times greater than quantum well lasers. Quantum dot lasers make use of quantum dots (electrons are confined in length according to the desired wavelength) as their active region for the transition of electrons. Quantum dots are used due to its small size ( $\sim 2$ - $10$  nm or  $10$ - $50$  atoms in diameter) and the emission frequency is sensitive to dots size and composition. In quantum dot laser freedom of electron, propagation is confined in all degrees of freedom as compared to quantum well lasers in which degree of freedom is limited to one direction. We can change the bandgap energy of quantum dot laser just by changing the geometry of the surface Huizi Diwu et al [45], written a review paper in which introduction of quantum dot lasers, history, and physics of quantum dot lasers, types of quantum dot lasers, their fabrication techniques and market need of quantum dot laser is explained. Quantum confinement of quantum dot laser is better than quantum well laser hence its tunability is better than quantum well lasers [46-48]. Thomas Frost et al [49], reported a nitride-based red laser with the help of InGaN/GaN quantum dots laser. The technique used for the growth of GaN, AlGaIn, and InGaIn on GaN substrate is plasma-assisted molecular beam epitaxy (PA-MBE). Here light-current characteristics are presented with a dot density of  $3 \times 10^{10}/\text{cm}^2$  emitting light at a wavelength of  $635\text{nm}$  with cavity length  $5\mu\text{m}$  and internal quantum efficiency to be 36% lesser than the quantum well laser. Laser arrays are complicated to design so a single band laser with high power laser operating at  $635\text{nm}$  is designed to overcome the complications of array lasers. The structure consists of a single quantum well of GaInP with waveguide barriers of AlGaInP and cladding layers of AlInP. This high power  $635\text{nm}$  laser finds its application in digital video disk and in data storage. The thinner quantum wells are preferred for high positive gain as compared to a thicker quantum well. The fabrication of quantum dot lasers involves commercial techniques like metal organic vapor phase epitaxy (MOVPE), Molecular beam epitaxy (MBE) and monolayer fluctuations [50-52].

#### 4. Biomedical Lasers

Currently, from the research of laser in biomedical, it comes to know that red lasers have wide applications in medicine also. The formation of the red laser diode with nitride is expensive as well as harmful. So, a study about other alternatives for this red laser is made, and it is proposed that phosphides can be used for the generation of red wavelength [53, 54]. The red lasers are widely used in photodynamic therapy (PDT) for the treatment of damaged human tissues. For PDT application a large beam divergence is required. For the biomedical application of laser the power is a limited factor and depends on the type of diseases. Diode lasers operating in the range of 630 nm to 740nm are suitable for PDT and dermatological applications. PDT makes use of photosensitizer drug injected with a specific wavelength of light to be absorbed by the cell [55-59].

FarhadH.Mustafa [13] reported the effect of laser wavelengths on PDT for the treatment of superficial skin diseases. He has compared illumination intensity of several wavelengths within the range of 308nm, 365nm, 405nm, 532nm and 635 nm in a skin sample with Advanced System Analysis Program (ASAP) software for the calculation of transport intensity of laser in the skin. In this work study of dose absorption by photosensitizer and melanin is done. The ability of short and long wavelength is studied to show power uptake effect in chromophore cell in human skin. A comparison between UV laser and red laser is for dose absorption is made. The results obtained are the peak power uptake by UV laser is 501mW/mm<sup>3</sup> and by the red laser, it is 71.5mW/mm<sup>3</sup> which is 7 times less and for the same skin depth ( $Z = 0.019\text{mm}$ ). By this, we conclude that UV laser transmits the minimum amount of laser as it is highly absorbed by the chromophore. This is the reason red laser is preferred over UV laser for treatment in PDT as there is less interaction by Red laser.

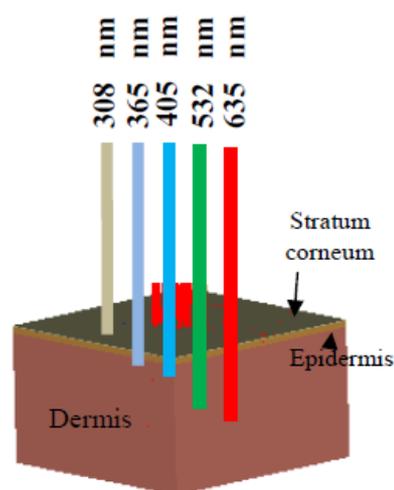


Figure 3. Stratum, corneum, epidermis and dermis layers of skin with 5 different laser wavelengths [13]

Table1. List of photosensitizers with activating wavelength [60]

