Monolithic integration of mode locked laser diodes with a fast absorber in InGaAsP/InP technology using MOVPE based local growth

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Publication Date: 2007

Permanent Link: https://doi.org/10.3929/ethz-a-005378454

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Monolithic integration of mode locked laser diodes with a fast absorber in InGaAsP/InP technology using MOVPE based local growth

A dissertation submitted to the SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH for the degree of Doctor of Technical Sciences

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2007
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Abstract

Optical pulse sources with sub-ps pulse width are required for a variety of applications.

Future optical networks will exploit the theoretical bandwidth limit of several 10 THz of the optical fiber. Since the average intensity has to be limited to avoid non-linear pulse distortion and cross talk effects, the optical time division multiplexing scheme is advantageous compared to the dense wavelength division multiplexing method. Therefore sub-picosecond pulse width are required to realize Tbit/s data rates.

Another promising application is to provide the clocking for future supercomputer systems. Electronic clock generation and distribution currently hit severe limitations such as high loss and signal distortion, whereas optical generation and distribution of several 10^16 of GHz is relatively simple.

For these purposes mode-locked laser diodes (MLLD) are promising candidates due to their intrinsic mechanical robustness, high energy efficiency, mass producibility and low foot print. Generally MLLDs consist of three different sections: an absorber, a gain and a passive waveguide. So far the gain and absorber sections are fabricated from the same material. The absorber is reversed biased to form a saturable absorber and the gain section is forward biased. Experiments show a limitation in pulse width of 2ps which is not sufficient for Tbit/s data rates and also clocking applications will profit from shorter pulse width due to relaxed requirements in jitter and skew.

This thesis deals with the investigation and experimental realization of MLLDs to identify and overcome the observed pulse width limit. For the first time the absorber and gain sections are optimized independently for mode-locking with sub-ps pulses. We demonstrate single pulse mode locking at a repetition rate of 42GHz with a pulse width of 0.9ps for a
MLLD with different absorber and gain material.

Satisfying of contradictory requirements of absorber and gain section leads to a butt-coupled regrowth technique to optimize the structures independently but still combine them in a monolithical device. Using a time domain model we identified the need of a fast absorber recovery time to overcome the pulse width limit of currently 2-3ps. The new absorber structure was realized as an uni-traveling carrier (UTC) structure. In contrast to conventional absorbers with recovery times of $\approx 10$ps, the UTC structure demonstrates recovery times between 2-3ps for a reverse bias of 2-3V. As gain material we used three unstrained InGaAs quantum wells in InGaAsP barriers. The analysis of the multiple quantum well (MQW) gain structure leads to a trade off between minimum gain requirements and high saturation energy. The latter must be higher than the absorber saturation energy to allow a pulse build up by mode-locking.

The accumulated heating exposure of the MQW during the monolithic integration process results in a wavelength shift of the emitted light between the grown MQW and the final device due to the quantum well inter-diffusion effect. The blue shift of the emission wavelength has to be taken into account and can be described with a simple theoretical model. Due to the material diffusion we assume a shrinkage of the effective quantum well width which shifts the discrete quantum well state energy to higher values. We observed an effective quantum well shrinkage per hour of growth of $8.3 \text{Å/d}$ for our geometry and growth temperature of 630°C.

For the wafer integration we used a metal organic vapor phase epitaxy (MOVPE) local regrowth process. The substrates were structured with a SiO$_2$ mask and subsequent wet etching. We could identify the pressure in the growth chamber and the mask overhang as important parameters to reduce enhanced growth rates at the mask borders. The growth enhancement is due to growth species diffusion over the mask. Whereas low pressure is advantageous to reduce the material piling, the mask overhang has to be optimized for low growth rate differences and to prevent voids under edge of the masked area.

To realize the implementation of three different structures in a single device on the same wafer, we have to split up the total growth process into five steps. This growth sequence solved the problem of the total material piling at the mask borders and allows us to reduce the internal
Abstract

reflections at the regrown interfaces. The experimental and theoretical investigations of the interface geometry identifies the internal reflection at the interfaces to be critical. Intensity reflections below $10^{-5}$ are required to allow for single pulse mode-locking. Higher internal reflections result in the build up of secondary pulses, which deteriorate the effectively usable pulse width. Two dimensional finite difference time domain calculations of the propagating optical field demonstrate the demand for an angled interface between the structures. With the tilted interfaces the light is reflected out of the plane of propagation and does not influence the mode-locking dynamics.

The final process comprises 14 lithographic masks, five growth steps, four metalization layers and a processing time of 2-3 month.

Despite of the encountered technological challenges we realized single pulse mode locking with monolithic integrated UTC-MQW MLLDs with pulse widths of 0.9ps and multiple pulses with single pulse widths of 0.6ps.
Zusammenfassung


Zusammenfassung

für die Verwendung als Zeitgeber in Supercomputern sind kurze Pulse von Vorteil, da mit kürzeren Pulsen die Anforderungen an die Pulsverzerrung und zeitliche Verschiebung geringer werden.

Diese Dissertation beschäftigt sich mit der Untersuchung und experimentellen Realisierung von MLLDs, um die Ursachen der Pulsbreiten Grenze zu verstehen und zu beheben. Zum ersten Mal wurden die Absorber und Verstärker Elemente einer MLLD unabhängig voneinander optimiert, um MLLDs mit Pulsbreiten unter 1ps zu realisieren. Mit diesen MLLDs konnten wir Pulse mit einer Breite von 0.9ps bei einer Wiederholrate von 42GHz erzeugen.


Die thermische Belastung des Verstärkermaterials während dem Integrationsprozess führte zu einer Wellenlängenverschiebung des erzeugten Lichtes auf Grund der Diffusion von Atomen der Begrenzungen in die Quantenfilme. Dieser Effekt lässt sich durch eine Verdünnung der Quantenfilme beschreiben, die der beobachteten Blauverschiebung des Lichtes zugeordnet werden kann. Wir beobachteten eine Breitenreduktion der Filme von $8.3^\text{nm}$ bei einem Wachstumstemperatur von $630^\circ\text{C}$. 
Für die Integration der verschiedenen Elemente benutzten wir eine Metall-Organische Gasphasen Epitaxie (MOVPE). Mit Hilfe einer strukturierten SiO₂ Maske kann die Epitaxie lokal eingegrenzt werden. Als wesentliche Parameter, die diesen Prozess beeinflussen kristallisieren sich der Kammer-Druck und die Unterätzung der SiO₂-Maske heraus. Diese Parameter beeinflussen den Wachstumsratenunterschied nahe der Maske und weit entfernt der Maske. Dieser Wachstumsunterschied entsteht durch die auf der Maske diffundierenden Wachstumsatome und deren Einwachsen an den Rändern der maskierten Bereiche. Um diesen Wachstumsratenunterschied zu minimieren sind tiefe Drücke im MOVPE Reaktor vorteilhaft. Die Maskenunterätzung muss für die spezielle Topology optimiert werden, um die Wachstumsunterschiede zu minimieren und um ein Loch unter der Maske zu verhindern.


Der technologische Prozess lässt sich durch folgende Eckdaten charakterisieren: 14 Lithographie-Schritte, fünf Wachstumsprozess, vier Metallisierungen und eine gesamte Prozesszeit von zwei bis drei Monaten.

Trotz der aufgetretenen technologischen Schwierigkeiten konnten wir MLLDs mit UTC-Absorber und MQW-Verstärker realisieren die Einzelpulse von 0.9ps Länge und Mehrfachpulse mit einer Einzelpulselänge von 0.6ps erzeugten.
Chapter 1

Introduction

1.1 Applications of mode-locked laser diodes

Mode-locked laser diodes are promising optical pulse sources for a diversity of applications. In the past mode-locked laser diodes (MLLDs) were developed with a focus mainly on telecommunication systems. In recent years a variety of additional applications were investigated such as optical processor clock, optical sampling scope and even frequencies standards with MLLDs to mention only some of them. In the following we will present in more detail the telecommunication and optical processor clock applications.

Optical communication systems

The high oscillation frequencies around 200THz favors the optical range of the electro-magnetic spectrum for high bit-rate data transmission. But only the reduction of optical losses in glass fibers from 1000dB/km down to less than 20dB/km [1] and the development of laser diodes operating at room temperature [2], which both happened around 1970, marked the starting point of the development of optical fiber communication systems. Current optical-fibers achieve a minimum loss of 0.25dB at a wavelength of 1.55μm and semiconductor laser diodes work over a temperature range up to 80°C.

In the last two decades an enormous progress was made regarding the realization of single fiber capacity as shown in Fig. 1.1. These high
fibre capacities were implemented by wavelength division multiplexing (WDM) or even dense wavelength division multiplexing (DWDM). Alcatel demonstrated in their laboratories a transmission of 10.2Tbit/s using 256 channels of different wavelength with a channel capacity of 40 Gbit/s.

Figure 1.1: Progression in fiber capacity since 1980. (source: CISCO systems)

Just recently Weber and co-workers demonstrated a new world record of a channel capacity of 2.56Tbit/s data transmission over a single 160km long optical fiber [3]. To realize such a high channel capacity they used a fiber laser with a subsequent pulse compressor delivering 420fs pulse width output and a repetition rate of 10 GHz. Subsequent optical time division multiplexing (OTDM), where several channels are interleaved in the time domain, was used to end up with the demonstrated channel capacity.

Nowadays industry is offering 1.6Tbit/s systems with a per-channel capacity from 2.5Gbit/s up to 40 Gbit/s using DWDM [4]. So far the per-channel capacity has been limited to 40Gbit/s by the available electro-optic modulators and electronics. For future Tbit/s optical networks it will be advantageous to use subsequent OTDM of short optical pulses instead of further increasing the number of channels for DWDM. The application of OTDM will decrease the number of required light sources and thereby will be more cost effective. Furthermore with OTDM the average light intensity in the fiber can be reduced which decreases non-
linear effects. These nonlinear effects induce optical pulse distortion and channel cross talk.

The development for high bit-rate systems was and still is driven by new bandwidth-demanding applications such as the world wide web (WWW), video-on-demand and mobile communication backbone networks. The WWW community is still tremendously growing due to the increasing computer access of the huge population of former developing countries such as China and India. Furthermore video-on-demand in high-definition TV quality increases the need for high bandwidth connection which must be available in real time. For instance, a HDTV channel requires 5-8Mbit/s whereas an ordinary phone connection only needs 16kbit/s. Also, the ongoing globalization generates the request for access to the confidential company network from all over the world from the managing staff to the technician, who needs special information to fulfill his task at a customer site wheresoever.

An optical-fiber transmission link comprises three main elements: a transceiver to transform the electrical data signal into optical signal, the optical fiber as the transmission medium, and a receiver to transform the optical signal back into the electrical domain.

The transceiver usually consists of an electronic driver circuit and an optical source. The optical source itself can either be driven directly by the modulated electrical signal or a continuous wave-light source is used with a subsequent electro-optical modulator.

The most efficient way to produce directly an unmodulated pulse train of short optical pulses suited for optical transmission waveguide is a mode locked laser. Future multiple Tbit/s optical networks will increase the requirements for short optical pulse width. Considering pulse dispersion in the optical fiber and admitting of 1dB dispersion induced penalty, we get as a rule of thumb for the required source pulse width $\tau$ [5]

$$\tau \approx 0.42 \times t_{\text{bit slot}}$$

(1.1)

where $t_{\text{bit slot}}$ is the time slot for one bit at a given transmission rate $B = 1/t_{\text{bit slot}}$. The following table summarizes the values for current and future transmission rates.
For long haul (>500km [6]) high repetition-rate optical networks the preferred transmission wavelength coincides with the minimum optical loss of the glass fiber around 1550nm. The International Telecommunication Union standardized a wavelength grid with a center frequency of 193.100 THz corresponding to a vacuum wavelength of 1552.52nm. For DWDM the wavelength accuracy of the light source depends on the employed channel capacity (per wavelength), i.e., for using multiple channels with 320Gbit/s per channel the emitted wavelength has to be stable within 1nm.

**Optical clocking**

Not only as an optical light source but also on the receiver side of optical networks mode-locked laser diodes are useful to extract the channel clock out of the aggregated data signal. Data rates above 40Gbit/s become increasingly difficult to be handled by optical-to-electrical conversion and subsequent electronic clock recovery. On the other hand, MLLDs demonstrated the potential for all optical clock extraction of e.g., a 40 GHz clock out of a 160 Gbit/s signal [7]. This 40 GHz clock can then be directly processed by the electronic circuit of the receiver. Also for high performance clustered computing systems, optical clocks become an increasingly interesting solution [8] as alternative to conventional electrical clock distribution. The important parameters for clocking accuracy are the pulse-to-pulse time of arrival variations (jitter) and the time variations of the bit slot due to signal propagation and synchronization of different clocks in the system (skew). Currently used quartz crystals for microprocessor clocking have a relative low resonance frequency around 32 MHz. Multiplying this frequency to reach the desired processor clock increases the jitter and skew of the signal dramatically. Thus, clock rates beyond 8 GHz-10GHz are hard to realize with the conventional technique [8]. Another issue is the clock distribution over classical copper wires. Distances over 1cm are becoming difficult at
1.1. Applications of mode-locked laser diodes

higher frequencies regarding the clock signal integrity which will suffer from loss and dispersion.

All these problems can be solved by using mode-locked laser diodes. The so far available repetition rates of mode-locked laser diodes will satisfy the international road map for semiconductor microprocessor [9] for decades. It is also advantageous to distribute the clock signal of a central clock unit via optical waveguides to several processor units [10] because the clock is then intrinsically synchronized over the whole system and the clock signal is nearly losslessly delivered to the CPUs.

Keeler and co-workers demonstrated [11], that also for these clocking applications the usage of very short optical pulses (<ps) is advantageous. The short pulse width reduces the requirements for timing jitter and higher peak power is beneficial for a lower receiver sensitivity. They also demonstrated perfect channel re-timing with short optical pulses. Shorter pulses will also allow higher data rates between future optical interconnects.

Optical pulse sources

To meet the specifications for optical communication systems and optical clock recovery, several kind of pulse sources were developed in industry and university research labs. As already stated, the simplest option is to directly drive a laser diode with the electrical data signal. Repetition rates up to 40Gbit/s were demonstrated [12] limited by the relaxation resonance of the semiconductor laser and the speed capability of the electronic driver circuits. An other possibility is the use of a cw-laser with an external electro-optic modulator.

Before discussing the advantages of mode-locked lasers the operation principle is briefly presented. Mode-locked lasers are commonly composed of a saturable absorber and a gain section in an optical cavity. The interplay of the absorber and gain dynamics will lead to a light pulse circulating in the cavity. At both ends of the cavity a part of the pulse is coupled out through the partially-reflecting mirrors. Therefore the length of the optical cavity determines the repetition rate of the out-coupled pulse train via the cavity round trip time of the pulse.

Harmonic mode-locking with an integer multiple of this inherent repetition rate is also possible. The order of harmonic mode locking i.e. the number of pulses circulating in the cavity can be determined by the number of absorber sections of the laser. The absorber sections have to
Chapter 1. Introduction

split the cavity length into equal parts in such a way that always two pulses in the cavity collided in one absorber section [13]. For instance if the absorber section is placed in the middle of the cavity two pulses can circulate and collided in the middle. Thus we get for $n$ absorbers $n + 1$ pulses in the cavity. This kind of mode locking is also called colliding pulse mode locking.

To reduce and manage the dispersion in the optical fiber link well defined and Fourier-limited pulses (i.e. with a minimal time bandwidth product) are a prerequisite. Whereas directly modulated lasers produce highly chirped pulses with an uncontrollable intensity profile and cw-lasers with subsequent modulator produce undefined pulse shapes, mode-locked lasers demonstrated the emission of Fourier limited Gaussian pulses.

Several kinds of mode locked lasers were demonstrated with high repetition rates. Recently, external cavity semiconductor and solid state mode-locked lasers were demonstrated with repetition rates up to 50GHz and 80GHz respectively [14, 15]. Another possibility is the use of fiber ring lasers [16], which require a relatively long cavity length to provide enough gain in an erbium-doped fiber segment. To reach the Gbit/s repetition rates these fiber-lasers operate in a high harmonic mode-locking mode [16].

The lasers with external cavities have the advantage of discrete components, which can be optimized and replaced independently. On the other hand the discrete component assembly increases the manufacturing costs. An other drawback of the fiber and external cavity lasers is the need of a sophisticated mechanical and thermal stabilization scheme to provide the required cavity length stability on a micro-meter scale. On the contrary monolithically integrated mode-locked laser diodes (MLLDs) are compact, mechanically stable, cost-saving due to a small footprint, and have an improved pump efficiency.

Concerning the computer clock applications the possibility of cost effective mass production on wafer scales is a prerequisite [11], and just recently very promising progress in InP/Si heterogeneous integration was demonstrated [17].
1.2 Integrated optics

We have seen in the previous section, that monolithically integrated MLLDs consist of two or three elements: a saturable absorber section, a gain section and optionally a passive waveguide section to extend the laser cavity to the desired length. The latter is advantageous for long (>1mm) cavities to avoid high pumping currents to reach transparency of the waveguide and the generation of additional noise due to an increase of spontaneous emission.

