Diplomarbeit

Electro Optical Characterisation of Short Wavelength Semiconductor Laser Diodes

Deutscher Titel:
Elektro-optische Charakterisierung von kurzwelligen Halbleiterlasern

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I’m not bound to please thee with my answers.

William Shakespeare

Preface

It was summer of 2006 as I came to Bremen. An engineering student who wants to try his chances and capabilities in physics. No simple pace. A challenging way to be. Lasers have been always fascinating; as they were introduced in lectures of optical communications, as I used them as tools for making holograms and measuring luminescence spectra or by hearing the versatile application fields with many to any time science fiction like aspects getting realised the other day; they were always fascinating. Getting familiar with some blue lasers happened in Freiburg. At that time an extremely expensive black box. One should be extremely careful with this tiny treasure, they said. Well, happening to cost that much, they should have been behaved as a VIP. This mixture of fear and respect remained till I got the first blue laser specimens for test. And the wide necessary knowledge behind this minute structure is still fascinating.

The information technology booms and information needs some storage more compact. And this at the first glimpse irrelevant issue is the most powerful driving engine of the blue laser research branch. The key word is Blu-ray Disc.

Is it possible to have any laser TVs? What would be then the colour system? Possibly an RGB. Well, a Red, a Green and a Blue laser would be then needed. Green is actually the colour by which the human eyes’ are sensitive at most. But making some marketable green laser devices is still challenging. The future will show us the improvements in making the green laser diodes.

The epitaxy group of the solid state institute of Bremen university deals with growth, processing and characterisation of III-V based as well II-VI based laser diodes. This wide terms of reference requires many people working in different subgroups having clear defined tasks and cooperating with each other. I was mainly responsible for the opto-electrical characterisation of the devices of both III-V and II-VI groups. This provided me the chance to cooperate with practically every member of the group. The result of this very happy cooperation is the following.

In the first chapter after taking a short look on the history of the semiconductor laser diodes, the basic physical concepts of these devices are delineated.

The second chapter deals with the used growth methods and processing technology in Bremen. Since neither crystal growth nor technology belong to the main scope of this thesis, detailed information is not obtainable here.

The third chapter belongs to the theoretical and practical prerequisites of understand-
ing the characterisation methods partly used.

The fourth chapter evaluates the raw data of measurements and discusses the results.

And a summary, as hopefully expected, is the end of the main matter of this thesis.
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Chapter 1

Basic Concepts

1.1 Historical Background

The concept of semiconductor lasers was introduced by Basov et al. in 1961 proposing that stimulated emission of radiation could occur in semiconductors by the recombination of across $p-n$ junction injected carriers [1]. He was rewarded with a Nobel Prize in 1964 for this attempt. In 1962 the first semiconductor lasers appeared in several laboratories independently (Hall et al. [2]; Holonyak Jr. et al. [3]; Nathan et al. [4]; Quist et al. [5]). All these groups used gallium arsenide, GaAs, in their approaches. Silicon could not be used because of its indirect bandgap although a matured fabrication technology existed. The required direct bandgap materials were found in compound materials which were at that time less understood. The main reasons behind the major surge in role played by semiconductor lasers are their continued performance improvements especially in low-threshold current, ultrashort optical pulse generation, narrow spectral linewidth, high optical output power, low electrical power consumption and low costs. Many of these achievements were based on theoretical understanding of the semiconductor materials and improvement of material growth technologies.

In 1969 the heterostructures were introduced [6]. In a heterostructure laser the simple $p-n$ junction is replaced with multiple semiconductor layers of different compositions. The first structures consisted of layers of different compositions of $\text{Al}_x\text{Ga}_{1-x}\text{As}$. Constant wave (cw) operation at room temperature became possible because of better carrier and optical confinement. Laser performance continued to improve as more advanced heterostructures such as quantum wells (QW) were developed. The pioneering works using molecular beam epitaxy $^1$ (MBE) (Cho, 1971 [7]; cho et al., 1976 [8]; Tsang et al., 1979 [9]) and metal organic chemical vapour deposition (MOCVD)$^2$ (Dupuis and Dapkus, 1977 [10]; Dupuis et al., 1978, 1979 [11, 12, 13]) to grow ultrathin semiconductor layers of the order of ten atomic layers, had paved the way for the development of new semiconductor lasers.

$^1$epitaxy is Greek formed from $\epsilon\pi\epsilon$ (on, onto) and $\tau\alpha\xi\eta$ (order)

$^2$alternative names for this process include Metalorganic vapour phase epitaxy (MOVPE), organometallic vapour phase epitaxy (OMVPE) and organometallic chemical vapour deposition (OMCVD)
Semiconductor lasers have the smallest size, highest efficiency and longest lifetime of all the existing lasers. The fact of existence of many different applications for opto-electrical devices enabled the field of semiconductor lasers to draw the attention and resources necessary for its development. Optical communication was probably the first issue profited by this. The idea of optical storage media was the next great boom. Bar-code readers, laser printers and many military applications kept the topic an evergreen. All these commercially available laser diodes covered an emission spectrum from the red to the infrared.

In order to be able to produce laser diodes emitting in green and blue other material systems were investigate. III-V nitrides such as gallium nitride, GaN, turned out to have a band gap in blue spectral region; II-VI selenides such as zinc selenide, ZnSe, in green. Although it was possible to manufacture light emitting devices, using deep luminescent centres, conducting p-type GaN was not obtained till 1988, when Akasaki and Amano accidentally discovered that the p-type dopant magnesium has to be activated [14]. This happened by scanning electron microscopy investigation of the cathodoluminescence of Mg-doped GaN. Observations showed that the luminescence intensity increased with the scanning time [15]. The passivity of Mg acceptors was later explained by the hydrogen atoms, which are released due to the energy of the electron beam. It took two more years until Nakamura developed an alternative activation technique. He removed the hydrogen by an annealing step in nitrogen [16]. The first injection laser was presented in 1995 [17], six years after the first p-type doping. Today is Blu-ray Disc a strong motivation among others to push the whole business. The research on ZnSe-based laser devices was stimulated by the development of a reliable p-type doping technique in 1990 and 1991 [18, 19]. In the following years these devices were brought from short life pulsed operation at low temperatures (77 K) to continuous wave (cw) operation at room temperature. However with a limited life time due to which the ZnSe based lasers haven’t been commercialised yet and are still in research stage.

1.2 Physics of Semiconductor Lasers

There are many different aspects needed to be observed by talking of semiconductor lasers. The building blocks of these structures are crystals. We also study the propagation of light in these crystal structures. Studying the crystals and the interaction of electromagnetic radiation and matter is therefore of importance.

1.2.1 Crystals

An ideal crystal is built as the infinite repetition of identical structure units in the three-dimensional space. In the simple crystals like copper, silver, iron, aluminium and the alkali metals the structure unit is only one atom. But in most of the cases there are different atoms or molecules which are contained in the crystal structure. Gallium nitride, zinc selenide and their related compounds can crystallise both in the zincblende as well as in the wurtzite structure. Crystallographically, the zincblende structure and wurtzite structure are very closely related. In a zincblende structure, a view along a [111] direction reveals that the atoms of a given kind are stacked in the sequence
\[ \cdots ABCABC \cdots \] while maintaining tetrahedral bonds with those of the other kind. This diamond-like structure consists of two interpenetrating face-centred cubic bravais lattices, displaced along the body diagonal of the cubic cell by one quarter the length of the diagonal [21]. The difference between a diamond and a zincblende structure is that a diamond has got an inversion centre in the middle of each connection line between two neighbours (Fig. 1.1) whereas the zincblende has no inversion symmetry (Fig. 1.2).

In case of wurtzite structure the tetrahedral bonding is preserved but the atoms of a given kind are stacked in the sequence \[ \cdots ABABAB \cdots \] and the underlying Bravais lattice is hexagonal. Fig. 1.3 shows a clinographic projection of the wurtzite structure. In the clinographic projection the cube is turned through an angle \( \theta \) about a vertical axis, making both the front and right hand faces visible. The cube is then projected on to a vertical plane by parallel straight lines, which are inclined to the horizontal so that the top face is brought into view [22]. For the wurtzite structure the lattice constants \( a \) and \( b \) are equal which means \( a = b \). The unit cell is described by \( c \) and \( a \). The substructure of the unit cell creates an asymmetry of the unit cell along the \( c \)-axis, i.e. the directions of the bonds are different along [0001] and [0001].

It is worth adding that in case of hexagonal crystals the Bravais-Miller indices instead of Miller indices are commonly used. By Bravais-Miller figure the four indices \( (hki) \) instead of the three \( (hkl) \) by Miller, whereas \( h + k + i = 0 \).

The group-III nitrides are commonly found to grow in the hexagonal crystal structure, as this is the thermodynamically more stable modification. It is possible to obtain films showing a cubic lattice, but this requires the epitaxy on suitable cubic substrates. An interesting feature of the group III-nitrides is their exceptional hardness and chemical inertness combined with a good thermal conductivity [14]. This issue makes the group III-nitride semiconductor devices stable, since high operation temperatures without destroying the lattice are possible. On the other hand
many problems appear during the processing phase of the devices [23] (see also chapter 2). The thermodynamically stable crystall structure of ZnSe is the zincblende structure. The wurtzite structure occurs at temperatures above 1425°C [24]. ZnSe can be cleaved along the [110] direction which allows a simple fabrication of mirror facets. ZnSe single crystals with a crystalline quality suitable for device fabrication are rare and usually only available in small sizes [25].

Band gap and lattice

Having a direct band gap is a prerequisite for an efficient radiative recombination. Due to the direct band gap there are no phonons necessary for momentum conservation. This leads to a much higher recombination rate compared to indirect semiconductors. The III-nitrides and II-VI compounds are such direct band gap semiconductors as can be seen in Fig. 1.4. The band gap energy at 300 K amounts 3.42 eV for GaN and 2.69 eV for ZnSe.

**Figure 1.4:** Electronic band structure along the symmetry directions of the first Brillouin zone of (a) wurtzite GaN [26] and (b) ZnSe [27]. (c) and (d) [28] are band crossing and band mixing points within the energy bands of the wurtzite phase of GaN respectively.
Besides the mentioned binary alloys, ternary and quaternary alloys are of enormous meaning for the production of laser diodes, as they allow a free design of the band structure. The band structure parameter can be adjusted depending on the composition of the alloy. In case of III-nitrides only the ternaries InGaN and AlGaN beside GaN are being used in the devices although studies on quaternary III-nitrides as AlInGaN are in progress [32, 33]. On the contrary, not only the ternary but also the quaternary alloys play a big role in the II-VI laser diode systems. ZnSSe, MgZnSSe, CdSSe and CdZnSSe are of the examples.

