1.55 µm High-Speed QDs Lasers for Optical Telecommunication Applications

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Summary

In this work investigation of the QDs formation and the fabrication of QD based semiconductor lasers for telecom applications are presented. InAs QDs grown on AlGaInAs lattice matched to InP substrates are used to fabricate lasers operating at 1.55 µm, which is the central wavelength for far distance data transmission. This wavelength is used due to its minimum attenuation in standard glass fibers.

The incorporation of QDs in this material system is more complicated in comparison to InAs QDs in the GaAs system. Due to smaller lattice mismatch the formation of circular QDs, elongated QDs and quantum wires is possible. The influence of the different growth conditions, such as the growth temperature, beam equivalent pressure, amount of deposited material on the formation of the QDs is investigated. It was already demonstrated that the formation process of QDs can be changed by the arsenic species. The formation of more round shaped QDs was observed during the growth of QDs with As$_2$, while for As$_4$ dash-like QDs. In this work only As$_2$ was used for the QD growth. Different growth parameters were investigated to optimize the optical properties, like photoluminescence linewidth, and to implement those QD ensembles into laser structures as active medium. By the implementation of those QDs into laser structures a full width at half maximum (FWHM) of 30 meV was achieved.
Another part of the research includes the investigation of the influence of the layer design of lasers on its lasing properties. QD lasers were demonstrated with a modal gain of more than $10 \text{ cm}^{-1}$ per QD layer. Another achievement is the large signal modulation with a maximum data rate of 15 Gbit/s. The implementation of optimized QDs in the laser structure allows to increase the modal gain up to $12 \text{ cm}^{-1}$ per QD layer. A reduction of the waveguide layer thickness leads to a shorter transport time of the carriers into the active region and as a result a data rate up to 22 Gbit/s was achieved, which is so far the highest digital modulation rate obtained with any 1.55 µm QD laser.

The implementation of etch stop layers into the laser structure provide the possibility to fabricate feedback gratings with well defined geometries for the realization of DFB lasers. These DFB lasers were fabricated by using a combination of dry and wet etching. Single mode operation at 1.55 µm with a high side mode suppression ratio of 50 dB was achieved.
Zusammenfassung

In der vorliegenden Arbeit werden die Formation von Quantenpunkten sowie die Herstellung von Halbleiterlasern für Anwendungen in der optischen Telekommunikation untersucht und vorgestellt. InAs Quantenpunkte werden auf AlGaInAs gitterangepasst zu InP abgeschieden und in Halbleiterlasern mit einer Wellenlänge von 1,55 µm verwendet. Wegen der geringen Absorption optischer Fasern wird diese Wellenlänge in der optischen Datenübertragung genutzt.

Die Nutzung von Quantenpunkten in diesem Materialsystem ist deutlich komplexer als z.B. im Falle von InAs Quantenpunkten im GaAs Materialsystem. Auf Grund der geringeren Gitterfehanpassung ist die Abscheidung von sowohl runden, aber auch verlängerten Quantenpunkten und Quantendrähten möglich. Der Einfluss verschiedener Wachstumsparameter wie Temperatur, Strahldruck, Menge abgeschiedenen Materials auf die Entstehung der Quantenpunkte ist untersucht worden. Es konnte bereits gezeigt werden, dass das Wachstumsverhalten der Quantenpunkte durch die verwendete Arsenspezies beeinflusst werden kann. Die Entstehung eher runder Quantenpunkte beim Einsatz von As₂ im Gegensatz zu strich-artigen Strukturen bei As₄ wurde bereits nachgewiesen. In dieser Arbeit wird daher nur As₂ eingesetzt. Verschiedene Wachstumsparameter wurden untersucht, um die optischen Eigenschaften wie die Photolumineszenz-Linienbreite zu optimieren und derartige Quantenpunkt-
Ensembles als aktives Medium in Laser-Strukturen zu integrieren. Dabei konnte eine Photolumineszenz-Halbwertsbreite von 30 meV erreicht werden.


Die Integration einer Ätzstoppschicht in die Laserstruktur erlaubte die Herstellung von oberflächenbasierenden DFB Gittern wohl-definierter Geometrie. DFB Laser konnten mittels einer Kombination von nass- und trockenchemischem Ätzen hergestellt werden. Die Laser arbeiten auf einer einzelnen longitudinalen Mode bei 1,55 µm mit Seitenmodenunterdrückungen von bis zu 50 dB.
Chapter 1

Introduction

Semiconductor laser diodes have a lot of applications not only in science but also in our everyday life. They have replaced the helium-neon lasers in different applications and are widely used in equipment, e.g., for reading of bar codes, storing and reading of information on CDs and DVDs, as laser pointers, and many others.

Another field of application of laser diodes is different medical diagnosis, therapies, or treatments. They allow making surgeries with minimal invasive intervention or without it. The big advantages of the surgeries with using of the laser diodes are the high accuracy of the operations, high local temperature which lead to the absence of infection, minimal recovery time and absence of bleeding during the surgery.

High-power lasers are used as high-efficient sources for the pumping of solid-state lasers. Semiconductor laser diodes are also used in the spectrometry and the material processing.

One very important application field of laser diodes is optical telecommunication. Today it is important to have safety channels for the transmission of the information in the global information nets. Because of the increase of the data bit rate it is necessary to use alternative materials to the
1. Introduction

copper wires for the data transmission. Due to the significant improvement of the fabrication technology of the optical fibers it is very perspective to use them instead of the copper wires. The main advantages of optical fibers are much higher data rates in comparison to electrical or wireless transmission, unreceptiveness to the electromagnetic radiation and much lower cost per bit transmitted. One information transmission channel consists of a light source to be modulated with the digital data to be transmitted, a receiver of the optical signal and the optical fiber as transmitting medium. Major problems which have been solved are enough low transmission losses within the fiber and highly efficient transmitters, e.g. semiconductor lasers, or combinations of lasers and modulators, which can provide high enough data rates.

Losses in optical fibers takes place due to several reasons: light absorption inside optical fibers is lower in case of lower light frequencies. In the same time higher signal losses take place for higher light frequencies. In addition the signal losses increase when there are bends of the cable with small radius. Nowadays the attenuation into the optical fibers is in the range of 0.2 – 0.5 dB/km for the wavelength in the range of 1.3 – 1.6 µm. Dependence of the light adsorption inside optical fiber on light wavelength is shown on the figure 1.1.

Fig. 1.1. Measured attenuation in silica fibers (solid line) and theoretical calculations of the scattering inside optic fiber (dashed lines) [1]
There are few regions with local absorption minima, which are used in telecommunication applications. Wavelength of 0.85 µm is used preferably for the data transmission over short distances and local area networks. Higher absorption inside optical fiber makes this wavelength less interesting for the data transmission over long distances. On the other hand system for the data transmission at 0.85 µm wavelength is less expensive and easier to install. The wavelength window around 1.3 µm is interesting for data communication applications because of minimum absorption inside glass fiber. For the transmission over long distances the attenuation of the cable should have minimum. Minimum attenuation in silica fibers takes place around 1.55 µm. Therefore this wavelength is preferable for the data transmission over long distances. Increase of the losses around 1.38 µm take place due to water within the glass [2].

Quantum dot (QD) based devices have some advantages for the direct modulated data transmission: room temperature operating quantum dot lasers have demonstrated a high differential gain, a low threshold current density and a temperature insensitivity of the threshold current over wide temperature ranges [3], [4]. Moreover, the optical gain function of quantum dot materials, arising from their zero dimension-like density of states, has a strong impact upon other laser characteristics such as chirp or sensitivity to optical feedback [5], [6]. These results made QD lasers promising candidates for optical telecommunication applications.

Usually for data transmission in the wavelength range of 1.3 µm the InAs QDs on GaAs are used. The growth process and the influence of the growth conditions for this system are well investigated. To provide the data transmission at 1.55 µm InAs QDs on InP are used. The GaAs based QD lasers with very good properties have already been demonstrated. On the other side devices based on InP substrates are studied much less in comparison to GaAs
based lasers and have much more room for the improvement of material and device properties. Therefore more detailed investigations of the influence of the growth process and laser structure on the laser properties are very important for the further development of InP based QD lasers in telecommunication applications.

All the samples were grown using molecular beam epitaxy in INA by author. Preparation of the grown lasers for further measurements was done by Florian Schnabel, Anna Rippien and Dirk Albert. The measurements of the samples were carried out by author and technicians of INA. High-frequency measurements were performed by our partners from “Technion” (Israel) and “Fraunhofer Heinrich Hertz Institute” (Berlin) in the frame of the European project DeLight.

Thesis is organized in four chapters. Second chapter contains the necessary theoretical background concerning low-dimensional structures and the description of the molecular beam epitaxy basics. Basic theory of the laser physics and different types of the laser structures, such as DFB, DBR and RWG laser are also described in this chapter. Experimental results concerning growth of the QD samples and optimization of the growth condition to obtain more narrow PL spectra are presented in third chapter. Growth of the lasers with the optimized QDs and influence of the layer design of laser diodes on their properties are presented in forth chapter. Conclusions with the obtained results are presented in the end of the work.
Chapter 2

Fundamentals

At the beginning of this chapter the brief description of the properties of low dimensional structures will be done. Then will be presented the theoretical background of the growth of QD structures and QD lasers. The second part introduces the basic principles of Molecular Beam Epitaxy (MBE) and basics of the sample growth. The third part presents the theory and the working principles of semiconductor lasers. Here will be described the types of the lasers and their most important parameters.

2.1 Nanostructures / Semiconductors.

During the last years big efforts are focused on the investigation of the fabrication of nanostructures and their applications in different devices. The physics of nanostructures is one of the most rapidly developed branches in applied sciences. There are a lot of achievements in the fabrication of devices based on low-dimensional structures.

Most of the electronic devices are based on silicon. The main reason is the lowest cost of the devices based on this material. Silicon is the most studied
material and technology of the fabrication of electronic devices. In spite of this, silicon is not usable for the application in light emitting diodes because of its band structure.

Semiconductors are divided in two different types depending on the carrier transition between conduction and valence bands. In case of the direct bandgap semiconductors minimum energy in conduction band and maximum energy in valence band occur at the same value of crystal momentum. Typical direct bandgap materials are InP and GaAs. The carrier’s momentum in these semiconductors is not changed during their transition from the valence band to the conduction band. The energy band structure of GaAs is presented in Fig. 2.1 (a).

![Energy band structure of GaAs and Si](image)

Fig. 2.1. Band structure of GaAs (a) and Si (b).

For indirect bandgap semiconductors minimum energy in the conduction band and maximum energy in the valence band occur at different values of the crystal momentum. Direct photon absorption with transition of the carriers between the valence band and the conduction band is forbidden in this case. Only processes with additional absorption or emission of phonon may cause the light absorption. Presents of additional impurities, dislocations, interfaces or electric
field also could provide the transition of the carriers from valence to conduction band. Indirect bandgap semiconductors are rarely used in the emitting devices due to smaller absorption coefficient. Typical indirect semiconductor is Si. Its band structure is presented in Fig. 2.1 (b).

The bandgap of the materials is related to their lattice constant. In the case of the compound materials the lattice constant is determined by the Vegard’s law. For two-component systems the lattice constant is expressed by the equation [7]:

\[ a_{AB} = a_A (1 - x_B) + a_B x_B \]  

(1.2.1)

Here \( a_A \), \( a_B \) and \( a_{AB} \) are the lattice constants of both materials and their compound, \( x_B \) is the mole fraction of the material B in the compound.

It is also possible to determine the lattice constant for three and four component systems. For example, the lattice constant for the quaternary material In\(_{1-x}\)Ga\(_x\)P\(_{1-y}\)As\(_y\) can be found from the empirical equation [8]:

\[ a(x,y) = xy a_{GaAs} + x(1-y)a_{GaP} + y(1-x)a_{InAs} + (1-x)(1-y)a_{InP} \]  

(1.2.2)

In this equation the values of the lattice constants for different materials are \( a_{GaAs} = 5,6536 \, \text{Å} \), \( a_{GaP} = 5,4512 \, \text{Å} \), \( a_{InAs} = 6,0590 \, \text{Å} \), \( a_{InP} = 5,8696 \, \text{Å} \).

III/V materials are used for the fabrication of different devices, and especially in the laser diodes for telecommunication applications. The laser structures consist of the materials with defined properties. It is necessary to know the exact dependence of the properties of the compound materials on the composition. In Fig. 2.2, the bandgap energies and the lattice constants for different III/V compounds are presented [9].

If we limit the movement of the carriers in some directions, this leads to the change of the electrons wave function and the electron will be confined in these directions, where the sizes are comparable to the electrons wavelength.
Concentration of the electrons in the conductive band can be calculated if the density of states of the system is known. In the case of three-dimensional electron gas the density of states increases proportional to the square root of the energy.

Fig. 2.2. Dependence of the bandgap on lattice constant for different semiconductor materials [9].

If the electrons are confined in one direction, the density of states will be constant between the different energy levels and it will be changed when the next level is reached. In the case of a one-dimensional electron gas the density of states increases by reaching the next energy level and decreases afterwards proportional to the square root of the energy. In the case of quasi zero-dimensional electron gas the density of states are represented by a set of different discrete levels. The density of states for different systems is schematically presented in Fig. 2.3 [10].
Due to their unique properties, quantum dots are the perfect candidates to be used as an active material for the fabrication of laser diodes. It is predicted theoretically, that the semiconductor lasers, based on quantum dots, should demonstrate better temperature stability of the threshold current and efficiency.
in comparison to quantum well lasers. On the other hand the threshold current for the QD lasers is much smaller in comparison to other types of semiconductor lasers. GaAs based QD lasers with very low threshold current [11], high output power [12] and high temperature stability [13] were already reported.

The comparison of the maximum values of the gain shows, that the quantum dots should provide more gain and therefore they should have higher efficiency. The dependence of the maximum gain on the current density is shown in Fig. 2.4.

The low dimensional structures can be fabricated by different epitaxial techniques. All samples presented in this work are grown by molecular beam epitaxy. Theoretical background concerning the growth condition is presented in the next part of this chapter. Optimization of the growth conditions and the characterization techniques of the grown samples will be presented in the next chapters.

2.2 Molecular beam epitaxy

Molecular beam epitaxy (MBE) is a technique for growing of thin epitaxial structures. In MBE thin films or other epitaxial structures crystallize via reactions between molecular or atomic beams of the constituent elements and a substrate surface. When the deposited structure has the same composition as the substrate, the process is called homoepitaxy, otherwise the growth is heteroepitaxy.

Depending on the type of the deposition techniques the epitaxy is divided basically into two groups, namely: Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) [15], [16]. The difference between these techniques consists in method of transfer of the grown material to the substrate.
In the PVD techniques the materials, which will be deposited, evaporates at high
temperature and is transferred in high-vacuum environment to the substrate. In
the CVD techniques the necessary compounds of the materials, which will be
grown, is prepared outside or inside of the vacuum reactor (chamber) and
transferred as gas flow to the reaction zone near the substrate. MBE, Pulsed
Laser Deposition (PLD) and its modifications belong to the PVD techniques,
while Metal Organic Chemical Vapor Deposition (MOCVD), Laser Assisted
Chemical Vapor Deposition (LACVD) and the related techniques belong to the
CVD techniques. All the samples used in this work were produced by solid
source molecular beam epitaxy.

Theoretical concepts of the basic principles and requirements for the high-
quality stoichiometric films based on III-V semiconductors were established by
Günter [16]. First successfully grown samples were fabricated at the end of the
50th. However those films were grown on polycrystalline substrates. Therefore
they were also polycrystalline. Only ten years later monocrystalline GaAs has
been grown using Günters method [17].

### 2.2.1 MBE setup

A typical scheme of a molecular beam reactor is described in Fig. 2.5. The
highly pure solid-state materials are evaporated from the effusion cells by
heating to the temperatures above the melting points of the deposited materials.
The fluxes of the deposited materials can be controlled by the heating of the
sources. During the growth the effusion cells are kept at high temperatures,
necessary for the evaporation of the materials. Mechanical shutters in front of
the cells prevent the materials to reach the substrate until it has to be deposited.
The substrate is placed in high-vacuum environment in front of the cells. The
heating of the substrate is provided by a heater, placed behind the substrate. It is
necessary to determine the suitable position for each cell in order to provide uniform growth conditions overall the surface of the substrate. It is very difficult task to determine the suitable geometry of the growth chamber and the sample position [18]. The problem of the uniform growth conditions is solving by continuous rotation of the sample during the material deposition and correctly position of the sample and effusion cells.

Different devices can be installed in the growth chamber for in-situ monitoring of the growth process such as Reflection High-Energy Electron Diffraction (RHEED), Auger electron spectroscopy, ellipsometry etc .

![Fig. 2.5 Scheme of the growth chamber of MBE system (based on [19])](image)

The vacuum into the growth chamber has to be very high to obtain the good quality samples. In the real case there are residual gases in the growth chamber, which decrease the quality of the grown structures. The basic parameters which are important to have excellent growth conditions are the mean free path of the
atoms of the deposited material and the concentration of the residual gas molecules. The mean free path is the average distance passed by the atoms between collisions with the residual gas molecules. From the assumption, that the residual gas in the MBE system behave as an ideal gas and using kinetic theory of the ideal gas, we obtain the free path for the atoms of the deposited material into the growth chamber [20]

\[ L = 3.11 \times 10^{-24} \frac{T}{pd^2} \quad (1.3.1) \]

Here d – diameter of the gas molecule, p and T are pressure and temperature correspondingly. The value of the mean free path for the atoms of the deposited material should be larger than the distance between the cells and the substrate. The calculations show that the maximum value of the residual gas pressure has to be in the range of $10^{-2} – 10^{-3}$ Pa. Taking into account the ratio between the deposition times of the beam $t_1(b)$ and the background vapor $t_1(v)$ [16]:

\[ t_1(b) = 10^{-5}t_1(v) \quad (1.3.2) \]

the pressure of the residual gas in the growth chamber has to be in the range of $10^{-9}$ Pa. At this vacuum condition typical growth rates for MBE are in the range of 1 µm/h.