Wavelength (nm)	Photosensitizer (Company)
630	Photofrin II (QLT)
630-635	ALA (DUSA, ESC)
652	mTHPC/Foscan (Scotia Quanta Nova)
665	SnET2 (Miravant)
688	HBP(QLT)

L. Brancalione et al [61] discussed the characteristics of light sources of PDT, including dye lasers pumped by argon, frequency doubled YAG lasers and non-laser sources such as tungsten filament, metal halide, xenon arc, and fluorescent lamps. Argon lasers are mostly used devices for PDT treatment. The argon pumped dye lasers are coupled with optical fiber to be used in the treatment of lung cancer, oral precancer, bladder cancer and for the treatment of superficial skin disease. The metal vapor pumped dye lasers [62] are also used in PDT but unlike argon laser, they are normally pulsed at a pulse width ranging from 10ns to 50ns. These lasers are able to deliver at irradiance up to several hundred

Nowadays PDT is not limited to lasers, it makes use of high power lamps for filtered output. They are preferred over lasers because they provide large spectral range as compared to lasers. They have a drawback that their output power can't be easily coupled to small optical fibers and hence is limited in the treatment of skin lesion only and not been used for endoscopic PDT. Tungsten filament Quartz Halogen lamps were first introduced by Pottier and Kennedy [60]. These lamps are used as they can deliver on a wide spectral range of (350-850 nm) with output power 250mW/cm<sup>2</sup>. Another category of lamps used is Xenon Arc lamps providing a higher spectral region for emission (300-1200 nm) along with high output power up to 8 W for direct exposure and up to 1W using liquid light guide.

PDT can be used for the treatment of tumors [63, 64]. The length of diffuser for the treatment of a tumor depends on the size of the tumor to be treated. The method of light delivering depends on the geometry of the tumor and the extent of the tumor. Sometimes surface illumination is not sufficient for the treatment, so interstitial illumination is required for that purpose balloon catheters are designed [65]. Balloon catheters are the latest development in the field of PDT. In this technique, a transparent balloon with cylindrical fiber positioned at the center is inflated in the patient esophagus. The diameter of balloon inflated is limited to 25mm only as large diameter can lead to serious tissue damage which further to blood flow. Many more advancements and research work are going on in PDT for other treatment with the help of various photosensitizer.

P. Babilas et.al [66] presented a comparison between in vitro and in vivo for photodynamic therapy with two different light sources. To understand the effectiveness of LED over incoherent lamp this comparison trial is done by using 5-aminolaevulinic acid (ALA) for the treatment of actinic keratosis (AK). For the treatment after incubation with ALA irradiation by LED system (40 Jcm<sup>-2</sup>, 80mWcm<sup>-2</sup>) on one side and on the other side irradiation is done by the incoherent lamp (100 J/cm<sup>2</sup>, 160 mW/cm<sup>2</sup>). The LED system used is operating on wavelength 633 nm and incoherent lamps range between 580nm-700nm respectively. This treatment was done on 40 patients for 24h the result shows the very minor difference between ALA-PDT using LED system and incoherent lamps. These light sources can be implanted also for treatment of various cancers and tumors. The results obtained provide us with the idea of implanting of multiple sources to get optimal energy for localized PDT. In PDT penetration depth needs to be measured to understand the effect of photosensitizer on human tissues. S. Stolik et al. [64] reported the results for the penetration depth of more than 10 tissues at different wavelengths.

Table 2. Penetration depths of different tissues with wavelength [64]

Tissue	Wavelength (nm)	$\Delta$ (mm)
Lung	630	0.81±0.06
Lung Carcinoma	630	1.68±0.15
Uterus	630	2.14±0.18
Brain	675	1.38±0.13
Liver	630	1.20±0.13

Earlier PDT used for cancer treatment involves injection by the light source but now Photosensitizers can be directly generated inside the tumor with the help of pre photosensitizer. So PDT is a specific method for destroying malignant, premalignant and other benign tissues while sparing the surrounding healthy cells. The IPDT (Interstitial Photodynamic therapy) is used for the treatment of deep-seated malignant tumors and brain tumor treatments. It is highly compatible with currently available standard and experimental treatment options for malignant glioma [67, 68].

## 5. Conclusion

In this paper, we came across various structural parameters and optical characteristics of semiconductor lasers. The requirement of the laser is the high optical gain and controllable performance. The review result also shows the effect of quantum well thickness, the effect of external strain and temperature on the optical gain for type-I and type-II heterostructure. The red laser is widely used in biomedical for treatment of various diseases. Currently, 635 nm red laser fabricated using the phosphides is widely used in PDT for the treatment of superficial skin diseases, because these lasers are less absorbing and can be precisely focussed to the infected tissue. A high optical gain is required in order to reduce the absorption of drugs in PDT.

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