Fig. 1.5 shows the the band gap energy versus the lattice constant for II-VI and III-V material systems. All the points shown on the Fig. 1.5 are binary materials. The composition change, i.e. making ternary or quaternary materials out of the binary ones, influences the lattice constant and the band gap energy. Modification of the lattice constants $a$ of A$_x$B$_{1-x}$C and A$_x$B$_{1-x}$C$_y$D$_{1-y}$ obeys the Vegard’s law [35]:

\[ a(x) = xa_{AC} + (1-x)a_{BC} \]  
\[ a(x, y) = xy a_{AC} + (1-x)y a_{BC} + x(1-y)a_{AD} + (1-x)(1-y)a_{BD}. \]  

For calculation of the band gap energy $E_g(x)$ the simple linear interpolation is not valid. A so called bowing parameter $b$ is introduced,

\[ E_g(x) = xE_{g,AC} + (1-x)E_{g,BC} - x(1-x)b \]  
\[ E_g(x, y) = xyE_{g,AC} + (1-x)yE_{g,BC} + x(1-y)E_{g,AD} + (1-x)(1-y)E_{g,BD} - x(1-x)[yb_{ABC} + (1-y)b_{ABD}] - y(1-y)[xb_{ACD} - (1-x)b_{BCD}]. \]  

It is of importance to mention that not all theoretical compositions are possible to form a ternary or quaternary alloy as certain ranges are not stable and phase separation occurs.
1.2.2 Light in Crystal

The interaction process of electromagnetic waves and matter can be studied in two different points of view; microscopic and macroscopic.

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**Figure 1.6:** The three different processes possible when describing the interaction between light and matter: absorption, stimulated emission and spontaneous emission. $E_V$ is the energy of the valence band; $E_C$ energy of the conducting band.

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**Microscopic Aspects**

The basic interaction mechanisms between light and matter are absorption, spontaneous emission and stimulated emission, as depicted in Fig. 1.6. These are transitions of charge carriers in the matter between different energy levels evoked by the photons. Different energy levels in a semiconductor material are determined by the band structures, see 1.4. The energy difference between the valence band and the conducting band is the band gap energy and is given by,

$$\Delta E = E_C - E_V = E_g.$$  \hfill (1.5)

The energy difference is a key value when dealing with the interaction between light and matter since the electron can only make transitions that involve an exchange of energy that equals $\Delta E$. With having this picture in mind and assuming an extremely simplified two state model, the following cases are conceivable,

- **Absorption.** The electron can begin from its ground state and make a transition to its excited state by absorbing a photon with frequency $\omega = \Delta E/\hbar$. The photon disappears as a result of interaction meaning the energy in the amount of $\Delta E$ is transferred from the electromagnetic field to the electron such that the total energy of the whole system is conserved.

- **Stimulated Emission.** If an incident photon with energy $\Delta E = \hbar \omega$ hits an electron with its electron in the excited state it can induce with a certain probability a transition of the electron from the excited state to the ground state. In this process a second photon is created which is identical in momentum, energy, polarisation and phase to the incident one. This process can be used to amplify a photon field. It is therefore
the basic mechanism for all lasers (Light Amplification by Stimulated Emission of Radiation). Absorption and stimulated emission are closely related events.

• **Spontaneous Emission.** This is when the excited atom emits a photon by releasing energy in the amount of \( \Delta E \) by transitioning from its excited state to its ground state.

In case of a laser the, *gain* is achieved if more photons of energy \( E_g \) leave the structure than enter it. This compensates the loss of energy due to spontaneous emission and non-radiative recombinations. This condition occurs in case of *inversion*, i.e., more carriers are in the excited than the ground state. This point is called *laser threshold*. Below the threshold, spontaneous emission dominates. Exactly at threshold, the semiconductor is transparent. Gain equals loss in this case (for detailed calculations see [36]). Above the threshold, stimulated emission dominates. This amplifies the light passing through.

Absorption and stimulated emission are closely related events and absorption is the dominating of them both due to the fact that the electron population in the valence band exceeds that in the conducting band. Thus it would be of interest to calculate the condition of *optical gain*. This is obtained from the occupation probabilities of electrons of the energy \( E_c \) in the conduction band \( f_c(E_c) \) and holes of energy \( E_v \) in the valence band \( f_v(E_v) \). These are determined by the *Fermi-Dirac statistics*, with the quasi-Fermi levels \( E_{fc} \) and \( E_{fv} \) in the conduction band and the valence band respectively [37],

\[
f_c(E_c) = \frac{1}{e^{\frac{E_c - E_{fc}}{k_B T}} + 1} \quad \text{and} \quad f_v(E_v) = \frac{1}{e^{\frac{E_v - E_{fv}}{k_B T}} + 1},
\]

(1.6)

where \( k_B \) is the Boltzmann constant and \( T \) is the temperature measured in Kelvin. If photons of energy \( E = h\nu = E_c + E_v + E_g \) impinge on the semiconductor of band gap \( E_g \), they can be absorbed, creating electrons of energy \( E_c \) and holes of energy \( E_v \) at a rate \( R_a \),

\[
R_a = B[1 - f_c(E_c)][1 - f_v(E_v)]\rho(E).
\]

(1.7)

\( B \) is the transition probability and \( \rho(E) \) is the density of photons of energy \( E \). It is of importance to be mentioned that the Fermi-Dirac statistics determines the statistical distribution of fermions. It is known that they obey the *Pauli exclusion principle*, i.e., no more than one particle my occupy the same quantum state at the same time. Thus \([1 - f_c(E_c)]\) delivers the probability that the electron state with the energy \( E_{fc} \) is not occupied whereas \([1 - f_v(E_v)]\) implies the probability of a free hole state of energy \( E_{fv} \).

Furthermore, the stimulated emission can occur at a rate \( R_e \),

\[
R_e = Bf_c(E_c)f_v(E_v)\rho(E).
\]

(1.8)

Stimulated emission dominates absorption if and only if

\[
R_e > R_a.
\]

(1.9)

Using Eqs. 1.7, 1.18 and 1.9 directly yields

\[
f_c(E_c) + f_v(E_v) > 1
\]

(1.10)
Basic Concepts

which by using 1.6 can be written as

$$E_{fc} + E_{fv} > E_c + E_v. \quad (1.11)$$

Adding up the band gap energy to both side leads to

$$E_g + E_{fc} + E_{fv} > E_c + E_v + E_g = h\nu > E_g. \quad (1.12)$$

Equation 1.12 represents the condition for optical gain. In the case of electrical pumping, this would imply that the externally applied electric field must result a separation of quasi Fermi energies, that exceeds the photon energy of the stimulated emission and the band gap energy of the semiconductor [37].

Macroscopic Aspects

Optical gain is necessary but not sufficient for lasing. A second aspect called optical feedback is also needed. The feedback enables the selectivity for the stimulated emission in terms of direction and wavelength and thus enables the laser oscillation. The optical feedback could be reached through two parallel semi-transparent mirrors brought on the both sides of the gain medium. This forms a Fabry-Pérot resonator.

From the macroscopic point of view the matter is considered as a homogeneous medium described by the complex dielectric $\varepsilon(\omega)$ or by the complex index of refraction $\tilde{n}(\omega)$. Laws of reflection, transmission and absorption can be described from this point of view. In case of a Fabry-Pérot resonator the concentration is on reflection and transmission, as depicted in Fig. 1.7. Transmission coefficients $t_1$ and $t_2$ and reflection coefficients $r_1$ and $r_2$ are defined respectively.

A plane wave propagating in the positive z direction could be written as $\vec{E} e^{-\Gamma z}$, whereas $\Gamma$ is the complex propagation constant. A wave $\vec{E}_i$ meets the input mirror at $z = 0$ perpendicular to the surface; a part will be reflected and a part transmitted. This happens every time the wave reaches any of both mirrors. For calculating the lasing conditions, it would be sufficient to only take the transmitted part on the output mirror at $z = L$ into consideration. Summing up the transmitted fields delivers a geometric progression,

$$\vec{E}_i = t_1 t_2 \vec{E}_i e^{-\Gamma L} + r_1 r_2 t_1 t_2 \vec{E}_i e^{-3\Gamma L} + \ldots = \vec{E}_i \left[ \frac{t_1 t_2 e^{-\Gamma L}}{1 - r_1 r_2 e^{-2\Gamma L}} \right]. \quad (1.13)$$

Exactly at the laser threshold the cavity is invisible for the light. If the denominator of Eq. 1.13 approaches zero, the condition of lasing oscillation is obtained because of a finite transmitted intensity $\vec{E}_i$ remaining from an incident wave with vanishing intensity $\vec{E}_i$;

$$r_1 r_2 e^{-2\Gamma L} \overset{!}{=} 1. \quad (1.14)$$

The complex propagation constant $\Gamma$ includes the damping factor $\alpha$ and the phase $\phi = \frac{2\pi}{\lambda}$ of the wave, where $\lambda$ is the wavelength.
\( t_1 r_1 r_2 \vec{E}_i e^{-2\Gamma L} \quad - \quad - \quad - \quad t_1 r_1 r_2 \vec{E}_i e^{-\Gamma L} \quad - \quad - \quad - \quad t_1 r_1 r_2 \vec{E}_i e^{-\Gamma L} \quad - \quad - \quad - \quad t_1 r_1 r_2 \vec{E}_i e^{-\Gamma L} \)

\[ \vec{E}_i \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad t_1 \vec{E}_i \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad t_1 \vec{E}_i e^{-\Gamma L} \quad - \quad - \quad - \quad t_1 \vec{E}_i e^{-\Gamma L} \quad - \quad - \quad - \quad t_1 \vec{E}_i e^{-\Gamma L} \quad - \quad - \quad - \quad t_1 \vec{E}_i e^{-\Gamma L} \]

Figure 1.7: Fabry-Pérot resonator of length \( L \). \( t \) and \( r \) are transmission and reflection coefficients. \( \vec{E}_i \) represents a plane wave, incident onto the input mirror [25].

\begin{equation}
\Gamma = \alpha + i \frac{2\pi}{\lambda}.
\end{equation}

The cavity of a laser is amplifying. This fact needs to be considered.