In real MBE systems the background pressure is in the range of $10^{-8} – 10^{-9}$ Pa and satisfies the requirements for ultra-high vacuum. An additional way to decrease the amount of the residual gas molecules is to cool down the walls of the growth chamber by liquid nitrogen.
2. Fundamentals

2.2.2. Measurement of the substrate temperature.

The substrate temperature is one of the most important parameters, which influence on the growth process. There are few possibilities to control the temperature of the sample surface during the growth. They are: thermocouple, RHEED, band-edge spectroscopy, optical pyrometer [21], [22], laser interferometric thermometry (LIT) [23], [24]. Each method has advantages and limitations. Also, the accuracy of the temperature measurements is different for each method. It depends also on the layers, which should be grown.

In the case of the temperature measurements by thermocouple there is no contact between the thermocouple and the sample surface. Therefore it is not possible to measure the real surface temperature by this method. The measurements of the temperature are very stable and they are used for the temperature adjusting by Eurotherm.

In the case of RHEED it is possible to measure the surface temperature by changing of the RHEED patterns. It works very well in the case of oxide desorption. In this case the transition between the amorphous and crystalline surface is monitored. In the case of GaAs the oxide desorption takes place at 582 °C [25]. This method is very limited because the transition between the patterns is very slow and lasts over few tens of Kelvin. Also, the RHEED patterns are very dependent on other growth conditions, like arsenic flux.

Band-edge spectroscopy is based on the changing of the absorption edge at different temperatures. Measurements of the absorption edge by spectrometer allow determination over a wide range. There is a lot of limitation of this method in comparison to the optical spectrometry. It does not allow the measurements of the high temperatures because of the absorption of thermally generated free carriers. It is not possible to measure the temperature of the highly doped substrates because of the shift of the band edge and the absorption
of the free carrier. This method is also not applicable in the case of samples with the band edge in UV-range and for the strained layers because the position of the band edge is sensitive to the strain. The temperature range, which could be measured in the case of InP and GaAs substrates, is from room temperature up to 650 °C [21]. Additional difficulties make the growth on some types of the substrates, for example double-side polished substrates.

In the case of optical pyrometry the temperature is obtained by measurements of the radiation from the sample and comparison of this radiation with black body radiation. The obtained data should be corrected by using the emission factor, which takes into account the changes of the emission characteristics of the sample holder and the transmissivity of the viewport. Also the heat from the effusion cells can have an impact on the temperature measurements when cell’s shutter is open. The temperature measurements works well in some temperature range especially for high temperatures. This method can be used for the determination of undoped GaAs, InP and Si temperature in the range of 350 °C – 800 °C, for doped GaAs, InP and Si in the range of 200 °C – 800 °C, for ZnSe, ZnTe, SiC and other transparent materials in the range of 400 °C – 1400 °C, for sapphire and other transparent in UV-range material in the range of 400 °C – 1400 °C, for GaN substrates and strained layers in the range of 400 °C – 1400 °C [21].

LIT is a variant of the optical pyrometry. As was mentioned above the control of the substrate temperature by pyrometer can be disturbed when the cell’s shutter is open. This limitation can be avoided by using a laser and measuring the interference pattern from the sample. Comparison with the reference interferograms will give the real substrate temperature.
2. Fundamentals

### 2.2.3. Growth process

The growth of the epitaxial layers or structures is performed on the surface of the substrate. Possible processes, which can take place with the atoms reaching the substrate surface, are presented schematically in Fig. 2.6.

There are four important processes, which take place when the atom reaches the sample surface. The first process when the atoms reach the substrate is called physical adsorption. Actually this is the first stage before the atom is incorporated into the lattice. The binding energy of the atoms to the surface is low enough that atoms can escape by thermal energies. Usually the incoming atoms have high enough energies to be also re-evaporated with a certain probability from the surface before they are incorporated into the lattice structure.

![Fig. 2.6 Processes, which take place on the substrate surface during the growth. Based on [26]](image)

The second process, which occurs during the crystal growth, is migration of the impinging atoms over the substrate surface. When these atoms interact with the
surface, they are losing a part of their kinetic energy to the substrate atoms and become in equilibrium with the surface. Also during the surface migration some atoms dissociate before they are chemically adsorbed.

The next process, which takes place on the surface, is the establishment of the bonds between the atoms of the substrate and the impinging atoms. This process is called chemical adsorption. After these bonds are created the impinging atoms becomes a part of the crystal lattice. In this case the probability for desorption of these atoms is much lower than in the case of physical desorption.

During all the processes, which were described above, the atoms can be desorbed from the surface. After the desorption they go away and will not be incorporated into the substrate lattice.

After the atoms come to the surface until they are incorporated into the lattice, they migrate over the substrate surface. The migration length of the atoms is very sensitive to the substrate temperature. A higher temperature increases the migration length of the atoms and the structural properties of the nanostructures can be controlled by this parameter. On the other hand, a too low temperature leads to the decreasing of the quality of the deposited nanostructures. The main reason is that the amount of the defects in the grown layer is increased.

The substrate temperature has also a big influence on the desorption of atoms from the surface. The desorption rate of atoms can be described by similar ratios and depends on the substrate temperature:

$$ R_{\text{des}} \sim f_{\text{des}}(\theta) \cdot e^{-\frac{E_{\text{des}}}{k_b T}} $$  \hspace{1cm} (1.3.3)

Strong atomic desorption can take place at certain temperatures, which vary for different materials. Heating of the GaAs substrate without applying of As leads to decomposition of As atoms from the substrate. It is necessary to apply additional As flux if the substrate temperatures higher than 350°C [27].
Significant desorption of the Ga and In atoms during growth of GaAs and InP under typical growth conditions starts at 620°C and 520°C correspondingly [28] - [31]. Desorption of different materials is strongly dependent on growth conditions. Therefore, when higher substrate temperatures are necessary during the growth the flux of the atoms from the cell has to be calibrated, taking into account desorption of the material from the sample surface.

The processes of the epitaxial growth of III-V semiconductors depend on the correlation between the species atoms. Usually in the MBE growth group V-stabilized growth conditions are necessary. This means that the elements of the group V are supplied at higher pressure to compensate desorption from the surface of the substrate at higher temperatures. Therefore it is necessary to apply the group V elements continuously during the epitaxial growth. It will prevent the surface from the destruction during the temperature changes. Using of the group III-rich growth conditions is not desirable because the amount of defects increases. By controlling of the amount of group V elements the migration length of the group III atoms on the substrate surface can be changed.

The lattice mismatch in the case of heteroepitaxy can be determined by the equation [32]:

\[
 f = \frac{a_s - a_l}{a_l} \quad (1.3.4)
\]

where \(a_s\) and \(a_l\) are the lattice constants of the substrate and the grown layer correspondingly. Epitaxial layer is relaxed in the case of a thick layer. In this case the lattice mismatch is defined by the expression [33]:

\[
 f = 2 \frac{a_s - a_l}{a_s + a_l} \quad (1.3.5)
\]

In the case of materials with a big difference in the lattice constants the amount of the defects is big. Typical example for such a system is Ge on Si substrates. The initial few micrometers of the Ge epilayer will contain a lot of defects. To
decrease the amount of the defects in the grown layer it is possible to grow a Si$_x$Ge$_{1-x}$ buffer layer by slightly decreasing the amount of Si in the compound during the growth [34].

A big role in the nanostructure formation has the substrate orientation. The atomic structure of the surface depends strongly on the substrate orientation. This leads to different results of the epitaxy even when all the other parameters are the same [35] - [38].

### 2.2.4. Growth modes

There are three possible growth modes during the epitaxy. They are presented in Fig. 2.7. The theoretical model of the epitaxial growth is determined by the free energy of the substrate surface, the surface free energy of the deposited layer and the interface free energy. When the energy of the substrate surface is less than the sum of the layer energy and the interface energy, islands formation is observed at the initial stage of the growth. The size of the islands increases with increasing the number of atoms reaching the surface of the substrate. This process takes place, because the energy of the bonds between the atoms is higher than the energy of the bonds between the atom and the substrate surface. This mode is called Vollmer-Weber growth mode. When the energy of the substrate surface is higher than the sum of the layer energy and the interface energy the next layer will start growing after the previous layer is completed. This growth mode is called Frank-van der Merwe growth mode. There is an intermediate mechanism between the two above mentioned growth modes. During the initial stage of this growth mode the formation of few monolayers is observed, as in layer-by-layer growth mode. This initial layer is called wetting layer. After the formation of the wetting layer an island formation is observed. This mode is
called Stranski-Krastanov growth mode and it is very important for the growth of nanostructures by MBE.

Fig. 2.7 Growth modes during the epitaxial growth: a) Frank-van der Merwe growth mode, b) Vollmer-Weber growth mode, c) Stranski-Krastanov growth mode. $\Theta$ is the thickness of the grown material in monolayers.

### 2.3 Laser fundamentals

The word “Laser” consists of the first letters of the description of the light interaction process “Light Amplification by Stimulated Emission of Radiation”. Theoretical basis of the principles of stimulated emission are developed by Dirac [39]. Stimulated emission is the basic process for every laser. The first working device was built in 1954. It worked in the microwave regime of the electromagnetic spectrum. Active medium for this laser was ammonia. Due to the technical difficulties it was not possible at that time to reach radiation in the visible part of the electromagnetic spectrum. First laser emission was
demonstrated in 1960 from ruby [40] and helium-neon lasers. The principles of the laser are described in this section.

2.3.1. Physical processes inside lasers.

The main processes, which take place inside the laser, are absorption and emission. Emission includes two processes, namely spontaneous emission and stimulated emission. These processes are shown in Fig. 2.8.

![Figure 2.8: Processes, which occur in the solid during the laser operation](image)

When a photon penetrates into the solid there is a possibility that it will be absorbed. As a result an electron will be transferred from the valence to the conduction band. The electron can stay in the excited state only for certain time and then it will go back to the valence band. At the same time a photon will be emitted. This process is called spontaneous emission and it is independent on the incident light. Also there is the possibility that incident light can induce the electron transition. This process is called stimulated emission. The emitting light has the same direction, wavelength and phase as the incident light. As a result of
2. Fundamentals

stimulated emission there are two identical photons. This means that the light can be amplified by using stimulated emission. During the stimulated emission a part of the light can be absorbed by the crystal lattice or can be lost by different processes, such as Auger recombination. In this case a so-called non-radiative recombination takes place. This processes decrease the amount of the photons obtained in result of the stimulated emission and will decrease the amplification of the incoming light.

In the normal state most of the electrons are in the states with lower energies. It means that most of the light will be absorbed. To provide a possibility for light amplification it is necessary to obtain the situation when there are more electrons in the high-energy state than at the low-energy state. This condition is referred to as population inversion. In semiconductors population inversion is obtained near the band edges by electrical current injection. During the operation of the laser some of spontaneously emitted photons stimulate spontaneous emission of additional photons with the same frequency and direction.

2.3.2. Three and four level lasers.

Depending on the energy levels which are used for the generation of the population inversion there are three-level and four-level laser schemes possible. Energy level diagrams for both types of lasers are presented in Fig. 2.9. In the case of a three-levels laser there is a transition of electrons from the ground level to the highest level with energy $E_3$ during the pumping of the laser. The lifetime of the electrons in this level is low and electrons will relax to the intermediate level with energy $E_2$ as a result of non-radiative recombination. Lifetime of the electrons on this level is much higher and it allows obtaining the inversion in
this system. In the case of four-levels lasers there are two intermediate levels in between the ground state and the highest level, which are used during the pumping of the laser. The lasing takes place during the transition between the intermediate levels with energy $E_3$ and $E_2$. Sometimes there are few levels used for pumping of the laser. In this case they are called *pump band*. There is one modified version of a four-level laser. Transition of the carriers from the valence band to the energy level $E_3$ is dominated in this scheme. In this case there are only three energy levels used for the creation of the laser generation. Main difference between this scheme and three-level laser is that in the case of three-level laser light is generated due to the electron transition between energy levels $E_2$ and $E_1$ while in the case of the modified four-level laser light generation is obtained after the electron transition between energy levels $E_3$ and $E_2$.

![Scheme of three- and four-levels lasers](image)

Fig. 2.9 Scheme of three- and four-levels lasers. Based on [41]

### 2.3.3. Structure of the semiconductor lasers.

Laser scheme is presented in Fig. 2.10. The laser consists of the gain medium which is placed in the optical resonator. There are different types of the optical resonators used in the lasers. They can be divided into three groups depending on the elements used in the resonators: mirrors, gratings and hybrid combinations of them.
There are two types of the optical resonators which consist of the mirrors. Fabry-Perot cavity consists of two mirrors, which are parallel each other. Ring cavities consist of few mirrors which provide the light to travel inside the active gain medium. In the case of semiconductor lasers cleaved facets are served as the mirrors. They reflect around 30% of the incident light. Such optical resonators as Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) resonators include gratings in their structure. Also there is some energy source, which used to create the population inversion inside the gain medium.

![Fig. 2.10 Scheme of the laser structure [8]](image)

Typically each semiconductor laser has a p-i-n diode structure. It consists of an active region, which is placed within a p-n junction to provide injection of the carriers to the active medium. The active region is usually undoped. Both parts of p- and n- doped parts of the laser are called cladding layers. To inject carriers into the active layers it is necessary to apply forward bias voltage.

Laser structures are usually double heterostructure and they have two heterojunktions inside the structure. The scheme of the energy diagram and the diagram for the refraction index is presented in Fig. 2.11. At the interfaces of the
different materials there are some band offsets for the valence band $\Delta E_v$ and for the conduction band $\Delta E_c$. Such kind of the structure provides confinement of the carriers in the active region. In semiconductors refractive index is usually higher for the materials with the lower bandgap energy. Therefore the refractive index of the active region is usually higher in comparison to the cladding layers. Due to this feature of the semiconductor materials there is also confinement of the light to the active region in this structure. It allows to have structures with a high amplification rate.

![Diagram of a double heterostructure](image)

Fig. 2.11 Double heterostructure: (a) energy of electrons (b) refractive index [41].

In the case of a simple structure of the p-i-n diode, the light is not confined well in the active layers because the thicknesses of doped parts are too small. To improve the confinement of the light inside a laser structure it is necessary to increase the thickness of the doped parts of the laser diode. Material with higher bandgap is uses for this purpose. It allows to have a much better confinement of the light in the active region.
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This type of structure is called Separate Confinement Heterostructure (SCH). The confinement of the carriers into the active region can be improved by using some grading of the bandgap as a part of cladding layers of the SCH structure with higher bandgap. This kind of structure is called Graded index Separate Confinement Heterostructure (GRINSCH). Both structures are presented in Fig. 2.12.

![Fig. 2.12 Band structure of the SCH (a) and GRINSCH (b) structures [42].](image)

2.3.4. Important parameters of lasers.

The most important parameters of the lasers, which used to describe their quality and determine their output characteristics, are presented in this paragraph. Description of the light output versus injected characteristics below and above threshold is presented. The change of the carrier concentration and photon density is described using rate equations. The definition and equations for the threshold gain, the modal gain, the internal losses, transparency current density, internal and external quantum efficiency are given.

The **threshold gain** is the optical gain required for the laser operation. At these conditions the output power is measured and there is no external input power,
applied to the laser. The ratio between the transmitted light intensity and the incident light intensity is [43]:

\[
\frac{I_t}{I_0} = \frac{T_1 T_2 G_s}{(1-G_s/\sqrt{R_1 R_2})^2 + 4G_s/\sqrt{R_1 R_2} \sin^2(n_r k_0 L)}
\]

(1.4.1)

In this ratio \(R_1, T_1\) and \(R_2, T_2\) are the power reflectivity and power transmittance of the both mirrors, \(n_r\) is the real part of the refractive index, \(L\) is the length of the resonator, \(G_s\) is determined by the next equation:

\[
G_s = \exp(gL)
\]

(1.4.2)

where \(g\) is the coefficient of the optical power gain. For the laser operation \(I_0 = 0\) and the denominator in (1.4.1) is zero. Taking this into account the next system of equations can be concluded:

\[
\sin(n_r k_0 L) = 0
\]

\[
1 - \sqrt{R_1 R_2} \exp(gL) = 0
\]

(1.4.3)

Therefore the expression for the optical gain follows:

\[
g = \frac{1}{L} \ln \left( \frac{1}{\sqrt{R_1 R_2}} \right)
\]

(1.4.4)

The right part of equation (1.4.4) expresses the optical losses at the mirrors.

The guided modes are confined to the active layer and therefore they propagate in the optical waveguides. The field of the guided modes penetrates partially in the cladding layers from both sides. Taking into account the optical confinement factors, the optical power gain coefficient and optical power loss coefficients in the n- and p-cladding layers, the optical gain for the optical waveguide can be calculated by the equation:

\[
g = \Gamma_a g_a - \Gamma_a \alpha_a - \Gamma_p \alpha_p - \Gamma_n \alpha_n
\]

(1.4.5)

Here \(\Gamma_a, \Gamma_p, \Gamma_n\) are the optical confinement factors for the active region, p- and n-type cladding layers, and \(\alpha_a, \alpha_p, \alpha_n\) are optical power loss coefficients for
the same regions. The last three terms in the equation (2.2.9) represent the internal losses of the laser structure. The first term is known as modal gain. The modal gain of the Fabry-Perot cavity can be determined by the equations (1.4.4) and (1.4.5):

\[ R_a g_a = \alpha_i + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \]  

By applying a small current a weak emission from the laser diode is observed, which is related to spontaneous emission. Any photons emitted spontaneously into the cavity will experience loss from the mirrors, from the waveguide, as well as from the active region. Photons will therefore not last for long inside the cavity and the photon density inside the cavity will be very small. By increasing the current at a certain critical value a strong increase of the output power from the laser is observed due to the contribution from stimulated emission. This current is called threshold current. Above threshold current all the generated electrons contribute to the stimulated emission. Due to this the carrier density in the laser medium remains constant. The number of photons above threshold current increases linearly. The dependence of the photon number and electron number is presented in Fig. 2.13.