For up to now in all reported MLLDs the same material was used for the absorber and gain section. However the absorber and gain sections have contradictory requirements for optimal mode-locking. To design and optimize them independently, a suitable integration process has to be identified and established.

As a material system, indium-phosphide (InP) and its ternary and quaternary alloys with GaAs are widely used because of the large direct-bandgap tunability range between 970 and 1600nm including the optical telecommunication bandwidths of 1300 and 1500nm. In addition, the electrical and refractive index properties of the InGaAsP material system are well suited for monolithic integration. For instance, low ohmic contact resistance and fast electrical modulation response were demonstrated [18]. The low refractive index contrast results in large optical mode areas which are less sensitive to waveguide perturbations introduced by monolithically integrating different structures.

In contrast to micro-electronics, optoelectronic integration has to deal with a large functional and material heterogeneity [19]. For instance, laser gain sections have to be integrated with passive waveguides, modulators, and detectors. Other examples of functional heterogeneities are found in optical detectors integrated with HBT-based electronic pre-amplifiers and an active Mach-Zehnder interferometer embedded in silicon-based passive waveguides.

Crucial for the active, i.e. light emitting or absorbing, structures is the efficient electrical isolation of the different sections with different electrical bias and modulation signals. Despite of the challenging requirements, an impressive progress in complex integrated passive devices was achieved during the last two decades (Fig. 1.2). For the even more complex integration of passive and active devices several integration schemes were developed in research labs during the last ten years [20].

We can distinguish four major integration approaches (see also Fig. 1.3):
8 Chapter 1. Introduction

Figure 1.2: Evolution of the integration density for all-optical MUX/DEMUX systems. (courtesy M. Smit COBRA TU-Eindhoven)

- twin waveguide coupling (TWC) technique
- quantum well intermixing (QWI)
- selective area growth (SAG)
- butt coupled regrowth (BCR).

All of them have specific advantages and drawbacks with respect to the generic goals of integrated optical circuits.

For the TWC process, the active layer stack is grown on top of a passive waveguide. Afterwards, the active layer is selectively etched away and mode couplers for the transition from the upper to the lower waveguide are formed. In principle this process is not limited to two layer stacks. However, only devices with two different structures were realized [21] so far. The main advantage of the TWC process is the growth of all structures in one single epitaxial step.

On the other hand the main drawback is the requirement of an area consuming at least 200μm long and lithographically challenging waveguide coupler [21]. In comparison to typical absorber lengths of 5-100μm for MLLDs, the taper lengths excludes the TWC process for MLLD fabrication. Furthermore the back reflection between the different sections due to imperfectly matched taper length were never addressed in any publication or experiment. Internal reflections are very critical for MLLDs...
1.2. Integrated optics

Figure 1.3: Processes for photonic integration: twin waveguide coupling (TWC), quantum well intermixing (QWI), selective area growth (SAG), butt coupled regrowth (BCR)
The QWI process starts with an epitaxially-grown quantum-well structure which is subsequently processed to change its composition by material interdiffusion. The result is a change of the electronic-band structure yielding a higher optical transition energy between conduction and valence band. Thus either the interdiffused parts are transparent for the photons emitted by the non-interdiffused sections, or the non-interdiffused parts are absorbing for the photons emitted by the interdiffused regions. Unfortunately the inter-diffused electronic-band profile are advantageous mainly for absorber and modulator applications. The interdiffusion process will transform the grown square like quantum well potential into a parabolic like potential. Whereas the square like QW-potential is desirable for gain sections to achieve a good carrier confinement, the parabolic potential is preferable for absorber and modulators to make a fast carrier extraction possible [22].

Several techniques such as laser induced [23] or mask induced strain [24] material diffusion make this process area selective. A big advantage of this technique is the smooth material interface between the different sections. So we can expect low optical losses and inter-section reflections. Even though great progress has been achieved in the QWI process [25], the different sections for different functions can not be designed independently.

The SAG process involves a patterned SiO$_2$- or SiN-mask on the wafer during epitaxy. The material composition and growth rates are determined by the width of unmasked areas on the substrate due to the diffusion of growth species on the mask. When growing e.g. quantum-well structures, the thickness of the quantum wells will hence depend on the unmasked stripe width providing areas with different optical transition energies and bandgaps respectively.

SAG exhibits the same benefits and constraints as the QWI process. Moreover the pre-growth processing of the wafer can lead to contaminated surfaces which results in a low device yield. Nevertheless, it is this process which is used for the only commercially available MLLD on the market [26]. Furthermore Kunimatsu and co-workers [27] used the SAG process for MLLD fabrication and demonstrated a reduction of output pulse width from 2.6 to 1.2ps by introducing a blue shift of the absorber transition wavelength of 24nm.

Only the BCR process offers full freedom to optimize the different structures independently. After growing the first layer structure of a BCR process, part of it is selectively removed down to the substrate or
1.3. Motivation of the thesis

From the previous sections it became clear that a monolithically integrated optical pulse source has a great potential for numerous applica-

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<tr>
<td>TWC</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>?</td>
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</tr>
<tr>
<td>QWI</td>
<td>++</td>
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<td>BCR</td>
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Table 1.1: Advantages (+) and disadvantages (-) for monolithic integration processes.

to a previously grown etch stop and overgrown by a new layer structure. Conceptionally, the regrowth can be repeated until all needed structures are integrated on a single wafer. With the BCR process the integration of up to four different layer structures was already demonstrated [28]. The BCR process is the most challenging option from the epitactiral point of view. This makes the device processing more complex and a good quality crystalline regrowth relies on a perfectly clean processed wafer surface. Although the fabrication of low reflecting interfaces is more challenging than for the SAG and QWI processes, previous work have shown that interfaces with reflections below $5 \cdot 10^{-5}$ and losses around 0.43dB can be realized [29]. Despite these technological challenges, the main advantage of the BCR process is the possibility to optimize the different layer structures independently. Tab. 1.2 summarizes the main advantages and disadvantages of the different technologies.

Only the BCR technology will provide us with the possibility to design and optimize the gain and absorber structure independently. As for the independently designed absorber and gain sections in solid state mode-locked lasers also for these MLLDs pulse widths in the fs-regime should be achievable. The development of a reliable integration process will provide us with a cheap compact and robust optical pulse source for a variety of interesting high-volume market applications.
tions. To overcome the present experimental pulse width “barrier” at around 2 ps deduced from literature for MLLDs a better understanding of the pulse formation process and the identification of the important and technically controllable parameters is required.

To understand how to break this “barrier” we demonstrated that an absorber structure with recovery time around 2-5ps is required [30] in comparison to 10ps of conventional absorber structures. Simulation of MLLDs with a fast absorber reveals mode-locking with spectral-gain bandwidth-limited pulses down to 100fs. Recovery times of ≈3ps can not be realized with a conventional reversed-biased gain section. Thus the absorber and gain sections have to be grown separately and have to be joined with a butt coupled regrowth process. The theoretical and experimental analysis of the fast absorber structure is presented in the thesis of R. Scollo [31]. His work is a complementary part to this thesis focusing mainly on the absorber section design and optimization. In R. Scollo’s work you can find a more detailed analysis of the gain and absorber dynamics interplay. In this work the modelling part focuses on the influence of the gain’s spectral width for MLLDs with optimized absorber.

The main focus of this thesis is on the development of a suitable process to integrate optimized absorber and gain structures monolithically into one chip. As will be demonstrated this process has also a major influence on the optimized quantum well gain structure.

Furthermore the reflections at the butt-coupled interfaces are considered in detail because of the following puzzle. On the one hand, the butt coupling interfaces seems to satisfy the requirements for monolithic mode-locked laser diodes stated in literature [32, 33](see Chap. 2). On the other hand, we demonstrated at our institute that an absorber structure integrated with a butt coupled regrowth process will prevent mode locking on monolithic MLLDs. We never observed so far a MLLD for a butt coupled process which does not show a deep modulation of the laser mode amplitude in the output light spectrum corresponding to the sub-cavity length of the absorber section.

Therefore the theoretical and experimental investigations on the internal interface reflections for butt-coupling process will be presented in the following. Several material and process imperfections are identified and methods to overcome them are proposed and demonstrated.
1.4 Outline of the thesis

This thesis mainly deals with the requirements and characteristics of the integration process for a multi-section mode-locked laser diode with an ultrafast absorber, a multiple quantum well gain section and a passive waveguide for extending the laser cavity. In chapter 2, a theoretical description of the mode locking process and the simulation of mode-locked laser diodes with a distributed time-domain model will be presented. The simulation results will clearly demonstrate the need for a fast absorber, which is supported by the state-of-the-art in MLLD research. Chapter 3 covers the design aspects of the gain section and the influence of the butt-coupled process on the gain characteristics. The details of the integration process are developed in chapter 4. The characterization of the etch and growth processes will lead to a final optimized integration process, which yields the desired high quality interfaces between the different MLLD structures. We will identify the use of a low pressure MOVPE growth process and of an angled butt-coupled interface as a prerequisite to realize low loss and low reflectivity between the interfaces. Finally, chapter 5 presents the results of realized integrated MLLDs and demonstrate the successful achievement of sub-ps optical pulse generation. Again the focus is on the interface characteristics which will be extracted out of the optical spectrum and threshold behavior of fully-processed MLLDs. The thesis ends with an outlook on alternative MLLD materials, structures, and technologies to further investigate the behavior of mode-locked laser diodes.
Chapter 2

Mode locked laser diodes

In this chapter we will present the basics of mode-locking and give an overview over the simulation results and current understandings of the pulse formation process in mode-locked laser diodes. Furthermore a description of the used distributed time-domain laser model and its simplifications and assumptions with the resulting limitations are presented. Applying this model we demonstrate the importance of an absorber with a fast recovery time.

Subsequently the state-of-the art mainly with respect to the achieved pulse width but also to other important pulse parameters for monolithically integrated MLLDs is summarized.

Finally we describe the fabricated monolithic structures and the fast absorber based on an uni-traveling carrier design and its characteristics.

2.1 Theory of mode locking

The emission spectrum of diode lasers consists of several resonance frequencies or modes \( \nu_m \) with \( m = 1, 2, 3...M \), separated by a mutual frequency difference \( \Delta \nu \) which is a function of the resonator length \( l \) and refractive index \( n \) as described by Eq. 2.1

\[
\Delta \nu = \frac{c}{2nl}
\]  

(2.1)

where \( c \) is the speed of light in vacuum. For the case of dispersion \( n(\nu) \) is also a function of \( \nu \). Since the refractive index and the gain are related
by the Kramers-Kronig transform, this dispersion is incorporated in our model via the group velocity dispersion term.

The total electric field of the emitted light can be written as a superposition of the single modes:

$$E(t) = \sum_{m} B_m e^{j(\nu_0 + mv)t + j\phi_m)} \quad (2.2)$$

where $B_m$ and $\phi_m$ are the amplitude and phase of the $m^{th}$ mode. The number of oscillating modes $M$ is practically limited by the spectral width of the laser gain material, which is around 30-50nm for typical semiconductor materials.

In conventional multi-mode lasers the phases fluctuate randomly resulting in a randomly varying (noisy) intensity output. Siegman defines the term mode-locking [34] as “a situation where all longitudinal modes are equally spaced in frequency and are arrayed in phase, i.e. have a constant phase relation to each other”. This situation leads to the build-up of short pulses by coherent interference of the frequency modes.

Mode-locking is established by an external or internal (so called self-) gain or absorption modulation with a frequency equal to the repetition rate. This modulation generates optical side-bands of each mode overlapping with the first, second, third, and so on neighboring modes. Thus refractive index dispersion will disturb mode-locking because the generated side bands will not overlap with the neighboring modes.

The temporal amplitude shape of the pulse envelope is related to the spectral envelope of the mode amplitudes via a Fourier-Transform. Commonly a Gaussian or a hyperbolic secans temporal pulse shape is assumed.

Concerning the mode amplitude distribution we have to distinguish between homogeneously broadened and inhomogeneously broadened gain material. For a homogeneously broadened gain material, all radiative transitions have the same spectral width and are coupled through a common pumping mechanism. Hence the reduction in material gain of one mode also lowers the gain of the other modes and the mode amplitudes $B_m$ interact strongly with each other. This situation is realized in semiconductor laser diodes because the gain of the modes are coupled via the carrier distribution. The effect is used for cross gain modulation schemes [35].

On the other hand, in inhomogeneously broadened gain material, the radiative transition have different spectral center wavelengths and widths.
For instance, different atom velocities in gas lasers, different local crystalline environment of the optically-active atoms in solid state lasers or different environments and shapes of quantum dot lasers results in inhomogeneously broadened optical gain. These gain materials naturally support the lasing of many laser modes with independent and constant amplitudes. Siegman stated [34] that these independent modes favors mode locking with well defined amplitude pulse shapes in inhomogeneously broadened gain material [34], because only the phases have to be fixed whereas in homogeneously broadened gain materials we further have to establish a dynamic equilibrium between the different mode amplitudes.

Once mode locking is achieved, the summation over $M$-modes with constant amplitudes $B_m$ existing in the cavity can be expressed analytically with Eq. 2.2. For the case of $M$ modes with amplitude $B_0$ the resulting optical intensity $I(t) = |E(t)|^2$ is:

$$I(t) = B_0 \frac{\sin^2(2\pi M \Delta \nu t/2)}{\sin^2(2\pi \Delta \nu t/2)}.$$  \hspace{1cm} (2.3)

Fig. 2.1 shows a time-slot of the infinitely periodic intensity output of five perfectly locked laser modes with equal amplitude.
The pulse repetition rate $T$ is given by:

$$T = \frac{1}{\Delta \nu} = \frac{2nL}{c}$$

and is hence mainly determined by the cavity length. The pulse width $\tau_{\text{pulse}}$ is given by the ratio of $T$ and the number of locked modes $M$. Since the latter is governed by the spectral gain bandwidth the pulse width is inversely proportional to the spectral gain bandwidth in the framework of this simple theoretical description.

Several techniques were developed to achieve mode-locking. One possibility for laser diodes is the active gain-current modulation in resonance to the repetition frequency.

By implementing a saturable absorber into the laser cavity the total cavity gain is modulated by the saturation of the absorption and gain by the pulse itself, hence a self-modulated mode-locking. This operation regime is called passive mode locking.

By combining the two methods we get hybrid mode-locking, with the advantage of locking the repetition rate to an external modulation.

For mode locked laser diodes several geometries were proposed and realized to implement a saturable absorber, a gain section, and a cavity as shown Fig. 2.2.
2.1. Theory of mode locking

First mode locked laser diodes were realized with external cavities as shown in Fig. 2.2a) [36]. The advantages of monolithic integration over external cavities such as better mechanical stability, smaller foot-

Figure 2.2: Mode locked laser diodes. a) external cavity, b) monolithic all active with reversed biased absorber section c) monolithic with passive waveguide extended cavity.
print space, and lower fabrication cost led to the development of all
active or extended cavity monolithically integrated laser diodes which
include two and three sections respectively [37]. The all-active MLLDs
consists of a gain and an absorber sections while for MLLDs with repeti-
tion rates below 10GHz the cavity is commonly extended with a passive
waveguide section. Thus the gain section can be kept short to reduce the
pumping current and noise generation due to spontaneous emission as
already stated in Chap. 1. In addition shorter gain sections reduces the
self phase modulation effect which causes chirped, non Fourier-limited
pulses, which was demonstrated by Scollo et al. with the length de-
pendence of the linewidth enhancement factor in semiconductor optical
amplifiers [38].
Traditionally the saturable absorber has conventionally been implemented
by simply reverse-biasing a part of the active section (Fig. 2.2b). Hence
the gain and absorber sections have to be electrically isolated by re-
moving the highly doped top contact layer between them. For extended
cavity MLLDs the passive waveguide could be placed between the active
structures (Fig. 2.2c) or at the end of the cavity resulting in an absorber,
gain, passive waveguide geometry. The latter is advantageous if the same
material is used for the absorber and gain sections to reduce the number
of interfaces and hence the internal reflections. The former can be ad-
vantageous if a different structure is used for the absorber as is explained
in Chap.5.
With respect to the time domain description, the pulse formation pro-
cess in mode locked laser diodes is subject to several pulse broadening
and pulse shortening mechanisms [32] until a self-consistent round trip
with a fixed out-coupled pulse width is reached. The pulse is shortened
by the active gain modulation or the saturable absorption. Pulse broad-
ening is due to gain saturation and dispersion. Bischoff and co-workers
[39] demonstrated that the former process is dominant for MLLDs.
The self phase modulation (SPM), which is due to a refractive index
change caused by the pulse itself, must also be considered for a mode
locking theory, because gain and refractive index are strongly coupled in
common semiconductor laser materials. SPM will result in pulse chirp
and pulse broadening or shortening depending on the dispersion in the
cavity [40].
2.2 Modeling of mode locked laser diodes

MLLDs are complex optoelectronic devices. The investigation of the interplay of fast (fs-ps) intra and slow (ns) inter-band dynamics with the optical field demands sophisticated modeling techniques. Unfortunately there is no commercial simulation tool currently available which include the dynamics further than the steady state.