\begin{equation}
\Gamma = (\alpha_i - g) + i \frac{2\pi n}{\lambda},
\end{equation}

where \( \alpha_i \) represents the whole internal loss, and \( g \) is the gain of the cavity. Propagation of light in matter of refractive index \( n \neq 1 \) leads to chromatic dispersion; thus \( \frac{\Delta}{n} \). Combining Eqs. 1.14 and 1.16 yields

\begin{equation}
r_1 r_2 e^{(g - \alpha_i)2L} e^{-i2L \frac{2\pi n}{\lambda}} \frac{1}{e^{i2L \frac{2\pi n}{\lambda}}} = 1,
\end{equation}

which is representative for a wave covering a distance of \( 2L \) inside the cavity, returning to the input mirror with the same amplitude and in phase. Equating the real and imaginary parts of Eq. 1.17, two lasing conditions are obtained

\begin{equation}
r_1 r_2 e^{(g - \alpha_i)2L} \cos \left( \frac{2L \frac{2\pi n}{\lambda}}{2} \right) \frac{1}{\cos \left( \frac{2L \frac{2\pi n}{\lambda}}{2} \right)} = 1
\end{equation}

\begin{equation}
\sin \left( \frac{2L \frac{2\pi n}{\lambda}}{2} \right) \frac{1}{\sin \left( \frac{2L \frac{2\pi n}{\lambda}}{2} \right)} = 0
\end{equation}
Eq. 1.19 delivers directly
\[
2L \frac{2\pi n}{\lambda} = m2\pi; \quad m = 1, 2, 3 \cdots
\]
\[
m\frac{\lambda}{n} = 2L
\]
from which the longitudinal mode separation in the cavity could be calculated by differentiation and a mode difference of \(\Delta m = -1\) to \(\Delta \lambda = \frac{\lambda^2}{2nL \left[1 - \frac{1}{m} \frac{dn}{d\lambda}\right]}.\)

For a small region the dispersion \(\frac{dn}{d\lambda}\) can be neglected; further the substitution of an effective refractive index \(n_{\text{eff}}\) for refractive index \(n\) yields
\[
\Delta \lambda \approx \frac{\lambda^2}{2n_{\text{eff}} L}.
\]

Eq. 1.18 is the second condition of lasing. It is already known from (Eq. 1.20) that the wavelength of the lasing regime in the cavity is given by \(\lambda = \frac{2nL}{m}\). Substituted in 1.18 the \(\cos\) part turns to unity. The threshold gain will be then
\[
g_{\text{th}} = \alpha_i + \frac{1}{2L} \ln \frac{1}{r_1r_2}
\]
Obviously the threshold gain \(g_{\text{th}}\) needs to compensate the internal losses \(\alpha_i\) and the mirror losses expressed in \(\frac{1}{2L} \ln \frac{1}{r_1r_2}\).

By electrically pumped laser diodes the gain has an experimentally proved dependency on the amount of injected carriers which is linear for high gain values \((50 - 400 \text{cm}^{-1})\) and quadratic, else. This was shown for conventional III-V as well as ZnSe laser diodes. In case of ZnSe laser diodes though, the thermal effects could lead to significant deviations \([38, 39]\). The linear relationship having the nominal current density \(J = \frac{n \eta d}{\Gamma}\) \(^\text{iv}\) and the transparency current \(J_0\) \(^\text{v}\) in mind, can be written as
\[
\Gamma = \beta (J - J_0),
\]
where \(\beta\) is a constant called 'gain factor’ with no further physical meaning . \(\Gamma\) is the confinement factor defining the overlap of light with the gain medium [25].

Using Eqs.1.23 and 1.24 yields directly the Eq.1.25 where the threshold current density \(j_{\text{th}}\) is calculated;
\[
j_{\text{th}} = \frac{J_0 d}{\eta \eta_i} + \frac{d}{\beta \eta_i \Gamma} \left(\alpha_i + \frac{1}{2L} \ln \frac{1}{r_1r_2}\right).
\]
The dependency of threshold current density on extrinsic parameters like cavity length and reflectivity of the mirrors leaves the option of modification after growth open.

\(^{iii}\Delta m = +1\) is also possible. Due to the reciprocal proportionality of \(m\) and \(\lambda\) this would result a negative \(\Delta \lambda\).

\(^{iv}\eta_i\) is the internal quantum efficiency defined as the ratio of injected carriers to emitted photons contribute stimulated emission and \(d\) is the thickness of the active region.

\(^{v}\)also called nominal threshold current density
1.3 Laser Device

A semiconductor laser doesn’t look similar to different people. An electrical engineer may think of it as a forward biased $p-n$ junction, while a crystal grower might be interested in the heterostructure. Nevertheless it is possible to roughly imagine a structure which does “lase”, as a common underlying picture.

A semiconductor laser is generally fabricated by growing a p-doped layer on top of an n-doped substrate. With n- and p-dopes, donor and acceptor impurities in the semiconductor are meant. Popular donors in the III-nitride and II-VI lasers are Si and Cl, respectively; the acceptors mainly used are Mg and N.

1.3.1 Heterostructures

The first semiconductor lasers were homostructure devices, i.e. each laser was fabricated with only one semiconductor material. The crucial problem with these lasers was the high threshold current densities, even when operated at low temperatures. Neither could they operate cw.

Eq. 1.25 shows the strong proportionality of the threshold current density and the active region thickness $d$, which is the distance a conducting electron travels from n-doped to p-doped region before recombination with a hole occurs. Retaining other factors, reduction of this thickness reduces the threshold current density. The problem is to trap the electrons in the active region in order to increase the chance of recombination while decreasing the thickness. The method generally adopted is the growth of a blocking layer of a material with a higher bandgap energy than the active region. The resulting structure is called single heterostructure if one blocking layer used and double heterostructure if a blocking layer is used on each side of the active region.

Using double heterostructures the thickness of the active region in III-nitride as well as II-VI based lasers is reduced to 4 nm. The fact that usually for two materials that can form a stable heterostructure, the larger bandgap material has a lower refractive index, leads automatically to an optical waveguiding for the laser field of double heterostructures. The next steps were increasing output power and lowering laser threshold current. For the double heterostructure described, sailing to higher power is a problem. The reason is that both the carriers and the laser modes are confined in the same thin region. It is desirable to keep the carriers in a thin layer to maximise the density, but the radiation field needs to be in a thick layer so that the intensity of the
light below the material damage threshold is ensured. Both criteria can be fulfilled with a more complicated heterostructure configuration, the separate confinement heterostructure (SCH) [40] seen in Pic. 1.8.

The Fig. 1.9 is the structures of a Multi-Quantum Well (MQW) III-nitride semiconductor laser diodes and the corresponding energy level of the bands. The SCH is very clearly determined. As it will be seen in the next chapters, this structure has led the lasers to achieve an acceptable output power and threshold current.

1.3.2 Epitaxy

For the fabrication of SCH laser diodes as already described, epitaxial methods are necessary. In such an epitaxy process (see 1.1), the semiconductor material is deposited on a seed crystal, the substrate.

![Figure 1.9: The laser structure of a III-nitride based laser diode [41]](image)

This substrate crystal determines the crystallographic orientation of the deposited layers. The substrate can be made of the same material as the deposited layers, which is called homoepitaxy, i.e. GaN or ZnSe layers on GaN or ZnSe crystals respectively.

Heteroepitaxy is the case if the material of substrate is different than the layer grown. For ZnSe-based devices the substrate is then for instance GaAs and for GaN-based devices sapphire\(^{vi}\)(Al\(_2\)O\(_3\)). Talking of heteroepitaxy there is always a challenge present with the lattice mismatch. It is generally valid

\[
f = \frac{a_l - a_s}{a_s}
\]

whereas, \(f\) is the lattice mismatch, \(a_l\) the lattice constant of the layer and \(a_s\) the lattice constant of the substrate. Lattice mismatch prevents growth of defect-free epitaxial film unless thickness of the film is below certain critical thickness; in this last case lattice mismatch is compensated by the strain in the film [23].

\(^{vi}\)There are also other substrates like SiC possible
Chapter 2

Developing Laser Diodes

2.1 Growth

As already mentioned there are different methods of epitaxial growth. At this moment there are mainly MOVPE to grow III-V and MBE to grow II-VI and III-V structures which are in use in Bremen. Since this thesis aims characterisation of the laser diode structures, no detailed information about applied epitaxial methods are necessary. Nevertheless, there has been many theses authored in the group which would notably deepen into the techniques (see [23, 25, 42] among others).

2.1.1 Metalorganic Vapour Phase Epitaxy

MOVPE is a crystal growth method using chemical reactions. The reactants are metalorganic molecules containing the metal of interest. These metalorganics are transported by carrier gases, commonly a mixture of hydrogen and nitrogen, to the substrate at whose surface the reaction occurs. Unlike MBE (see 2.1.2) no ultrahigh vacuum conditions are needed. The growth takes place at pressures ranging from 10 hPa to 1000hPa; thus it is of absolute importance to have the involved gases and chemicals pure in order to avoid impurity concentrations in the growth sample.

Figure 2.1: The MOVPE system in use in Bremen [23]
Developing Laser Diodes

Metalorganics are compounds in whose structures metal atoms are bonded to organic groups like methane or ethane so that the bond energy of metal and organic group is lower than that of the molecules. The temperature required to break these bonds is so below the growth temperature ensuring that the organic groups are not involved in the reaction. GaN growth is usually conducted at 1050°C. Common reactants are trimethylgalium (TMG) and ammonia (NH₃) for the growth of GaN and triethylgallium (TEG) and arsine (AsH₃) for the growth of GaAs. Fig. 2.1 shows the reactor in use in Bremen which realises a vertical gas flow onto the substrate with two separate gas distribution chambers for the group-III and the group-V elements.

2.1.2 Molecular Beam Epitaxy

MBE is generally speaking the controlled evaporation of high pure materials in a ultrahigh vacuum (UHV) chamber which deposit on a heated substrate. Due to the UHV a mean free path of the atoms is guaranteed such that all source atoms impinge onto the substrate without any interactions with other atoms. Thus, many sources can be used simultaneously whose molecular beams intersect above the substrate and form a mixture of vaporised elements. This vapour is in contact with the substrate where the crystallisation takes place [43].

The Bremen MBE system shown in Fig. 2.2 consists of two growth chambers and an X-ray Photon Spectroscopy (XPS) analysis chamber. All three chambers are connected via a UHV transfer system which is fully controlled by external magnets and does not have any contacts with the lab atmosphere. Each chamber has 9 cell ports for different materials like Zn, Se, Mg, Cd etc. The growth process can be controlled by computer. This ensures a high reproducibility of the growth runs.