![Fig. 2.13 Dependence of the carrier density (a) and photon density (b) on the injection current [42].](image-url)
Rate equations for the photon density and carrier concentration in the laser are

\[
\frac{dn}{dt} = \frac{J}{ed} - G(n)S - \frac{n}{\tau} \tag{1.4.7}
\]

\[
\frac{dS}{dt} = G(n)S - \frac{S}{\tau_{ph}} + \beta_{sp} \frac{n}{\tau_r} \tag{1.4.8}
\]

Here \( J \) is injection current density, \( n \) is the electron concentration, \( d \) is the thickness of the active region, \( e \) is the elementary charge, \( n \) is the electron concentration, \( \tau \) is the lifetime of the carriers, \( G(n) \) is the amplification rate due to the stimulated emission, \( S \) is the photon density, \( \beta_{sp} \) is the spontaneous emission coupling factor, \( \tau_{ph} \) and \( \tau_r \) are the photon lifetime and the radiative recombination lifetime, respectively.

The rate equation below threshold current is defined by the equation (1.4.9):

\[
\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau} \tag{1.4.9}
\]

From the equation (1.4.9) the expression for the threshold current can be determined:

\[
J_{th} = \frac{ed}{\tau} n_{th} \tag{1.4.10}
\]

Here \( n_{th} \) is threshold carrier concentration. Equation (1.4.10) is satisfied for the injection current up to the threshold current. Threshold current concentration above the threshold current is expressed by the equation:

\[
n_{th} = \frac{1}{\Gamma_{agt} \tau_{ph}} + n_0 \tag{1.4.11}
\]

Substituting (1.4.10) into (1.4.11) leads to:

\[
J_{th} = \frac{ed}{\tau} \left( \frac{1}{\Gamma_{agt} \tau_{ph}} + n_0 \right) \tag{1.4.12}
\]
Other important parameters of the laser diode structures are **internal quantum efficiency**, which is defined as the number of photons emitted into the optical cavity per injected carrier, and **external differential quantum efficiency**, which shows the number of photons emitted outward per injected carrier. The external differential quantum efficiency can be found from the dependence of the output light power on the injection current. It is given by expression:

\[
\eta_i = \frac{\Delta P}{\Delta I} \frac{e}{\hbar \omega}
\]  

\((1.4.13)\)

The first multiplier in this equation is called **slope efficiency** and shows the increase of the total output power of the laser with increase of the injected current.

External differential quantum efficiency can be expressed through the internal quantum efficiency:

\[
\eta_d = \eta_i \frac{\ln \frac{R_1 R_2}{2 \alpha_i L + \ln \frac{1}{R_1 R_2}}}{2 \alpha_i L + \ln \frac{1}{R_1 R_2}}
\]  

\((1.4.14)\)

By substituting (1.4.4) into (1.4.14) the equation for the inverse external differential quantum efficiency is obtained:

\[
\frac{1}{\eta_d} = \frac{\alpha_i}{\eta_i \ln \frac{1}{\sqrt{R_1 R_2}}} L + \frac{1}{\eta_i}
\]  

\((1.4.15)\)

As can be seen from the equations (1.4.6), (1.4.13), (1.4.14) and (1.4.15) the modal gain, internal quantum efficiency and absorption of the laser structure are dependent from the cavity length. These values can be obtained from the measurements of the laser structures with different cavity lengths. After the measurements the values of these laser parameters can be found from linear interpolations of the experimental values.
The **transparency current density** $J_{th0}$ is the minimal current density at which the material becomes transparent for any photon with energy larger than bandgap. This value is connected with the threshold current by the equation:

$$J_{th} = \frac{J_{th0}}{\eta_i} \exp\left(\frac{2}{\Gamma a g_0} \left(\alpha_i + \frac{1}{2L} \ln \frac{1}{R_1 R_2}\right)\right)$$  \hspace{1cm} (1.4.16)

From this equation the expression for the threshold current follows:

$$\ln(J_{th}) = \ln\left(\frac{J_{th0}}{\eta_i}\right) + \frac{2\alpha_i}{\Gamma a g_0} + \frac{1}{L \Gamma a g_0} \ln\left(\frac{1}{R_1 R_2}\right)$$  \hspace{1cm} (1.4.17)

By the linear fitting of the dependence of the threshold current as a function of the inverse cavity length the transparency current density is determined. Supposing the cavity length is equal to infinity the threshold current density of the laser can be calculated without mirror losses.

### 2.3.5. Dynamical properties of lasers

Applied current modulation changes operating characteristics of the laser diodes. Solution of the rate equation shows that current modulation leads to modulation of photon density and carrier density. Modulation of carrier density leads to modulation of the gain and refractive index of the active region. This leads to modulation of resonant mode frequency and output power of the laser. Frequency modulation is not desirable for intensity modulation applications because of broadening of the modulated spectrum of the laser [42]. Nonlinear changes of carrier and photon densities take place during large signal modulation. The presence of nonlinear effects limits application of laser diodes also in other applications [44] – [46]. In this section dynamical properties of semiconductor lasers are described.
The dynamical properties of the lasers are investigated by applying a pulsed current. The length of the pulse is larger than the carrier lifetime. The bias current is lower than the threshold current. After applying the current to the laser the concentration of the carriers increases starting from the bias value and reaches the threshold carrier concentration. The time at which the carrier concentration reaches the threshold value is called turn-on delay time. At this point the carrier concentration and the photon density show relaxation oscillations. It is shown in Fig. 2.14 (b) and (c) [43].

By using the rate equation the turn-on delay time can be determined. From the equation (2.2.13) and the modulation current density the current density can be described in the form

\[ J = J_p u(t) + J_b \]  

(1.4.18)

\[ u(t) = \begin{cases} 
0 & (t < 0) \\
1 & (t \geq 0) 
\end{cases} \]  

(1.4.19)

After mathematical transformation the turn-on delay time is described by the equation [42]:

\[ t = \tau \frac{J - J_b}{J - J_{th}} \]  

(1.4.20)

Here \( \tau \) is the lifetime of the carriers, \( J_b \) is the bias current density, and \( J_{th} \) is the threshold current density.
For lasers, which generate high-speed signals, the turn-on delay time is short. From equation (1.4.20) one can conclude that lasers with a long carrier lifetime, a large bias current density and a low threshold current can be suitable for high-speed applications.
The oscillation frequency can be calculated by using the relaxation oscillation. The change of the carrier concentration and photon density can be found from the small signal analysis. The carrier concentration, photon density and current density can be expressed as a sum of their value in the steady state and increased part, which is much smaller in comparison to the steady state values.

The rate equations for the changed part of the photon density and carrier concentration are [42]:

\[
\frac{d}{dt} \delta n = \frac{\delta I}{ed} - \frac{\delta S}{\tau_{ph}} - \Gamma a_{0}S_{0} - \frac{\delta n}{\tau} \\
\frac{d}{dt} \delta S = \Gamma a_{0}S_{0} \delta n
\] (1.4.21)

(1.4.22)

Using the equation (1.4.21) and (1.4.22) the relaxation oscillation on the deviation of the photon density can be defined:

\[
\frac{d^2}{dt^2} \delta S + \left(\Gamma a_{0}S_{0} + \frac{1}{\tau}\right) \frac{d}{dt} \delta S + \frac{\Gamma a_{0}S_{0}}{\tau_{ph}} \delta S = \frac{\Gamma a_{0}S_{0}}{ed} \delta I
\] (1.4.23)

From the equation (1.4.23) the decay coefficient and the oscillation angular frequency can be expressed as:

\[
\gamma_0 = \Gamma a_{0}S_{0} + \frac{1}{\tau} \\
\omega_r^2 = \frac{\Gamma a_{0}S_{0}}{\tau_{ph}}
\] (1.4.24)

(1.4.25)

The relaxation oscillation frequency can be found from the equation (1.4.25).

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{\Gamma a_{0}S_{0}}{\tau_{ph}}}
\] (1.4.26)

The equation can be rewritten using the current density. By using the equations (1.4.10) and (1.4.11) the decay coefficient and the relaxation oscillation frequency can be written as:
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\[ \gamma_0 = \frac{1}{\tau} \frac{J - J_0}{J_{th} - J_0} \]  

(1.4.27)

\[ f_r = \frac{1}{2\pi} \sqrt{\frac{1}{\tau_{ph} \tau} \frac{J - J_{th}}{J_{th} - J_0}} \]  

(1.4.28)

Here \( J_0 \) is the current density at which the material is transparent.

For the high speed signals the optical pulses have to return quickly to the steady state during the modulation of the semiconductor laser by injection current. Therefore the relaxation oscillation frequency and the decay coefficient have to be large. From the equation (1.4.25) and (1.4.26) it can be concluded that the small values of the lifetime, the carrier lifetime and large differential gain are necessary for the high-speed signal generation. Quantum well and quantum dots satisfy such conditions and can be used for high-speed telecommunication applications.

Due to the change of the carrier concentration during relaxation oscillations the optical gain and the refractive index of the medium change also. Change of the optical gain leads to multimode laser operation during the relaxation oscillation. The number of the relaxation oscillation decreases in the case of multimode laser operation. The change in the refractive index leads to deviations of the position of the longitudinal modes from the steady state values. This dynamic change of the wavelength position during modulation of refractive index is called “chirping”. As a result of chirping the linewidth of the light output spectra become broadened. The multimode operation and chirping are not desirable for optical fiber communication systems because of the dispersion in the optical fibers.

Physically, the chirp is determined by coupling of the real and imaginary parts of the susceptibility of the laser medium. To define the coupling strength a “linewidth enhancement factor” (LEF) was implemented, which is defined in the form [3]
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\[ \alpha = \frac{\frac{\partial \chi_{real}}{\partial N}}{\frac{\partial \chi_{imag}}{\partial N}} = \frac{-4\pi}{\lambda} \frac{dn}{dN} \frac{dg}{dN} \]  \hspace{1cm} (1.4.29)

Here \( \chi_{real} \) and \( \chi_{imag} \) are the real and imaginary parts of the material susceptibility, \( n \) is the refractive index of the material, \( g \) is the material gain. LEF can be calculated from the gain spectrum of the laser using the Kramers-Kronig relation. The lower value of the LEF means that the chirp of the laser will be also lower. In the best case LEF has to be equal to zero. The theoretical calculations shows, that quantum dots samples with Gaussian energy distribution has a symmetrical spectrum around the energy of the gain peak [3].

As a result the change of the refractive index around the lasing wavelength is zero. The real distribution of the energy levels in a quantum dots sample differs from the theoretically predicted one and this leads to non-zero values of the LEF. In spite of this fact the values of the LEF for semiconductor lasers, based on quantum dots, is 5 times less than the LEF for lasers, based on quantum wells [3]. This shows, that the quantum dots based semiconductor lasers with ideal energy distribution of quantum dots can be operated without chirp, which makes these lasers ideal for the data transmission in wavelength division multiplex (WDM) networks.

For the transmission of signals through optical fibers modulated signals are used. For the encoding of the signals either intensity modulation formats (e.g., NRZ = non return to zero) or phase shift keying (like QPSK = quadrupol phase shift keying) are used, where phase and amplitude are independently modulated in so-called coherent systems. The signal modulation can be performed by laser (direct modulation) or by external sources (external modulation). The intensity modulation system is more simple and cheap in comparison to the coherent system. The disadvantage of this system is that there is a big decay of the signal during the transmission over long distances. In this case it is necessary to use semiconductor optical amplifiers to provide long-haul signal transmission. In the
coherent system there are two lasers with the requirements to have narrow spectral linewidth and the same polarizations.

In direct modulation of the semiconductor lasers the signal modulation is provided by injection current in the semiconductor lasers. In this case chirping, multimode operation and turn-on delay time appear. In the external modulation of the lasers the injection current is kept constant and the laser beam is modulated by an external optical modulator. There are no relaxation processes in this system and no multimode operations or chirp inside the laser, but there is some chirp inside the optical modulator. In the optical modulator the amplitude of the refractive index changes only little in comparison to the amplitude in a laser and this leads to a lower chirp value in those systems.

There are two possible types of modulations in the directly modulated semiconductor lasers. In the case of the analog modulations the change of the injection current is transformed into the modulation of the light intensity. Analog modulation allows transmitting more data in comparison to the digital modulation, but can be easily affected by distortion of optical signals during the transmission. Therefore it is not suitable for the transmission of the information over long distances. In the case of digital modulation the presence and absence of the light intensity is assigned to the “1” and “0” signals. The change between the signals is provided by applying of the current to the semiconductor laser. This modulation method is also known as “on-off keying”. The signal modulated by digital modulation is less affected to the distortion during the transmission and can be used for the transmission over the large distances.

The width of the pulse during the modulation of the signal depends on the speed of the data transmission. In the case of high speed bit rates the width of the pulse is in the order of nanoseconds. In this case the system will not reach steady state during the pulse. As a result carriers are generated due to the previous optical pulse. The presence of the carriers from the previous pulse leads to the
modification of the turn-on delay time. This on the other hand leads to the
decreasing of the receiver resolution and to inability to use this laser for signal
modulation. Large signal modulation is used for the analysis of digital signal
transmission. For this purpose an optical signal is formed by superimposing of
an optical signal with a reference electrical signal. This generated optical signal
looks like an eye, which is called “eye pattern”. The analysis of the transmitted
signal shows, that this semiconductor laser can be used for a given data bit rate.

2.3.6 Structure of the ridge waveguide and single mode
lasers.

There are two possible designs of the laser structure, which provide the
possibility to emit light in different directions in comparison to the direction of
the injected current. When the laser emit in direction parallel to the injected
current we have a Vertical Cavity Surface Emitted Laser (VCSEL) while the
lasers, which emit perpendicular to the injected current are called edge-emitting
lasers.

All the lasers, which are investigated in this work, are edge-emitting lasers. As
was mentioned above for the first measurements broad-area lasers are used.
Improvement of the properties of lasers can be achieved in different ways. The
first type of the laser designs is called stripe laser. The idea of this laser type is
to leave only some stripe with the contacts. It can be achieved by etching of the
grown wafers. Due to high difference between the laser material and the air
there is a strong optical confinement of the light in the lateral direction. Due to
the possibility of the oxidation of the facets and as a result number of the defects
are generated it is possible to replace the etched material by other semiconductor
material. In this case the number of the generated defects is reduced, but the
optical confinement is worse due to lower difference between the laser material
and the material, which will be deposited. The next step of the improvement of the optical confinement was to decrease the injection time for the carriers. Therefore the thickness of the contact layers should be done as thick as possible. Also there is no necessity to etch a complete structure but only the top cladding layer before the active layers. It makes possible to protect the active region from the formation of additional defects. The obtained structure is called Ridge-Waveguide (RWG) Laser. Scheme of this laser is presented in Fig. 2.15.

This type of structure is easy to modulate at high speed. The main disadvantage of this type laser is the lateral restriction of the injected current which makes them not usable for the high-power applications. Also at high injection currents multimode operation can appear, which is not desirable. Also the optical field profile as well as refractive index profile in RWG lasers may change with power level. It is necessary to make design of the RWG laser, which allows lasers to work over the entire range of required power.

In the case of the Fabry-Perot cavity several longitudinal modes are amplified within the cavity. Therefore lasers with this type of resonator emit light at several wavelengths. But for different applications it is necessary to have lasers
with only one emission wavelength. However, it is possible to suppress the undesirable modes by using feedback gratings instead of mirrors. The emission wavelength is defined by the period of the grating, which is used by the following expression:

\[ m\lambda = 2n_e\Lambda \]  

(1.4.30)

Here, \( n_e \) is effective refractive index and \( \Lambda \) is the period of the grating.

If gratings are added in one or both sides, those lasers are called Distributed Bragg Reflector (DBR) lasers. Here gratings serve to filter out all the wavelengths except the wavelength, which corresponds to the reflected wavelength due to Bragg reflections. This wavelength can be determined by equation (1.4.30). The current is injected through the ridge section of the laser. It is possible to change the emission wavelength by applying an additional current to the grating section. The scheme of the DBR laser is shown in Fig. 2.16 (a).

The second possibility is to make the grating section along the active region. This design is called Distributed Feedback (DFB) laser. In a standard DFB laser the active cavity length is the same along all grating and equal to a quarter-wavelength long. Configuration with a half-wavelength mirror spacing, which corresponds to a quarter-wave shift between two gratings, is called “quarter-wave shifted DFB laser”.

Fabrication of DFB lasers is complicated, expensive and time-consuming process. The process of the fabrication of the typical DFB laser include growth of good laser structure by methods of epitaxial growth, etching of grating with defined period below or above the gain region, overgrowth of etched grating to complete the guiding structure followed by formation of the ridge structure or buried heterostructure [48], [49]. Big disadvantage is necessity to provide the cleaning of the sample surface after each step [50]. The grating can be done after the growth of active region or during the processing of the laser after the growth.
The second method is simpler, because there is no necessity to make a growth stop as in the first case. Electron-beam lithography is favorable technique to make the grating. Advantages of this technique are greater resolution in comparison to optical lithography method and possibility to fabricate more complex structures. The main disadvantages of this process are the high cost and the time-consuming [51]. Another possibility is the realization of the grating by holographic lithography [52], [53]. Fabrication of ridge guide includes deposition of the insulator on the top surface of the laser structure. Windows in the insulating layer are made then by photolithography. Evaporation of the metal p-type contact completes the device structure. DFB lasers can also include metal gratings made by lithography [50] – [55]. The presence of the metal gratings has some disadvantages. The light absorption in the metal is non-saturable, what deteriorates the laser properties. It is possible to improve the properties of the processed lasers by replacing of the gratins material from the metal by dielectric or semiconductor. One possibility is to use the material, which is different from the material of the laser structure. For example, the SiO$_2$ grating on InP [56] or Si$_3$N$_4$ grating for (Al, Ga, In)N system [57]. The possible realization of the semiconductor gratings is the deep etching of the grown laser structures [58] – [60]. The last method is used for fabrication of the DFB lasers, presented in this work.