First theoretical descriptions of mode-locked laser diodes (MLLD) introduced by H.A. Haus [41] were based on theories of mode-locked dye lasers and did not consider self-phase modulation and group-velocity dispersion. The theory was soon extended to include these two effects [42]. Most of these models are based on a self-consistent round-trip of the pulse in the laser cavity with only small changes of the pulse properties per pass. They had the advantage to yield analytical results, e.g., for the pulse width which gives first insights in the general process of pulse build-up.

Nevertheless their predictions remain qualitative at best and sometimes are not consistent at all with the experimental behavior of MLLDs. This is mainly due to two effects. First the gain in semiconductors as well as the out-coupling losses are usually relatively high and hence the pulse shape will be distorted strongly during one round trip. Second the saturation of the gain in a semiconductor contains slow inter-band effects on a ns time scale and fast intra-band effects with relaxation times of fs-ps. The latter are due to deviations of the energy distribution of electrons and holes from quasi equilibrium such as carrier heating and spectral hole burning.

Therefore it is necessary to use more accurate however computationally challenging models either in the frequency or in the time domain.

2.2.1 Frequency Domain Models

Frequency domain models of MLLDs have received less attention than time domain models but nevertheless have led to some important results in the past [43, 44]. Especially where high spectral resolution is required to describe the laser output behavior e.g. for the case of coupled cavity mode locking, frequency domain models are the only ones which can investigate the effects so far [45].

For the more advanced frequency models such as the one presented in [40] the optical field is expanded into its frequency modes. Each mode is
Chapter 2. Mode locked laser diodes

represented by a standing wave which fulfill the resonant condition for the laser cavity. The time dependence of the resonance condition due to the dynamics of the refractive index is neglected [46]. The spectral dependency of the gain and absorber dynamics are incorporated by additional mode selection terms. Thus some modes are more absorbed or amplified than others. The mode-coupling terms are complex functions of the induced material polarization due to the internal light induced carrier dynamics and the external modulation of the carrier concentration. Due to these complex functions it is hard or nearly impossible to study the influence of the gain and absorber dynamics on the mode-locking output.

With these models it was demonstrated, that lasers with lower cavity losses were more likely to show stable mode locking. The higher optical field results in a stronger absorber modulations generating more intensive optical side-bands which support the mode-locking process. This was confirmed experimentally by J. Palaski and K.Y. Lau [47]. Adding high reflection coatings to the facets of MLLDs, they could demonstrated reliable mode locking without being affected by self-pulsating. However, it must be borne in mind, that the frequency domain models are small signal models in the sense that the gain and absorption modulations must remain small. As already mentioned, this is in principle incorrect for semiconductor based MLLDs and makes the results untrustworthy.

In the time domain, fully distributed models [40] have been extensively used in the last few years to obtain a realistic picture of fast MLLD dynamics and transients. The implementation of fast gain saturation effects can be approximated with carrier rate equations. This kind of model was also used for the simulation results shown in this thesis.

2.2.2 Time-Domain Model

In the following a description of the used time domain model is given. We also present the implemented simplifications and resulting limitations. The detailed numerical implementation is reviewed in the appendix (App. A).

The evolution of the optical field in a non-magnetic, dielectric medium with macroscopic polarization \( \mathbf{P} \) is described by the wave-equation based on the macroscopic Maxwell Equations and the so called constitutive
relation between the electric flux $\mathcal{D}$, the electric field $\vec{E}$ and the polarization $\mathcal{D} = \epsilon \vec{E} + \mathcal{P}$ and is given by:

$$-\nabla^2 \vec{E} + \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = -\mu_0 \frac{\partial^2 \vec{P}}{\partial t^2}. \tag{2.5}$$

$\mu_0$ is the permeability in vacuum which is identical to the permeability of semiconductor materials interesting for optoelectronic applications.

Considering the fact that even for a 100fs long pulse the carrier frequency oscillates $\approx 20$ times the carrier frequency can be separated and the envelope approximation is applied in the following. Supposing a wave traveling in z-direction the electrical field can be written as:

$$|\vec{E}(\vec{r}, t)| = \frac{1}{2}[E(\vec{r}, t)e^{j(\omega_0 t - \beta_0 z)} + \text{c.c.}] \tag{2.6}$$

with the amplitude $E(\vec{r}, t)$

$$E(\vec{r}, t) = F(x, y)A(t, z). \tag{2.7}$$

If we substitute Eq. (2.6) in Eq. (2.5), we can separate the variables and get three different differential equations. For the carrier wave term $e^{j(\omega_0 t - \beta_0 z)}$ we get the dispersion relation. Due to this separation of the carrier frequency, interference effects such as the compound cavity mode-locking and frequency depending effects as for Fabry-Perot filters inside the cavity can not be simulated with our model which is focused on the calculation of the envelope function $A(z, t)$. This simplification is also mandatory to limit the required time resolution to a computable value. Otherwise a sub fs time resolution is required which increases the amount of data to describe the device under simulation to a level which exceeds the addressable memory in nowadays computer systems.

The differential equation for $F(x, y)$ defines the transverse mode profile whereas the equation for $A(z, t)$ describes the evolution of the light field envelope along the propagation direction.

Instead of separating the phase and amplitude of $A$ as is used for example in [39], we consider $A$ as a complex number describing the phase and amplitude dynamics with a single differential equation.

The complex nonlinear material response is simplified with a spectral domain expansion of the complex susceptibility $\chi(\omega)$[48]. The resulting differential equation for $A(t)$ in the time domain (Eq. 2.8) can be simplified, if we make use of the slowly varying envelope approximation. Details of this complex deviation can be found in [49, 50, 48]. The result
is the following equation:

\[ \frac{\partial A}{\partial z} + \frac{1}{v_g} \frac{\partial A}{\partial t} + j \beta_2 \frac{\partial^2 A}{\partial t^2} = \frac{1}{2} (1 - i\alpha) gA - \frac{1}{2} \alpha_{ext} A \]  

(2.8)

In Eq. 2.8 \( v_g \) is the group velocity in the semiconductor material. The linewidth enhancement factor \( \alpha \) describes the correlation between the gain and the refractive index changes and represents together with the gain \( g \) the material susceptibility thus the material response to the electrical field [51]. The slowly varying envelope approximation allows us to neglect the second derivatives of the pulse envelope \( A \) with respect to distance \( z \).

The effect of gain dispersion can be included in the model by considering the gain spectral profile \( \hat{g}(\omega) \) where the hat over \( g \) is a reminder that the gain is being considered in the frequency domain. If the pulse is longer than the intra-band relaxation time constants for spectral hole burning (\( \tau_{SHB} \approx 100 \text{fs} \) [40]), we can expand \( \hat{g} \) in a Taylor series around \( \omega_0 \) up to the second order to consider spectral dispersion:

\[ \hat{g}(\omega) = \hat{g}(\omega_0) + \hat{g}'(\omega - \omega_0) + \hat{g}''(\omega - \omega_0)^2 \]  

(2.9)

This implies, that the carrier frequency coincides with the maximum of the gain spectrum. The spectral gain function is thus approximated by a parabola and deformations due to spectral hole burning can not be considered. Mocozzi and Mork [52] demonstrated with simulations that spectral hole burning will not lead to pulse deformation in gain sections for pulse widths down to 200fs. Furthermore Xing and Avrutin [53] illustrated recently with their time-frequency model that the spectral hole burning has a pulse shortening effect for quantum dot lasers. The pulse shortening was explained with a spectral broadening. The different lasers modes suffer less from cross gain correlation, if they are more independent due to the hole burning effect in the carrier distribution.

Experimentally pulse width at 477fs and 390fs were reported for semiconductor external cavity lasers [54] and quantum dot monolithically laser diodes [55], respectively. Therefore we can suppose that the spectral gain deformation effects will not limit the output pulse width down to 400fs, the required pulse width for Tbit/s communication systems.

Applying the Fourier transform into the time domain, which essentially is equal to replacing \( (\omega - \omega_0) \) with \( j(\partial/\partial t) \) then Eq. (2.8) can be written...
2.2. Modeling of mode locked laser diodes

in the following form [56]:

\[
\frac{\partial A}{\partial z} = (\tilde{g} - \alpha_{int})A
\]

\[
+ \left( -\frac{1}{\nu_g} - \frac{\Gamma}{2}\tilde{\gamma}|\omega_0\frac{\partial A}{\partial t}
\right)
\]

\[
+ \left( \frac{\beta_2}{2} - \frac{\Gamma}{4}\tilde{\gamma}''|\omega_0\frac{\partial^2 A}{\partial t^2}
\right)
\]

(2.10)

Where \( \Gamma \) is the optical confinement factor and the complex total local gain and phase deviation \( \tilde{g} \) can be expressed as:

\[
\tilde{g} = \frac{\Gamma}{2} \left[ g_N(1 + j\alpha_N) + g_T(1 + j\alpha_T) \right]
\]

(2.11)

which includes the gain and the associated linewidth enhancement factors. The material interaction with the optical field is described by the gain and linewidth enhancement factors for the carrier distribution \( N \) and the intra-band carrier heating \( T \) by two sets of parameters: \( g_N, \alpha_N \) and \( g_T, \alpha_T \). The carrier heating gain compression \( g_T \) is described as a deviation from the gain \( g_N \) due to the carrier concentration and thus is simply added in Eq. 2.11.

Internal waveguide losses are included in the factor \( \epsilon_{ext} \). The second and third lines in Eq. (2.10) contain the propagation and dispersion terms. The group velocity dispersion is implemented with the parameter \( \beta_2 \).

The gain dynamic response is approximated by with rate equations:

\[
\frac{dg_i}{dt} = -\frac{g_0 - g_i}{\tau_i} - \frac{g_c |A|^2}{E_{sat,i}}
\]

(2.12)

Here \( i \) stands for \( N \), and \( T \) meaning carrier dynamics and carrier heating, respectively. \( g_0 \) is the unsaturated gain, \( \tau_i \) the corresponding relaxation time and \( E_{sat,i} \) the corresponding saturation energy. Whereas \( E_{sat,N} \) is given as a function of Planks constant \( \hbar \), the light frequency \( \omega \), the active area cross section \( \sigma \) and the modal differential gain \( \Gamma a \) as:

\[
E_{sat,N} = \frac{\hbar \omega \sigma}{\Gamma a}
\]

(2.13)

Whereas \( E_{sat,T} \) is in our model a material parameter. The interplay of this two gain contributions with different time constants \( \tau_i \) and saturation energies results in a complex pulse width dependent effective gain relaxation.
Chapter 2. Mode locked laser diodes

and saturation energy of the total gain $\tilde{g}$. These effects are discussed in detail in [31]. A similar dynamic equations can be written for the absorption saturation [57]:

$$\frac{d\alpha_{abs}}{dt} = -\frac{\alpha_0 - \alpha_{abs}}{\tau_{abs}} - \frac{\alpha_0}{E_{sat,abs}} |A|^2 \quad (2.14)$$

in which $\alpha_0$ is the unsaturated absorption, $\tau_{abs}$ is the absorption recovery time and $E_{sat,abs}$ is the absorber saturation energy. The overall mode-locked laser diode performance is crucially dependent on the ratio of the saturation energies and time constants in the absorber and the gain section.

For the numerical implementation of the model, the laser diode cavity is divided into slices of length $\Delta z$ along the propagation direction $z$. In each slice the local gain/absorption and amplitude $A$ are calculated for the time step $\Delta t = \frac{\Delta z}{v_p}$ and subsequently transmitted to the neighboring slices considering a field propagating to the left and right direction. The light out-coupling is considered at both cavity boundaries with a amplitude reflection of $r = 0.55$. Model parameters are summarized in the appendix (App.A).

Fig. 2.3 presents a simulation result for a 4mm long MLLD with a repetition rate of 11GHz for our simulation parameters. The self-starting was realized by adding a white Gaussian noise term to the amplitudes in every $\Delta z$-slice of the gain section representing the spontaneous emission [58]. After a ramp-up phase of 5-6ns, the steady state is reached, which is in agreement with other modeling and experimental results [40].

The plots of the gain and absorber dynamics depict also the pulse-formation process as shown in Fig. 2.4. The interplay of the absorber and gain dynamics opens a time slot with absolute positive gain a so called net gain window, which allows the build up of a single pulse traveling in the cavity. The details of the dynamics determine the pulse duration and the pulse shape.

With this model several important parameters for the MLLD performance were identified [59]. First of all the saturation energy of the absorber $E_{sat,abs}$ has to be less than the one of the gain $E_{sat,gain}$ in order to open a net gain window. Therefore, the saturation of the absorber opens the gain window which is closed by the saturation of the gain. This requirement is often quantified as the ratio of the two saturation energies:

$$s = \frac{E_{sat,gain}}{E_{sat,abs}} \quad (2.15)$$
2.2. Modeling of mode locked laser diodes

Figure 2.3: Modeling of the output for a mode locked laser diode. From top to bottom: output light intensity, total gain, amplifier gain, and absorber gain

$s$ is an important figure of merit. For YAG-based solid state mode locked lasers with semiconductor saturable absorbers Paschotta and co-workers used a slightly different definition for $s$ as the ratio of the absorber saturation energy over the pulse energy in the cavity which is mainly determined by the gain saturation energy. They reported a optimum pulse shortening for $s = 5$ [60] because the net gain window is reduced and especially the time with net gain after the pulse is shortened. For higher $s$-values the pulses become only subtly shorter and for values higher than 20 the pulse formation process become unstable resulting in multiple pulsing.

For mode-locked laser diodes the situation is more complicate due to the fast intra-band effects. The effective saturation energy is hence also dependent on the pulse width. A detailed discussion is given in the complementary thesis of R. Scollo [31]. Our simulations showed that a $s$ value larger than 5 is necessary to follow the bandwidth Fourier limit down to sub-pico second pulses. For smaller $s$-values the need of a fast absorber is necessary as will be shown later.
As can be seen in Fig. 2.4 the pulse is shorter than the net gain window because the still unsaturated absorber truncates the first part of the pulse. This results in an effective drag in time of the pulse center. Therefore the light emitted due to the net gain behind the pulse is collected by the pulse itself.

Even though the typical gain bandwidth of 30-50nm in semiconductor materials should allow for Fourier-limited pulse width down to 200fs, the experimentally pulse width observed up to now seems to have a limit above 1-2ps. Bischoff and co-workers demonstrated [39] that the gain saturation is the main pulse broadening mechanism.

In addition SPM effects in long gain sections seem to double the pulse width [32] and result in a red chirp of the pulse. This red chirp can be counteracted in the absorber section, which usually induces SPM with the opposite sign. This explains the observation of blue and red chirped output pulses [57]. Therefore a small linewidth enhancement factor is favorable in order to avoid the complex chirping effects. So gain and absorber sections with low linewidth enhancement factors e.g. quantum
2.2. Modeling of mode locked laser diodes

Wells are favorable for MLLDs. Our simulations of MLLDs provide evidence, that we can counteract the pulse broadening due to gain saturation and a low s-value of $\approx 2-3$ by using an absorber with a fast recovery time constant [30]. Fig. 2.5 shows the simulated FWHM pulse width for absorber recovery times of 10ps and 2ps as a function of the assumed spectral gain bandwidth. The 3dB-bandwidth $B$ of the gain section with length $L$ is related to the gain parameter $\gamma''$ by Eq. (2.16) [61].

$$B = \frac{\lambda_0^2}{2\pi c} \sqrt{\frac{\ln 2}{\Gamma \gamma'' L}}$$  \hspace{1cm} (2.16)

where $\lambda_0$ is the wavelength in vacuum, $c$ is the velocity of light in vacuum, and $\Gamma$ is the optical confinement factor. From this formula it becomes evident, that a shorter gain section can realize a broader gain spectrum with the same $\gamma''$ parameter. Therefore short gain sections are required to utilize most of the material bandwidth effectively.

All other material parameters were fixed in the simulation and the pumping current was adjusted to get stable mode-locking. For slow reversed biased semiconductor absorbers with a time constant around 10ps we can reproduce the experimentally observed pulse-width limit of $\approx 1-2$ps.

Figure 2.5: Simulated pulse width versus gain bandwidth for MLLDs with two different absorber recovery times.
However a reduction of the absorber recovery time down to 2ps will lead to pulse width in the 100fs regime. Whereas for such short pulses the simplification of neglecting the spectral hole burning is not valid anymore, the pulse widths for commonly experimentally observed bandwidths at of approximately 30nm are still in the valid regime around 400fs. For broader gain width the spectral hole burning is supposed to split up the mode locked spectra into two separately mode-locked sections leading to a pulse break up or double pulsing as stated by Xing and Avrutin in [53]. When this mode spectrum separation will occur and how it can be avoided is still under investigation.

2.3 State-of-the-Art for MLLDs

As already mentioned the 'pulse-width barrier' around 2ps was observed in several experiments and is confirmed by our time-domain simulation tool for conventional slow absorbers with recovery times of approximately 10ps. Several different approaches were proposed and realized for MLLDs since the first monolithic mode locked laser diode was presented in 1990 by S. Sanders and co-workers [62]. Comprehensive reviews are given in [40, 59, 63].