1 in this case the active region, InGaN, is grown at 820°C

10⁻⁹ Torr. 1 Torr equals 133.322 Pa. This unit is still common in the vacuum technology instead of the SI one Pa.
2.2 Processing Technology

The most important to do after the growth of the structures is the processing which needs to be done as precisely as the epitaxy itself. No good functioning laser structure is expected if any of the steps delineated below isn’t done appropriately.

The size of the wafers is usually 2" both MBE and MOVPE grown. In order to be able to process the same specimen with different parameters, this needs to be cleaved. Due to the different crystal forms, the cleave direction is different by II-VI and III-VI. In case of a ZnSe laser the structure is cleaved in [110] direction whereas a GaN laser in [2110] direction. Else, the steps of preparing the laser structures are almost the same. The difference is by the GaN at the beginning step where a so called \textit{p-activation} needs to be done.

2.2.1 Planar waveguide

Following, the standard steps from a grown wafer to a planer laser device are roughly shown. (Please find detailed information in [44] and [42]).

1. \textbf{p-activation(GaN only):} The p-doped layer is activated by a thermal annealing method called \textit{RTA} (Rapid Thermal Annealing) in nitrogen atmosphere at 850° for 30 seconds in order to crack the hydrogen bonds.

2. \textbf{Injection stripe:} Metal layers are evaporated on the specimen. In case of ZnSe the layers are 10 nm palladium and 50 nm gold; for GaN this would be 20 nm nickel and 80 nm gold. The next step would be \textit{spin coating} in which a photo resist layer is brought on the metal layer (Pic. 2.3.a). The exposure of the photo resist with a mask\textsuperscript{iv}(lithography) (Fig. 2.3.b) and subsequent etching of the metal layer (Fig. 2.3.c) leads to the injection stripes. The latter step could be a wet etching or an IBE (Ion Beam Etching) followed by a contact annealing in case of nickel and gold typically in air by 500°C.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2_3}
\caption{(a) spin coating; (b) lithography; (c) metal layer etching}
\end{figure}

3. \textbf{Isolator:} A 75 nm isolator layer made of aluminium oxide (Al\textsubscript{2}O\textsubscript{3}) is brought on the structure (Fig. 2.4.a).

\textsuperscript{iii}1/6 and 1/2 of a 2" substrate are also occasionally grown.

\textsuperscript{iv}stripes 2 – 10μm wide.
4. **Lift off:** The structure remains 2 hours in a bath of NMP\(^\text{v}\) based resistant stripper by 75°C. The isolator layers over the metal stripe lift off (Fig. 2.4.b).

![Figure 2.4: (a) isolator; (b) lift off](image)

5. **Contact pad and separation:** In this step a metal layer of 400 – 1500 nm is brought on the structure followed by a photo resist layer (Fig. 5.a). Then in a lithographic step by a mask the resistant is removed (Fig. 5.b) and the metal layer at the removed photo resist region is etched (Fig. 5.c). This could be a chemical wet etch or an IBE. In the end the surface is cleaned by acetone to remove the remained photo resist (Fig. 5.d).

![Figure 2.5: (a) spin coating; (b) lithography; (c) metal layer etching; (d) photo resist removal](image)

6. **Backside contact:** The backside n-contact could only be brought on homoepitaxial structures (see 1.3.2) and contains 5 nm titanium and 300 nm aluminium in case of GaN or 5 nm palladium and 250 nm AuGe alloy for ZnSe.

7. **Mirrors:** For GaN as the last step the mirrors are brought on the both sides of the cavity. These are pairs of SiO\(_2\) and TiO\(_2\) layers. The number of the layers brought depends on the reflection ability sought [45]. ZnSe is cleaved very smoothly along [110] and thus doesn’t need any mirrors.

\(^{\text{v}N\text{-Methyl-2-pyrrolidone}}\)
2.2.2 Ridge waveguide

The structure developed above is not the only possible. This standard structure, also called planar structure, has got an important disadvantage; current spreading. This means that the current injected to the structure spreads on its way from metal contact to the quantum well leading to not only a thermal load but also a high amount of current injection needed because of a large effective area and a low current density respectively. The only practical way to stop this spreading is to physically restrict the current path in the structure and exactly this is aimed with the ridge waveguides. There are two different ridge structures done in the group: shallow ridge and deep ridge. If the semiconductor material beside the injection stripes is removed down to the active region, the structure is called a shallow ridge (Fig. 2.6.a); In case of a removal through the quantum wells, a deep ridge is meant (Fig. 2.6.b). It is then filled with an isolator (see step 3 in 2.2.1).

![Figure 2.6: (a) Shallow ridge structure, (b) deep ridge structure](image)

The steps to reach a ridge structure are more or less as the above mentioned. The difference is that before the first lift off a dry etching step is done by a CAIBE (Chemically Assisted Ion Beam Etching) system\(^\text{vi}\) to remove the semiconductor material beside the injection stripes. The characterisation of the laser diodes proves a good performance of the ridge structures. Nevertheless it is of importance to mention that the development of a ridge structure especially a deep ridge is a tough task. It is very good possible that some devices get broken. Therefore there are ideas to optimise the ridge structure development process in the group.

\(^\text{vi}\)The gases used in the system are Cl\(_2\) and BCl\(_3\)
Chapter 3

Characterisation

One is always enthusiastic to see the results of the job done. It is not much different by the laser diodes. There is too much physics behind every crystal being grown and processed to laser diodes. After each of these two main steps (growth and technology) methods are possible to check the results. Characterisation is actually nothing but this result check. In the following sections the different characterisation methods, i.e. structural characterisation and opto-electrical characterisation are delineated. As the main concern of this thesis is the opto-electrical characterisation which will be delved, there will be only a brief introduction to some of the possible methods of structural characterisation with no deep going details.

3.1 Structural and Optical Characterisation

Two main purposes are aimed doing structural characterisation. One is the verification of the sample structure concerning layer compositions; and the other one is the determination of the crystalline perfection which is more or less the density of the defects in the material.

3.1.1 High Resolution X-Ray Diffraction

The most important structural characterisation method is the high resolution x-ray diffraction (HRXRD or short XRD).

X-ray diffraction technique is based on the elastic scattering of the photons at the electron cores of the atoms forming the sample and collecting the scattered radiation by a detector. The scattered beam direction contains information about the crystal structure and the plane spacing $d$ [46] which satisfies the Bragg condition

$$2dsin\theta = n\lambda; \quad n = 1, 2, 3, \ldots$$

where $\theta$ is the angle of incidence and $\lambda$ the wavelength of the incident beam. As can be seen from this equation, the plane spacing can be calculated out of the given information of the wave.
In the reciprocal space, the Bragg condition transforms to the Laue condition for incoming wave $\vec{k}_0$ and the scattered wave $\vec{k}_A$,

$$\Delta \vec{k} = \vec{k}_A - \vec{k}_0 = \vec{A} = \vec{G}. \quad (3.2)$$

Thus, the Laue condition is satisfied, if the scattering vector $\vec{A}$ equals the reciprocal lattice vector $\vec{G}$. This is illustrated in the Ewald construction in Fig. 3.1. The Ewald construction is a method for reconstructing a crystal structure by examining and interpreting an x-ray diffraction pattern [21].

### 3.1.2 Photoluminescence

Generally, luminescence is a physical process in which a sample emits a photon after an excitation. Depending on the source of excitation different kinds like cathodoluminescence (CL, electrons), thermoluminescence (heat), sonoluminescence (sound), electroluminescence (EL, current injection) or photoluminescence (PL, photons) are distinguishable. The PL is the foundation of the optical characterisation of semiconductors. The principle of operation is rather simple. Its results can provide access to numerous physical aspects of the sample, ranging from ultra fast carrier dynamics to defect characterisation.

In a PL measurement the sample is illuminated with photons, typically from a laser. Inside the sample, these photons can excite the electrons of the crystal to a higher state leading to creation of a pair of an electron and a hole. The excited carriers then relax into the ground state. During the transition into the ground state which is a recombination of an electron with a hole, energy is released. The recombination could either be radiative (emission of a photon) or non-radiative (emission of phonons). In both cases the total recombination energy corresponds to the energy separation between the excited and the final state. Standard PL measurements are routinely performed at low temperatures (about 8 K). The PL spectra from the samples are then recorded with a CCD camera.
3.1.3 SEM & FIB

The Scanning Electron Microscope (SEM) is a type of electron microscope capable to make high resolution photos of a sample surface. In an SEM the electrons are emitted from a cathode and are accelerated through an anode. The electron beam with energies ranging from a few hundred eV to 50kV is then focused by one or two capacitor into a beam with a very fine focal spot sized 1nm to 5nm. The beam passes through pairs of scanning coils in the objective lens, which deflect the beam in a raster fashion over a rectangular area of the sample surface. The most common imaging mode monitors low energy (< 50 eV) secondary electrons. Due to their low energy, these electrons originate within a few nanometres from the surface. The electrons are detected by a photomultiplier device and the resulting signal is rendered into a two-dimensional intensity distribution that can be viewed and saved as a Digital image.

Focused Ion Beam (FIB) is an instrument that resembles a scanning electron microscope. However, whereas the SEM uses a focused beam of electrons to image the sample in the chamber, a FIB instead uses a focused beam of gallium ions. These ions are then accelerated to an energy of 5-50 keV (kilo electronvolts), and then focused onto the sample by electrostatic lenses. Unlike an electron microscope, the FIB is inherently destructive to the specimen. When the high-energy gallium ions strike the sample, they will sputter atoms from the surface. Because of the sputtering capability, the FIB is used as a micro-machining tool, to modify materials at the micro- and nanoscale. Within the scope of this thesis, FIB was used to cut the laser devices in order to be able to check the ridge depths and the active zone.

3.2 Opto-Electrical Characterisation

The opto-electrical characterisation of the lasers is contrary to the structural one mostly concerned with devices. The main point lies then on the operational characteristics of the laser diodes. It is of absolute importance and as already mention the focus of this thesis to investigate what happens during the current injection.

3.2.1 Current Injection

The lasing process of a semiconductor laser diode is controlled by the density of the carriers inside the active region of the device. Thus, current injection is the most important factor by the characterisation and operation of such devices. As already pointed out, the critical parameter is the current density inside the active region.

The life time of the laser diodes are in case of continuous wave (cw) mode extremely limited. Therefore it is important to operate in pulsed mode which enables a better characterisation. A precision pulsed current source is accordingly needed.