During the operation of a standard DFB laser the Bragg wavelength is not allowed for propagation. Light with the wavelength, which is given by equation (1.4.30), is reflected and amplified. The light with other wavelengths is transmitted and not amplified. Two modes should be equally emitted during the operation of standard DFB laser. Additional reflections can be used to suppress an unwanted emitted wavelength. The mode selection is dependent on phase of the reflection from the cleaved facet. It makes the process of the DFB laser tricky and unreproducible. The scheme of the DFB laser is shown in Fig. 2.16 (b).
Fig. 2.16 Different types lasers with gratings: (a) DBR laser (b) DFB laser (c) external cavity laser
There is also the possibility to use an external grating together with a Fabry-Perot resonator. These lasers are called “external cavity lasers”. These types of lasers cold be optimized for very narrow-line (less than 1 MHz) continuous output [47]. In this case the emitted light is transmitted to the grating. Reflected light is then transmitted again inside the laser. Therefore the amplification of the light with wavelength defined by the grating period is much higher in comparison to other emitted wavelengths. The scheme of the external cavity laser is shown in Fig. 2.16 (c).
Chapter 3

Growth of QDs structures

In this chapter the results regarding the growth conditions of QDs structures and lasers, based on these QDs as an active media, will be presented. At the beginning the system used for the growth of the QDs samples will be described. Then the discussion will continue with the description of the optimization procedure of the growth conditions for the QDs formation. Finally the structures and growth conditions for the lasers based on the QDs samples will be presented.

3.1 QDs for telecommunication applications.

Historically the first substrates used for the investigation of the growth conditions for the preparation of the semiconductor lasers are GaAs. Nowadays growth process and growth conditions for this system are the most studied. The availability of a material, such as AlAs, with very small difference in the lattice constant to GaAs makes the growth of the semiconductor laser structures easier. The reason is the possibility easily to vary the bandgap of the ternary material by changing of Al composition. The small difference in the lattice constants allows fabricating perfect interfaces without defects between GaAs and Al$_x$Ga$_{1-x}$As for
every composition of the ternary material. As an active region it is possible to use InAs for the quantum dot formation. Difference between the lattice constants of GaAs and InAs is 7.2% and in this system the formation of the round shaped quantum dots with high density can be easily achieved. To compensate the losses inside the QD semiconductor lasers it is necessary to have enough gain. Usually a few layers of QDs are used to increase the output power of the lasers. A high enough density of QDs allows increasing the output power of a single QD layer. As a result the number of the QD layers can be decreased.

On the other side the high strain limits the formation of big dots, which can be used for the growth of the samples for emission wavelengths of 1.3 or 1.55 µm, which are usually used for telecommunication applications. Usually the emission wavelength of the InAs quantum dots grown on GaAs is limited up to 1.2 µm. By using different approaches it is possible to extend the emission wavelength to 1.56 µm. One way is to use small growth rates, which allows to form the quantum dots with bigger sizes [61]. Another possibility is to use bandgap engineering. Bandgap engineering is the process based on the controlling or altering the band gap of a material by controlling the composition of certain semiconductor alloys. It is found that implementation of the quantum dots in the material with smaller band gap allows to shift the emission wavelength to higher values. If the material with larger band gap is used the emission wavelength will be shifted to smaller values. In the case of InAs/GaAs system it is possible to grow quantum dots incorporated in the InGaAs quantum wells. Depending on the composition of the quantum wells the emission wavelength of 1.56 µm was achieved [62]. To expand the emission wavelength of the InAs/InGaAs/GaAs system it is necessary to increase the amount of indium in the quantum wells [63]. But this leads to the formation of non-radiative recombination centers [64]. As a result the optical quality of the quantum dots will rapidly degrade [62]. Also the increase of the threshold current of the lasers was observed [64], [65]. Another way is to use quaternary
3. Growth of the QDs structures

materials like InGaNAAs or InGaSbAs instead of an InGaAs barrier layer. But it will make the growth more complicated and decreases the optical quality of the quantum dot structures [66], [67].

Another possibility is to grow InSbAs quantum dots on an InP substrate. In this case it is also easy to achieve the formation of round-shaped quantum dots due to the large lattice mismatch. But the semiconductor lasers based on this quantum dots have shown much worse efficiency and they cannot be used for high-power applications. Also the temperature changes have big influences on the properties of these lasers [68].

Usually for the application in devices with the emission wavelength of 1.55 µm InAs quantum dots grown on InP substrates are used. In comparison to the InAs/GaAs system the growth of such a system is more complex. As it is shown by other groups, there is the possibility to incorporate different nanostructures in this material system, such as quantum wires [69], [70], elongated QDs or quantum dashes [71], [72] and round-shaped QDs [73]. Examples of the different structures are presented in Fig. 3.1.

![AFM pictures for the quantum wires, quantum dashes and quantum dots.](image)

There are many physical principles involved in the process of the formation of different InAs structures grown on the InAl(Ga)As buffer layer. The most
important factors are the anisotropic strain field on the InAl(Ga)As surface and the phase separation, which cause a morphological undulation [74], [75]. It is known that InAl(Ga)As alloys can generate phase separation during the growth, which leads to a partial relaxation of the intrinsic strain energy. Due to the phase separation also an anisotropic strain on the surface can arise. The surface of the InAl(Ga)As grown at normal As-rich condition has a (2x4) reconstruction surface and contains the As-dimers and ridges. The orientation of them for (2x4) reconstructed surface is [-1 1 0]. The strain in this direction is less than in perpendicular one and the migration length for the In adatoms is larger in the direction [-1 1 0] [76]. In the case of the InAs growth under As-lacking conditions the strain on the surface is less in the direction [1 1 0] [77]. In this case the elongation of the quantum dot will take place in this direction. Formation of the round-shaped InAs quantum dots by changing the growth conditions from As-rich to As-lacking during the growth of the buffer layer is demonstrated [78].

Another possibility is to use InGaAsP quaternary instead of InAl(Ga)As. But in this case it is necessary to have precise fluxes of the elements group V due to the difference in the sticking coefficients for As and P atoms. It makes the growth more complex, especially for the growth of the laser structures.

The quantum dash sample shows a behavior similar to quantum wires. Also these structures show worse optical properties in comparison to round-shaped quantum dots. Typical values of the full width on half maximum for quantum dashes are usually in the range of 50 – 100 meV [69], [79]. At the same time samples with round shaped quantum dots shows reduced values of 30 – 50 meV [80], [81].

One of the growth parameter, which has a big influence on the formation of InAs quantum dots, is the substrate temperature. The formation of the QDs occurs in the big range of growth temperatures from 430 °C up to 590 °C.
3. Growth of the QDs structures

[82] – [84]. The QDs with the best optical and morphological properties could be grown when the substrate temperature is in the range of 490 °C up to 520 °C [84], [85].

Another important growth parameter for the dot formation is the beam flux ratio of the elements group V to elements group III (V/III ratio). It is shown that the As flux plays big role in the process of the nanostructure formation on misoriented substrates. Growth of the QDs at high As flux leads to low density round shaped quantum dots. In the case of low As flux the formation of elongated quantum dots (quantum dash) is observed. Orientation of the substrate plays crucial role on the quantum dots shape [72]. The formation of the smaller quantum dots with high density on the high index InP (311) at lower As flux is also observed. The density of the quantum dots decreases significantly after increasing the As flux. The formation of quantum dots with bigger sizes at high As fluxes is also observed [85]. The formation of the round shaped quantum dots on the InP (001) substrates is demonstrated by using the As$_2$ species during the dot formation [87].

Another approach to prevent the formation of the quantum dashes is to use high index InP substrates [85]. The formation of high density round shaped quantum dots on the InP (113) substrates is demonstrated for the application as an active region of the laser diodes. This type of the substrates has more steps which can be described as additional defects on the substrate surface and therefore they behave as centers of the quantum dots formation. The main problem with the tilted substrates is that they are not fully compatible with the technology as the normal substrates. Due to this reason they are not widely used in the industry. Another way is to use misoriented InP substrates along the direction [0 0 1]. This substrate also has a big amount of steps, which change the migration length of the In adatoms on the surface. As a result the formation of the high density quantum wires or dots can be achieved. The growth process of the InAs QDs on
misoriented InP substrates and the influence of the growth conditions on the QDs formation is described in different published works [88], [89].

The possibility to grow round-shaped quantum dots by using of low growth rates for InAs is demonstrated [61]. On the other side it is shown that decreasing of the InAs growth rate can significantly change the density of the quantum dots. It is established, that the dependence of the density of the quantum dots on the InAs growth rates is linear [90]. It is also demonstrated that the growth rate of the cap layer has a big influence on the density and sizes of quantum dots. It is found that at lower growth rates the size of the quantum dot decreases and the density of the quantum dots decreases [91].

A big influence of the arsenic species on the QDs formation during the growth of InAs QDs on InP substrates is observed. A simple method for the control of the morphological properties of the QDs in this system is demonstrated [87], [92]. The formation of the QDs by applying of the As$_4$ and As$_2$ species is investigated. It is shown that the formation of the elongated QDs took place by applying of As$_4$ molecules and the growth of the round shape occurs immediately after the switching to the As$_2$ molecules. The observed behavior can be explained by using the following mechanism: it is known from the investigations of the growth process that only arsenic atoms can be physically adsorbed and incorporated into the lattice constant. After the As$_4$ or As$_2$ molecules reach the surface, they dissociate to the arsenic atoms, which form chemical bonds. Therefore As$_2$ molecules dissociate to two arsenic atoms. The dissociation to the atoms in the case of As$_4$ molecules includes two steps: dissociation of the As$_4$ molecule into two As$_2$ molecules and dissociation of each As$_2$ atom into two As atoms.

The migration length of the group III atoms in this case increases. InP substrates have an additional feature. It is established that the migration length of the atoms on the surface is different in different directions. Therefore the formation of the
3. Growth of the QDs structures

elongated nanostructures is preferable in some directions. Taking into account
the properties of the InP substrates and the additional step during the
incorporation of the As atoms in the lattice the formation of the QDashes in the
case of As$_4$ and QDs in the case of As$_2$ can be explained.

It is very important to find the condition for the formation of homogeneous
round-shaped quantum dots, which can be used as an active material for laser
diodes. As it was shown in Chapter 2, the linewidth enhancement factor is the
smallest in the case of ideal quantum dots. This means that the dynamical
properties of the semiconductor lasers based on the elongated quantum dots will
be much worse and it will limit using these lasers for high-speed data
transmission. Therefore the influence of different growth parameters is
investigated in order to obtain the optimum conditions for the formation of
different types of the nanostructures in this system.

Low efficiency and size fluctuation of the quantum dots create some difficulties
for their applications as an active element of laser diodes. Usually it cannot be
collected enough gain from one layer of quantum dots to overcome the losses
inside the laser. To overcome the problem with low efficiency it is necessary to
grow few stacked layers divided by barrier material. It is found that up to the
critical thickness of the barrier material the quantum dots are vertically aligned
and their size increases with every following layer [93], [94]. For the buffer
thicknesses higher than this critical thickness there is no alignment. Vertical
alignment is provided due to the residual tensile stress from quantum dots which
cannot be compensated by growth of the thick barrier material between the
different quantum dot layers. The number of QDs layers is also limited because
the residual stress leads to decrease the quality of the crystal lattice and at
critical number of dot layers a lot of defects appear in the barrier layers, which
decrease the quality of the laser structures. To improve the homogeneity of the
quantum dots sizes in different layers the thickness of the layer between the
3.1. QDs for telecommunication applications

Quantum dot layers is decreased [95]. On the other side a thick spacer is not desirable for the application in the laser diodes because it deteriorates the dynamical properties of the lasers. Another technique for the improvement of the quantum dots properties is to use short time annealing at higher temperatures [96]. It is found that both approaches showed improvement only for the samples with a small number of quantum dot layers. Increasing the number of quantum dot layers leads to increased strain and as a result to the growth of quantum dots with degraded properties. To increase the number of the stacked quantum dot layers it is proposed to use the spacer layer, which compensates the strain. In the case of InAs quantum dots grown on InP substrates it is possible to use In$_{1-x-y}$Ga$_x$Al$_y$As material because it allows to compensate the strain for any number of quantum dot layers by changing of the lattice constant of the spacer. High homogeneous quantum dots with a high density of 10$^{12}$ cm$^{-2}$ were obtained using the strain-compensated layers between the quantum dot layers [97].

3.2 Growth of quantum dot samples.

All the samples are grown by solid source molecular beam epitaxy (MBE). For the growth the commercial setup Veeco Varian Gen II MOD was used.

For the generation of the gallium and indium fluxes Sumo effusion cells are used. The material with high purity is loaded into the cell and the flux of the material is obtained by heating of the cells. The precise control of the flux is achieved by control of the cell temperature during the growth. To prevent the formation of material droplets on the front parts of the crucible, the front part of the cell is heated by the second heater. Formation of the droplets leads to the formation of additional oval defects on the sample. 30 - 40% of the total power was used for heating the material while the remaining power was used to heat the top part of the cell.
3. Growth of the QDs structures

For the supply of group V elements special valved cracker cells are used. The advantages of this type of cells are the possibility to provide a precise control of the beam flux and the low partial pressures of the group V elements inside the growth chamber when the valves are closed. The flux of the materials from these cells is controlled by setting the internal cell valve. This cell allows to change the flux of the element rapidly. This leads to the growth of the structures with the desired properties. It is very important for the growth of the complicated structures and for the growth of the quaternary materials, which should be lattice-matched to InP. Small changes in the material fluxes during the growth of $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ results in large changes of the lattice matching condition.

The source material inside the arsenic cell is maintained at the same temperature. A high-temperature operated cracker zone is used to crack the sublimated $\text{As}_4$ to $\text{As}_2$ molecules. When the cracker is heated up to 800 °C, the flux consists of $\text{As}_4$ atoms. At temperatures higher than 800 °C, atoms of mainly $\text{As}_2$ are generated.

Phosphorous exist mainly in two modifications – red phosphorous and white phosphorous. Usually for the growth of the phosphorous containing materials the white phosphorous is used. But phosphorous in this modification is very reactive. With contact to air it is highly pyrophoric and very toxic. White phosphorous can be obtained by the heating of the red phosphorous at temperatures above 250 °C. Initially the red phosphorous is loaded into the cell and the necessary amount of the white phosphorous is obtained after heating. Only a small amount of the white phosphorous is converted from the red phosphorous because it was observed that the quality of the grown material is deteriorated after conversion of a large quantity of white phosphorous. Similar to the arsenic cell the $\text{P}_4$ molecules are obtained with a cracker temperature below 800 °C while mainly $\text{P}_2$ molecules are generated at higher temperatures.
3.2. Growth of the quantum dot samples

All the samples are grown on InP (100) substrates doped by sulphur. To improve the optical properties of the QDs the influence of different growth parameters on the QDs formation are investigated. Optimized QD structures are used as an active material for the growth of semiconductor lasers. Typical growth rates are near 1 µm, what correspond to about 1 ML per second.

It is shown that the round-shaped quantum dots are perfect candidates to be used in high-speed lasers for telecommunication applications [4]. Their small size provides three-dimensional confinement of the carriers. Formation of discrete states allows to achieve superior properties in QD lasers, such as low threshold current, low temperature sensitivity and small chirp [98] – [103]. These properties make QD lasers the best candidate for application to provide high-speed data transmission.

A cross-section of the QD sample used for the optimization of the growth conditions is presented in Fig. 3.2. At the beginning an InP buffer layer with a thickness of 100 nm is grown. It is well known, that the most consistent sources of the deep-level impurities during the growth on GaAs are the used substrates [16]. Growth of the buffer layer allows to reduce the amount of unintentional impurities, which can deteriorate optical properties of the grown samples. Then the first layer of QDs is formed. This layer of QDs is used for the investigation of the optical properties of the QDs by photoluminescence (PL) spectroscopy. All QDs are grown on an In$_{0.528}$Al$_{0.238}$Ga$_{0.234}$As surface, which is lattice-matched to InP. The composition of the quaternary layer is chosen to have a bandgap of 1.1 eV. The QDs are then covered by an InP layer with a thickness of 100 nm. To allow morphological investigations by atomic force microscopy a second layer of QDs is grown on top.

Prior to the growth the sample has to be cleaned by removing adsorbed materials and the native oxide layer from the surface. The oxide desorption was performed in two steps. The main part of the contamination was removed in the buffer
3. Growth of the QDs structures

chamber by heating of the sample to 300 °C. The oxide layer is removed into the growth chamber in phosphorous atmosphere. Oxide desorption is done by heating of the sample to 490 °C for 5 minutes [104].

![Sample structure for the optimization of the growth conditions of quantum dots](image)

Fig. 3.2 Sample structure for the optimization of the growth conditions of quantum dots

The substrate temperature during the growth of the InP layers is 460 °C. The growth temperature for the QD formation varies from 480 °C up to 530 °C. It was observed that a growth interruption has a bad influence on the optical properties of the QDs [92], [105]. Therefore the growth process is optimized to avoid growth interruptions. However, during switching between phosphorous to arsenic containing materials a growth stop is needed.

The investigations regarding the influence of the substrate temperature, equivalent beam pressure of group V elements and growth rates on the QD formation is described in the next paragraph.
3.3 Influence of growth conditions on the QD formation

The condition for the growth of the QDs sample has to be optimized in order to obtain the sample with the suitable properties for the application as an active element of semiconductor lasers. Increasing the density of QDs leads to an increase of the modal gain of semiconductor lasers. Bigger dots have a lower energy separation between the QD electronic sublevels and results in reduced laser performance at room temperature [72]. One of the very important characteristics of a QDs sample is the size homogeneity of the QDs. It allows to improve the quality of the semiconductor laser, such as temperature stability, higher modal gain, lower threshold current, narrow laser linewidth. In this manner the optimization of the growth conditions is performed in order to improve the optical quality of the QDs samples. The influence of the growth parameters, such as, the equivalent beam flux pressure, the nominal thickness of the deposited material for dot formation, the substrate temperature, the growth rates and the composition of the buffer layer on the structural and optical properties is investigated by changing one of the parameters while keeping the remaining ones constant.

3.3.1. Equivalent beam flux pressure

The equivalent beam flux pressure has a big influence on the growth process. The growth is performed in an overpressure ambient of group V materials. The main reason is the necessity to compensate the arsenic desorption from the sample surface, which leads to a surface destruction and formation of group III clusters. Depending on the group V flux a group V-rich and a group III-rich
growth conditions are distinguished. The growth of samples under group V-lacking conditions is not desirable due to the formation of additional defects and deterioration of the optical properties of QD samples.