Tab. 2.1 gives an overview of the results published from 1996 to 2006. The table presents the data of:

1. the used structures
2. the gain material
3. the mode-locking mode
4. the repetition rate
5. the observed pulse width
6. the time bandwidth product TBP
7. the energy of the pulses

We focused the summary on monolithic integrated mode locked laser diodes. For comparison, the last two rows show the data from external-cavity mode-locked laser diodes to demonstrate the performance of the semiconductor absorber and gain material for an other cavity implementation. To provide a structure to the table the repetition rate of the
MLLDs increases from top to bottom. For monolithic integration of an absorber structure, a short section of the laser is usually reversed biased, separated by the gain structure with a short channel etched into the highly doped cap contact layer. Monolithic integrated laser diodes exhibit repetition frequencies from less than 10 GHz to several hundreds of GHz [40] and even up to the THz regime [64, 65] by using so called compound-cavity mode locking (CCML). For CCML the laser cavity is separated into two sub-cavities by an internal reflection. The laser will under certain conditions mode-lock at a repetition rate which is determined by one of the sub-cavities round-trip time. The second sub-cavity delivers the required gain to reach laser threshold. However pulse widths of reported MLLDs with repetition rates used in actual optical networks (10-40 GHz) are limited around 1-2 ps and are suffering from small mode locking ranges with respect to pumping current and reverse bias [59, 40].

MLLDs with repetition rates up to 40 GHz are mainly hybrid mode-locked to demonstrate the feasibility of locking and synchronize the laser to an external clock, which is mandatory for application as a pulse source for high speed optical networks. For higher repetition rates, only passive mode locking is possible because external electrical modulators did not reach this frequency range so far. A weak correlation between higher repetition rates and shorter pulses can be identified in Tab. 2.1.

To reduce the SPM effects and also the threshold current needed for long current pumped active cavities, several integration technique for extended passive cavities were demonstrated. For example selective-area growth has been demonstrated [37] and first MLLDs based on this technique have been commercialized [26]. Recently extensive work has been published using quantum well intermixing for passive waveguide extension [66]. These devices however offer a reduced degree of freedom compared to the butt-coupled regrowth technique for the individual design of the different sections.
### Table 2.1: State of the art for monolithic integrated mode locked laser diodes

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Struct.</th>
<th>Gainmat.</th>
<th>Modul.</th>
<th>Reprate</th>
<th>( \tau_{FA} )</th>
<th>TBI (^a)</th>
<th>( E_{PD} )</th>
<th>( f_{PD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[69]</td>
<td>AVV</td>
<td>MQW, InGaAs/InGaAsP</td>
<td>CPM, passive</td>
<td>40 GHz</td>
<td>3.5 ps</td>
<td>0.62</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>[69]</td>
<td>AVV</td>
<td>MQW, from IQE 1550</td>
<td>CPM, hybrid</td>
<td>10 GHz</td>
<td>9 ps</td>
<td>2.1</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>[53]</td>
<td>AV</td>
<td>InGaAs QD</td>
<td>passive</td>
<td>18 GHz</td>
<td>10 ps</td>
<td>Fourier limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[53]</td>
<td>AV</td>
<td>InGaAs QD 1300 nm</td>
<td>passive</td>
<td>21 GHz</td>
<td>2 ps-39 fs</td>
<td>1</td>
<td>1.2-2 ps</td>
<td></td>
</tr>
<tr>
<td>[70]</td>
<td>AVP</td>
<td>InGaAs QD 1300 nm</td>
<td>passive</td>
<td>25 GHz</td>
<td>1.7 ps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[71]</td>
<td>AVV</td>
<td>MQW, from IQE 1550</td>
<td>CPM, passive</td>
<td>40 GHz</td>
<td>6.4 ps</td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[72]</td>
<td>DBR P V P/VA</td>
<td>MQW, 1325 nm</td>
<td>passive</td>
<td>10-40 GHz</td>
<td>1 ps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[73]</td>
<td>VFA</td>
<td>MQW, InGaAsQD</td>
<td>Hybrid</td>
<td>43.5 GHz</td>
<td>4.3 ps</td>
<td>C:0.87 ps</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>[74-75]</td>
<td>VAV</td>
<td>MQW, 1550 nm</td>
<td>hybrid</td>
<td>40 GHz</td>
<td>2.8 ps</td>
<td>0.4</td>
<td>180 fl</td>
<td></td>
</tr>
<tr>
<td>[76]</td>
<td>VAV</td>
<td>MQW, 1550 nm</td>
<td>hybrid</td>
<td>40 GHz</td>
<td>2 ps</td>
<td>0.5</td>
<td>25 J</td>
<td></td>
</tr>
<tr>
<td>[77]</td>
<td>VAV</td>
<td>MQW, InGaAs/InGaAsP</td>
<td>CPM, passive</td>
<td>40/50/60 GHz</td>
<td>1.1/0.94/ ps</td>
<td>0.34/0.31/ ps</td>
<td>30 fs</td>
<td></td>
</tr>
<tr>
<td>[78]</td>
<td>VAV</td>
<td>MQW, 1560 nm</td>
<td>CPM, passive</td>
<td>104 GHz</td>
<td>2.8 ps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[79]</td>
<td>VPAV</td>
<td>MQW, InGaAsQD</td>
<td>CPM, passive</td>
<td>115 GHz</td>
<td>0.64 ps</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[80]</td>
<td>FPLaser</td>
<td>MQW, 1550 nm</td>
<td>passive</td>
<td>133 GHz</td>
<td>0.31 ps</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[81]</td>
<td>DBR VEA</td>
<td>MQW, 1550 nm</td>
<td>active (90 GHz)</td>
<td>160 GHz</td>
<td>3.05 ps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[82]</td>
<td>VAV</td>
<td>MQW, InGaAsP</td>
<td>passive</td>
<td>480 GHz</td>
<td>0.52 ps</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[83]</td>
<td>AVV PDBR</td>
<td>MQW, InGaAs/InGaAsP</td>
<td>harmonic</td>
<td>500 GHz-1.5 THz</td>
<td>580 fs</td>
<td>Fourier limit</td>
<td>30 fs</td>
<td></td>
</tr>
<tr>
<td>[84]</td>
<td>Extern/Grating</td>
<td>Hitachi HLP 5450</td>
<td>Passive</td>
<td>1-14 GHz</td>
<td>C:150 fs-17 ps</td>
<td></td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>[85]</td>
<td>VECSPR</td>
<td>MQW, 1040 nm</td>
<td>passive SESAM</td>
<td>1.21 GHz</td>
<td>477 fs</td>
<td>0.586</td>
<td>88 fs</td>
<td></td>
</tr>
</tbody>
</table>

\( f_{PD} \): Peak frequency, \( E_{PD} \): Peak power density, \( \tau_{FA} \): Full width at half maximum, TBI: Time Bandwidth Index, \( \tau \): Relaxation time, QD: Quantum dot, CPM: Continuously mode-locked, DBR: Distributed Bragg reflector, HR: High reflection coating, B: Bulk.
In order to reduce the chirp of the pulses due to unbalanced linewidth enhancement factors of the gain and absorber sections, DBR-mirrors were incorporated into the cavity [67, 72, 76, 65, 81]. With this method the pulse chirp was effectively decreased by bandwidth limitation and Fourier-limited pulses were achieved. But the artificial decrease in bandwidth prohibits the generation of shorter pulse width.

A variety of materials such as bulk [79, 84], quantum well, and quantum dot [69, 55] were used for MLLDs to obtain emission at the telecommunication wavelengths of 1300nm and 1550nm. Caused by interstate relaxation quantum dot based materials (QD) show very fast absorber recovery times around 1 ps [85] and due to the low cross section a low absorber saturation energy [86]. Furthermore QD gain sections can provide very broad spectral width (~100nm [87]) and low linewidth enhancement factors [88]. These properties favor the QD-material to be used in MLLDs. Two sections GaAs-based QD laser diodes with a simple reversed biased gain section as an absorber and a high reflection coating at the absorber side to enhance the absorption demonstrated 393fs wide Fourier limited pulses with 25mW average output power [55]. On the other hand, Other groups are only reporting of optimized pulse width of for QD MLLDs of 890fs [89]. The main drawbacks so far are the relatively low gain which prevents the realization of repetition rates higher than 20GHz requiring shorter laser cavities. Further theoretical and experimental investigations will are necessary to understand the QD-laser performance in more detail.

For mode-locked laser diodes mainly quantum well material has been employed. This is also the case for this work. Compared to bulk semicon-
ductor, quantum wells offer several advantages which will be discussed later in chapter 3.

The most obvious difference between monolithically-integrated laser diodes and external cavity mode-locked laser diodes is the achieved pulse energy. External cavities do not suffer from two photon absorption which limits the pulse energy in our semiconductor waveguides below 1pJ [84]. An other advantage of external cavities is the availability of different mode profile cross sections in the cavity. So the absorber can be placed in the cavity at the position of minimal beam profile. This confined mode profile results in an decreased cross section and therefor in a lower saturation energy. This effect will increase the ratio of the saturation energies and hence facilitate the mode-locking process. These two effects could explain why external cavity lasers have less problems to saturate the absorber and provide more stable pulse trains with nearly Fourier-
limited pulses. To reach pulse widths below 1 ps these lasers also require a fast absorber. For example Garnache and co-workers [54] used a special semiconductor absorber structure, which takes advantage of fast surface states.

2.4 MLLD Practical Realization

Summarizing the findings presented in the previous sections for the different structures of a MLLD we conclude that the ideal structures have to fulfill the following criteria:

- **gain material**
  - short gain section length to prevent SPM, additional noise and high pumping currents
  - low linewidth enhancement factor for low chirped pulses
  - high saturation energy in comparison to the saturation energy of the absorber for the desired modulation interplay with the absorber structure

- **absorber structure**
  - low saturation energy for the preferable total gain dynamics
  - fast recovery time to assist for short pulse formation and to overcome the limitations due to gain saturation

- **passive waveguide section**
  - low loss to avoid additional noise from high pumping currents

The different requirements for the MLLDs gain and absorber sections are inconsistent with each other. For the gain we need a high saturation energy and a carrier capture time $τ_{\text{cap}}$ exceeding the optical transition time constant in the order of ns to favor the stimulated emission process. On the other hand for the absorber a low saturation energy and a fast sweep-out time $τ_{\text{sweep}}$ are required. Even though the absorber and gain have different bias conditions, it is difficult to realize the opposite requirements for $τ_{\text{cap}}$ and $τ_{\text{sweep}}$ with the same bandgap engineering. We thus decided to use the butt-coupled regrowth technique to combine separately optimized gain and absorber structures together with a passive waveguide whenever the cavity length needs to be extended for low
(<10GHz) repetition rates.

The insertion of an additional structural interface due to the butt-coupling regrowth between the gain and absorber section forces us to consider possible reflections. For external cavity laser diodes this problem is common and high performance anti-reflection coatings are requested. An upper limit for the internal reflection (Fig. 2.2a)) of $R_{\text{int}} < 10^{-5}$ was found by simulations [33] to avoid multiple pulse formation for gain modulated external cavity lasers without an absorber structure.

Derickson and co-workers [90] used a reversed biased saturable absorber section of the laser diode for passive mode-locking and to suppress these internal reflections. They report good mode-locking up to $R_{\text{int}} < 10^{-3}$. Thus the secondary pulses are effectively suppressed by the saturable absorber.

Let us consider now the case of monolithic integrated MLLDs. Fig. 2.6 illustrates the two possible reflections at the gain-absorber section interface. As already mentioned in Chap. 1 Kwakernaak claimed in his internal report [57] that the separation of the absorber structure by a butt-coupled interface prohibits single pulse mode-locking. This is in contradiction to the before mentioned results and the fact that reflections at butt-coupled interfaces as low as $10^{-6}$ were reported [29]. This reflection coefficient is an order of magnitude smaller than the limit of $10^{-5}$ for good mode-locking for external cavities without an absorber structure. The high sensitivity on the internal reflection coefficient of the

![Figure 2.6: Realized MLLD with different layer structures for absorber gain and passive waveguide](image)

absorber section can be explained as follows. The main pulse is traveling through the whole structure, being amplified and absorbed in the gain and absorber sections, respectively. One part of the pulse, traveling to
the left in Fig. 2.6 will be back reflected into the absorber. Considering a typical absorber length around 50µm and a pulse length of 100µm corresponding to a 1 ps long pulse, the absorber is still saturated when the pulse is back reflected into the absorber. Thus this secondary pulse is out-coupled at the right hand side facet without further absorption. The energy of this secondary pulse is directly proportional to the internal reflection value.

If the main pulse in the cavity is traveling to the right in Fig. 2.6 one part of the pulse will be back reflected in the gain section. The amplitude of the reflected pulse will be enhanced in comparison to the non-reflected main pulse due to the absorption of the main pulse in the absorber. On the other hand we still expect a reduction of the satellite pulses due to the internal reflections by the absorber.

Even though our model can not simulate the exact interference behavior of the carrier frequency due to the internal cavity we modified our model to simulate internal reflections of the amplitude [91]. We found a upper limit of $10^{-4}$ for the internal reflection to prohibit multiple pulse formation [31]. So the value of $10^{-5}$ is a conservative estimate of the allowed internal reflection maximum to provide mode-locking.

To get a better understanding of the influence of the internal cavity reflections on the mode-locking performance we therefore decided to investigate the butt-coupled interface in detail to minimize the internal reflections. These optimized interfaces were then applied for monolithic integrated MLLDs. Single pulse mode locking was demonstrated for internal reflection coefficients of $\approx 10^{-5}$ (Chap. 5).

Besides the all-active geometry shown in Fig. 2.6 we investigated two geometries with passive waveguide extended cavities (Fig. 2.7). The geometry in Fig. 2.7a has advantages from a process technology point of view, as both active sections are separated by a passive section and are thus electrically isolated, the geometry in Fig. 2.7b could be advantageous to reduce the secondary pulses, because the still saturated gain will not amplify the back reflected part of the pulse.

### 2.5 Fast Absorber Structure

In the previous section, we have shown that the practical realization of monolithically integrated MLLDs requires a subtle control of the reflections at the interfaces of the different structures.
2.5. Fast Absorber Structure

Whereas the gain section is described in detail in the next chapter we will shortly present in the following the fast absorber structure we selected to achieve sub-ps pulse widths. Details of the design can be found in [31].

As shown in Fig. 2.5, an absorber recovery time of 2ps is sufficient to create sub-ps optical pulses from MLLDs. The absorber recovery time for commonly used MLLDs absorbers is limited by the slow diffusion of the holes out of the absorbing layer [84]. To obtain a faster absorber recovery time we proposed a uni traveling carrier (UTC) structure which was initially developed to realize ultrafast photo-detectors [92]. The UTC principle becomes obvious from the band diagram under reverse bias shown in Fig. 2.8. The key elements are the 50nm thick p-doped InGaAsP absorbing layer and the 170nm thick collecting layer for the fast photo-electrons. The photon generated electrons undergo a uni-directional drift diffusion process towards the n-doped InP cladding layer. The p-doped InP cladding on the left hand side works as an electron blocking layer due to the conduction band offset of $\Delta E_c \approx 0.25$eV between the p-doped InP and p-doped InGaAsP layers. This band-offset prohibits the diffusion of electrons to the “wrong” p-cladding contact which would result in a longer electron extraction time. The usually much slower hole drift-diffusion process is circumvented by the p-doping such that the holes are majority carriers. As a majority carrier the hole dynamics is governed by the fast dielectric relaxation process ($\sim 100$fs @ $p=10^{17}$cm$^{-3}$). Considering a saturated electron velocity of $v_e \approx 4 \times 10^7$ cm/s [93] we can...
estimate the electron transit time to be \( \sim 0.5\text{ps} \). Hence the absorption recovery time must be of the same order or even less. Fig. 2.9 shows the measured absorber recovery time with a pump-probe setup. Whereas for zero V bias the absorber recovery time is comparable to conventionally used reverse biased gain sections, a reverse bias of 2V results in a sufficiently fast recovery time of 2ps.

As mentioned previously, the saturation energy is an important parameter for mode-locking. For the material we measured a saturation energy of \( \sim 1\mu\text{J}/\mu\text{m}^2 \) [94]. Fig. 2.10 presents the saturation energy measurements for a 70\( \mu\text{m} \)-long UTC waveguide absorber. From these experiments we can deduce a saturation energy \( E_{\text{sat}} \) around 1pJ and a wavelength dependence of the transmission. Therefore the saturation energy of the gain section has to exceed 5pJ and the emission wavelength of the gain section has to match to the UTC bandgap as a further requirement.

### 2.6 Conclusion

To conclude we have identified design strategies for the amplifier and absorber section of the monolithically-integrated MLLD. The gain struc-
Figure 2.9: Pump-probe measured UTC-absorber recovery-time for different reverse bias voltages [31].