The pulsing condition of the applied current by such current sources can be varied. A representative of the repetition rate is thus given by duty cycle, defined as the ratio of the pulse width and the total pulse duration:

\[
duty\ cycle[\%] = \frac{\text{pulse width}}{\text{pulse width} + \text{delay}} \times 100. \tag{3.3}\]
Characterisation

During the measurements of this thesis three different current sources were in use. The most used most precise one is the precision pulsed/cw current source LDP-3811 from ILX Lightware [48]. The pulse width of the applied current by this source which is up to 500mA can be varied from 0.1µm to 6.5ms with a duty cycle variation of 0.01% to 100%

Another source in use was an HP/Agilent 8114A pulse generator [49] with an output current of 40mA to 2A and pulse periods variable between 66.7ns to 900ms with a pulse with of 10ns to 150ms. This source is actually a voltage source with an output current measured over an impedance. Due to this fact and because of lesser accuracy this source was only in use if currents more than 500mA were to applied to the laser diodes.

In case of cw supply a Keithley 2400 sourcemeter [50] with a current output range between 1µA to 1A was in use. This can also be used as a measuring instrument.

3.2.2 Current-Voltage Characteristics

The electrical characteristics of a laser diode structure basically determines the device stability. In case of a lasing operation high current levels are necessary. If the achievement of this is only at high voltages possible, an excessive heat is generated in the device which accelerates the degradation process. The operation voltage of a laser diode is determined by several factors. The most important ones are the doping level in the upper p-type cladding and the quality of the p-side contact. The optimisation of each of the named features reduces the ohmic resistance; therefore an unhindered way for electrons to reach the active region is guaranteed.

Contributions of these factors can be identified in the current-voltage (I/V) measurements. The p-side contact forms a barrier for the current transport the same as the pn-junction itself. Only if the voltage (energy) is high enough the current can flow. A pn-junction exhibits an exponential I/V characteristic which turn out to be linear at higher operating voltages due to the limitation of the current transport in the device by the serial resistance.

At the beginning of this thesis a KI 197 from Keithley Instruments [50] as voltmeter was in use. No satisfying results were achieved because of the relative low resolution of this instrument for the very short current pulses supplying. Thus a high resolution oscilloscope of TDS3000 series from Tektronix Inc. [51] was taken into operation.

Both the source and the measuring device are connected to a computer, as depicted in Fig. 3.2, via a GPIB line. The control programme on the computer is LabView [52]; in which a new programme is written to control the operation of the needed devices.

The current source is connected to a positive and a negative needle whose position can be changed in all dimensions through some screws. The positive needle has to get in touch with the p-contact of each device and the negative needle with the n-contact respectively. In case of a backside n-contact, the sample bar is by means of silver conductive varnish stuck on a metal film on which there is a common n-contact. Thus the position of the ”negative needle” is unimportant and this could be at any place on the metal film.

---

1 General Purpose Interface Bus

2 Laboratory Virtual Instrumentation Engineering Workbench; a platform and development environment for a visual programming language from National Instruments.
3.2.3 Output Light-Current Characteristics

Determination of the threshold current of a laser is one of the important information to be gained when characterising a device. This can be achieved simply through an L/I characteristic measurement. By increasing the current applied to the device the output light intensity increases gradually. Reaching the current threshold the device starts to lase. This means a rushed increase of the output light intensity. Thus the L/I characteristic curve of a laser diode has always got a kink. Besides, it is possible to calculate the quantum efficiency of the laser diodes.

The experimental setup of the L/I characteristic measurement is depicted in Fig. 3.2. The light coming out of the device is led to the entrance of the Si power head OMH-6701B of the optical multimeter OMM-6710B, both from ILX Lightware Inc. The power head is designed as an integrating sphere (Ulbricht sphere). Integrating spheres operate by allowing light to enter the sphere through a sample port, then through multiple reflections is scattered uniformly around the interior of the sphere by the diffuse internal sphere coating. The diffused light is then detected at a port configured with a detector device as depicted in Fig. 3.3.

In pulsed mode the integrated output power that the optical multimeter measures can be converted into the output power of a cw current supply by using the following equation:

\[ L_{\text{cw}} = \frac{L_{\text{pulsed}} \times 100}{\text{duty cycle}} \]  

(3.4)

Another point to mention is that in case of uncoated facets only the light coming out of one facet can be collected by the power head. Thus, the measured value has to be multiplied...
Characterisation

by 2 in order to obtain the total light output of a device.

![Diagram of a sphere and its components](image)

**Figure 3.3:** When a ray of light enters the sphere from any direction, it strikes the inner wall and is reflected diffusely as a diffuse Lambertian source. Each of these reflected rays is again reflected by the wall and again, etc. Very quickly the light is randomised within the sphere. Hence, the detector "samples" the light within the sphere regardless of how the light entered the sphere.

### 3.2.4 Electroluminescence

Electroluminescence (EL) is an opto electrical phenomenon where a material emits light in response to an electric current passed through it, or to a strong electric field. Emission wavelength is if not the most, one of the most important characteristics of a laser diode which is determined by the composition of the materials in the active region. Although a PL measurement roughly predicts the spectral region in which a device emits, in order to obtain the precise wavelength, the emission spectrum needs to be measured under electrical current injection.

Electroluminescence spectra of a laser diode can be obtained using a spectrometer. A spectrometer is consisting of a monochromator, generally using a diffraction grating, and a photo detector.

Fig. 3.4 depicts the electroluminescence measuring site in use during this thesis.

The light coming out from the device is focused by a system of lenses on the entrance slit of the spectrometer *FHR 1000* from *Jobin-Yvon* [53]. Due to the long focal point of 1m,
the spectral resolution of this spectrometer is 0.008nm [54]. The system is fully computer controlled using a software package delivered by the spectrometer manufacturer. The laser diode devices measured in this thesis are all electrically pumped up to their current threshold, as this was determined through L/I & I/V characterisation. In case of LEDs, a moderate current, also measured, is applied.
Chapter 4
Data Analysis

This chapter contains the main concept of this thesis. Many different devices of both III-V and II-VI group underwent tests in order to characterise their L/I, I/V behaviour as well as the wavelength of the output light. To have an arrangement in the data there are two main sections in this chapter, one over GaN and the other over ZnSe devices. It is worth mentioning that the approaches are not all the same for both material systems.

4.1 ZnSe Devices

The ZnSe devices measured were of three series s1171, s1172 and s1173. They were all grown in 2002 and were the same Arne Gust worked with in his master thesis [44]. They are all similar except for barriers brought to the structures which are not the case in the principle assembly (see Fig. 4.1).

![Figure 4.1](image-url)  
*Figure 4.1: Principle assembly of a II-VI laser diode made in Bremen*
As it can be seen there are two ZnSSe layers on the both sides of the quantum well. The sulphur content of them both amounts 5.9%. The diffusion of nitrogen dopants into the other layers and especially into the quantum well reduces the lifetime of the devices. In order to stop this effect, a filter like layer is needed which screens. Thus, the idea to bring 95nm ZnSSe with 5.9% sulphur and a 5nm ZnSSe layer with 25% sulphur so that the thickness remains 100nm as in the normal case [44]. This layer could be brought on either sides of the quantum well or on both. s1171 has got it on the n-side, s1172 on the p-side and s1173 on both sides. As already mentioned this modification has only got effects on the lifetime of the devices and not on any electrical or optical characteristics. Thus it is possible to process the termed structures and handle them as if they were similar which they characteristically are.

The whole devices measured were processed as planar structures as well as three different ridge depths; 600nm, 1200nm and 1800nm whereas the 1800nm ridge depth is deep through the active zone. s1171 is processed to ridge widths of 2µm; s1172 to 10µm and s1173 to 6µm. Thus, there are 12 differently processed structures possible (see table 4.1). The only totally defective ones were the 2µm wide 1800nm deep ridges. This is due to the extreme sensibility of the ZnSe laser diodes generally which may lead to damage in case of very thin ridge devices.

<table>
<thead>
<tr>
<th></th>
<th>planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2µm (s1171)</td>
<td>LED</td>
<td>lasing</td>
<td>lasing</td>
<td>defect</td>
</tr>
<tr>
<td>6µm (s1173)</td>
<td>lasing</td>
<td>lasing</td>
<td>lasing</td>
<td>lasing</td>
</tr>
<tr>
<td>10µm (s1172)</td>
<td>LED</td>
<td>lasing</td>
<td>lasing</td>
<td>lasing</td>
</tr>
</tbody>
</table>

Table 4.1: ZnSe Laser diodes measured in this thesis

The pulse width applied for the measurement was constantly 1µs with a duty cycle of 0.1% by the LDP-3811 from ILX LightWare [48]. Although measurements with other pulse width and duty cycles were also done, the mentioned pulse conditions seems to be the most appropriate. This matches to the conditions used in the theses of M. Klude [25] and A. Gust [44]. Too divergent conditions than the mentioned lead either to lighting in LED regime or even total malfunction of the device.

4.1.1 Characterisation of ZnSe laser diodes

As already seen the laser devices have got different sizes physically. This wouldn’t make life easier to be able to compare the devices electrically. Because of this very reason it is usual to avoid curves with current as a coefficient and use the current density instead. This would also match well to the theoretical formula already derived (see Eq. 1.25). To be able to calculate the current density the length of the devices needs to be measured. This was done individually for the devices by an optical microscope. Pic. 4.2 shows an example of the length measurement of the devices. The length of the ridge is determined by means of a software installed to the computer connected with the microscope.
Multiplication of the length with the width of the ridge calculated in cm yields the quantity needed to specify the current density.

The whole devices on each bar underwent tests. A few number of them were lasing and the others behaved as LEDs. This could be due to the age of the grown structures and the problems by the processing steps. The whole processing procedure is done manually in Bremen due to which the similarity of the devices even of the the same batch is not guaranteed. Furthermore the position of each bar on the wafer from which it was cut is of importance. The device bars coming from the margin of the wafer (which are usually cut off after processing steps) are practically useless.

2µm wide ZnSe laser diodes

Fig 4.3 shows the output light power vs. current density for two devices processed in 2µm width and two different ridge depths. As it can be seen from table 4.1 the two other possible structures for 2µm didn’t lase. The curve demonstrated here are the best lasing devices. As expected the threshold current density decreases with increasing ridge depth. This is due to the less current spreading as discussed in 2.2.2. Another point to mention is the length of the devices. In case of the 2µm wide 600nm deep structure some processed devices were much longer than the others due to a misalignment by cleaving. As it can be gathered from the theoretical considerations (Eq. 1.25) this has got an impact on the threshold current density, i.e. the longer the cavity the less the threshold current density.
Data Analysis

![Graphs showing output light power vs. current density for different wavelengths and device lengths.](image)

**Figure 4.3:** output light power vs. current density

It is expectable that the average value is higher than the one of this device and this is true indeed (compare Tables 4.2 and 4.5). Following the trend the threshold current density value for the planar structure would be too high to be tolerated. High currents would lead to heat and degradation. Deep ridges through the active zone in case of a 2µm are of a very sensitive nature. An SEM picture (Fig. 4.4) taken after cutting one of the devices by FIB shows a V-shape intruding of the metal contact into the crystal so deep that the active region is damaged. Therefore it is not extraordinary that the devices remain dark.