In the same way the dependence of the morphological properties on the equivalent beam pressure can be explained. AFM pictures for the QD samples grown at different equivalent beam flux pressures are presented in Fig. 3.3. It is observed the formation of the elongated structures in the case of low equivalent beam pressure of 7.5. Increasing the equivalent beam pressure to 15 leads to the formation of some mixture of elongated QDs and some amount of round shaped QDs. Further increase of the equivalent beam flux pressure leads to the formation of an ensemble of more round-shaped QDs. The increasing of the equivalent beam flux pressure decreases the migration length of the atoms on the sample surface. As a result the formation of the round shaped QDs is observed at high equivalent beam flux pressure [92].

![AFM pictures for the samples with V/III ratio of: (a) 7.5 (b) 15 (c) 30. Scan size is 1µm·1 µm](image)

As it was mentioned before the round shaped QDs have favorable optical properties for the application as an active element of semiconductor lasers. Therefore the samples grown with As$_2$ species were used for further
3.3 Influence of the growth conditions on the QDs formation

optimization of the growth conditions. Also the values in the range of 20 – 30 are preferable to form the QDs with better structural and optical properties for the next applications in the active region of semiconductor lasers.

3.3.2 Nominal thickness of QDs.

The next parameter, which has an influence on the dot formation, is the nominal thickness of the deposited material necessary for the formation of QDs. The variation of the nominal thickness of the material for the QDs formation leads to the change of their structural parameters (height and lateral sizes). It is well known, that the shape and size of the QDs has a strong influence on their emission wavelength due to the change of the structure of the energy levels in the quantum dots. Parallel to the shift of the emission wavelength the optical quality of the quantum dots changes also [106]. It was already shown that samples with a nominal thickness of the material deposited for quantum dot formation higher than the thickness of 2D/3D transition have very good optical quality. The best properties are obtained for the sample with 4 MLs of InAs quantum dots. Peaks of the PL spectrum, which correspond to the main transition are at 1.55 µm and have a full width at half maximum (FWHM) value of 22 meV [106].

In case of InAs QDs grown on AlGaInAs surface lattice matched to InP substrates the formation of the QDs starts after the deposition of 4 MLs of InAs. In the current experiments the nominal thickness of the material for QDs formation is changed in the range of 4.5 – 6.5 MLs. AFM pictures of the samples grown with different amount of nominal material for quantum dots formation are shown in Fig. 3.4. It is clearly seen that increasing of the nominal thickness of the QDs leads to big changes in the morphological properties of the
3. Growth of the QDs structures

QDs. It is observed a formation of the elongated QDs (QDashes) for the sample with 4.5 MLs InAs QDs. On the other side with increasing the nominal thickness of the deposited material, the length of the QDashes decreases. Formation of the round QDs is observed for the sample with 6.5 MLs InAs QDs. It is also observed changes of the QDs height and lateral sizes. An increase of the amount of material for the QDs formation leads to the formation of QDs with larger heights.

![AFM pictures of the samples with different nominal thickness of the material for quantum dots formation: (a) 4.5 MLs (b) 5 MLs (c) 6.5 MLs. Size of the scans is 1µm·1 µm.](image)

The density of the QDs also changes with the change of the QDs shape and sizes. Initially there is a slight decrease of the QDs density. However the density of the QDs again increases and reaches near the same value for the QDs with 4.5 MLs and 6.5 MLs of InAs QDs.

The changes in the optical properties of the grown QDs follow the change of their morphological properties. PL spectra of the sample, which are presented in Fig. 3.4, are shown in Fig. 3.5. The emission wavelength shifts to the higher emission wavelengths and this behavior is a sequence of the increase of the QDs height. It is also observed an improvement of the PL linewidth for the sample
with bigger amount of the deposited material. Values at FWHM decrease from 89 meV to 33 meV. These values correspond to the sample with 4.5 ML and 6.5 MLs of InAs QDs. The improvement in the optical properties can be explained by the improved size uniformity of the QDs and better 3D confinement of the carriers in the case of round shaped QDs.

![Fig. 3.5 PL spectra of the samples with different nominal thickness of the material for quantum dots formation: (a) 4.5 MLs (b) 5 MLs (c) 6.5 MLs.](image)

It is found that an increase of the nominal thickness of the deposited material for QDs formation leads to the formation of the more uniform QDs with better...
optical properties. However the emission wavelength shifts with the increase of the nominal thickness of the QDs. The emission wavelength of 1.55 µm was observed for the sample with 4.5 ML of InAs QDs.

3.3.3. Growth temperature

The substrate temperature is one of the key parameter for the QDs formation. Even small changes in temperature change completely the properties of the grown QDs.

The growth temperature for the QDs formation is varied in the range of 470 °C up to 535 °C. The AFM pictures of the samples, grown at different temperatures, are presented in Fig. 3.6. A nominal InAs thickness of 4.5 MLs is used for QDs formation for all the samples.

Only a small number of QDs is observed on the surface of the sample grown at 470 °C (Fig. 3.6 (a)). An increase of the growth temperature to 480 °C demonstrates an increase of the density of QDs. An increase of the growth temperature to 480 °C results into an increase of the QDs density to $9.6 \times 10^9$ cm$^{-2}$. Here round-shaped QDs with a very small amount of elongated QDs are observed. A corresponding AFM picture is presented in Fig. 3.6 (b). A further increase of the growth temperature to 510 °C and 535 °C leads to a further increase of the QDs density to $2.56 \times 10^{10}$ and $4.84 \times 10^{10}$ cm$^{-2}$, respectively. In addition, there is no observed formation of elongated QDs for these samples. The AFM pictures of these samples are presented in Fig. 3.6 (c) and (d). The height of the QDs is decreased from 26 nm for the sample grown at 480 °C to 16 nm for the sample grown at 535 °C.
3.3. Influence of the growth conditions on the QDs formation

Fig. 3.6 AFM pictures of the samples grown at different temperatures: (a) 470 °C, (b) 480 °C, (b) 510 °C, (c) 535 °C. Size of the scans is 1µm × 1 µm.

Changes of the QDs density show opposite results in comparison to the previously observed ones. Usually an increase of the growth temperature leads to the increase of the QDs height. The changes of the density of QDs are usually inverse to the changes of the growth temperature. For higher temperatures also the formation of elongated QDs are observed. The reason is the increase of the migration length of the atoms on the sample surface at higher temperatures [92].

PL spectra of the sample, presented in Fig. 3.6, are shown in Fig. 3.7. The PL spectra show for these samples a shift of the emission wavelength to higher value for the sample grown at 480 °C and further shift to lower value for the sample grown at highest temperature. Observed shift is in a good agreement with the investigations of the morphological properties of the QDs. Formation of
3. Growth of the QDs structures

the QDs with smaller height at higher temperatures leads to the observed shift of the emission wavelength. The values of FWHM are in the same region for all samples. Obtained results can be explained by the inhomogeneous distribution of the QDs size.

Unusual changes in the morphological properties of the QDs grown at higher temperatures are observed. The obtained behavior needs further investigations. The optimal temperature is supposed to be in the range of $490 \, ^\circ C – 535 \, ^\circ C$.

Fig. 3.7 PL spectra of the samples grown at different temperatures: (a) 470 °C, (b) 480 °C, (c) 510 °C, (d) 535 °C.
3.3. Influence of the growth conditions on the QDs formation

3.3.4. Growth rates

The morphological and optical properties of the QDs can be improved by the reduction of the migration length of atoms on the sample surface. One approach is to decrease the time of the material deposition. It also allows the formation of more symmetrical QDs. The formation of bigger QDs is observed in the case of higher growth rates. QDs with a smaller dispersion of the QD sizes are formed [82]. In addition, an increase in the QDs density is expected. Another parameter, except the substrate temperature for the control of the migration length of the atoms, is the growth rate of the material. In this section the influence of the growth rate on the QDs formation is presented.

AFM pictures of the samples grown at different growth rates are presented in Fig. 3.8. The growth rate of InAs is 450 nm/h and 600 nm/h, respectively. As it is expected, the formation of the slightly elongated QDs is observed at lower growth rate. More round shaped QDs were formed at higher growth rates. The density of the QDs was increased from $1.05 \times 10^{10}$ cm$^{-2}$ (Fig. 3.2.7 (a)) to $2.56 \times 10^{10}$ cm$^{-2}$ (Fig. 3.2.7 (b)). However the formation of the QDs with big dispersion of QDs sizes is observed. This leads to a deterioration of the optical properties of the QDs.

PL spectra for these samples are presented in Fig. 3.9. Shift to the longer wavelengths is observed for the sample with higher growth rates. It is associated with the formation of the higher QDs at these growth conditions.
3. Growth of the QDs structures

![AFM pictures of the samples grown at different growth rates. Growth rate of InAs is: (a) 450 nm/h, (b) 600 nm/h. Scan size is 1µm × 1 µm.](image)

Fig. 3.8 AFM pictures of the samples grown at different growth rates. Growth rate of InAs is: (a) 450 nm/h, (b) 600 nm/h. Scan size is 1µm × 1 µm.

![PL spectra of the samples grown at different growth rates. Growth rate of InAs: 450 nm/h, (b) 600 nm/h.](image)

Fig. 3.9 PL spectra of the samples grown at different growth rates. Growth rate of InAs: 450 nm/h, (b) 600 nm/h.

As it was expected, the values of FWHM for this sample have higher values. The reason of this is the formation of a QDs ensemble with big differences in size.
The formation of the QDs with higher density is observed in the case of higher growth rates. This means that for the growth of QDs laser structures it is better to use higher growth rates.

3.3.5. Buffer layer with different composition.

Another possibility to improve the optical properties of the QDs is to perform the growth process on strained layers. The strain between barrier materials and QDs can be changed by including an additional layer with a different composition before the formation of the QDs. Implementation of the strained layer may increase density of QDs [107]. It was also observed, that using of initial InAlAs layer leads to improvement of QDs homogeneity [106]. It was demonstrated that the optical properties of the QDs can be improved in comparison to QDs, which were grown on unstrained layer [107].

To investigate the influence of the barrier material on optical and morphological properties of QDs, two sets of samples are grown. The first group of samples includes a barrier material of In$_{0.528}$Al$_{0.238}$Ga$_{0.234}$As, which is lattice-matched to InP. In the second group of samples the additional layer of quaternary material with increased aluminum content is included. The thicknesses of the barrier layer and additional layer are 10 nm and 3 nm, respectively.

AFM pictures of the as described samples are shown in Fig. 3.10. The formation of the QDs with slightly higher density is observed in the case of the sample with additional barrier layer. The possible reason for this can be the formation of additional regions on the sample surface with lower surface energy. As a result a larger number of QDs are formed.
3. Growth of the QDs structures

![AFM pictures](image)

Fig. 3.10. AFM pictures of the samples grown on the buffer layer without (a) and with additional buffer layer (b). Scan size is 1µm x 1 µm.

PL spectra of these samples are shown in Fig. 3.11. There is no shift of the emission wavelength in the case of increased barrier layer due to the formation of the QDs with the same height. But the value of the FWHM is smaller in this case. It can be related to the formation of more uniform QDs. The improvement of the optical properties is observed for all the samples with QDs grown on the strained buffer layer. In the same time an increase of the thickness of the strained layer leads to the deterioration of the optical properties of the QDs.

Based on these investigations of the growth conditions the sample with the optimized properties is used for the application as an active region of the semiconductor lasers. The nominal thickness of 4.5 MLs of InAs is used for the QDs formation. The substrate temperatures during QDs formation are selected to be 490 °C and 510 °C, respectively. All the layers are grown with growth rates of 450 nm/h for InAs and corresponding growth rates of other materials for the formation of the quaternary material lattice-matched to InP.
3.3. Influence of the growth conditions on the QDs formation

Due to the problems with our MBE system there was not enough time to grow lasers with higher growth rates of the materials. Also the application of strained buffer layers into the active QD region was not done. An As equivalent beam pressure of 20 during the QDs formation was used.

Morphological and optical properties of the sample with optimized growth conditions are presented in Fig. 3.12.

Fig. 3.11 PL spectra of the samples grown on the buffer layer without (a) and with additional buffer layer (b).

Fig. 3.12 Properties of the sample grown at the optimized growth conditions: (a) AFM spectrum. Size of scan is 1µm × 1 µm. (b) PL spectrum
3. Growth of the QDs structures

The morphological investigation show the formation of the round-shaped quantum dots with a high density of $6.3 \times 10^{10}$ cm$^{-2}$. The formation of a small number of quantum dashes in between of quantum dots also observed. The emission peak is at 1525 nm at low temperature. There is a small shift of the peak position after increasing the excitation power. The FWHM value for this sample is 32 meV. This value and the symmetrical PL spectra indicate the formation of QDs with uniform sizes.
Chapter 4

Growth and characterization of QD Lasers

This chapter describes the results of the growth of semiconductor lasers. Theoretical investigations of the modulation properties of the lasers and the influence of the laser design on the modulation bandwidth as well as the influence of the laser structure on the static and dynamic properties are discussed. The details of the growth process of semiconductor lasers, the processing of the DFB lasers and the measurements of the dynamical properties of semiconductor lasers are also presented.

4.1 Growth of the semiconductor QD lasers.

The design of the laser structures, which were grown and investigated in this work, is based on the laser structure of R. Schwertberger and co-workers [105]. Few semiconductor lasers with different designs were grown, investigated and compared in order to determine the laser design, which improves the laser modulation properties. The description of the basic structure and the growth process is presented below.

All the lasers were grown on 2 inch InP(100) substrates doped with sulfur. The doping level of the substrates is in the range of $5 \times 10^{18}$ cm$^{-3}$. The growth process
is similar as in the case of QDs growth. First step of the growth was the oxide desorption. It was done at 490 °C under phosphorous atmosphere for 10 minutes. Because a laser structure consists of a typical PIN diode, layers below the active region are doped with n-type dopant and the layers over the active region are p-doped. The active region is undoped.

Firstly the InP buffer layer with a thickness of 200 nm was grown at 460 °C. A V/III beam equivalent pressure ratio of 10-12 was used. This condition minimizes the layer roughness. The doping level of the buffer layer was the same as in the substrate. During the growth of the next 20 nm of the buffer layer the doping level was decreased from $5 \times 10^{18}$ cm$^{-3}$ to $2 \times 10^{18}$ cm$^{-3}$.

Afterwards a layer of 200 nm of In$_{0.523}$Al$_{0.477}$As was grown. The phosphorous containing atmosphere was exchanged with As. During the changes of the flux of group V elements the growth was interrupted for 30 sec to allow a complete change between phosphorous and arsenic background. The growth temperature of this layer is 490 °C. The V/III beam equivalent pressure of 15 Torr was used for the growth of Al containing materials. The first 20 nm of this layer have a doping level in the range of $5 \times 10^{17}$ cm$^{-3}$. Most of the layer was grown with a lower doping level of $2 \times 10^{17}$ cm$^{-3}$. The substrate together with an InP buffer and In$_{0.523}$Al$_{0.477}$As layers serve as n-type cladding layer of the lasers.

The QD layers should be enough far away from the highly doped region of the laser. It is one of the purposes of the as grown InAlAs layer to prevent the penetration of the optical mode inside the highly doped InP. In addition the higher bandgap of the InAlAs in comparison to InP and InAlGaAs quaternary layer provide a better confinement of the optical mode inside the laser structure. The growth of the quaternary layer with defined composition around the QD layers allows obtaining a structure with the necessary properties. The growth of thick layers with a low doping level leads to a significant increase of the internal absorption of the semiconductor lasers. As an alternative method to suppress the
4. Growth and characterization of QD Lasers

internal absorption is to increase the thickness of the quaternary layer around the QD layers instead of the growth of InAlAs layers. The big disadvantage of this method is the increase of the transport time of the carriers into the active region. The modulation properties of the lasers will significantly deteriorate and these lasers will not be used for the high-speed data transmission. The presence of the InAlAs layer with a low doping level allows shifting the active region away from the highly doped substrate. The relatively high doping level of the interface between the InAlAs and InGaAlAs layers allows the free transport of the carriers inside the active region. Another advantage of the growth of the InAlAs layer before the quaternary material is the absence of the phosphorous atoms inside the active region. It was already established that at the temperatures higher than 360 °C the As/P exchange takes place [110]. As a result the formation of the InAsP QDs with very inhomogeneous distribution of the QD sizes or the formation of the QDashes is observed [111] - [112]. In addition the broad PL linewidth and low intensity of the PL signal from QDs was reported [79], [109], [115].

The $\text{In}_{0.528}\text{Al}_{0.238}\text{Ga}_{0.234}\text{As}$ waveguide layer was grown afterwards. To grow the material with a given composition the temperature of Al cell has to be changed. A growth interruption is introduced to allow the change of the cell temperature. Our investigations show that the interruption time of 2 minutes is enough to change the cell temperature to the desired one and reach the stable flux from the cell.

The first 20 nm of the quaternary material are doped with the doping level of $2 \times 10^{17}$ cm$^{-3}$. The last 80 nm before and after the QDs layers are undoped. Last 20 nm of InAlGaAs were p-type doped with the doping level of $2 \times 10^{17}$ cm$^{-3}$. The growth temperature of the active region and the QD layers varied from 490 °C to 510 °C. During the growth of the undoped part of the waveguide core the temperature of the silicon cell was decreased and the temperature of the
beryllium cell was increased. This can prevent the parasitic doping of the p-type part with silicon. The active region consists of few stacked QD layers divided by 20 nm of quaternary material. This thickness is enough to avoid the strain coupling effects for each QD layer and therefore for the formation of the same QDs in each layer. As it was mentioned above the active region of the grown lasers consist of the QDs grown at optimized growth conditions.

The rest part of the laser structure is p-doped. The doping level of this layer is changing from $2 \times 10^{17}$ cm$^{-3}$ to $5 \times 10^{17}$ cm$^{-3}$. After the active region a 200 nm thick In$_{0.523}$Al$_{0.477}$As layer was grown. The InAlAs layer is followed by 1.7 µm of InP. The doping level continuously increased during the growth of the InP layer. At the end of the layer the doping level is in the range of $2 \times 10^{18}$ cm$^{-3}$. A highly doped layer of In$_{0.532}$Ga$_{0.468}$As on the top of the structure serves as a contact layer.