The UTC-structure is proposed to be integrated in a butt-coupled process for monolithically integrated MLLDs. A saturation energy of 1pJ and a recovery time of 2ps were measured. According to the time domain simulations such a short recovery time is sufficient for optical pulses generation in the sub-ps regime with MLLDs. The requirement to optimize the contradictory specifications for the gain and absorber sections independently compels us to use a butt-coupled regrowth process as the best available technology for monolithic MLLDs despite of its considerable complexity. The additional integration of the absorber leads to internal reflections. Our time-domain modelling results in a required internal intensity reflection below $10^{-4}$ and from other publications we can deduce a conservative estimate below $10^{-5}$.

In the next chapter we present the choice, trade-offs and characteristics of the gain material followed by a detailed process description in chapter 4. In chapter 5 the experimental results of processed MLLDs and the influence of the internal reflections are presented.
Figure 2.10: UTC absorber saturation for a 70μm long waveguide absorber for different wavelengths [31].
Chapter 3

Multiple quantum well gain material

3.1 Introduction

The main requirement for the gain section of a MLLD is to provide sufficient amplification to overcome the losses introduced by the absorber section, the out coupling losses at the mirror facets, the internal waveguide scattering, and the losses at the butt-coupled interfaces. The unsaturated absorber losses lead to a transmission of ≈30% [57, 95]. The output coupling for uncoated cleaved facets for InP laser diodes is given by the reflection coefficient R≈30% for the semiconductor air interface. For butt coupled interfaces an intensity transmission loss of 6% was reported [29]. The internal waveguide losses are typically 15 cm⁻¹ for a rib waveguide structure as used in this project [84]. Considering all these numbers we get for a 1mm long 40GHz MLLD a threshold gain gth of the amplifier section of ~6dB, which has to be provided by the gain section. To fulfill the requirements described in the previous chapter for the gain material of mode-locked laser diodes, quantum wells offer several advantages over bulk material due to their specific properties and additional design parameters. For example the higher T0 value implies a lower temperature dependence of the threshold gain, which means that higher pumping currents can be applied [96].

One important pulse broadening mechanism in MLLDs is based on self-
phase modulation (SPM) in the gain section. SPM is caused by the correlation of the refractive index and the gain described by the so-called linewidth enhancement factor ($\alpha$-factor). The correlation between the index change and the gain is due to the refractive index changes caused by carrier density changes which will also alter the gain. The $\alpha$-factor is intrinsically lower in QW material [97] because of the smaller active volume which generates gain and carrier density changes. Hence the pulse broadening due to SPM is smaller for MLLDs with QW gain sections.

Furthermore, the saturation energy of the gain section is a very important characteristic for MLLDs for two main reasons. First, the saturation energies of the gain has to be larger than the saturation energy of the absorber structure to ensure the absorber saturation before the gain saturation. This is necessary to open a net gain window as explained in Chap. 2 and we found a good mode-locking behavior for a ratio $s = E_{\text{sat}}^{\text{gain}} / E_{\text{sat}}^{\text{abs}}$ larger than 5. Second, the main pulse broadening mechanism in MLLDs is due to gain saturation [39]. Therefore a high saturation energy for the gain will limit the pulse broadening and shorter pulses can be achieved.

The saturation energy of the gain section can be expressed by Eq. 3.1 [39]:

$$E_{\text{sat}} = \frac{\hbar \omega \sigma}{a \Gamma}$$

where $\hbar \omega$ is the photon energy, $\sigma$ is the cross-section of the active area, $a$ is the differential gain, and $\Gamma$ is the optical confinement factor. Since the geometric factors $\sigma$ and $\Gamma$ mainly scale in the same way, the difference in the saturation energy is mainly due to the differential gain and hence the carrier density in the gain section.

In comparison to bulk active layers the differential gain is higher for QW at threshold but decreases considerably at high carrier densities below the value of bulk material [98] due to the density of state characteristics. To get a high saturation energy in the gain section we therefore need a small differential gain and hence a high carrier density. The high carrier density can be achieved by using a short gain section in a cavity extended by a passive waveguide or by using fewer quantum wells. Thus MQW material provides an additional degree of freedom in the design for the gain material. The reduced-length solution was mainly chosen for MLLDs with long cavities and repetition rates of 10 GHz [57, 99, 100] whereas the latter solution was demonstrated by [95, 101] for shorter MLLDs with repetition rates of 40 GHz.

Compared to bulk material, quantum wells are also suited to obtain
3.2. Optical Gain in Quantum Wells

To verify that the gain section features the desired properties and to design the number of quantum wells we present in the following the used QW gain model in more detail. The optical gain of the quantum well structures investigated in this work is calculated with the GEBAS software which is part of the commercial technology CAD program package.
DESSIS$^M$ to simulate semiconductor structures [103]. The working principle will be explained in the following. A rigorous treatment of the subject can be found in [104, 105].

GEBAS uses the so-called self-consistent semi-classical approximation to calculate the interaction of the electro-magnetic light field $\vec{E}(\vec{r}, t)$ with the semiconductor material. The material properties are described quantum-mechanically whereas the light field is described by the classical Maxwell equations. The light field induces microscopic electric dipoles $\vec{p}_i$ by carrier separation. The summation over all these microscopic dipoles yields a macroscopic polarization $\vec{P}(\vec{r}, t)$. The polarization itself interacts with the light field resulting in absorption or amplification (Fig. 3.1).

\begin{equation}
\vec{E}(\vec{r}, t) \xrightarrow{\text{quantum mechanics}} \vec{p}_i \xrightarrow{\text{statistical summation}} \vec{P}(\vec{r}, t) \xrightarrow{\text{Maxwell equation}} \vec{E}'(\vec{r}, t)
\end{equation}

**Figure 3.1:** Principle of the self-consistent semi-classical theory

As already described in Chap. 2 the Maxwell equations for a polarizable medium can be written as:

\begin{equation}
-\nabla^2 \vec{E}(\vec{r}, t) + \left( \frac{1}{c^2} \right) \frac{\partial^2 \vec{E}(\vec{r}, t)}{\partial t^2} = -\mu_0 \mu_r \frac{\partial^2 \vec{P}(\vec{r}, t)}{\partial t^2}
\end{equation}

where $c$ is the speed of light in vacuum and $\mu_0$ is the permeability of the vacuum which is equal to the permeability in semiconductor structures for laser diodes hence $\mu_r=1$.

The electro-magnetic field in the waveguide can be approximated by a plane wave traveling in the $z$-direction with amplitude $E(z)$ and phase $\phi(z)$. Considering the relation between the field amplitude $E(z)$ and the polarization amplitude $P(z)$:

\begin{equation}
P(z) = \varepsilon \chi(z) E(z)
\end{equation}

in which $\varepsilon$ is the material permittivity of the semiconductor, and $\chi$ the material susceptibility. We can deduce from Eq. 3.2 the following expres-
3.2. Optical Gain in Quantum Wells

Solutions for the amplitude $E(z)$ and the phase $\phi(z)$:

$$\frac{dE(z)}{dz} = -\frac{\omega n}{2c} \chi''(z) E(z) \quad (3.4)$$

$$\frac{d\phi(z)}{dz} = -\frac{\omega n}{2c} \chi'(z)$$

where $\chi'(z)$ and $\chi''(z)$ are the real and imaginary parts of $\chi(z)$, respectively. $\omega$ is the oscillation frequency of the electro-magnetic field. This equation leads to the local amplitude gain $g$:

$$g = \frac{\omega n}{2c} \chi''(z) \quad (3.5)$$

which is related to the usually used intensity gain by a factor of 2. Thus to determine the optical gain $g$ we need to calculate the susceptibility $\chi$ by the evaluation of the macroscopic polarization $P$ using quantum mechanics.

As a first step a description of the band structure structure is required. To solve the Schrödinger equation for the crystal structure several approximations have to be applied. First of all, the Bloch theorem states that for a crystal with a lattice constant $R$ the quantum mechanical wave-functions $\Psi_{n,k}(r)$ for a band $n$ and a wave-vector $k$ are periodic with $R$ and can be written as:

$$\Psi_{n,k}(r) = u_{n,k}(r) e^{i k \cdot r}. \quad (3.6)$$

Substituting Eq. 3.6 equation into the time independent Schrödinger equation results in the following equation for $u_{n,k}(r)$:

$$\left( \frac{p^2}{2m_0} + V_0 + \frac{\hbar}{m_0} \vec{k} \cdot \vec{p} \right) u_{n,k}(r) = (E_{nk} - \frac{\hbar^2 k^2}{2m_0}) u_{n,k}(r) \quad (3.7)$$

where $m_0$ is the electron mass, $V_0$ is the crystal potential, and $p$ is the electron momentum. The states of interest for optical gain calculations are around the conduction-band minimum and the valence-band maximum ($\Gamma$-point) for direct bandgap material such as InGaAsP. Hence they have $k$ values in the vicinity of $k = 0$. Therefore we can expand Eq. 3.7 around $k = 0$. Since the Hamiltonian includes a perturbation term with the product $\vec{k} \cdot \vec{p}$, this method is called kp-method. Because of the high symmetry at the $\Gamma$-point the wave-functions can be
expressed in series of the hydrogen atom s- and p-functions. Taking into account the coupling of the different number of bands the Hamiltonian can be presented by a 4x4-matrix or an 8x8 matrix. Whereas the 4x4 matrix only considers the valence band coupling, the 8x8 matrix also includes the coupling of the valence bands with the conduction bands. Luttinger and Kohn derived the matrices for both cases [106].

For a quantum-well structure we can separate the confined coordinate (e.g. $k_z$) from the other two unconfined ones ($k_x, k_y$).

As an example Fig. 3.2 shows a calculated band structure with 8x8 kp-method for a 7.5nm thick In$_{0.53}$Ga$_{0.47}$As quantum well with Q1.2 barriers corresponding to a transition energy of 1.55μm.

![Figure 3.2](image_url)

Figure 3.2: Band structure for a 7.5nm thick In$_{0.53}$Ga$_{0.47}$As quantum well in In$_{0.76}$Ga$_{0.22}$As$_{0.48}$P$_{0.52}$ (Q1.2) barriers ($k_\perp = (k_z^2 + k_y^2)^{1/2}$).

The discrete energy steps of the separated z-direction are also included in this calculation and they are visible as a slight energy offset.
3.2. Optical Gain in Quantum Wells

below 0eV for $k_{\perp} = \sqrt{k_x^2 + k_y^2} = 0$ of the valence bands. The transition energy $h\nu$ as indicated with the arrow in Fig. 3.2 depends on the quantum-well thickness and the barrier composition.

The System Hamiltonian $H$ describes the interaction of the light fields and the electrons in the semiconductor band potential [105]. To calculate the expectation values of the microscopic polarization $\vec{p}_i$ the Heisenberg equation of motion has to be solved [107]:

$$i\hbar \frac{\partial}{\partial t} \vec{p}_i = [\vec{p}_i, H]$$

(3.8)

where the right hand side stands for the commutator of $\vec{p}_i$ and $H$. The Hamiltonian can be approximated up to different degrees of accuracy. The simplest approximation is the so-called free electron approximation which treats the electrons and holes as free particles in the potential of the band structure. The multiple particle scattering effects are subsequently included by a line-width broadening function which has to be convoluted with the gain function.

The GEBAS software uses a more advanced technique by considering the many-body effects quantum mechanically within the second born approximation. The Hamiltonian contains several products of single particle operators. The Heisenberg equation of motion then couples these operators two products of four operators. The Heisenberg equation for these four operator products results in expectation values for products of six operators and so forth. Thus the solution will be a hierarchy of equations, where each succeeding equation includes products of operators which number succeeds the forgoing. The second Born approximation truncates this infinite number of equations up to expectation values with products of four operators. The truncation is somehow arbitrary assuming that the interaction of more and more particles (hence operators) is weaker and weaker. The resulting equations describe quantum mechanically the many-body effects which manifest themselves as plasma screening, bandgap renormalization, interband Coulomb attraction, and carrier-carrier scattering.

The summation of the $p_k$ weighted by the quantum-mechanically computed dipole elements $\mu_k$ over the whole k-space and divided by the volume $V$ results in the macroscopic polarization $P(z, t)$.

$$P(z, t) = \frac{1}{V} \sum_k \mu_k p_k$$

(3.9)

Finally $\chi$ can be calculated by inserting Eq. 3.9 into Eq. 3.3. A detailed
description of all the calculations together with the numerical implementation is described in [108].

Gebas requires the following parameters to run a simulation:

- the mole fraction of the In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material for the used well and barrier materials

- the well and barrier thicknesses

- a so called Gauss parameter to account for quantum well thickness variations

- the grid size for the finite element grid.

Furthermore the start and end point as well as the resolution of the desired frequency, temperature and carrier density sweep has to be defined. Gebas calculates the material parameters from the mole fractions by interpolation of the published results of binary compounds as is presented by J. Piprek [109]. The Gauss parameter is usually in the range between 10 and 30 meV.

For a first comparison of theory and experiment we derive a relation ship between the calculated transition energy ($\lambda_{trans}$) and the photoluminescence(PL)-peak wavelength $\lambda_{PL}$. The excitation power of the PL-mapper of $\approx 10\text{mW}$ and the excitation beam focus of $\approx 1\text{mm}^2$ results in a relatively low average carrier concentration of $\approx 10^{11}\text{cm}^{-2}$. Therefore we expect that the $\lambda_{PL}$ is a good measure of $\lambda_{trans}$. We investigated the QW thickness dependence of InGaAs wells with two different thicknesses in Q1.28 barriers. For this purpose we measured the photoluminescence (PL) peak of the grown quantum wells and compared the associated thickness with the QW thickness measured from transmission electron microscope (TEM) micrographs (Fig. 3.3).
3.2. Optical Gain in Quantum Wells

Figure 3.3: TEM micrograph of a grown multiple quantum well structure.

Fig. 3.4 shows the comparison of the calculated transition energies (GEBAS) and the PL-peaks as a function of the QW thickness.

Figure 3.4: Transition energy - photoluminescence peak as a function of calculated - TEM measured QW width respectively.
The two measured QW-widths show only a slight red shift of 1-2 nm. So we can conclude that the photoluminescence peak is a good measure of the transition energy and we deduce a QW width of ≈7 nm to get a transition energy at the desired 1.55 μm. As will be explained in Sec. 3.4 this MQW design leads to a low carrier confinement and hence a low characteristic temperature and low quantum efficiencies. Thus we changed the barrier material to Q1.2 to obtain a deeper QW with a better carrier confinement. Since the emission wavelength have to be further on at 1.55 μm the wells must be ≈8 nm thick with Q1.2 barriers.

3.3 Gain measurements

In order to verify the GEBAS calculations and to extract the parameter for a gain model for the design of our gain structure we measured the optical gain of a transverse single mode Fabry-Perot laser containing three quantum wells in the active region. Since we did not know beforehand how the quantum well structure will behave under a multiple regrowth process, we started our investigations with conventional unstrained In0.53Ga0.47As quantum wells separated by 12 nm thick In0.71Ga0.29As0.45P0.55 barriers to avoid quantum well coupling. For such a structure we can resort to many investigations about its performance and the behavior under thermal heating [110]. Furthermore we avoid the time consuming development of a strained material growth process.

Hakki and Paoli proposed a method [111, 112] to evaluate the material gain from the emitted optical spectrum below lasing threshold. By considering the infinite number of round trips of the optical field in a Fabry-Perot cavity with gain, Hakki and Paoli derived a relationship between the adjacent maxima $P_{\text{max}}$ and minima $P_{\text{min}}$ of cavity modes in the output spectrum, the single-pass gain $G$ and the reflection $R$ of the cavity-mirrors:

$$\frac{P_{\text{max}}}{P_{\text{min}}} = \frac{(1 + RG)^2}{(1 - RG)^2}$$

The experimental setup for these measurements consist of the Fabry-Perot laser under test, which is pumped with a current $I_{\text{pump}}$, a single mode anti-reflection coated lensed fiber to collect the out-coupled light, and an optical spectrum analyzer (OSA) (Fig. 3.5).
3.3. Gain measurements

Other reported Hakki Paoli setups uses a polarization filter to separate the TE (electrical field in the quantum well plane) and TM gain [113]. However we claim that this filter will not reveal the polarization dependent material gain. Indeed, either the optical mode in the cavity is TE (respectively TM) polarized and hence we would not expect any TM (respectively TE)-gain visible in the emitted light, or the optical mode is a mixture of both polarizations. In the latter case however we have to identify the real angle $\Theta$ of the polarization and to deal with the gain cross talk of the material between the polarizations to separate the TE and TM gains.

For our structures a detailed theoretical optical field analysis [114] revealed that the propagating optical mode is 99.9% TE-polarized. Furthermore the calculated TM gain is small for unstrained InGaAs QWs. These results were confirmed by measuring the polarization of the out-coupled light of a Fabry-Perot laser diode. Below lasing threshold the TM-polarized component of the field was below the sensitivity of the power meter. Above lasing threshold a ratio of 30dB between TE- and TM-polarized outputs was observed. Hence it is safe to omit the polarizer in the setup.