Fig. 4.5 shows the I/V behaviour as well as the spectrum of a device belonging to the 600nm series as an example. The threshold voltage is comparably high which could be due to the bad quality of the metal contacts brought onto the structures. Furthermore the quality of the signal measured is not satisfying so that the curve needed to be fitted to be able to get the threshold voltage. This also could be a consequence of bad metal contact quality and also limited resolution of the oscilloscope with which the voltages were measured in comparison to the low pulse widths applied (see 3.2.2).

The spectrum shows its lasing peak at 525nm. The unit of the y-axis is counts per second which is the number of counted light pixels on the CCD camera connected to the spec-

<table>
<thead>
<tr>
<th>wavelength</th>
<th>planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2µm LED</td>
<td>3661.76 A/cm² (2040.03 µm)</td>
<td>2053.9 A/cm² (1096.77 µm)</td>
<td>defect</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.2:** Threshold current density. The values in the parentheses are the lengths of the devices.
Figure 4.4: cross section SEM picture of a 2µm 1800nm ridge after FIBing

Figure 4.5: $I/V$ behaviour as well as spectrum of a device belonging to the 600nm series.
Data Analysis

This could be understood as arbitrary. A very good lasing spectrum is achieved since this shows no emission at any other wavelengths but the lasing peak.

6µm wide ZnSe laser diodes

All four possible processing routines for the ZnSe laser diodes in this thesis (planar, 600nm, 1200nm and 1800nm ridge depths) lased in case of 6µm as can be seen in Fig. 4.6.

![Graphs showing output light vs. current density for different ridge depths](image)

**Figure 4.6:** Output light vs. current density

It is also expected that the threshold current density decreases with ridge depth increasing. The specimens happen to be rebellious as can be learnt from Table 4.3. Since the devices whose results were shown in Fig. 4.6 have been chosen more or less due to their
good functionality, a statistically correct trend can not be determined unless some more results are also considered. Table 4.5 shows the average values of the measured devices and a trend as expected can be observed. The fact that some devices with a shallower

<table>
<thead>
<tr>
<th></th>
<th>planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6µm</td>
<td>3310.67 A/cm² (1111.79 µm)</td>
<td>750.62 A/cm² (1081.42 µm)</td>
<td>769.77 A/cm² (1189.87 µm)</td>
<td>775.24 A/cm² (1086.27 µm)</td>
</tr>
</tbody>
</table>

Table 4.3: Threshold current density. The values in the parentheses are the lengths of the devices.

ridge have got less threshold current density than the others with a deeper ones can be backtracked to idea of energy loss. It is possible that due to some imperfections in the structures which have happened by the processing some resistant like spots have occurred which prevent the desired current route into the active zone. Furthermore defects in the crystal could lead to non-radiative emission because of which more electrical energy needs to be applied to reach the same results as in case of a crystal without defects.

Furthermore it is to be noted that the L/I curves with one exception have got a stair form. This could be explained by the fact the optical multimeter OMM-6710B operates in different sensitivity steps. This means that a rapid increase of the output light of the laser leads the multimeter to saturation in the automatically preset sensitivity. This saturation value is then reported to the computer which saves the records and a new sensitivity step is set and will be reached by the next current increasing.

Due to this fact the measured curves needed to be fitted by suitable functions to be able to find out the threshold current densities sought. Fig. 4.7 shows the I/V behaviour as well as the spectrum of a 600nm device taken exemplary. The threshold voltage is almost the same as in case of the 2µm ridge width which is an implication for the similarity of the metal contacts brought to the laser structures.

About the spectrum it is visible that a multimode lasing has happened. This could be due to the unsteady Cd content in the active zone. This leads to different energy band gaps along the active region, i.e. the light achieved by the radiative recombinations taking place in different physical places have different energies thus different wavelengths.

10µm wide ZnSe laser diodes

A fully functioning series from planar to deep ridge was in case of 10µm expected. Unfortunately the planar processed structures didn’t lase. This prevents the comparison to the measured data in the thesis of A. Gust [44]. The reason could be malfunctioning by processing or having caught a suboptimal part of the grown crystal.

Fig. 4.8 shows the threshold current densities of the devices lased. Also here a decreasing trend is expected which can be seen by comparing tables 4.4 and 4.5 considering the error bars (see Fig. 4.10).

The average threshold current density value A. Gust has reported in his thesis [44] for the same series s1172 with 10µm ridge width and planar processed is 1220 A/cm².
Figure 4.7: $I/V$ behaviour as well as spectrum of a device belonging to the 600nm series.

<table>
<thead>
<tr>
<th>Planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10µm</td>
<td>LED</td>
<td>1314.71 A/cm² (1387.72 µm)</td>
<td>671.27 A/cm² (1027.19 µm)</td>
</tr>
</tbody>
</table>

Table 4.4: Threshold current density. The values in the parentheses are the lengths of the devices.
Figure 4.8: Output light vs. current density
Data Analysis

Following the trend of decreasing threshold current density with increased ridge depth this value matches good in the measurements done in this thesis (see Table 4.5 and Fig. 4.10). It is worth mentioning that the crystals at the time of publishing this work are over 4 years old and have become obsolete.

Fig. 4.9 shows the I/V behaviour and the spectrum of an exemplary chosen device. The threshold voltage doesn’t show any immense differences to the cases already had. The spectrum demonstrates a stronger multimode lasing than in case of 6µm ridge width. Let’s put it this way, there is no good reason because of which a non-multimode lasing occurs when a length of approximately a millimetre of the active region a trouble-free cohabitation of standing waves with different wavelengths guarantees.

4.1.2 ZnSe results in brief

Table 4.5 shows the average values of all the lasing devices measured in each category. As already mentioned a decreasing trend is observable from left to right of each row. This is due to the aimed current apply to the active zone. It is possible to depict this trend dependent on the ridge depth (see Fig. 4.10). The error bars shown are the differences between the highest and the lowest threshold current density measured, applied on both sides of the average value. The deeper the ridge the smaller the divergence in measured valued. In order to be able to compare these results with the older measurements the average value of the threshold current density mentioned in the thesis of A. Gust [44] have been obtained for the 10µm ridge, planar structure. Fig. 4.10 shows that even this earlier value obeys the trend expected in the structures.

The threshold voltage values were all more or less the same and not too satisfying which

---

1 Please find the whole values measured, from which these averages are calculated, in Appendix B
Table 4.5: Average threshold current density values. The values in the parentheses are the average lengths of the devices.

<table>
<thead>
<tr>
<th>ridge depth [µm]</th>
<th>planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2µm</td>
<td>LED</td>
<td>3895.45 A/cm² (1360.53 µm)</td>
<td>2505.3 A/cm² (1098.42 µm)</td>
<td>defect</td>
</tr>
<tr>
<td>6µm</td>
<td>2864.46 A/cm² (1115.39 µm)</td>
<td>1113.30 A/cm² (1083.55 µm)</td>
<td>844.41 A/cm² (1192.75 µm)</td>
<td>689.98 A/cm² (1083.91 µm)</td>
</tr>
<tr>
<td>10µm</td>
<td>LED</td>
<td>1213.77 A/cm² (1390.10 µm)</td>
<td>745.94 A/cm² (1024.79 µm)</td>
<td>849.1 A/cm² (1066.35 µm)</td>
</tr>
</tbody>
</table>

† this value is obtained from the A. Gust’s thesis [44]

Figure 4.10: The average value of threshold current density vs. the depth of the ridge structure.
Data Analysis

can be due to the suboptimal metal contact brought on the structures. The spectra show a multimode lasing in most of the cases. The different peaks are energetically very close to each other though.

Fig. 4.11 shows a far field picture of one ZnSe laser device taken by a regular digital camera. A white piece of paper was kept in front of the laser diode. The far field of the laser can be captured this way. The sharp vertical light line is the actual sign of lasing.

4.2 GaN Devices

Fig. 4.12 shows the principle assembly of the homoepitaxial GaN laser diodes grown in Bremen. Four different series of structures have been investigated. Three series, g0937, g0938 and g0942, are almost the same except for the n-doped AlGaN cladding layer thickness. This is 1.5µm for g0937, 2µm for g0938 and 1µm for g0942. The rest of the structure is exactly the same grown as depicted in Fig. 4.12 for all three named crystals. They are grown on an LED-grade GaN substrate. Generally there are three different grades possible for the GaN substrates which are LED-, transistor- and laser-grade with $10^{-8}$, $10^{-7}$ and $10^{-6}$ defects/cm$^2$ respectively. Thus, the g0975 series grown on a transistor-grade substrate are qualitatively better than the g0937, g0938 and g0942 series. The g0975 is besides grown as a standard structure, i.e. an n-doped AlGaN cladding layer of thickness 0.5µm. The g0975 is processed in three different ridge widths (2µm, 6µm and 10µm). Each width is then processed ones as a planar structure as well as a shallow ridge and a deep ridge. As it can be obtained from Figs. 4.12 and 4.13 the shallow ridge is the case when the semiconductor material beside the quantum well is etched down to the undoped GaN wave guide. Whereas in case of a deep ridge the material is etched down to the middle of the Si-doped GaN wave guide, thus through the active region (compare to 2.2.2).
GaN Devices

MOVPE: High Mg-doped GaN-contact layer, d=20nm
MOVPE: GaN:Mg, d=80nm
MOVPE: Al\textsubscript{0.08}Ga\textsubscript{0.92}N:Mg cladding, d=500nm
Electron blocking layer: Al\textsubscript{0.2}Ga\textsubscript{0.8}N, d=40nm
Undoped GaN waveguide, d=100nm
3x In\textsubscript{0.09}Ga\textsubscript{0.91}N/GaN quantum well, each ~10nm
MOVPE: Si-doped GaN waveguide, d=100nm
MOVPE: Al\textsubscript{0.1}Ga\textsubscript{0.9}N:Si cladding, d=500-2000 nm
MOVPE: GaN:Si, d=500 nm
HVPE: (Lumilog) n-doped GaN substrate d=300µm (LED-, transistor- or laser-grade)

**Figure 4.12:** Principle assembly of a III-V laser diode made in Bremen

**Figure 4.13:** Different ridge depths [55]
It is worth mentioning that the g0975 is grown on a half GaN substrate. In case of MOVPE growth the quality of the devices coming from the the centre of the grown crystal is much better than the ones which don’t. There is so to say a quality gradient from the centre of the substrate to the margin.