The modulation properties of the semiconductor lasers depend very strongly on different parameters. As it was already mentioned, the transport time of the carriers into the active region is one of the important parameters. Therefore one of the possibilities to improve the modulation properties of the lasers is to decrease this time. The improved structure of the laser included only 100 nm of InGaAlAs around the QD layers. To avoid the problem with the increased internal absorption in the lasers the distance between active region and the highly doped regions was increased by growing of 300 nm of InAlAs from the bottom side of the QD layers instead of 200 nm. Also the thickness of the top layer of InP was increased to 1.9 µm. The base and advanced structure of the lasers is presented in Table 4.1.
### Table 4.1 Layer structures of semiconductor lasers grown. The values in brackets correspond to the improved laser design.

<table>
<thead>
<tr>
<th>Function</th>
<th>Thickness, µm</th>
<th>Material</th>
<th>Doping level, cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower cladding</td>
<td>350</td>
<td>InP substrate</td>
<td>5·10¹⁸</td>
</tr>
<tr>
<td></td>
<td>0,2</td>
<td>InP</td>
<td>2·10¹⁸</td>
</tr>
<tr>
<td></td>
<td>0,02</td>
<td>In₀.₅₂₃Al₀.₄₇₇As</td>
<td>2·10¹⁸ → 5·10¹⁷</td>
</tr>
<tr>
<td></td>
<td>0,18 (0,28)</td>
<td>In₀.₅₂₃Al₀.₄₇₇As</td>
<td>5·10¹⁷</td>
</tr>
<tr>
<td>Lower waveguide</td>
<td>0,1</td>
<td>In₀.₅₂₈Al₀.₂₃₈Ga₀.₄₇₄As</td>
<td>2·10¹⁷</td>
</tr>
<tr>
<td></td>
<td>0,08</td>
<td>In₀.₅₂₈Al₀.₂₃₈Ga₀.₂₃₄As</td>
<td></td>
</tr>
<tr>
<td>Active region</td>
<td>4ML / 20</td>
<td>InAs QDs / In₀.₅₂₈Al₀.₂₃₈Ga₀.₂₃₄As</td>
<td>Undoped</td>
</tr>
<tr>
<td>Upper waveguide</td>
<td>0,08</td>
<td>In₀.₅₂₈Al₀.₂₃₈Ga₀.₂₃₄As</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0,1</td>
<td>In₀.₅₂₈Al₀.₂₃₈Ga₀.₂₃₄As</td>
<td>2·10¹⁷</td>
</tr>
<tr>
<td>Upper cladding</td>
<td>0,18 (0,28)</td>
<td>In₀.₅₂₃Al₀.₄₇₇As</td>
<td>5·10¹⁷</td>
</tr>
<tr>
<td></td>
<td>0,02</td>
<td>In₀.₅₂₃Al₀.₄₇₇As</td>
<td>1·10¹⁸</td>
</tr>
<tr>
<td></td>
<td>1,7 (1,9)</td>
<td>InP</td>
<td>1·10¹⁸ → 2·10¹⁸</td>
</tr>
<tr>
<td>Contact</td>
<td>0,2</td>
<td>In₀.₅₃₂Ga₀.₄₆₈As</td>
<td>2·10¹⁹</td>
</tr>
</tbody>
</table>

It is well known that the shape and the geometrical sizes of the grating have strong influence on the properties of the DFB lasers. Due to this reason the etching process has to be performed very precisely.
To realize this idea additional layers of $\text{In}_{x}\text{Ga}_{1-x}\text{As}_{y}\text{P}_{1-y}$ were implemented into the p-type cladding layer. These layers play a role as etch-stop layers and provide a precise control of the grating thickness. As composition $\text{In}_{0.745}\text{Ga}_{0.255}\text{As}_{0.547}\text{P}_{0.453}$ was used with a bandgap of 0.99 eV.

The change of the refractive index and conduction band for the lasers with and without etch-stop layer is shown in Fig. 4.1.

![Fig. 4.1 Conduction band and the refractive index for the semiconductor lasers without (a) and with (b) etch-stop layer](image-url)
The growth of the etch-stop layer InGaAsP compound meets some difficulties. The sticking coefficients for the arsenic and phosphorous atoms are different. As a result the direct measurement of the fluxes by beam flux monitor does not allow to control directly the composition of the grown InGaAsP layer and the lattice-matching condition.

To overcome this problem the ratio of beam equivalent pressure for arsenic and phosphorous $Z = \frac{As_2}{As_2+P_2}$ was used. To achieve the optimum composition the value of $Z$ was investigated in the range of 0.25 to 0.5. The good lattice-matching conditions of the sample were obtained for the material with the ratio $Z$ equal to 0.242. The lattice-mismatch for this sample is only $3.72 \times 10^{-4}$. A corresponding XRD spectrum of a test sample with a 300 nm thick GaInAsP layer is shown in Fig. 4.2.

![XRD scan for the optimized Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ test sample](image)

Fig. 4.2 XRD scan for the optimized Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ test sample
4.1. Growth of the semiconductor QD lasers

The RMS value is also small enough and varies in the range of 0.35 – 2.5 nm. The optical spectrum of the optimized test sample is shown in Fig. 4.3. The emission wavelength of this sample is at about 1200 nm at 10 K and shifted to 1260 nm at room temperature. The linewidth at FWHM is about 24 meV.

The laser structure with etch-stop layers is presented in Table 4.2. It is based on the improved design of laser structure. Two layers of In$_{0.745}$Ga$_{0.255}$As$_{0.247}$P$_{0.453}$ with thicknesses of 10 and 14 nm were implemented into the InP layer. The distance between bottom layer and the active region is equal to 100 nm. The same distance was kept between both InGaAsP layers.

Fig. 4.3 PL spectrum for the optimized Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ test sample
4. Growth and characterization of QD Lasers

<table>
<thead>
<tr>
<th>Function</th>
<th>Thickness, ( \mu m )</th>
<th>Material</th>
<th>Doping level, ( cm^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower cladding</td>
<td>350</td>
<td>InP substrate</td>
<td>( 5 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,2</td>
<td>InP</td>
<td>( 2 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,02</td>
<td>( In_{0.523}Al_{0.477}As )</td>
<td>( 2 \cdot 10^{18} \rightarrow 5 \cdot 10^{17} )</td>
</tr>
<tr>
<td></td>
<td>0,28</td>
<td>( In_{0.523}Al_{0.477}As )</td>
<td>( 5 \cdot 10^{17} )</td>
</tr>
<tr>
<td>Lower waveguide</td>
<td>0,1</td>
<td>( In_{0.528}Al_{0.238}Ga_{0.234}As )</td>
<td>( 2 \cdot 10^{17} )</td>
</tr>
<tr>
<td></td>
<td>0,08</td>
<td>( In_{0.528}Al_{0.238}Ga_{0.234}As )</td>
<td></td>
</tr>
<tr>
<td>Active region</td>
<td>4ML / 20</td>
<td>InAs QDs / ( In_{0.528}Al_{0.238}Ga_{0.234}As )</td>
<td>Undoped</td>
</tr>
<tr>
<td>Upper waveguide</td>
<td>0,08</td>
<td>( In_{0.528}Al_{0.238}Ga_{0.234}As )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0,1</td>
<td>( In_{0.528}Al_{0.238}Ga_{0.234}As )</td>
<td>( 2 \cdot 10^{17} )</td>
</tr>
<tr>
<td>Upper cladding</td>
<td>0,18</td>
<td>( In_{0.523}Al_{0.477}As )</td>
<td>( 5 \cdot 10^{17} )</td>
</tr>
<tr>
<td></td>
<td>0,02</td>
<td>( In_{0.523}Al_{0.477}As )</td>
<td>( 1 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,01</td>
<td>InP</td>
<td>( 1 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,01</td>
<td>( In_{0.745}Ga_{0.255}As_{0.247}P_{0.453} )</td>
<td>( 1 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,09</td>
<td>InP</td>
<td>( 1 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>0,014</td>
<td>( In_{0.745}Ga_{0.255}As_{0.247}P_{0.453} )</td>
<td>( 1 \cdot 10^{18} )</td>
</tr>
<tr>
<td></td>
<td>1,6</td>
<td>InP</td>
<td>( 1 \cdot 10^{18} \rightarrow 2 \cdot 10^{18} )</td>
</tr>
<tr>
<td>Contact</td>
<td>0,2</td>
<td>( In_{0.532}Ga_{0.468}As )</td>
<td>( 2 \cdot 10^{19} )</td>
</tr>
</tbody>
</table>

Table 4.2 Laser structure with etch-stop layers.
4.2 Small signal response of the QD lasers with different active region.

The modulation properties of the QD lasers are dependent on many parameters. Many investigations of the modulation properties of the QD lasers were carried out. Most of the theoretical models do not take into account a lot of parameters, like the spatial distribution of the carriers along the active region. In this section the influence of the laser structure on the modulation properties is analyzed by using a detailed model. The theoretical calculations were performed by our partners from “Technion”.

To determine the modulation response of the semiconductor laser, the rate equations (1.4.7) and (1.4.8) are used. The analytical solution of these equations is not possible. The problem can be simplified by representing of the current, carrier and photon densities as a sum of the steady-state solution and small signal deviation from this solution. The gain is supposed to be independent from the photon density. Otherwise the nonlinear gain saturation should be taken into account [116]. Considering this model the intrinsic modulation response can be written in the form:

$$|H(\omega)| = \frac{\omega^2}{\sqrt{(\omega^2 - \omega^2)^2 + \gamma^2 \omega^2}}$$  \hspace{1cm} (3.1.1)

Here, parameter $\omega^2$ is the relaxation frequency and $\gamma^2$ is the damping factor. They can be expressed in the form:

$$\omega^2 = \frac{G(n)S_0}{\tau_{ph}}$$  \hspace{1cm} (3.1.2)

$$\gamma = G(n)S_0 + \frac{1}{\tau}$$  \hspace{1cm} (3.1.3)
Both factors are dependent from the photon density $S_0$ which can be found from the expression:

$$S_0 = \frac{n_i \tau_{ph}}{V_e} (I - I_{tr})$$  \hfill (3.1.4)

Here, $V$ is the active volume of the laser, $I_{tr}$ and $I$ are the threshold and the injected current. The correlation between these factors describes the modulation properties of the laser. The maximum bandwidth of the laser can be found from the equation (3.1.1) and is expressed as:

$$f_{3dB,\text{max}} \approx \frac{2\pi \sqrt{2}}{4\pi^2 \tau_{ph}}$$  \hfill (3.1.5)

As can be seen from equation (4.1.5) the realization of high-speed lasers requires a small lifetime of the photons. Other important properties of high-speed lasers are a large differential gain, strong optical confinement and a small active volume.

Theoretical simulations of the small signal response for lasers with different designs are presented in Fig. 4.4. The solid lines correspond to the laser with a waveguide thickness of 500 nm, whereas the dashed line corresponds to a laser with a waveguide thickness of 300 nm. For the simulations of the small signal response a dynamic model is used, which includes the spatial distribution of electrons and holes. Also the influence of the Coulomb interaction of electrons and holes on the bands structure is taken into account [117].
4.2. Small signal response of the QD lasers with different active region

![Graph showing the small signal response of QD lasers with different active region thicknesses.](image)

**Fig. 4.4** Calculations of the small signal response for the QD lasers with a thickness of the waveguide layer of 500 nm (solid line) and 300 nm (dashed line)

It can be seen that in the case of thick waveguides the maximal bandwidth is limited to 12 GHz. Decreasing of the waveguide thickness leads to a significant improvement of the dynamical properties of the laser. In this case the modulation bandwidth can be extended up to 20 GHz. The reason for this is a decreasing transport time to the active region. The experimental results concerning the measurements of the RWG lasers with a different waveguide thickness are presented in section 3.4.

The influence of other structural parameters on the modulation bandwidth was also investigated [118]. The first parameter is the barrier thickness between the QD layers. The small signal response for two laser devices with different barrier thicknesses is shown in Fig. 4.5. Both lasers have 4 layers of QDs in the active region. By decreasing the barrier thickness an increase of the modulation bandwidth can be observed. As in the case of the changes in the waveguide thickness the observed improvement is related to a faster transport of the carriers into the QD layers. However, the properties of the QDs could be much...
deteriorated after decreasing of the barrier layer between individual QD layers. Decreasing of the barrier layers leads to large shift to the low energy with increasing of the number of QD layers. Observed shift is explained by increase of the QD size during the stacking due to strain accumulation. As a result, reduced modal gain during the laser operation for a given bandwidth could be measured. In addition, if the misfit strain is not properly controlled, the crystal quality of grown material could be much deteriorated. For example, nucleation of the defects in multiple period QDs was observed [119].

![Diagram](image)

Fig. 4.5 Small-signal response for a 1.55 µm QD laser with 300 nm waveguide thickness and different barrier between QD layers: (a) 20 nm (b) 10 nm. The enlarged view of the responses near -3 dB is shown on the inset [118].
4.2. Small signal response of the QD lasers with different active region

Fig. 4.6 Small-signal response for a 1.55 µm QD laser with 300 nm waveguide thickness and 10 nm barrier between QD layers with (a) 6 and (b) 8 QD layers in active region. The enlarged view of the responses near -3 dB is shown on the inset [118].

The next step is the investigation of the influence of the number of QD layers on the modulation bandwidth. Increasing of the number of QD layers leads to an increase of the modal gain of the structure. As a result the modulation properties of the lasers also improve. On the other side increasing the number of the QD layers leads to an increase of the active volume of the lasers and therefore it has negative influence on the modulation properties of the lasers. The small signal response from the structures with 6 and 8 QD layers are presented in Fig. 4.6. The maximum bandwidth of the laser is increased by increasing of the number of QD layers from 4 (Fig. 4.5(b)) to 8 (Fig. 4.6(b)). The implementation of the additional layers leads to a decrease of the maximum reachable bandwidth. The reason for this is the bigger influence of the increased transport time in comparison to the larger modal gain for the structures with the large number of QD layers. The calculation of the small signal response for the lasers with 8 and 10 QD layers are presented in Fig. 4.7.
Fig. 4.7 (a) Small-signal response for a 1.55 µm QD laser with 8 and 10 QD layers in the active region. The widest response for the lasers with 8 and 10 QD layers is observed at $I=125$ mA and $I=250$ mA, respectively. (b) Small signal responses for a 1.55 µm QD laser with 10 QD layers with symmetric and asymmetric waveguide [118].

Another way to increase the modulation bandwidth is to use the structure with an asymmetric waveguide. This idea comes from the fact that the electrons have higher mobility in comparison to the holes and they need less time to reach the active region. The holes have short diffusion length and they are usually accommodating near the p-side of the active region. The comparison of the modulation bandwidth for the structures with the symmetric and asymmetric waveguide is shown in Fig. 4.7(b). The bandwidth of the asymmetric structure is broader due to the shorter migration length of the holes to the active region.

4.3 Static measurements of semiconductor lasers.

The basic characterization of the internal parameters of the grown laser structures is performed on so called “broad area laser” structures. Usually the fabrication of
the complicated structures like DFB and DBR lasers are done after the characterization of the broad area lasers. The main purpose of the measurements of broad area lasers is to avoid the influence of the process steps during the processing of complicated structures on the measured properties of the lasers. Also the broad area lasers provide more homogeneous pumping of the lasers in comparison to lasers with another design. The n-type contact has been deposited on the backside of the wafer and covers the entire surface. It consists of successive deposited 5 nm nickel, 5 nm germanium, 5 nm gold and 5 nm nickel, followed by 200 nm of gold. To improve the homogeneity of the contact layer a rapid thermal annealing step for 40 s at a temperature of 290 °C and 20 s at a temperature of 390 °C was performed, respectively. The p-type contacts represent two sets of the stripes with thicknesses of 100 µm and 50 µm. For the standard measurements only the stripes with a thickness of 100 µm were used. Contacts with a thickness of 50 µm were used only when the measurements on 100 µm stripes cannot be performed due to the high threshold current. The p-type contact consists of 20 nm titan followed by 80 nm of platinum and 300 nm of gold.

After the deposition of the contacts the lasers with different cavity length were cleaved to provide the length-dependent measurements. Usually four to six different lengths were used to determine the internal parameters of the laser structure. Typical values of the cavity lengths are 0.6 mm, 0.8 mm, 1 mm, 1.3 mm and 1.7 mm. About 10-20 lasers were measured to provide high enough accuracy for the evaluations.

Measurements of the laser structures were performed in pulsed regime. The lasers were electrically pumped with 500 ns long pulses with a repetition rate of about 1.5 ms. In this regime the measured laser structure is not significantly heated and as a result the changes of the laser properties are negligible.
4. Growth and characterization of QD Lasers

4.3.1 Characterization of QW laser.

Before the growth and characterization of the QD semiconductor lasers a reference QW laser structure were fabricated. The active region of the laser consists of three InGaAs QWs with a thickness of 7 nm separated by 20 nm of In_{0.528}Al_{0.238}Ga_{0.234}As barrier layers.

PL spectra of the QW laser, measured at different excitation powers, are presented in Fig. 4.8. Two peaks were observed during the measurements. One of them corresponds to the PL signal from the QWs and is situated near 0.9 eV. This value corresponds to the expected value for the actual composition of the QWs. The position of the second peak is near 0.8 eV and corresponds to the PL from the InGaAs contact layer. The physical reason for the appearance of this peak is the Fermi level pinning at the interface of highly doped InGaAs p-type contact layer and p-type InP cladding layer due to high doping level of the top contact layer [120].

![Photoluminescence spectra of the QW laser. Peak near 0.9 eV corresponds to the PL from active region, the high energy peak corresponds to the PL from the InGaAs contact layer.](image.png)
The SEM picture is shown in Fig. 4.9. The measurements of the SEM did not show big discrepancy of the size of the layers in comparison to the expected values. The interfaces between different layers are also very smooth without any defects.

![Fig. 4.9 SEM picture of the QW laser.](image)

The XRD spectrum of the QW laser is shown in Fig. 4.10. The sizes of the different layers and the lattice matching conditions were obtained from this measurement. As can be seen from the picture there are two shoulders on both sides from substrate peak. They correspond to peaks from ternary and quaternary materials, most probably from InAlAs and InAlGaAs. The lattice mismatch of $2.2 \times 10^{-4}$ was obtained from the simulation of the XRD spectrum. This value is small enough and can be neglected.
4. Growth and characterization of QD Lasers

Fig. 4.10 XRD spectrum of the QW laser. The blue spectrum corresponds to the measured values; the red curve is the simulation of the laser structure [92].