Fig. 3.6 shows a measured spectrum of a 500$\mu$m long Fabry-Perot laser, displaying very clearly the minima and maxima in the spectrum. To assure single transverse mode operation of the laser a 2.5$\mu$m wide and 1.3$\mu$m deep ridge waveguide was used.
Figure 3.6: Measured optical spectrum of a 500μm-long single transverse mode Fabry-Perot laser diode pumped with a current of 30mA. bottom: wide scan, top: detail to demonstrate $P_{\text{max}}$ and $P_{\text{min}}$

The single pass gain $G = \exp(g_n L)$ depends on the modal gain $g_N$ and the length $L$ of the cavity. Inserting this expression into Eq. 3.10 and solving for the modal gain we get:

$$g_n = \frac{1}{L} \ln \left( \frac{\sqrt{V} - 1}{\sqrt{V} + 1} \right) + \frac{1}{L} \ln \frac{1}{R}$$

(3.11)

where $V = \frac{P_{\text{max}}}{P_{\text{min}}}$ is also called the residual gain ripple.

The net modal gain can be expressed as a function of the material gain
3.3. Gain measurements

$g_m$, the optical confinement factor $\Gamma$, and the internal waveguide propagation loss $\alpha_W$:

$$g_m = \Gamma g_m - \alpha_W$$

(3.12)

Hence we can derive the following expression for the material gain $g_m$:

$$g_m = \frac{1}{\Gamma} \left( \frac{1}{L} \ln \left( \frac{\sqrt{\nu} - 1}{\sqrt{\nu} + 1} \right) + \alpha_W + \alpha_M \right)$$

(3.13)

where $\alpha_M = \frac{1}{L} \ln \frac{1}{R}$ is the mirror loss. Furthermore we have to determine several geometric and loss parameters of the laser to extract the material gain from the measured intensity ratios. The length $L$ can be measured with a calibrated microscope.

If an uncoated straight-cleaved laser is used, the reflection coefficient can be deduced from the same spectral measurement. Indeed the distance $\Delta \lambda$ between two maxima is given by:

$$\Delta \lambda = \frac{\lambda^2}{2n_{eff}L}$$

(3.14)

Thus we can compute the effective index $n_{eff}$ from the spectrum and calculate the reflection of the untreated output facets using the Fresnel equation:

$$R = \left( \frac{n_{eff} - 1}{n_{eff} + 1} \right)^2$$

(3.15)

by approximating the refractive index of air as 1. For the spectrum shown in Fig. 3.6 we deduce a value of $R = 0.314 \pm 0.001$.

So far we can compute the net modal gain $g_n$ out of the spectral measurements. Fig. 3.7 shows the net modal gain for a 500 $\mu$m long Fabry-Perot laser diode with pumping currents from $I_{pump} = 13$ mA up to 37 mA in steps of 1 mA.
To determine the material gain we need to know the optical confinement factor $\Gamma$. With the finite elements-program LUMI, which is also part of the DESSIS program package, the confinement factor was computed to be $\Gamma=0.0387$. Furthermore, as was shown in Eq. 3.12 the net modal gain is expressed as the material gain multiplied by the $\Gamma$-factor minus the waveguide losses. Therefore, plotting the peak net modal gain against the pumping current and fitting the measured data for unsaturated gain with a linear regression, the intersection of the fitted line with the gain axis for zero pumping current reveals the waveguide losses as is indicated in Fig. 3.8.
3.3. Gain measurements

Figure 3.8: Net peak modal gain versus pumping current. Near threshold the gain saturates and is clamped at a value of $23 \text{ cm}^{-1}$, corresponding to the mirror losses $\alpha_M$.

For pump currents below 23mA the gain current curve is linear (unsaturated gain) and follows the function:

$$g_n(\lambda_{\text{peak}}) = \Gamma g_m(\lambda_{\text{peak}}) - \alpha_W$$

(3.16)

Thus we can extract a waveguide loss $\alpha_W$ of $(16.0 \pm 0.1) \text{ cm}^{-1}$ for $I_{\text{pump}}=0\text{mA}$. Finally the material gain is theoretically calculated as explained in the previous section and the peak gain is fitted with the GEBAS software as shown in Fig. 3.9 by adjusting the carrier density $N$. The Gauss parameter is chosen as 20meV to better fit the spectral gain width.
Figure 3.9: Material gain measurements and simulation results for three 7.5\text{nm} thick InGaAs quantum wells with Q1.2 barriers with pumping currents of 13, 14, 15, 16, 18, 19 and 21 mA and carrier densities of 3.03, 3.10, 3.15, 3.20, 3.30, 3.33, 3.42 \times 10^{18}\text{cm}^{-3}.

The relation between \( N \) and \( I \) can be used to calculate the carrier life time \( \tau = N/I \) in the laser. For the values given in the caption of Fig. 3.9 we calculate a carrier dependent life time between 1ns and 2ns which is a usually observed carrier life time in InGaAsP material lasers [115]. With the below threshold parameter extraction we can extrapolate with Gebas the gain also for higher current densities above threshold. From now on we use a two parameter fit for the peak-gain carrier-density relation as follows [116]:

\[
g_{\text{peak}} = g_0 \ln \left( \frac{N}{N_{\text{tr}}} \right) \tag{3.17}
\]

In this equation the two parameters \( g_0 \) and \( N_{\text{tr}} \) represents the gain and carrier density at transparency, respectively and \( N \) the actual carrier density in the device. The two parameter fit usually provides good
3.3. Gain measurements

agreement with experiment for carrier densities above transparency for quantum well material [116]. Fig. 3.10 shows a fit of this relation to the measured material peak gain $g_m^{peak}$.

![Graph showing material gain peak $g_m^{peak}$ versus ln(N) and fitted with Eq. 3.17 for the three quantum-well gain structure.](image)

Figure 3.10: Material gain peak $g_m^{peak}$ versus ln(N) and fitted with Eq. 3.17 for the three quantum-well gain structure.

From this fitting procedure we can extract the two parameters $g_0 = (3160 \pm 30) \text{cm}^{-1}$ and the transparency density $N_{tr} = (2.77 \pm 0.02) \times 10^{18} \text{cm}^{-3}$. The value of $g_0$ per quantum well is only 60% of the value reported by Coldren [117] for InGaAs/GaAs at 980nm emission wavelength. This can be explained by the higher Auger combination rate for InGaAsP lasers at 1550nm emission wavelength and by the assumption of equal distribution of the carriers over all three quantum wells. The values of the transparency density is in good agreement with published results for lattice-matched InGaAs quantum wells [104].

To conclude we have extracted out of the Hakki-Paoli measurement an simple model for the gain (Eq. 3.17) which is the basis for the gain structure design for the MLLDs presented in the following sections.
3.4 Multiple Quantum Well Design

Several constraints influence the design of the quantum-well structure. First, to achieve a high gain saturation which is advantageous to obtain mode-locking, we can either lower the optical confinement factor $\Gamma$, hence using a wide, weak confining separate confinement structure (SCH), or lower the differential gain $a = \frac{d\gamma}{dN}$ by using fewer quantum wells. Fig. 3.11 represents the computed material gain for one, two and three quantum wells. Since we assume a homogeneous carrier density distribution over all three quantum wells we calculated the transparency carrier density $N_{tr}$ and gain $g_0$ by dividing the values for three QWs by 3 and 3/2 for one QW and two QWs respectively. It should be noted that whatever the number of wells, the gain section of the MLLD has to provide the threshold gain to overcome all sources of loss. As can be seen from Fig. 3.11, the differential gain, which is given by the slope of the gain curves, is lower for fewer quantum wells at a given gain level. This results in the targeted higher saturation energy.

![Material gain for 1, 2 and 3 quantum wells](image)

Figure 3.11: Material gain for 1, 2 and 3 quantum wells calculated from Eq. 3.17.

Fewer quantum wells also lead to a decreased $\Gamma$-factor which further...
lowers the available gain and increases the requirement for higher carrier densities in the gain section. This implies also a decrease in the slope of the curves in Fig. 3.11 hence an increase in $E_{\text{sat}}$ as shown in Fig. 3.12.

Figure 3.12: Computed saturation energy $E_{\text{sat}}$ for 1, 2, and 3 quantum wells and required gain for a gain section length of 1000μm.

As has been demonstrated in the introduction of this chapter the required gain for our MLLDs is at least 6dB which corresponds to a modal gain for a 1000 μm long gain section of $g_m=40$. In order to achieve this gain we can determine a saturation energy of 20, 2.7 and 1.9 pJ for 1, 2, and 3 QWs respectively. So the condition for mode locking that the absorber saturation energy has to be lower than the gain saturation energy is hard to fulfill for a 1000μm long gain section with 3 QWs but is easily achievable for one and two QWs. The condition for short pulse output that $E_{\text{gain}}/E_{\text{abs}} > 5$ can only be full filled with a single QW. Thus for the two and three quantum well design a fast absorber is mandatory to produce short pulses [31]. A reduction of the modal gain can also be achieved by using cavities extended with monolithically-integrated passive waveguides to shorten the gain section length. This solution is favorable for long MLLDs (10GHz repetition rate, i.e. 4mm long cavity) as in addition the amount of spontaneous emission can be reduced,
which is a main source for noise.
On the other hand threshold-gain $g_{th}$ must be delivered by the chosen
gain section length of the mode locked laser diode (MLLD). So there
is a trade off between the number of QWs and the gain section length.
Fig. 3.13 shows the achievable gain for the three different gain section
length for one, two and three quantum wells. The gain exceeds for car-
rier densities the required threshold gain $g_{th} = \Gamma N L = 4$ for all three gain
section lengths $L$ only when three quantum wells are employed. For the
single QW structure the threshold gain is never exceeded and for two
QWs only for 500\,\mu m and 1000\,\mu m. Because the full MLLD process as
described in Chap. 4 is very time-consuming we focused our study on one
QW design to cover the range of MLLDs with repetition rates of 10\,GHz,
40\,GHz and 80\,GHz. To introduce also a safety margin we decided to use
the three QWs design. The different lengths correspond to saturation
energies $E_{sat,N}$ of 3.7\,pJ, 2.5\,pJ and 1.9\,pJ for gain sections with three
quantum wells and length of 300\,\mu m, 500\,\mu m, and 1000\,\mu m, respectively.

![Figure 3.13: Total gain for L_1=300\,\mu m, L_2=500\,\mu m, and L_3=1000\,\mu m for
1, 2, and 3 quantum wells.](image)

```plaintext
Figure 3.13: Total gain for L_1=300\,\mu m, L_2=500\,\mu m, and L_3=1000\,\mu m for
1, 2, and 3 quantum wells.
```
3.4. Multiple Quantum Well Design

Another design constraint for the vertical gain layer structure design is a high optical-mode overlap with the other structures used in the MLLD. Additionally, a low reflection between the different sections is required. An intensity-reflection coefficient of $10^{-5}$ between the different structures demands for a structural homogeneity which results in an effective refractive index difference $\Delta n$ lower than 0.02.

To fulfill these requirements we need a SCH which confines the optical mode of the gain section to fit the modes of the absorber and passive waveguide sections very accurately. Therefore the degree of freedom in the design of the SCH structure is very limited and a weakly-confining vertical structure to lower the saturation energy cannot be realistically envisaged.

To satisfy mode-matching condition, a quantum well barrier of the same material as the passive waveguide core layers (Q1.28) would be required. Unfortunately it turns out that quantum-well lasers with Q1.28 barriers have a high threshold current and a low characteristic temperature. Furthermore the quantum efficiency is low. All these effects can be explained by the low carrier confinement in the wells due to the moderate conduction-band offset $\Delta E_c \approx 2k_B T$ at room temperature between the wells and the barriers resulting in a high leakage current.

Thus we used the larger band-gap quaternary material Q1.2 as barrier material. Due to the higher material inhomogeneity the reflection at the interfaces between the monolithically integrated laser sections will be increased. However, this problem can be mitigated by using angled interfaces as described in Chap. 4. Furthermore, since the gain material is not used as an absorber in our MLLDs, we do not have to design a fast carrier-extraction structure for which low barrier band-gap discontinuities are beneficial.

Fig. 4.2 shows a schematic of the final MQW vertical layer structure. The MQW gain material consists of nominally unstrained 8nm thick InGaAs wells with 12nm thick InGaAsP barrier layers. The barriers have a photoluminescence (PL) peak at 1.2$\mu$m. The MQWs are embedded within a 50nm Q1.2 lower cladding and a 50 nm Q1.2 plus 80nm Q1.1 upper cladding, which form the separate confinement heterostructure. The Q1.1 layer is only adopted at the p-doped side to ensure less abrupt band discontinuities for the hole injection. All layers are lattice-matched to the InP substrate.
Further details of the chosen layer structure are discussed in the context of all three integrated vertical layer structure in Chap. 4. The lateral optical confinement is provided by a rib waveguide structure to provide a single transverse mode waveguide. The 2.5\textmu m wide ridges are etched into the optical cladding down to the top layer of the SCH structure to assure a transverse single mode operation.
3.5 CW Characteristics of MQW Lasers and SOAs

In this section we discuss the static behavior of MQW laser diodes. The threshold current and spectral characteristics of Fabry-Perot laser diodes will subsequently be used to characterize the interface losses of the processed MLLDs and the spectral behavior of the MQW gain material during the fabrication of the MLLDs which requires a complex regrowth process. Therefore we describe in the following the basic behavior of as grown (i.e., wafer directly processed into laser diodes without subsequent regrowth for the integration of absorber and passive waveguide section) MQW Fabry-Perot (FP) lasers and extract the associated continuous-wave (cw) parameters.

The light-current (PI)-characteristic above lasing threshold can be described by [104]:

\[ P = \frac{h \nu}{q} \eta_d (I - I_{th}) \]  \hspace{1cm} (3.18)

where \( h \) is the Planck constant, \( \nu \) is the light frequency, \( q \) is the elementary charge of an electron, and \( I_{th} \) is the threshold current. The differential quantum efficiency \( \eta_d \) is the product of the internal quantum efficiency \( \eta_i \) and of a fraction composed of the waveguide loss \( \alpha_W \) and the reflection loss \( \alpha_M = \frac{1}{2} \ln \frac{1}{R} \) as follows:

\[ \eta_d = \eta_i \frac{\alpha_M}{\alpha_W + \alpha_M} \]  \hspace{1cm} (3.19)

Fig. 3.15 shows the measured PI-curves for 700, 1200, and 2100\,\mu m long lasers. The lasers were driven in cw-mode.
Chapter 3. Multiple quantum well gain material

Figure 3.15: Light-current characteristics of laser diodes with 700\(\mu\)m (L1), 1200\(\mu\)m (L2), and 2100\(\mu\)m (L3) long cavities. The inset shows a top-view micrograph of a chip with 4 lasers. The 2100\(\mu\)m-long chip is built of several modules that can be diced into separate FP-lasers. The cleaving channels between the modules can be seen, too.

The transverse single-mode lasers show threshold current densities around 1kA/cm\(^2\). This is a fairly low value for a rib waveguide laser with unstrained QWs. On the other hand buried structure lasers with similar material demonstrated threshold current densities as low as 0.7kA/cm\(^2\) [118]. The higher threshold current density for our rib structure can be explained by higher leakage currents. The quite strong increase of \(I_{th}\) for the laser with 2100\(\mu\)m long cavity can be explained by the fact, that not all sections of this multi-section laser (inset Fig. 3.15) are directly connected to the current source via a contact needle. As the different sections are connected only by the 2\(\mu\)m wide p-contact on top of the rib waveguide the pump current is not spread sufficiently over the hole cavity length. Therefore we only consider in the following lasers with 700\(\mu\)m and 1200\(\mu\)m long cavities.

The differential quantum efficiency \(\eta_d\) can be extracted as the slope of
3.5. CW Characteristics of MQW Lasers and SOAs

the PI-curves above threshold. Since Eq. 3.18 can be transformed into

\[ \frac{1}{\eta_d} = \frac{\alpha_w}{\eta_k \ln \left( \frac{L}{L_0} \right)} L + \frac{1}{\eta_k}, \]\n
(3.20)

the internal quantum efficiency \( \eta_k \) can be extracted by plotting the reciprocal of the differential quantum efficiency \( \eta_d \) against the cavity length \( L \). Fig 3.16 shows the extracted differential quantum efficiency against cavity length for 700 and 1200\( \mu \)m long laser diodes.