Fig. 4.14 shows the g0975 schematically. The margin of practically every MOVPE grown crystal can be neglected because of low quality. An ellipse demonstrates a possible zone of better quality structure. This doesn’t necessarily mean that the devices achieved from out of this ellipse malfunction. The wafer is then split to 9 parts and each part has been processed differently.

In case of the other three (g0937, g0938 and g0942) the crystals have all been grown on a quarter wafer and then processed in 10µm ridges and planar.

### 4.2.1 Characterisation of GaN laser diodes

All GaN devices characterised in this thesis were supplied at 100ns pulse width and 1%-10% duty cycle. Because of the typical relatively high threshold current of the GaNs, HP/Agilent 8114A pulse generator was beside ILX-3811 in use. In case of cw measurement keithley 2400 was taken.

The lengths of the devices for calculation of current density, as also in ZnSe case, were measured using an optical microscope.

#### g0975 series

**unmirrored devices** After being processed, the unmirrored devices underwent some characterisation steps. Table 4.6 gives a brief information of the unmirrored GaN devices measured in this thesis.

The 2µm deep ridge although coming from the theoretically best grown part of the wafer (see Fig. 4.14) was completely defect. This structure is not at all easy to wangle because of the necessary deftness and accuracy in processing\(^{ii}\).

The 2µm shallow ridge structure seemed to light initially but because of extreme sensitivity malfunctioned very soon. Thus, no measurements were possible.

\(^{ii}\)It is worth reviving that the 2µm deep ridge structure in ZnSe case was also defect.
Another point to mention is about \(10\mu m\) deep ridge. Here was a yellow light (instead of blue) to observe. The spectrum of this light depicted in Fig. 4.15 also proves a weak yellowish emission. Yellow output light and generally red shift in spectrum is due to emission of the impurities in the crystalline. Referring to Fig. 4.14 these devices are coming from the part of the wafer near the margin. Therefore a high defect density is very good possible. So this type of problem comes from growth and not from technology steps.

<table>
<thead>
<tr>
<th></th>
<th>planar</th>
<th>shallow ridge</th>
<th>deep ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2\mu m)</td>
<td>LED</td>
<td>defect</td>
<td>defect</td>
</tr>
<tr>
<td>(6\mu m)</td>
<td>lasing</td>
<td>LED</td>
<td>LED</td>
</tr>
<tr>
<td>(10\mu m)</td>
<td>LED</td>
<td>lasing</td>
<td>yellow light</td>
</tr>
</tbody>
</table>

**Table 4.6:** Unmirrored GaN devices (g0975) measured in this thesis

\[\text{g0975/deep ridge/10um}\]

\[\text{Figure 4.15: Spectrum of the } 10\mu\text{m deep ridge devices. A noticeable red shift is to observe.}\]

The only devices happened to lase were the \(6\mu m\) planar structure and the \(10\mu m\) shallow ridge. It is to remark that in both cases there were only one device being able to lase. This could be due to the manual processing steps which cannot guarantee the quality equality
Data Analysis

for the whole devices on a bar.
For the 6µm planars most of the devices needed a large amount of current to start emitting and degraded very fast. This indicates a bad metal contact with relatively high resistance and high amount of impurities in the crystal which lead to non-radiative recombinations. Applying more and more current will consequently lead to heat and degradation of the device. Fig. 4.16 shows the output light power vs. current density diagram as well as the spectrum of the only lasing device of 6µm planar . A high threshold current density (28.9 KA/cm²) is observable.

Figure 4.16: L/I behaviour as well as spectrum of the only unmirrored lasing device belonging to 6µm planars

At the first glimpse at the spectrum there is no lasing available. By zooming in, some details get cleared. Fig. 4.17 shows the zoomed spectrum of the lasing device as well as the far field photo taken by a regular digital camera. As it can been seen from the spectrum there is indeed a multimode lasing which happens to occur on top of an LED regime. The fact that a multimode lasing happens is just normal and because of the many standing waves which are achieved in different physical places of the active region with possibly different indium contents which leads to different energy gaps. The strongest modes seem to be at around 390nm. The LED regime which can be seen as a long bowing blue light perpendicular to the lasing ray in the far field photo (Fig. 4.17), is actually due to the photoluminescence of the substrate. As already mentioned the III-V crystals characterised in this thesis are all homoepitaxially grown, i.e. growth on GaN substrate. Because of the lower refracting index difference than in sapphire (Al₂O₃) case, it is possible that the wave propagates into the GaN and causes luminescence. To stop this, one way would be increasing the thickness of the Si-doped AlGaN cladding layer. This possibility had been taken as a basis for growing g0937, g0938 and g0942.

As mentioned on device of the 10µm shallow ridge structure was also able to lase exactly
with the same properties as in case of 6µm planar; with a lower threshold current density. This amounts 26.86 KA/cm² for a device length of 671.49µm. As already proved in 1.25 the length of the cavity is reciprocally proportional to the threshold current density. Thus, under equal other conditions a higher threshold current density is expected. This effect is compensated, among others, by the shallow ridge structure processed.

Another quite interesting aspect observed was a shifted mode in far field by the 2µm planars. One of the devices had a dark mode exactly at a place where in case of lasing the main lasing mode is expected. This could be because of non-parallel facets of the cavity. Fig. 4.18 shows an optical microscope as well as two SEM pictures. The picture taken by the optical microscope shows that the ridge doesn’t look the same along the cavity. At the transition point of optical difference, the device has been cut by FIB. The two SEM pictures show both sides respectively. It can be seen that the device is damaged from one side; the metal contact is lifted up. Thus the light emitted by the device is achieved only on a fraction of the length. Besides, this damage in the middle could have led to non-parallel facets. Hereby is the unusual behaviour cleared.

**mirrored devices**  The devices were then mirrored as the next step. The mirrors brought to the cavity facets are three pairs of SiO₂ and TiO₂ layers. Table 4.7 clears the fact that beside the 6µm planar, which already lased unmirrored, only two groups (6µm and 10µm deep ridge) lased, being mirrored. Also here was only one device of a whole bar good and that with a very low lifetime. Due to this fact no reasonable spectra could be taken.

Fig. 4.19 shows the output light power vs. current density. Comparing the threshold current densities of the both mirrored and unmirrored 6µm planar device, it is seen that a reduction of 8.284KA/cm² (≃ 28%) has occurred which is due to the loss decreasing and expectable. On the other hand a threshold current density of about 36 KA/cm² for the same width in deep ridge is not legitimate. 1.54-time smaller cavity length wouldn’t cause a threshold
Figure 4.18: Optical microscopic as well as SEM picture of a device belonging to 2μm planars.

<table>
<thead>
<tr>
<th></th>
<th>planar</th>
<th>shallow ridge</th>
<th>deep ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>2μm</td>
<td>LED</td>
<td>defect</td>
<td>defect</td>
</tr>
<tr>
<td>6μm</td>
<td>†lasing</td>
<td>LED</td>
<td>lasing</td>
</tr>
<tr>
<td>10μm</td>
<td>LED</td>
<td>LED</td>
<td>lasing</td>
</tr>
</tbody>
</table>

† lased also unmirrored

Table 4.7: Mirrored GaN devices (g0975)
Figure 4.19: Output light power vs. current density by the mirrored lasing devices
current density 1.75 time higher by its own, while a lower threshold due to the deep ridge is expected. Other reasons like suboptimal metal contact and crystal quality could have collaborated.

The lowest threshold current density ever reached in the whole series belonged to the 10µm deep ridge with 15.632 KA/cm\(^2\) by 389.19µm. Therefore it must be possible to decrease the threshold with the same crystal quality to the record values only by making longer devices.

**g0937, g0938 and g0942 series**

As already mentioned, substrate photoluminescence is a problem by homoepitaxially grown GaN crystals. Thus, the idea to make the Si-doped AlGaN cladding layer thicker. Following this target, g0937 series were grown with 1.5µm, g0938s with 2µm and g0942s with 1µm named cladding layer. All devices were grown homoepitaxially on an LED-grade substrate and processed as 10µm ridge width and planar.

The pulse conditions were all the same as it was the case by g0975; in addition some cw measurements(non-pulsed current applying) were also done.

None of the series were able to lase. This fact is proved by the L/I behaviour, far field of the output light and the spectra taken. A remarkable point about the spectra of these series is that they all own shoulders on the lower energy side\(^{iii}\) of the spectrum as it can be seen in Fig. 4.20.

![Figure 4.20: Spectra of two specimens from g0937 & g0938 series.](image)

The markedness of these shoulders is different even by devices of the same series and the same bar. The more the devices are at the both ends of the bar the bolder are the side shoulders. This is due to the crystal quality difference in MOVPE growth as already

\(^{iii}\)Lower energy corresponds to higher wavelength
GaN Devices

Generally the achieved waves in each of the three wells of a GaN laser could be energetically different, if the thickness and/or indium content of the wells are not the same. It would be a relief finding a theoretical method to predict the exact problem of a grown emitting crystal only by seeing the spectra. This could keep back the arduous preparation of the specimens for TEM\textsuperscript{iv} to determine the thickness of the active region. Fig. 4.21 sketches some attempts being done for this sake.

\textbf{Figure 4.21:} Fitted spectra of two devices from g0942 series. The wavelength is converted to the corresponding energy.

The measured spectra were fitted with Gaussian functions, as a spectrum is expected to be Gaussian. The best fit achieved was with three different Gaussian functions as the Fig. 4.21 shows. This could mean three differently emitting sources, but not necessarily. The procedures inside the active region could be much more complicated. Processes like constructive or destructive interference etc. could always take place and this doesn’t allow too easy interpretations.

Whatever have been done, there was always a variable too much, so that this problem cannot be solved without a TEM picture with statements about the thickness of each of the wells or an HRXRD with the exact indium contents.