Measured spectra of the emission wavelength for the QW laser with different cavity lengths are shown in Fig. 4.11 (a). The emission wavelength of the laser is in the range of the 1500 – 1540 nm. The red shift of the emission wavelength with increasing the cavity length is related to the redistribution of carriers, which takes place due to the increase of the cavity loss [121].

The dependence of the output power on the injection current is shown in Fig. 4.11 (b). The slope of the different curves is changed from 0.24 W/A for the laser with 0.617 mm cavity length to 0.11 W/A for the laser with 1.821 mm cavity length, respectively.
4.3. Static measurements of semiconductor lasers

The internal parameters were obtained from the dependence of the threshold current density on the inverse cavity length. The external efficiency of the laser is equal to 33%. The internal quantum efficiency, which corresponds to the external efficiency, is 40%. Typical values of the internal quantum efficiency for the laser emitting at 1.55 µm are not exceed 70-75% [122]. Internal quantum efficiency is equal to the fraction of current above threshold and decreases due to carrier losses. Possible reasons of carrier losses are lateral carrier leakage, carrier escape from active region and non-radiative recombination losses, e.g. Auger recombination, intervalence band absorption, Shokley-Read-Hall recombination and spontaneous emission. Strong Auger recombination is a typical problem for long-wavelength lasers [123]. It raises proportional to the cube of the local carrier density [124]. Carrier escape from active region dominates at higher current and causes thermal power roll-off [125]. Relatively low absorption of 12 cm$^{-1}$ was obtained. This value is in the range of typical values for InGaAlAs/InP material system [105], [126]. The modal gain per QW layer is calculated to 37 cm$^{-1}$. The data concerning the modal gain of InP based QW lasers are also in the range of 30 – 40 cm$^{-1}$ [127]. One of the factors, which may reduce value of total gain by 30 – 40 %, is the intraband relaxation [128].

Fig. 4.11 Selected emission spectra (a) and P-I curves (b) for the QW laser
4.3.2 Characterization of QD lasers.

The next step is the growth of QD based semiconductor lasers. The gain of the active layer should be enough to overcome losses, which take place during the laser operation. The estimated gain of the QDs supposed to be lower in comparison to the QW. There are several reasons of lower gain in case of QDs. The values of optical confinement factor are in the order of the ratio of total volume of quantum confinement material and the total volume of the waveguide. Usually value of the optical confinement factor of QWs is one order of magnitude higher than in QDs due to big difference of the volume of QDs and QWs. Confinement factor of the QDs could be increased by increasing of the QDs number (horizontal confinement factor) and number of QD layers (vertical confinement factor). Also the relaxation of the carriers is faster in the case of the QWs. The typical value for the modal gain for the QDs is in the range of $2 - 7 \text{ cm}^{-1}$ [98], [129]. The properties of the QDs are strongly dependent on the substrate orientation. It was already shown that using of InP (113)B substrates allow to obtain QD layers with higher QD densities and with improved size homogeneity in comparison to QD layers grown on InP (100) substrates [85], [130]. As a result, the maximum values for the modal gain were supposed to be higher in the case of lasers, grown on InP (113) B-oriented substrates. Analysis of the laser with a single QD layer in the active region leads to the modal gain of $13 \text{ cm}^{-1}$ for ground state transition [131]. There are some difficulties concerning lasers growth on InP (113) substrates. Stable laser emission was obtained only from the samples, which were grown with the use of double-cap technique. Properties of the laser with QDs grown without double-cap technique are much worse. Spontaneous emission at high temperatures becomes asymmetric. It can be explained by thermal redistribution of carriers in the first excited state [132]. Decreasing of the cavity length leads to significant increase of the threshold current density and shift of the emission wavelength, which corresponds to a shift from the ground state to first excited state. Observed behavior is explained by great
overlap between ground state and excited state for this material system. When mirror losses increase, the excited state starts to be filled before the ground state level is completely filled [131]. Also using the InP (113)B substrates has a big disadvantage in further processing of the devices. The facets of the laser based on InP (113)B substrates should be obtained by special processing of the grown structures, while lasers based on InP (100) substrates can be measured after cleaving.

The main focus on laser research is concentrated on the lasers, based on InP (100) substrates, due to difficulties in laser processing and problem to achieve stable lasing operation at room temperature in the case of InP (113)B substrates. Also much higher values of modal gain for nanostructures grown on InP (100) substrates in comparison to InP (311)B substrates were measured. Obtained results could be attributed to a better quality of the nanostructures grown on conventional InP (100) substrates [133]. To obtain enough gain a laser with 6 QD layers was grown. The PL spectrum of this laser is presented in Fig. 4.12. The lasers have the same structure as described in table 3.2. The same laser structure was grown after the system service to compare the laser properties before and after opening the MBE system, especially the high modal gain and low internal absorption. After the calibration of the system it was established, that the optimum temperature for the QD formation was increased to 510 °C. Therefore the active region of the QD laser and quaternary material were grown at 510 °C.

It was mentioned before, that the PL signal from highly doped contact layer is near 0.9 eV. The signal from the QDs was supposed to have the same position. To avoid any problems with the influence of the contact layer on the optical characterization of the QDs it was decided to etch the contact layer. The PL spectrum, shown in Fig. 4.12 (a), was measured from the laser with etched contact layer.

The residual contact layer can have big impact on the PL measurements of the sample. Even few nanometer of highly doped InGaAs layer can show strong
4. Growth and characterization of QD Lasers

enough emission. Therefore for the next samples it was decided to etch not only the contact layer, but also a part of the InP cladding. The PL spectrum of this sample is shown in Fig. 4.12 (b).

The two peaks of the PL spectrum, shown in Fig. 4.12 (a) at 1.35 eV and at 0.9 eV correspond to the emission from the doped InP layer and QDs respectively. In addition, the PL signal from the QDs is strongly non-symmetric and has additional shoulder, which is very clearly observed at low excitation power. From the Gaussian fit of the low energy PL signal two peaks are identified with FWHM values of 28 meV and 49 meV [92]. One of the possible reasons for the appearance of the second peak is the formation of QDash structures in addition to the round-shaped QDs. In addition, obtained second peak in the region of 0.9 eV could be related to emission from residual InGaAs contact layer.

![Graph](a)

![Graph](b)

Fig. 4.12 PL spectra of the lasers having 6 QD layers in the active region. The growth temperature of the active region: (a) 490 °C (b) 510 °C. The measurements were done at low temperature [92].

The sample with an active region, which was grown at a higher temperature, shows better properties in comparison to the earlier grown laser. The FWHM in this case
is slightly higher and is equal to 33 meV. However no formation of additional peaks or shoulders is observed. Therefore we suppose that more uniform QDs are formed in this sample. Emission wavelength is shifted to 1592 nm. The possible reason is the formation of QDs with larger heights.

The emission spectra for both lasers are shown in Fig. 4.13. There is also a shift of the emission wavelength for the lasers from 1.55 to 1.62 µm. This shift is in close agreement with results of the PL measurements of the laser.

The selected curves of the lasers, which were grown at different temperatures, are shown in Fig. 4.14. In the case of the lasers with an active region grown at a higher temperature the threshold current is 1.5 times lower.

![Emission spectra of the lasers with 6 QD layers in the active region. The growth temperature of the active region is: 490 °C (a) 510 °C (b).](image)

Fig. 4.13 Emission spectra of the lasers with 6 QD layers in the active region. The growth temperature of the active region is: 490 °C (a) 510 °C (b).
4. Growth and characterization of QD Lasers

Fig. 4.14 Selected P-I curves and linear dependent measurements for the QD laser with 6 QD layers, grown at 490 °C (a, c) and 510 °C (b, d).

The internal absorption for both lasers is near the same value and is equal to the absorption of the QW laser. Both lasers have shown relatively high modal gain of near 10 cm$^{-1}$. As was mentioned before, typical values of the modal gain for the laser on InP (100) substrates are 2 times less in comparison to the obtained value. It was observed much lower internal absorption of 4 cm$^{-1}$ for the laser grown at lower temperature. In addition, the slope of the laser, which was grown at higher temperature, is higher. It changes from 0.18 W/A to 0.23 W/A, depending on the cavity length. The slope for the laser, grown at lower temperature, is in the range of 0.15 W/A to 0.2 W/A. All the internal parameters for QW laser and both QD lasers are presented in Table 4.3.
4.3. Static measurements of semiconductor lasers

<table>
<thead>
<tr>
<th></th>
<th>$J_{ir}, \text{A/cm}^2$</th>
<th>$\eta_{ir}, %$</th>
<th>$\alpha_i, \text{cm}^{-1}$</th>
<th>$\Gamma_{g0}, \text{cm}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>31</td>
<td>12</td>
<td>120</td>
</tr>
<tr>
<td>QD laser, 6 QDL, 490 °C</td>
<td>317</td>
<td>31</td>
<td>7.8</td>
<td>60</td>
</tr>
<tr>
<td>QD laser, 6 QDL, 510 °C</td>
<td>201</td>
<td>30</td>
<td>4.2</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 4.3 Internal parameters of the QW lasers and QD lasers with different growth temperature of the active region.

The high modal gain of the as grown QD lasers allows to decrease the number of the QD layers for the next generation QD laser. Therefore the QD lasers with 5, 4 and 3 layers were grown. The measurements demonstrated good internal parameters for all the lasers. All the results are presented in Table 4.4. Internal quantum efficiency of the lasers is in the range 25-30%. The possible reason of such small values can be presence of InAlAs cladding layer. This material has higher bandgap and can act as a blocking layer for the carriers. Another reason for increasing of the carrier losses could be formation QDs with defects. Such defect QDs may cause additional photon scattering and lead to decreasing of internal quantum efficiency [134]. The modal gain of the QD lasers was in the range 10-15 cm$^{-1}$. The internal absorption for all the lasers was lower than 10 cm$^{-1}$. Lower internal absorption of QD lasers in comparison to QW laser could be explained by reduction of the confinement factor of the QD lasers due to lower active volume. The high absorption of the laser with 3 QD layers can be explained with the technical problems during the growth process. The thickness of the InP cladding layer is 300 nm lower in comparison to the other lasers. Therefore highly doped material is nearer to the active region and this can have big influence on the absorption properties of the laser.
The next optimization step of the laser structure is decreasing of the waveguide thickness. Theoretical calculations, which were presented in section 4.2, shows an improvement of the modulation properties of the laser, when the simulation is performed with a thinner waveguide layer.

The emission PL spectra of the lasers with the initial design and with a decreased waveguide layer thickness are presented in Fig. 4.15. The emission wavelengths for both lasers have nearly the same value of 1.595 µm. Decrease of the FWHM for the laser with decreased waveguide layer thickness was observed. As a result of the improvement of the laser optical properties better dynamical properties of the lasers are achieved, as will be discussed later.
4.3. Static measurements of semiconductor lasers

Fig. 4.15 PL spectra for the laser with a waveguide thickness of 500 nm (a) and 300 nm (b), respectively.

The emission wavelength of the laser with the initial structure is in the range of 1.61 µm to 1.625 µm for the different cavity lengths. There is a shift of the emission wavelength for the laser with the improved structure design. The emission wavelengths for this laser are in the range of 1.58 µm to 1.6 µm. Emission spectra for the lasers with different waveguide thickness are presented in Fig. 4.16.

Fig. 4.16 Emission spectra for laser with a waveguide thickness of 500 nm (a) and 300 nm (b), respectively.
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The P-I curves for the different cavity length for the lasers with different waveguide thicknesses are presented in Fig. 4.17 (a) and (b). Only slight shift of the threshold current for a similar cavity length of both lasers was observed. As a result the significant difference of the internal parameters of both lasers is not expected. The absorption of the laser with decreased waveguide is increased to 7.3 cm\(^{-1}\). In the case of the laser with a thicker waveguide layer the internal absorption was 4.15 cm\(^{-1}\).

![Fig. 4.17 P-I curves and linear dependent measurements for the QD laser with 6 QD layers with the thickness of the waveguide of 500 nm (a, c) and 300 nm (b, d).](image)
Further improvement of the modal gain in the laser with thinner waveguide was observed. The value of the modal gain per QD layer was increased from 9 cm\(^{-1}\) to 12 cm\(^{-1}\). An increase of the output power in the case of the laser with a thinner waveguide was observed.

The slope for the laser with a thinner waveguide changes in the range of 0.25 W/A to 0.15 W/A. The internal parameters for the lasers with different waveguide are presented in Table 4.5. Laser with a thinner waveguide has shown slightly higher internal absorption and further improvement of modal gain. Higher internal absorption can be related to decreased thickness between active region and doped layers. Improved modal gain may be related to improve of optical confinement of the laser with thinner waveguide.

<table>
<thead>
<tr>
<th>Waveguide thickness, nm</th>
<th>(J_{tr}), A/cm(^2)</th>
<th>(\eta_{i}), %</th>
<th>(a_i), cm(^{-1})</th>
<th>(\Gamma g_0), cm(^{-1})</th>
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<tbody>
<tr>
<td>500</td>
<td>201</td>
<td>31</td>
<td>4.15</td>
<td>53</td>
</tr>
<tr>
<td>300</td>
<td>305</td>
<td>38</td>
<td>7.3</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 4.5 Internal parameters of the QD lasers with different thickness of the waveguide.

The next step of the investigations was the growth of QD lasers with different numbers of QD layers with comparable waveguide designs. The lasers with 4 and 8 QD layers were grown and their properties were investigated. The P-I curves for the lasers with different numbers of QD layers and different cavity lengths are shown in Fig. 4.18 (a – c). The dependences of the threshold current density and inverse internal efficiency are shown in Fig. 4.18 (d – f).
Fig. 4.18 P-I curves and Length dependent measurements for the QD laser with a thickness of the waveguide layer of 300 nm with 4 (a, d), 6 (b, e) and 8 (c, f) QD layers in the active region.
The results of the length dependent measurements are presented in Table 4.6. The value of the internal absorption for the other lasers is in the same level near 10 cm\(^{-1}\). The threshold current is higher for the QD lasers with a larger number of QDs layers because of the larger active volume.

<table>
<thead>
<tr>
<th>Number of QDL</th>
<th>(J_{tr}, \text{A/cm}^2)</th>
<th>(\eta_i, %)</th>
<th>(\alpha_i, \text{cm}^{-1})</th>
<th>(\Gamma g_0, \text{cm}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>210</td>
<td>45</td>
<td>12.28</td>
<td>49.37</td>
</tr>
<tr>
<td>6</td>
<td>305</td>
<td>38</td>
<td>7.3</td>
<td>70.87</td>
</tr>
<tr>
<td>8</td>
<td>351</td>
<td>33</td>
<td>8.44</td>
<td>63.52</td>
</tr>
</tbody>
</table>

Table 4.6 Evaluated parameters for the laser with optimized design and different numbers of QD layers.

The P-I curves for the lasers with the same cavity length of 1 mm and different numbers of QD layers are shown in Fig. 4.19. The same gain of 12 cm\(^{-1}\) per QD layer was obtained also for the laser with 4 QD layers, but the laser with 8 QD layers has demonstrated smaller gain of 7.9 cm\(^{-1}\) per layer.

It is possible that the problems during the contact deposition or cleaving of the cavities leads to deterioration of the laser properties. The measurements of the RWG laser based on the laser with 8 QD layers, which will be presented later, also have demonstrated quite good results, which were not possible, if the laser have lower gain.
Fig. 4.19 P-I curves for the QD lasers with 4, 6 and 8 QD layers in the active region and a cavity length of 1 mm.

### 4.4 Fabrication and properties of RWG lasers.

The results of the measurement of RWG lasers with 3 different structures are presented in the following. For comparison the results of the laser with waveguide thickness of 500 µm will be partially presented first. The full results of the measurements for this laser were already presented in [92]. Then the results concerning the measurements of the laser with a waveguide thickness of 300 nm having 8 QD layers will be presented. In the end the measurements of the laser with etch-stop layers and with 6 QD layers will be discussed.

A part of the investigations presented here, are related to the preparation of RWG lasers. The aim is to decrease the injected current. Due to the small width of the ridge the thermal effects are significantly reduced. Usually in the laser application continuous-wave regime (cw regime) operation is used. Therefore all the RWG and DBR laser are measured in cw regime. The position and thickness of the ridge are defined by optical lithography and by dry etching. Afterwards the metal contacts for the current injection were deposited. To provide the
contact to the ridge the volume between ridges was filled by benzocyclobutene polymer (BCB). The contact layer was deposited as in the case of broad area lasers. A part of the contact was electroplated with gold to increase the durability of the contacts. The injection current is applied to the electroplated parts of the p-contact.

To reduce the heat resistance of the lasers for the measurements the lasers were polished and their thickness was decreased to 130 µm. Obtained structures are cleaved for the measurements.

4.4.1 QD lasers with waveguide thickness of 500 nm.

The P-I curves and the current-voltage characteristics of the RWG laser with a waveguide thickness of 500 nm and 4 QD layers in the active region are shown in Fig. 4.20. The measurements were done for the different cavity lengths on cleaved facets [92]. The measurements were started from the applied current, which was slightly lower than threshold current. It was done to decrease the time of the measurements. The threshold current is varied in the range from 90 mA up to 150 mA. The maximal output power of the laser is found to be 18 mW. For the shortest devices a decrease of the output power at high injected current is observed. This effect is referred as thermal roll-over effect and is related to the faster increase of the internal absorption in comparison to the modal gain, which increases due to the heating of the laser as a result of the increased injection current [135]. The high modal gain of 11 cm⁻¹ was determined by the measurements of the lasers with different cavity lengths. This value is in a good agreement with the measurements of broad area lasers.

The measured U-I curves shows a characteristic voltage of near 1 V. This value is slightly higher than expected one for the lasers with operation wavelength near 1.55 µm [92]. The typical charasteristic voltage in laser diodes operated at 1.55 µm is calculated to be in the range of 0.85 V [136]. Series resistance of
longer devices is near \(1.57\ \Omega\). Lasers with smaller cavity length shows twice higher values of series resistance. Observed increase of series resistance with cavity length decreasing was also observed in previous measurements of the QW lasers [137].