![Figure 3.16: Extracted reciprocal differential quantum efficiency \( \eta_d^{-1} \) for laser diodes with 700\( \mu \)m (L1) and 1200\( \mu \)m (L2) long cavities](image)

To demonstrate the statistical variation we plot data from two different lasers for each length. Fitting Eq. 3.20 to these values results in an internal quantum efficiency \( \eta_k \) of 65\% and a waveguide loss \( \alpha_w \) of (15.7\pm0.4)\( \text{cm}^{-1} \). The latter value agrees very well with the waveguide losses deduced from the Hakki Paoli net gain measurements of (16.0\pm0.1)\( \text{cm}^{-1} \). The internal quantum efficiency is in good agreement with the reported \( \eta_k \) of 50-70\% for comparable MQW structures [118] even though it includes the leakage currents. Further, applying the two-parameter gain model for the threshold gain, the corresponding threshold carrier density \( N_{th} \) can be expressed as:

\[ N_{th} = N_{tr} \exp \left( \frac{g_n}{g_0} \right) = N_{tr} \exp \left( \frac{\alpha_w + \alpha_M}{\Gamma g_0} \right) \]

(3.21)
where $N_{tr}$ is the transparency carrier density. For the second equation the threshold condition was used which states that the gain compensates the losses at lasing threshold. Considering that the spontaneous bimolecular recombination expressed as $BN^2$ is dominating at threshold [104], we have:

\[
I_{th} \cong \frac{1}{\eta} BN_{th}^2 qV \tag{3.22}
\]

Thus, with Eq. 5.3 and Eq. 3.21 the threshold current can be written as:

\[
I_{th} \cong \frac{qBVN_{th}^2}{\eta} \exp[2(\frac{\alpha \omega + \alpha_M}{\Gamma g_0})] \tag{3.23}
\]

It is therefore possible to determine the bimolecular recombination coefficient $B$ from the threshold current. For the lasers with cavity lengths L1 and L2 we get $B = 1.68 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$ and $B = 1.70 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$ respectively whereas for the L3 cavity length we get $B = 1.41 \times 10^{-10} \text{cm}^3 \text{s}^{-1}$. The lower value for the L3 cavity length can be explained by the insufficient pumping of the multi-section device as explained for the threshold current.

The knowledge of the B-parameter will allow us later to determine the internal losses of MLLDs from the threshold current with Eq. 3.23. Finally Fig.3.17 shows laser diode spectra below threshold and at a pumping current of $2.5I_{th}$. The pumping current was this time pulsed with a pulse width of 100ps to avoid heating of the laser structure. It is important to note for the investigation of the following section, that the maximum of the spectra coincide very well with the PL-peak measured at 1.55μm and that this maximum does not shift with the pulsed pumping current.

Thus we can compare the emission peak wavelength of the laser diodes with the photoluminescence peak of the MQW-layers before MLLD processing.
3.6 Influence of Multiple Regrowths on MQW Characteristics

It is well-known that the MQW material is sensitive to post-growth heating steps and will suffer from material interdiffusion between the barriers and the wells [119]. As the MQW gain structure is first grown on a planar epi-ready wafer, the subsequent integration of the absorber and passive waveguide structures necessitates the repeated heating of the MQW structure up to the growth temperature of 630°C. Thus we have to consider these material interdiffusion effects.

The relation between the photoluminescence peak of the as grown MQW structure (see Sec. 3.2) and the final lasing wavelength is important to match the standardized wavelength for optical communication systems. Furthermore, the bandgap of the absorber material has to be matched to the MQWs emitting wavelength [31]. Therefore the influence of regrowth on interdiffusion processes will be carefully investigated in this section.

Figure 3.17: Output light spectra for a 500μm long laser diode with pumping currents of $I_1 = 0.8 \ I_{th}$ and $I_2 = 2.5 \ I_{th}$. 
Table 3.2: Influence of regrowth on emitting wavelength. The QW thickness (see Tab. 3.3) was adjusted for each run which is reflected in the different PL-peaks, in order to achieve best matching to the UTC absorption band edge.

<table>
<thead>
<tr>
<th>run</th>
<th>PL Peak [nm]</th>
<th>LS Peak [nm]</th>
<th>shift [nm]</th>
<th>cumulative heating time</th>
<th>% over-growth</th>
</tr>
</thead>
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<td>1550</td>
<td>0</td>
<td>0min</td>
<td>0</td>
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<tr>
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<td>1h20min</td>
<td>1</td>
</tr>
<tr>
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<td>1510</td>
<td>-45</td>
<td>2h52min</td>
<td>4</td>
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<tr>
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<td>1540</td>
<td>-34</td>
<td>3h00min</td>
<td>5</td>
</tr>
</tbody>
</table>

3.6.1 Wavelength shift

For the analysis of the impact of the regrowth temperature-cycle on the MQWs, a direct comparison of photoluminescence (PL) peaks before and after fabrication proved not to be possible as the remaining MQW-material area after etching and regrowth was too small to allow a proper focusing of the PL excitation beam. Furthermore, experiments consisting in thermally cycling MQW layers without etching and regrowth show different blur shifts of the PL spectra than those observed in processed FP-lasers (see figure 3.18).

Since the output spectra of the processed FP-lasers match well the output spectra of the MLLD on the same wafer, the FP-laser characteristics is useful to study the wavelength shift due to partial quantum-well intermixing. We measured the FP-lasers spectra with a pulsed pump current slightly above laser threshold and investigated the relation between the spectral peaks and the initial PL-peak measurements.

Furthermore as mentioned previously, the PL-emission peak before processing coincides well with the output spectral peak of as grown FP-lasers (LS-Peak) from wafers without regrowth (run P234 in Tab. 3.2). In comparison to quantum well intermixing for passive waveguide generation [120] the temperature during regrowth is relative low and therefore we suppose that the interdiffusion is not large enough to change gain characteristics dramatically [104].

Tab. 3.2 shows the comparison of the PL peak at room temperature of the as grown MQW structures and the laser spectral (LS) peak wavelength of the processed single-mode Fabry-Perot ridge waveguide lasers. The
five investigated wafers show a blue shift between 0 and 45 nm depending on the cumulative heating time and the initial PL-peak wavelength. After four and five regrowth steps the spectra show the strongest blue shift. Quantum-well intermixing (QWI) which is believed to be the origin of this blue shift, is a well-known phenomena and has been studied in detail for a vast amount of material systems (e.g. [119] and references therein). In the InP-material system mainly InGaAs wells with binary InP barriers were investigated. From the four possible interdiffusion species in our InGaAsP/InGaAs MQWs group III and group V atoms begin to interdiffuse at 800°C and 500°C, respectively [121, 122]. It is therefore expected that only arsenic and phosphorus atoms interdiffuse at our growth temperature of 630°C. Interesting to mention is the work by Mukai and co-workers [123] who investigated a similar structure but observed lower wavelength shifts of 10nm for a 2h thermal load at 680°C. They used simple thermal cycling and PL measurements and not such a complex etching and regrowth procedure as in our study. This indicates that the size and coverage of the remaining MQW-Structures on the wafer is important. It also explains why we cannot relate the observed blue shift in Fabry-Perot lasers with the shift of the PL peak in thermally-cycled full-coverage MQW layers (see Fig. 3.18,circles versus squares).
In our opinion the topology and regrowth play an important role for two reasons. First, during regrowth, the MQW layers are covered with SiO$_2$ and/or InP layers of various thicknesses and it is well known that this can influence the QW intermixing process [124]. This technique is used, e.g., for QW disordering whereby a thick SiO$_2$ section is selectively applied on top of active regions that should be converted into passive waveguiding sections by inducing stress in the layers.

Second, the exact temperature gradient in the structure also varies depending on etched areas and coverage. However, in spite of all the reported experiments on QWI the underlying atomic diffusion process and interdiffusion profiles are still not fully understood and under investigation [125]. Nevertheless several authors reported that the interface abruptness between well and barrier is conserved during QWI for our material system. Thus the overall rectangular shape of the MQWs remains unaffected by the regrowth process, so that a square-like shape of the MQWs potential can still be assumed [121, 126, 127]. Therefore, we can introduce an effective quantum-well width computed from the optical characteristics.
3.6. Influence of Multiple Regrowths on MQW Characteristics

Table 3.3: Influence of regrowth on the effective QW width computed from the PL emission peak wavelength or from the FP-laser peak spectrum

<table>
<thead>
<tr>
<th>Run</th>
<th>QW width PL Peak [Å]</th>
<th>QW width LS Peak [Å]</th>
<th>Δ QW width [Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P234</td>
<td>80</td>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>P356</td>
<td>76</td>
<td>72</td>
<td>-4</td>
</tr>
<tr>
<td>P556</td>
<td>86</td>
<td>76</td>
<td>-10</td>
</tr>
<tr>
<td>P644</td>
<td>84</td>
<td>60</td>
<td>-24</td>
</tr>
<tr>
<td>P783</td>
<td>100</td>
<td>75</td>
<td>-25</td>
</tr>
</tbody>
</table>

before and after regrowth although the exact kinetics of the interdiffusion process is not known.

Finally, before discussing the results of the investigation on the impact of the regrowth on the MQWs emission characteristics, it is worth mentioning that the inspection of the structure by TEM measurements is not possible, due to the insufficiently large area coverage of the QW material remaining after processing.

Assuming that the PL peak and the laser-spectral peak wavelength (LS) correspond to the transition between the ground energy states in the conduction and valence bands (Sec. 3.2), we can assign every PL-peak and spectral-gain peak a corresponding quantum-well width. The transition energy calculation are given in Sec. 3.2. We have used the following material parameters for our calculations: lattice temperature $T = 273 K$, effective conduction-band electron mass $m_e = 0.041 m_0$, effective valence-band hole mass $m_h = 0.457 m_0$, where $m_0$ is the free electron mass, and a band-offset ratio of $\Delta E_c / \Delta E_v = 0.4 / 0.6$.

The calculated quantum-well widths are summarized in Tab. 3.3 for the associated emission wavelengths from Tab. 3.2. In addition the resulting shrinkage for the observed wavelength shifts is listed.

Interesting to note is that the wavelength shifts for runs P644 and P783 (with different initial QW width and emission wavelengths) are -45nm and -35nm, respectively for a cumulative heating time of 3h. The calculations show that the resulting change in effective quantum-well width is 25Å for both samples.

This can be interpreted that the absolute value of the QW shrinkage is independent of the initial thickness of the well. Therefore the regrowth will have a stronger influence on the transition energies in thinner quan-
Chapter 3. Multiple quantum well gain material

tum wells. Fig. 3.18 displays the dependency of the quantum-well width shrinkage on the cumulated heating time. Independently of the initial quantum-well width and associated PL peak, the QW width shrinkage fits very well to a linear relation of $8.3\frac{\text{nm}}{\text{sec}}$ at a growth temperature of $630^\circ\text{C}$.

This linear relationship is expected to show a saturation behavior for longer overgrowth times and the $\sim 8.3\frac{\text{nm}}{\text{sec}}$ figure is only applicable to our particular system and process, though the trend, of course, is general. We applied our model to the data published in [123] where the authors used a comparable diffusion process and the same material system. For InGaAs quantum wells with a binary InP barrier we extracted an effective quantum well width shrinkage of $1.2\frac{\text{nm}}{\text{sec}}$ for QW widths of 7.5nm and 10nm at a growth temperature of $650^\circ\text{C}$. The lower shrinkage in comparison to our observations can be explained by a different coverage of their quantum wells during heating in a rapid thermal annealer and a different barrier material.

For thinner ($5\text{nm}$) and thicker ($15$ and $20\text{nm}$) QWs our model does not fit the data. For the thicker QWs the transition energy calculations show the existence of a second conduction band within the well. Therefore the assumption that the PL-peak coincides with the transition energy loses its validity. For thinner QWs the diffusion spreads over the total well width, which makes the assumption of an unchanged QW shape and the use of an effective quantum well width obsolete.

3.6.2 Diffused Well Gain Calculations

We have seen in the previous paragraph that the PL and FP peak wavelength are very accurate monitors to quantify the impact of regrowth on the QWs. The theoretical investigation of the gain reveals another possible explanation of the emission wavelength shift. It has to be admitted that in our research environment with a low number of growth runs per year the material parameters vary from run to run considerably. So it is difficult to compare results from different wafers if the effects are small but nevertheless important and we remain in the following on a qualitative argumentation.

In this section we will compare the gain calculations with GEBAS of an as grown FP-laser (P234, QW width= 8nm) with a FP-laser from a fully processed wafer (P783, effective QW-width= 7.5nnm).

Fig. 3.19 shows the computed material gain for a QW structure with
3.6. Influence of Multiple Regrowths on MQW Characteristics

three quantum wells of 7.5nm and 8nm width for carrier densities of $3 \times 10^{18} \text{cm}^{-3}$, $3.59 \times 10^{18} \text{cm}^{-3}$, and $4.3 \times 10^{18} \text{cm}^{-3}$.

A slight red shift in the peak wavelength for the wider quantum well corresponds to the observed wavelength difference. Furthermore the narrower quantum well structure provides a very small increase in gain at a given carrier density. However the increase in gain is so small, that we can not expect a significant change in observable gain characteristics. Fujii and co-workers claimed [121] that the square potential of the well is maintained during the interdiffusion, because of a higher mobility of the group V atoms in the well. Thus we also calculated the gain for changes in the P-concentration of a 10nm wide well and 12nm wide barrier due to diffusion (Fig. 3.20). The different curves in Fig. 3.20 are calculated for an increased amount of P-atoms in the well. Strain effects due to material composition mismatch were automatically included by the Gebas program into the calculations.
Figure 3.20: Calculated material gain for three quantum wells with width of 7.5nm and a carrier densities of \(4.3 \times 10^{18} \text{cm}^{-3}\). The material composition of the well changes from \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) to \(\text{In}_{0.53}\text{Ga}_{0.43}\text{As}_{0.06}\text{P}_{0.07}\) within steps of the P concentration of 1%, 2%, 4%, to 7%.

To realize the observed wavelength shift a P-concentration of at least 2% is required. This will lead to an decrease of the gain of 15% with respect to the gain of a 7.5nm un-diffused quantum-well. Thus an increase in threshold current would be expected to counteract this decrease in material gain.

### 3.7 Conclusion

Gain calculations for a multiple quantum well structure were performed based on a semi-classical model. The computed gain curves were fitted to the measured gain by adjusting the carrier density. The gain measurements were realized with the Hakki Paoli method. The consistent carrier density to pump current correlation for different process runs remains difficult for our research environment. Nevertheless a simple two parameter model was extracted from the measurements and calculations.
to design the gain section of our MLLD. With this model the influence of the gain section length and the number of quantum wells on the saturation energy was investigated. We found that at least three quantum wells are required to reach the lasing threshold for all reasonable gain section lengths of 300\(\mu\)m, 500\(\mu\)m, and 1000\(\mu\)m. This leads to saturation energies \(E_{\text{sat}}^{\text{gain}}\) between 1.8pJ and 3.7pJ, which has to be compared to the absorber saturation energy \(E_{\text{sat}}^{\text{abs}}\) of 1-2pJ. Considering the condition for mode-locking that \(\frac{E_{\text{sat}}^{\text{gain}}}{E_{\text{sat}}^{\text{abs}}} > 1\) we expect a severe impact of the gain section length on the mode locking behavior. On the other hand we can not reach the condition of \(\frac{E_{\text{sat}}^{\text{gain}}}{E_{\text{sat}}^{\text{abs}}} > 5\) for short pulse mode-locking. Thus an absorber section with a short recovery time is required to obtain sub-ps pulses [31].

We have demonstrated, that the shift in the emitting wavelength of the InGaAs/InGaAsP MQW gain material due to the heating during regrowth can be predicted by taking into account a reduced effective width of the quantum wells. The change of this effective width during multiple regrowth MOVPE steps is linearly dependent on the cumulative heating time with a rate of 8.3\(\AA/\text{h}\) at a growth temperature of 630°C and does not depend on the initially grown quantum-well width.

Thus the interdiffusion effect can be included in the design for the as grown MQW-structure. The as grown structure can be verified by PL-measurements before further MLLD structure processing.

The QW interdiffusion effect has to be taken into account if more complex photonic integrated circuits which uses QW gain material are considered, e.g. if different material bandgaps have to be adjusted to the emission wavelength.

In the next chapter the details of the regrowth process to integrate the desired structure into a single chip MLLD are given. Especially the losses and reflections between the different structures are considered. The losses will also have an influence on the gain requirements discussed in this chapter.
Chapter 4

Multiple Structure Integration Process

4.1 Introduction

In the previous chapters we demonstrated the requirement for a fast absorber structure to reach shorter pulses from MLLDs as conventional MLLDs with reversed biased gain section absorbers do not reach the expected pulse width limited by the gain bandwidth. We proposed the use of the unit-traveling carrier (UTC)-structure which demonstrated carrier relaxation times as low as 2 ps [94]. Furthermore the advantages of multiple quantum well (MQW) gain material in comparison to bulk material was justified and design guidelines for MQW-structures with high saturation energy were given in Chap. 3. Also the use of a passive waveguide section is necessary to provide high saturation energies of the gain section. Additionally, passive waveguides are required to prevent high noise levels resulting from spontaneous emission in long (4mm) cavity MLLDs.

In Chap. 1 we already demonstrated that only the butt couple regrowth (BCR) process offers the full freedom to design the different layer structures independently. The trade-off is a more complex etching process and a MOVPE regrowth process which has to be optimized for low reflections and losses at the interfaces of the different integrated structures. For the BCR process interface losses as low as 0.4dB and internal intensity re-
flections lower than $10^{-5}$ were already demonstrated [29]. Additionally, the contamination of the wafer due to photo-resist or etchant residuals before the MOVPE growth must be considered, because they could affect the device yield.