Another point observed was a systematic threshold voltage shifting by \textit{cw} measurements as seen in Fig. 4.22. Lasing or not the devices here are all diodes. Thus, a diode like behaviour is expected and is indeed the case. The threshold voltage shifting due to the differences in AlGaN cladding layer seemed to be unusual. The length a layer shouldn’t have anything to do directly with the energy barriers (see Fig. 1.9). But a higher threshold voltage means a higher needed energy to overcome the barrier. Therefore, it would be useful to solve the Schrödinger-Poisson equation for each structure. The Poisson equation yields the distribution of the charge carriers and the structure of the conducting and the valence band. This band structure is then the basis of the Schrödinger equation to find the energy

\textsuperscript{iv}Transmission Electron Microscopy
levels of the quantised states.
To do this simulation, the 1D Schrödinger-Poisson solver software written by Prof. G. Snider from the university of Notre Dame, USA, has been used [56]. The results of the simulation don’t seem that satisfying. The cladding layer thickness of the structures seem to be the only difference with no influence on the energy barriers. Fig. 4.22 shows the conducting band energy of all three series versus the thicknesses with an applied voltage of +10V to overcome the energy barriers of all three due to Fig. 4.22. The calculated barriers are energetically absolutely coinciding. Even the energies of the waveguide, as a merging peak between the cladding layer and the quantum wells, seem to be similar.
From that all could be concluded that either the crystal structures of the named series are not completely similar, so that the input information to the software doesn’t match to the reality, or the method being used in this software (see Appendix C) doesn’t fit this problem.

4.2.2 GaN results in brief
All devices coming from series g0937, g0938 and g0942 were LEDs. The unhappy consequence of this fact is that the structures couldn’t have been tested of reduced bulk luminescence.
In case of the g0938 series (2µm Si:AlGaN cladding layer) the devices had all very rough
to cracked surfaces. This is due to the thick cladding layer.

g0975 series were generally speaking successful. Except for some problems mostly by the thinner ridges and due to the technology, they were capable. Mirroring turned up to be of great importance to increases the functionality of the laser devices.

Figure 4.23: Conducting band energy barriers vs. thickness of the layers; calculated for all three series.
Chapter 5
Summary and Outlook

The main focus of this thesis has been opto-electrical characterisation of the laser diodes made in the semiconductor epitaxy group in Bremen. These are subcategorised in two main streams; the II-VI group and the III-V group based semiconductor lasers. The growth and the processing steps were all done internally. Therefore, it was a great situation to get familiar to the wide world of epitaxy and the proceeding device processing technology. Structural characterisation, even not belonging to the narrow issue of this thesis in comparison to the whole job being done in the group, is vital. Only through the feedbacks hereby and by the opto-electrical characterisation is reaching an optimal laser diode possible. And like any other characterisation theses the optimisation remarks are the last words said.

The crystal quality of the ZnSe laser diodes pretty fine (putting aside the fact that the ZnSe based lasers have generally low lifetimes). As the measurements in the thesis show the most efforts should be done by the processing technology to make devices with narrow and deep ridges. This helps the reducing of the threshold current density and consequently less heat. The lifetime of the devices are then influenced positively. As a remark, since dealing with the $2\mu m$ structures is no easy task and on the other hand the optimum of the measured devices was by the $6\mu m$, new structures can be processed in all ridge widths possible between $6\mu m$ and $2\mu m$ to obtain the optimal results for the reachable accuracy.

Another point to mention in this connection is that wet etching could often make life much easier. This method, if controlled, could lead to faster and more uniform processing of devices. Some attempts during the technology steps of preparing the samples of this thesis showed the difficulties. But it’s worth continuing.

No ZnSe laser would even come to the idea to light with the impurities which are the case by the GaNs. This intractable feature possibly constitutes the attractiveness of GaN. On the other hand reaching a crystal with less impurities is a tough task. This is the long-term aim of the growers. Like in case of ZnSe reaching the $2\mu m$ ridge widths is desired but not easy at all. Improvements in technology steps could realise this wish, due to which and hand in hand with improving the crystal quality a long lifetime and a reasonable consumption is guaranteed. The idea of making the cladding layer thicker in order to reduce or even stop the substrate luminescence needs to be developed with having in mind that too thick layers lead to a

Great things are not done by impulse, but by a series of small things brought together.

Vincent van Gogh
cracked surface. Here a backtracking thickness optimisation method would act fair.
Mirroring of the GaN devices lead to an obvious improvement of the quality of the laser.
Optimising the mirrors regarding their material and thickness is therefore of importance.
Appendix A

Electrical Sources & Measuring Devices

The list below shows the electrical devices used in this thesis to apply current and perform optical and electrical measurements.

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDP-3811</td>
<td>ILX Lightware Inc.</td>
<td>precision pulsed/cw current source</td>
</tr>
<tr>
<td>8114A</td>
<td>HP/Agilent</td>
<td>pulse generator</td>
</tr>
<tr>
<td>Keithley 2400</td>
<td>Keithley Instruments</td>
<td>sourcemeter</td>
</tr>
<tr>
<td>KI 197</td>
<td>Keithley Instruments</td>
<td>voltmeter</td>
</tr>
<tr>
<td>TDS3000</td>
<td>Tektronix Inc.</td>
<td>oscilloscope</td>
</tr>
<tr>
<td>OMH-6701B</td>
<td>ILX Lightware Inc.</td>
<td>Si power head</td>
</tr>
<tr>
<td>OMM-6710B</td>
<td>ILX Lightware Inc.</td>
<td>optical multimeter</td>
</tr>
<tr>
<td>FHR 1000</td>
<td>Jobin-Yvon</td>
<td>spectrometer</td>
</tr>
</tbody>
</table>

Table A.1: List of current sources and measuring devices
Appendix B

ZnSe threshold current density values

Following the list of the average values of the threshold current densities (Table B.1) and all ZnSe threshold current densities measured during this thesis (Table B.2)

<table>
<thead>
<tr>
<th></th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>planar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2µm</td>
<td>LED</td>
<td>3895.45 A/cm²</td>
<td>2505.3 A/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1360.53 µm)</td>
<td>(1098.42 µm)</td>
</tr>
<tr>
<td>6µm</td>
<td>2864.46 A/cm²</td>
<td>1113.30 A/cm²</td>
<td>844.41 A/cm²</td>
</tr>
<tr>
<td></td>
<td>(1115.39 µm)</td>
<td>(1083.55 µm)</td>
<td>(1192.75 µm)</td>
</tr>
<tr>
<td>10µm</td>
<td>LED</td>
<td>1213.77 A/cm²</td>
<td>745.94 A/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1390.10 µm)</td>
<td>(1024.79 µm)</td>
</tr>
</tbody>
</table>

Table B.1: Average threshold current density values. The values in the parentheses are the average lengths of the devices.
ZnSe threshold current density values

<table>
<thead>
<tr>
<th>Planar</th>
<th>600nm</th>
<th>1200nm</th>
<th>1800nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2(\mu\text{m})</td>
<td>LED</td>
<td>3821 A/cm(^2) (1204.57 (\mu\text{m}))</td>
<td>2956.7 A/cm(^2) (1100.07 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4715.4 A/cm(^2) (1097.78 (\mu\text{m}))</td>
<td>* 2053.9 A/cm(^2) (1096.77 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3383.65 A/cm(^2) (1099.74 (\mu\text{m}))</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>* 3661.76 A/cm(^2) (2040.03 (\mu\text{m}))</td>
<td></td>
</tr>
<tr>
<td>6(\mu\text{m})</td>
<td>1890.7 A/cm(^2) (1115.83 (\mu\text{m}))</td>
<td>1368.95 A/cm(^2) (1083.02 (\mu\text{m}))</td>
<td>961.765 A/cm(^2) (1196.49 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td>3764.36 A/cm(^2) (1117 (\mu\text{m}))</td>
<td>1220.32 A/cm(^2) (1086.20 (\mu\text{m}))</td>
<td>801.71 A/cm(^2) (1191.89 (\mu\text{m}))</td>
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<tr>
<td></td>
<td>2491.13 A/cm(^2) (1116.96 (\mu\text{m}))</td>
<td>* 750.62 A/cm(^2) (1081.42 (\mu\text{m}))</td>
<td>* 769.77 A/cm(^2) (1189.87 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* 3310.67 A/cm(^2) (2040.03 (\mu\text{m}))</td>
<td></td>
</tr>
<tr>
<td>10(\mu\text{m})</td>
<td>LED</td>
<td>1285.98 A/cm(^2) (1389.73 (\mu\text{m}))</td>
<td>797.12 A/cm(^2) (1020.8 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1040.63 A/cm(^2) (1392.86 (\mu\text{m}))</td>
<td>635.7 A/cm(^2) (1023.99 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* 1314.71 A/cm(^2) (1387.72 (\mu\text{m}))</td>
<td>879.68 A/cm(^2) (1027.18 (\mu\text{m}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 671.27 A/cm(^2) (1027.19 (\mu\text{m}))</td>
</tr>
</tbody>
</table>

* These values are the ones used in Tables 4.2, 4.3 and 4.4.

**Table B.2:** Threshold current density values measured. The values in the parentheses are the average lengths of the devices.
Appendix C

Band structure simulation using 1D Poisson-Schrödinger equation solver

The software was written by Prof. G. Snider, university of Notre Dame, USA. It numerically calculates the one dimensional band structure of a semiconductor heterostructure based on the method of finite differences [56]. The structure is divided into several finite sections with a variable density of the mesh points. It is of importance to choose the mesh spacing precisely, in particular at the interfaces of the individual layers and inside the quantum wells. The free charge carrier concentration is determined from the thermal activation of the doping atoms using Boltzmann statistics. The programme is limited to calculations in thermodynamical equilibrium, i.e. current flow is not calculated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AlGaN</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap [eV]</td>
<td>$3.42 + 2.25x + 0.53x^2$ (x&lt;0.20)</td>
<td>[57]</td>
</tr>
<tr>
<td>Conduction band offset [eV]</td>
<td>$1.28 + 0.60x$</td>
<td>[58]</td>
</tr>
<tr>
<td>Stat. dielectric constant</td>
<td>$9.7 - 3.4x$</td>
<td>[58]</td>
</tr>
<tr>
<td>Donor binding energy</td>
<td>$0.022 + 0.033x$</td>
<td>[59]</td>
</tr>
<tr>
<td>Rel. eff. electron mass</td>
<td>$0.22 + 0.11x$</td>
<td>[58]</td>
</tr>
<tr>
<td>Rel. eff. hole mass</td>
<td>$2.2$</td>
<td>[58]</td>
</tr>
</tbody>
</table>

Table C.1: Parameters used for the simulation of the AlGaN cladding layer.

The rest of the needed parameters (GaN and InGaN) can be obtained from the T. Böttcher’s PhD. thesis [23].
Bibliography


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Everythings finds an end. At this very end of this thesis I would like to express my thankfulness to all those without whom this job wouldn’t have existed.

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