![P-I curves](image1)

![Current-voltage characteristic](image2)

Fig. 4.20 P-I curves (a) and current-voltage characteristic for the RWG laser with 4 QD layers in the active region for different cavity lengths [92]. Waveguide thickness is 500 nm.

The next measurements are performed on the lasers with a relatively short cavity length in the order of 340 \(\mu\)m. Emission from this laser at room temperature was not observed. To investigate the structure, the laser was cooled down to 12 °C by a thermoelectric cooler. Further cooling of the lasers is not possible because of the condensation of the water on its surfaces. Lasing was observed at a maximum output power of 2 – 3 mW. The deposition of a high reflection coating on one of the facets allows to perform the measurements on the laser at room temperature. Losses of the laser with a high-reflection coating were decreased to 23.3 cm\(^{-1}\).
The spectra for the RWG laser with different ridge widths are presented in Fig. 4.21 (a). The maximum output power of the covered RWG laser is obtained from a laser with a ridge width of 3 µm and is equal to 16 mW. The corresponding P-I spectrum and current-voltage characteristics are presented in Fig. 4.21 (b). The threshold current of the structure is found to be 38 mA and the slope is equal to 0.21 W/A.

![P-I curves](image)

Fig. 4.21 P-I curves for the different ridge width (a). P-I curve and current-voltage for the RWG laser with ridge thickness of 3 µm (b) [138].

The optical spectra for an injection current of 45 mA and 150 mA are presented in Fig. 4.22. The emission wavelength is red-shifted by 17 nm at a higher current due to the heating of the laser during the measurements. The gain profile of the laser material is temperature dependent and the emission wavelength is changing together with position of maximum gain. Such a small wavelength shift shows that the modal gain of the lasers is enough high to prevent big shift of the emission wavelength even at high injection current. This is an additional confirmation that the laser has a high modal gain [138].
4. Growth and characterization of QD Lasers

4.4.2 QD lasers with waveguide thickness of 300 nm.

Evaluation of the properties of the RWG laser with 8 QD layers and a waveguide thickness of 300 nm is presented below. As it was mentioned before, this laser shows worse parameters in comparison to the previous devices.

The emission spectra of the laser with different cavity lengths are shown in Fig. 4.23. The laser with a cavity length of 0.279 mm was cleaved and demonstrated an emission wavelength at 1540 nm. Lasers with a cavity length of 1.012 mm emit at 1586 nm. The lasers with a cavity length of 0.258 mm work only in pulsed regime and no emission is obtained from the lasers with shorter cavities.
The P-I curves and the current-voltage characteristics for the lasers with different cavity lengths are presented in Fig. 4.24. The laser with a very small cavity length of 0.279 mm is demonstrating stimulated emission at 12 °C. The devices with cavity lengths of more than 0.339 mm work even at room temperature. In the case of the previously demonstrated laser with 4 QD layers and a waveguide thickness of 500 nm, the devices with 0.34 mm work only at 12 °C. No emission was obtained from the lasers with shorter cavities.

The threshold current for the laser is near 50 mA. The obtained output power for the laser with the smaller cavity length is reach the level of 2 – 6 mW and then thermal roll-over takes place. The output power in the range of the 18 mW is reached for the lasers with a cavity length of 1.012 mm. This value is limited by the setup. No thermal effects were observed up to an applied current of 200 mA for the laser with the longest cavity.

The characteristic voltage is in the range 0.85 – 0.9 V. These values are slightly lower in comparison to the values for the laser with a waveguide thickness of
4. Growth and characterization of QD Lasers

500 nm, which are in the range of 1 V. Series resistance of device with cavity length of 1 mm is near 3.5 Ω. High series resistance values for a lasers may indicate the low quality of metal contacts, deposited on the device for further measurements.

![Fig. 4.24 P-I curves (a) and current-voltage characteristics for RWG lasers with 8 QD layers in the active region.](image)

The length dependent measurements demonstrated much better internal properties of this laser in comparison to the measurements of broad area lasers. The value of the modal gain is near 78 cm⁻¹ what is corresponding to 9.75 cm⁻¹ per QD layer. This value is in good agreement with the modal gain values for previous presented structures.

After investigation of properties of the laser with different number of QD layers the InGaAsP etch stop layers were embedded into the laser structure with the best parameters for the fabrication of the DFB lasers. Prior to the processing of the DFB lasers RWG lasers were fabricated and measured to check if there is not a big impact of the etch stop layers on the internal parameters of the lasers. Lasers with cavity lengths of 0.38 mm and 0.83 mm were cleaved and
investigated. Both lasers operate also at room temperature. The optical spectra for the RWG laser with different cavity lengths are presented in Fig. 4.25. The shift of the emission wavelength is similar to previously measured lasers and has a value of 30 nm.

![Intensity vs Wavelength for RWG lasers](image)

Fig. 4.25 Spectra of RWG lasers with embedded etch stop layers for cavity lengths of 0.38 mm and 0.83 mm, respectively.

P-I curves and current voltage characteristics of lasers with a cavity length of 0.38 mm and 0.83 mm are presented in Fig. 4.26. The measurements of the laser with a longer cavity were performed only at room temperature while the laser with shorter cavity was measured at 11 °C and at room temperature. A thermal roll-over is observed for the shorter lasers. Threshold currents of the lasers are in the range of 50 – 60 mA for the shorter devices and 80 – 85 mA for the longer lasers. The slope efficiency is varying in the range of 0.18 – 0.25 W/A for different lasers with a cavity length of 0.38 mm and 0.15 – 0.18 W/A for the lasers with a cavity length of 0.83 mm, respectively. The measurements of the lasers with shorter cavity lengths have shown a maximum output power of 2 mW per facet for the measurements at room
temperature and 7.5 mW per facet for the measurements, which were done at 11 °C. The maximum output power is in the range of 8 mW per facet for the cavity length of 0.83 mm.

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

Fig. 4.26 P-I curves and current-voltage characteristics for RWG lasers with 8 QD layers in the active region. The cavity lengths are (a, b) 0.83 mm and (c, d) 0.38 mm, respectively.

The characteristic voltage obtained from the current voltage characteristics is in the range of 1.0 – 1.3 V for the longer devices and in the range of 0.8 – 0.9 V for the shorter devices. These values are similar to the lasers with a thicker waveguide layer.
4.5 Fabrication and properties of DFB lasers.

After the optimization of RWG lasers with two etch stop layers, DFB lasers were processed from those materials. Lasers with waveguide thickness of 300 nm were used for the fabrication of DFB lasers. DFB lasers with different grating periods were produced and measured. The grating period for different lasers varies from 240 nm to 249 nm.

The emission spectra of the lasers with different grating period are shown in Fig. 4.27 (a). For the side mode suppression ratio (SMSR) of the produced lasers up to 50 dB could be measured. For comparison typical values of the SMSR values of semiconductor DFB lasers are in the range of 20 to 50 dB [53], [56], [57], [139]. Therefore the value of the SMSR is quite high for our DFB lasers.

The measured emission wavelength and linear fitting of the measured values are presented in Fig. 4.27 (b). The emission wavelength changes linearly from 1546 nm to 1595 nm. Such linear dependence is in a good agreement with the
4. Growth and characterization of QD Lasers

Bragg condition (1.4.30) and it indicates the DFB laser activities. Linear fit of the dependence of emission wavelength on grating period allow to investigate the spectral behavior of laser parameters as the effective refractive index and the laser threshold under operating conditions. The effective refractive index of the guided mode for our lasers can be determined to 3.09 at a wavelength of 1.55 µm.

The experimental measurements show a good reproducibility of the results. This means, that lasers could be fabricated with well defined emission wavelengths.

Measured P-I curves and voltage current characteristics for the different cavity lengths are presented in Fig. 4.28. The cavity lengths from 0.38 mm up to 0.88 mm were cleaved. The lasers with shorter cavities than 0.644 mm have not shown any emission neither at room temperature nor at low temperature measurements. The devices with cavity lengths of 0.644 mm and larger are lasing at room temperature. The P-I curves for measured DFB lasers have demonstrated non-linear behavior. The reason of the non-linearities may be the mode competition between the dominant optical modes with the gain. All the potential lasing modes have peaks in the gain spectrum of the laser. During laser operation some mode reaches threshold, but then the gain can still be increased and the next mode could blow up at other wavelength [42]. Other reasons of nonlinearities in P-I spectra are thermal roll-over phenomena and presents of minor defects in the laser or on the facet reflections. The reason of kinks on P-I spectra could be jumps between different optical modes.

The maximum output power of the device is near 12 mW per facet for the device with a cavity length of 0.83 mm, and 9 mW per facet for the laser with a cavity length of 0.644 mm.
Fig. 4.28 P-I curves and current-voltage characteristics for DFB lasers with different grating periods. Cavity length is 0.830 mm (a, b) and 0.644 mm (c, d), respectively.

The characteristic voltage for the lasers with a cavity length of 0.83 mm varied in the range of 0.9 – 1.3 V. For the laser with cavity length of 0.644 mm the characteristic voltage is near 1 V. The resistance of the devices with longer cavities is in the range from 4 up to 6 Ω while the shorter devices have resistance near 7 Ω. The results of the measurements are quite good especially for the first samples, which were produced.
4.6 Dynamic properties of RWG lasers.

The results regarding the modulation measurements are presented in this section. Measurements were done by our partners at Technion and Fraunhofer Heinrich Hertz Institute. The results are published in [138], [140].

The results of the small signal modulation experiments of the laser with a waveguide thickness of 500 nm are presented in Fig. 4.29 (a). The measurements were done with a RWG laser with a cavity length of 340 µm. One facet was coated with antireflection coating. A strong damping of the signal is observed in this laser. The reason of the signal damping is the nonlinear gain compression [138]. A maximum bandwidth $f_{3dB,max}$ was observed in the range of 5 GHz. Some resonance frequency was observed at 9.5 GHz.

The main reason of the small bandwidth is the long carrier transport time between the cladding layer and the active region. The confirmation of this suggestion was obtained by theoretical calculations, based on the model from [141] with parameters of the measured devices.

The improved laser with a waveguide thickness of 300 nm demonstrates a better small signal response. The results of the small signal modulation experiment are presented in Fig. 4.29 (b, c). Measurements were done with a RWG laser with ridge width of 2 µm. The cavity length of the measured laser was varied from 275µm to 350 µm.
4.6. Dynamic properties of RWG lasers

Fig. 4.29 Small signal response for a laser with a waveguide thickness of 500 nm (a) and 300 nm (b, c). Measurements were carried out at 20 °C. (a) QD laser with 6 QD layers in the active region and cavity length of 340 µm (b) QD laser with 6 QD layers in the active region and cavity length of 350 µm, (c) QD laser with 8 QD layers and cavity length of 275 µm.

An increase of the maximum bandwidth is observed in this case up to 8.1 GHz for the laser with 6 QD layers in active region and cavity length of 350 µm. Further increase of the maximum bandwidth up to 9.1 GHz is observed for the laser with 8 QD layers in active region and shorter cavity length of 275 µm. This is in close agreement with simulation results presented in section 3.2. The obtained results show better dynamical properties of the lasers with the smaller
waveguide. This means that it is possible to achieve higher binary data rates with these lasers.

Fig. 4.30 Large signal response of lasers with a waveguide thickness of 500 nm (a, b) and 300 nm (c, d): (a) uncoated RWG laser with a cavity length of 756 µm, (b) RWG laser with a cavity length of 340 µm, (c) RWG laser with a cavity length of 350 µm, (d) closed eye for the RWG laser with a cavity length of 275 µm

Although the results of the small signal modulation are limited, the lasers demonstrated very high digital modulation capabilities. The eye-diagrams for the different lasers are presented in Fig. 4.30. The uncoated RWG laser with a waveguide thickness of 500 nm shows an “open eye” diagram up to a data rate of 14.5 Gbit/s. The coated laser with a cavity length of 340 µm shows a slight improvement of the modulation properties and shows an “open eye” diagram up
to a bit rate of 15 GBit/s. The decrease of the waveguide thickness leads to a further improvement of the modulation characteristics of the lasers. In this case an “open eye” diagram was observed up to 22 Gbit/s.

A similar behavior was observed for GaAs based QD lasers [142]. For those lasers a large signal modulation of 25 Gbit/s is possible while a maximum small signal bandwidth of only 11 GHz was observed. A similar large difference between small and large signal modulation is usually not observed in QW lasers. It was found, that the measurements of small signal modulation could be inconsistent with large signal modulation in the case of QD lasers with high modal gain and large nonlinear gain compression factor. As a result, in QD lasers the frequencies, where the large signal modulation takes place, are highly damped. The same situation could not be realized in the case of QW lasers, because it is not possible to reach enough high values of nonlinear gain compression factor to limit the small signal bandwidth [143].
Conclusions

The work has been focused on the realization of InP-based QD lasers for high-speed telecommunication applications. The main focus of the research was concentrated on improvement of the optical properties of QD samples and implementation of QD sample with the best properties in the active region of the laser structure. The formation of more dense and homogeneous QDs will increase the modal gain of laser material. Also the optimization of the laser design was done to improve the dynamical properties of the lasers.

With QD test samples a low temperature PL linewidth of 32 meV (FWHM) at a wavelength of 1525 nm could be obtained. After the implementation in a laser structure the PL linewidth of 30 meV could be demonstrated.

There are still possibilities to improve the optical properties of QD samples. Firstly, the implementation of thin strained layer could lead to formation of QDs with higher density. It was also reported, that presents of strained layer could lead to formation of more homogeneous QDs. As a result an improvement of optical properties of QD samples and further increase of modal gain of laser material could be achieved. Due to technical problems with MBE system the influence of growth rates on properties of QD samples was not investigated. Increase of growth rates could lead to significant decrease of the growth time of the laser. It can favour the improvement of the laser properties due to decrease the material intermixing between QD layers and surrounding materials.
The optimization of the growth conditions of QDs results in a direct improvement of properties of the QD lasers. The lasers with very high modal gain and low absorption are realized due to an improvement of the optical properties of the QD ensemble. The value of the modal gain of the lasers was increased up to 12 cm\(^{-1}\) per QD layer. Obtained values for modal gain are two to three time higher in comparison to the earlier published works. The investigations of the influence of the laser design on their dynamical properties allow us to reach bit rates up to 22 Gbit/s, which is the highest value for this material system. Further decrease of the waveguide thickness will decrease the transport time from the cladding to active layer. As a result, further increase of the bit rates could be achieved. Discrepancy between the measurements of small signal modulation and large signal modulation were explained by the high modal gain of the lasers and high nonlinear compression factor. It leads to restriction of small signal bandwidth. At the same time laser can be modulated at large bit rates.

By the implementation of etch stop layers into the laser structure DFB lasers with quite good properties were realized. DFB lasers with different grating periods were fabricated by deep etching of the laser structure with implemented etch stop layers. Single mode operation at 1.55 µm with a SMSR of 50 dB was observed.
Publications / Conference contributions

Publications


C. Gilfert, V. Ivanov, N. Oehl, M. Yacob, J.P. Reithmaier, “High gain 1.55\textmu m diode lasers based on InAs quantum dot like active regions”, Applied Physics Letters 98, 201102 (2011)


Conference contributions

C. Gilfert, V. Ivanov and J.P. Reithmaier, “1.55 \textmu m lasers based on shape-engineered InAs/InAlGaAs/InP (100) quantum dots”, Euro MBE Conference, L‘Alpes d‘Huez, France (March 2011)

C. Gilfert, V. Ivanov and J.P. Reithmaier, “1.55 \textmu m Quantenpunktmateriaal mit erhöhter spektraler Verstärkung für Kommunikationslaser und optische Halbleiterverstärker (SOAs)”, 12. ITG-Fachtagung “Photonische Netze”, Leipzig, Germany (May 2011)
D. Gready, C. Gilfert, V. Ivanov, J.P. Reithmaier, G. Eisenstein "1.55 µm high-speed quantum dot lasers for telecommunication applications", CLEO International Conference on Lasers and Electro optics, San Jose, CA, USA (May 2012)


Vitalii Ivanov, Vitalii Sichkovskyi, J.P. Reithmaier, "High-speed 1.55 µm InP-based quantum dot lasers for telecommunication applications", European Semiconductor Laser Workshop, Brussels, Belgium (September 2012); DOI: 10.1109/IPCon.2012.6358482.


J.P. Reithmaier, V. Sichkovskyi, V. Ivanov, K. Koshuharov, G. Eisenstein, "InP based 1.55 \( \mu \)m quantum dot materials and lasers for ultra-narrow linewidth applications", Int. Conf. on Sol. State Dev. & Mat. (SSDM), Fukuoka, Japan (Sept., 2013, invited)

**Additional articles**

O. Karni, A. Capua, G. Eisenstein, V. Sichkovskyi, V. Ivanov, J.P. Reithmaier, "Rabi oscillations and self-induced transparency in InAs/InP quantum dot semiconductor optical amplifier operating at room temperature", Optics Express **21** (22), 26786 (2013).
Bibliography


[60] M. Imada, S. Noda, H. Kobayashi, G. Sasaki, „Characterization of a distributed feedback laser with air/semiconductor gratings embedded by


[66] Mirja Richter, Benjamin Damilano, Jean Massies, Jean-Yves Duboz and Andreas D. Wieck, “InAs/In_{0.15}Ga_{0.85}As_{1-x}N_{x} quantum dots for 1.5 µm laser applications”, *MRS Proceedings* 891, p. 185 (2006)


[126] Peter J.A. Thijs, Luuk F. Tiemeijer, J.J.M. Binsma, Teus van Dongen “Progress in long-wavelength strained-layer InGaAs(P) quantum-well


[142] Yu. Tanaka, Mitsuru Ishida, Kan Takada, Tsuyoshi Yamamoto, Hai-zhi Song, Yoshiaki Nakata, Masaomi Yamaguchi, Kenichi Nishi, Mitsuru Suguwara, Yasuhiko Arakawa “25 Gbps direct modulation in 1.3-µm InAs/GaAs high-density quantum dot lasers”, *Conf. on lasers and electrooptics (CLEO) and quantum electronics and laser science conference (QELC)* (2010)

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