In this chapter we first discuss the vertical layer structure of the three different sections to be integrated in one single MLLD chip. Subsequently the theoretical investigation of the most challenging requirements regarding reflections and losses of the butt-coupled interface is presented. To fulfill these requirements the experimental details of the etching and regrowth processes are exposed in the following two sections. Afterwards we describe the full MLLD integration process. Finally the experimental characterization of the interfaces is presented in the light of the theoretical investigations.

### 4.2 Vertical Structure Design

Let us now start with the design of the vertical layer stacks for the final MLLDs. We will first describe the layer functionalities for each structure separately. In the following the solution for the optical mode-matching between the sections and the expected internal reflections are presented.

#### 4.2.1 Layer Functionalities

All layers were grown lattice matched onto (100) oriented n-doped InP wafers in a metal organic chemical vapor phase epitaxy (MOVPE) reactor AIX200/4 from AIXTRON. In the following pages the vertical layer stacks for the gain, absorber and passive-waveguide sections will be discussed in detail, whereby in the figures the material composition is coded with a grey scale (the darker the layer, the smaller the bandgap and the higher the optical refractive index).

Apart from the electrically and optically relevant layers several types of growth and processing relevant so called sacrificial layers need to be included in the vertical layer design (Fig. 4.1).
4.2. Vertical Structure Design

The most often used sacrificial layers are *etch-stop* layers, which define an etch depth for material selective chemical etching and serve as seed layers for subsequent regrowth steps (e.g. layer 4 in Fig. 4.2). These layers need not to be very thick as material-selective etchants usually show selectivities better than 1:100. Therefore thicknesses in the range of 10-15nm are sufficient. Furthermore these thicknesses are so small that these layers so not disturb the optical mode in noticeable way.

For the sake of completeness it should be mentioned that the underlying etch stop (layer 2 in Fig. 4.2) is only grown for safety reasons, in case that the top etch stop layer was perforated accidentally by a non-selective etch. Otherwise this will lead to deep etched holes into the substrate, which could disturb the following regrowths and the planarity of the wafer.

Other semiconductor layers will serve as a mask for material-selective wet etching, e.g., for the laser rib etching process (layer 14 in Fig. 4.2). Hence these layers should provide a high etch selectivity with respect to the underlying layers for the designated etching process.

A third kind of very important functional layers for the regrowth process are so called *clean-up* layers. They are initially grown to be removed before the following regrowth to provide a clean and well defined crystal surface. Also these layers must be selectively wet etched to an underlying etch-stop layer, because only wet-etching provides the required epi-ready surfaces and a sufficient structural homogeneity over the whole wafer.

To ensure a smooth crystalline growth start binary InP growth-buffer layers are advantageous because the growth of this binary material is not so sensitive to crystalline defects in the seed layer than the more
complex ternary or even quaternary materials. Finally, etch-buffer layers are required for the non-selective etching of inhomogeneous layer stacks, such as e.g. the separate confinement heterostructure (SCH) and the MQW layers for the gain structure and the absorbing and electron diffusion/blocking layers for the absorber structure (Fig. 4.3). Due to local etchant exhausting processes, non-selective etchants are very sensitive to the mask topology. The differences in local etching speeds need to be absorbed by the etch buffer.

The main design aspects for the semiconductor layers can be divided into optical and electrical requirements. For the vertical optical confinement, a light-guiding core layer is needed with a higher refractive index than the surrounding cladding layers. These correspond to the dark and light-grey layers of Q1.1X material as core material surrounded by the white InP layers as cladding material in Fig. 4.2, 4.3, and 4.4. For the MQW layers a separate confinement heterostructure (SCH) is used to confine the electrons and the light mode separately. To avoid optical absorption in the absorbing InGaAs contact layers for the active structures, the InP cladding layers for the MQW and UTC stacks must be at least 1.3μm thick [128]. This thickness results in waveguide losses for the active gain structure of 16cm⁻¹ which is very close to the value of 15cm⁻¹ reported by [84] for a cladding thickness of 1.8μm for bulk active waveguides.

The MQW and absorber layer stacks are PIN diodes with a zinc p-doped layer, non intentionally doped (n-id) intrinsic layers and silicon n-doped layers. The passive waveguide structure with no electrical functionality (Fig. 4.4) uses solely nid layers. Since Zn is known to be a dopant with a high diffusion constant, we incorporated a 10nm thick diffusion buffer layer into the design for p-doped cladding as well as for the p-doped absorbing layer of the UTC-structure (layer 3 in Fig. 4.3). The electronic requirements of the MQW based gain structure were presented in Chap. 3. A good ohmic contact to the pad metalization is guaranteed by the highly-doped InGaAs top-layer. To avoid large conduction- and valence band discontinuities and potential spikes between the InP cladding layers and the InGaAs contact layer a two step grading of Q1.1 and Q1.3 material is incorporated in between.

The multiple regrowth process necessitates to grow wider quantum wells than expected for the envisaged emitting wavelength of 1.55μm. The initial photoluminescence peak should be at 1580nm to end up with an emission wavelength of 1550nm after processing, caused by the blue shift.
4.2. Vertical Structure Design

- 14. 170nm InGaAs Zn $2 \cdot 10^{19}$ cm$^{-3}$ contact layer
- 13. 15nm Q1.3 Zn $6 \cdot 10^{18}$ cm$^{-3}$ contact bandgap grading
- 12. 15nm Q1.1 Zn $6 \cdot 10^{18}$ cm$^{-3}$ contact bandgap grading
- 11. 1300nm InP Zn $1 \cdot 10^{18}$ cm$^{-3}$ optical cladding
- 10. 10nm InP nid Zn doping diffusion buffer
- 9. 80nm Q1.1 nid SCH layer
- 8. 50nm Q1.2 nid SCH layer
- 7. 69nm MQW nid 3 quantum well active structure
- 6. 50nm Q1.2 nid SCH layer
- 5. 490nm InP Si $2 \cdot 10^{16}$ cm$^{-3}$ etch buffer
- 4. 8nm Q1.1 Si $2 \cdot 10^{18}$ cm$^{-3}$ etch stop layer
- 3. 100nm InP Si $2 \cdot 10^{18}$ cm$^{-3}$ growth buffer layer
- 2. 8nm Q1.1 Si $2 \cdot 10^{18}$ cm$^{-3}$ security etch stopp layer
- 1. 50nm InP Si $2 \cdot 10^{17}$ cm$^{-3}$ growth buffer layer
- 350 μm InP Si $3 \cdot 10^{19}$ cm$^{-3}$ substrate

Figure 4.2: The MQW layer stacks for the integration process. All layers are lattice-matched to the InP substrate.
Figure 4.3: The UTC layer stack as grown on top of the upper etch stop layer (layer 0) of the MQW stack (layer 4 Fig. 4.2).
4.2. Vertical Structure Design

Figure 4.4: The waveguide layer stack for the integration process.
occurring during the high temperature regrowth steps, as is discussed in Chap. 3.

The active layers of the absorber structure implement a uni-traveling carrier structure (UTC) (see Chap. 2). To center the optical mode to the p-doped UTC-absorbing layer an additional mode centering layer (layer 6 in Fig. 4.3) above the electron blocking layer is required. The band-gap is red-shifted by 40nm with respect to the emission wavelength of the MQW to provide the best mode-locking condition [94]. Further details and discussions of the design of the absorber structure can be found in [31].

Different thicknesses of the lower InP buffer layers for the gain, absorber and waveguide sections are required to match the optical modes of each layer stack as will be explained in the following section. For the lateral optical confinement we will etch a rib waveguide with a width of 2.5μm to ensure single transverse mode operation. The etching procedure is described in Sec. 4.6.3.

4.2.2 Mode Matching between the three Structures

The losses and reflections between the different structures were investigated with two different approximations. The waveguide to waveguide transmission were estimated by the mode overlap integral of the guided optical modes [129]. Since the reflections are usually small, we assume, that the losses are given by the non-transmitted intensity. The reflections were evaluated by the differences in effective indices.

To minimize the losses between the different integrated structures the optical modes have to be matched. The waveguide modes for the different structures were computed with a finite element mode solver [130]. The refractive indices for the different materials were calculated with a single oscillator model proposed by Afromowitz [131] and are summarized in Tab. 4.1. The different optical modes are shown in Fig. 4.5.

Several constraints limit the degree of freedom for the design of the layer stacks. First of all, the design of the light-guiding layers of the UTC-layer stack was determined from carrier transport considerations. Hence we have to match the core layer of the MQW and passive-waveguide structures to the UTC structure and the difference in the effective indices have to be minimized. This requirement can be fulfilled by using materials with similar compositions.

The influence of the rib etch depth on the mode profile is negligible for two reasons. First, the rib etch depth is highly reproducible and reliable
4.2. Vertical Structure Design

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP</td>
<td>3.1678</td>
</tr>
<tr>
<td>Q1.1</td>
<td>3.2957</td>
</tr>
<tr>
<td>Q1.2</td>
<td>3.3571</td>
</tr>
<tr>
<td>Q1.3</td>
<td>3.4136</td>
</tr>
<tr>
<td>Q1.53</td>
<td>3.5446</td>
</tr>
<tr>
<td>InGaAs</td>
<td>3.7202</td>
</tr>
<tr>
<td>MQW</td>
<td>3.4676</td>
</tr>
</tbody>
</table>

Table 4.1: Refractive indices for the used material for an optical wavelength of 1.55 \( \mu \text{m} \).

because a wet-etch process down to an etch-stop layer is used. Second, even etching through the whole light guiding layers of the waveguides would change the mode overlap only by 4% resulting in a loss of 0.14dB which is in the order of the minimal experimentally observed losses.
To match the optical modes the thickness of the InP etch buffer layer (layer 1 in Fig. 4.4 and 4.3) is adapted for each stack. As a starting point the minimum InP p-doped buffer layer thickness for the MQW structure is determined by the process requirements of the etching procedure described later in this chapter. Then the thicknesses of the InP etching buffer layers for the UTC and waveguide structures were adapted to this value to realize a mode overlap better than 99%. Fig.4.6 shows the
matched vertical intensity profile of the three structures for the MQW, UTC and waveguide structure. The waveguide mode has a little larger FWHM value, but the overall mode expansion is very similar for all structures. Furthermore Fig. 4.6 demonstrates, that the light intensity does not penetrate into the absorbing InGaAs contact layer.

Figure 4.6: Vertical intensity profiles for the MQW, UTC, and waveguide structure from inner to outer profile. Furthermore the boundaries to the InGaAs contact layer and the InP substrate are presented.

The determined mode overlap represents a theoretical butt-coupling loss of 0.04 dB between the different structures.

The reflection coefficients between the structures can be estimated from the effective indices assuming a direct vertical butt coupling between the structures. The resulting reflectivities calculated with the Fresnel equation:

\[ R = \left( \frac{n_1^{\text{eff}} - n_2^{\text{eff}}}{n_1^{\text{eff}} + n_2^{\text{eff}}} \right)^2 \]  

(4.1)

are summarized in Tab. 4.2. These values do not satisfy the high demands for MLLD interfaces as reflection coefficients around $10^{-5}$ are required. Hence a simple straight butt coupling is not sufficient for
Table 4.2: Reflection coefficients from effective index differences between the individual structures.

these layer stacks and a better design and analysis of the interfaces is necessary.

### 4.3 Theoretical Investigation of the Butt-Coupled Interface

To investigate the butt coupled interface theoretically we have used a two-dimensional finite-difference time domain (2D FDTD) solver [132], because the effective index method does not account for details of the layer alignment and offsets. We concentrate our analysis on the influence of the structural topology at the interfaces of the light-guiding core layers, where most of the light is confined. Since we neglect any topological disturbances of the rib-structure at the interfaces so far, a two-dimensional simulations is sufficient. In Sec. 4.7 we will present the losses and reflections caused by rib damages.

In the following we restrict ourselves to the MQW passive-waveguide interface, because it is the only one which also can be investigated experimentally regarding losses and reflections. The conclusions drawn from this study regarding the geometry of the interfaces must be extended to the other butt-coupled interfaces occurring in the final MLLDs.

For the simulation, a 600 fs long pulse with a center wavelength of $\lambda = 1.55\mu m$ was launched through the considered device with a butt-coupled interface. By using a pulsed excitation we could investigate the wavelength dependence of the interface characteristics with a single simulation. Numerical dispersion is avoided by using a high grid resolution of $\frac{\lambda}{20}$.

We first tested the accuracy of the FDTD code for the reflections coefficients by investigating the artificial vertical interface of two waveguides with different refractive indices of the core layer as shown in Fig.4.7.
4.3. Theoretical Investigation of the Butt-Coupled Interface

The cladding layer has a refractive index of 3.1678 (InP) and \( n_1 \) was chosen to be 3.4136 (Q1.3). Then the refractive index \( n_2 \) of the core layer in waveguide 2 was shifted by \( \Delta n \) with respect to \( n_1 \). The results were compared to the reflection calculated with the effective-index method and are summarized in Tab. 4.3. The numerical error introduced by the FDTD grid seems to be of the order of \( 10^{-16} \) extracted for the \( \Delta n=0 \) case. For \( \Delta n=0.1 \) both methods yield similar reflection coefficients in the range of \( 10^{-6} \) which is relevant for the following studies. Therefore we conclude that we can use the FDTD approach to model reflections from butt-coupled interfaces with the required accuracy and that we can compare the FDTD simulations with results of effective index calculations in the range of interest at \( 10^{-6} \).

We now consider in Fig. 4.8 two possible butt-coupled geometries found in the literature. The vertical interface is obtained by selective wet etching [133] or reactive ion etching [134]. On the other hand a combination of non-selective and selective wet etchants gives rise to an angled interface [135] with typical angles around 40°.

From the FDTD simulations for the vertical interface we found a minimal reflection coefficient of \( 5 \cdot 10^{-4} \) in qualitative agreement with our effective-index calculations. Comparing this value with the requirement

<table>
<thead>
<tr>
<th>( \Delta n )</th>
<th>( R(n_{eff}) )</th>
<th>( R(2D \text{ FDTD}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>( 10^{-16} )</td>
</tr>
<tr>
<td>0.022</td>
<td>( 8 \cdot 10^{-8} )</td>
<td>( 1.0 \cdot 10^{-10} )</td>
</tr>
<tr>
<td>0.031</td>
<td>( 1.6 \cdot 10^{-7} )</td>
<td>( 1.2 \cdot 10^{-8} )</td>
</tr>
<tr>
<td>0.100</td>
<td>( 1.6 \cdot 10^{-6} )</td>
<td>( 1.1 \cdot 10^{-6} )</td>
</tr>
</tbody>
</table>

Table 4.3: Comparison of reflections calculated by effective index method and 2D FDTD code.

in the literature. The vertical interface is obtained by selective wet etching [133] or reactive ion etching [134]. On the other hand a combination of non-selective and selective wet etchants gives rise to an angled interface [135] with typical angles around 40°.
Figure 4.8: (a) Schematic cross-section and (b) 2D-FDTD simulation results for the vertical and angled butt-coupled interfaces.
4.4. Semiconductor Etching for a Butt Coupling Process

for reflections lower than $10^{-5}$ we can conclude that this interface geometry is not suited for application in MLLDs. On the other hand for the angled interface a reflections coefficient as small as $2 \cdot 10^{-6}$ was calculated over a large bandwidth. This value fulfills our requirement and is also consistent with the upper reflection limit of $5 \cdot 10^{-6}$ measured by Brenner and co-workers [29] for an angled interface. It is therefore mandatory to use angled interfaces to suppress multiple pulse formation in MLLDs.

Another important process requirement is the alignment of the core layers. Whereas the interface structure is relatively robust to simple vertical offsets up to 100 nm [135] we identified a severe performance degradation due to the bending of the light-guiding layers as shown in Fig. 4.9. The bending is due to material piling at the mask edges (see Sec. 4.5) during local regrowth epitaxy.

The 2D FDTD simulations shown in Fig. 4.9 demonstrate that this bending will produce high losses in the order of 5dB. High losses will prevent the use of a low-gain material with higher gain saturation energies, which are advantageous for MLLD operation [75]. Additionally the resulting reflectivity for the deformed interface of $3 \cdot 10^{-5}$ is above the multiple-pulse formation limit. Usually the reflection is calculated with reference to the incoming amount of light. But for the MLLD it is the reflected pulse which competes with the transmitted pulse. Thus if we also take into account that only 15% of the pulse energy is coupled into the absorber section we get an effective reflection at this interface of $2 \cdot 10^{-4}$ with respect to the transmitted intensity. Thus, we must expect multiple pulse operation from MLLDs with bent interfaces.

4.4 Semiconductor Etching for a Butt Coupling Process

The final MLLD process requires several etching techniques to define the different structure sections and the rib-waveguide. For the etching of III-V materials two main process families can be distinguished. The so-called dry-etching techniques, such as reactive ion etching (RIE), inductively-coupled reactive ion etching (ICP), reactive ion-beam etching (RIBE), and ion milling are based on plasma driven chemical reactions or energetic ion beams to remove material. Dry etching can provide a well-controlled and cost-effective solution for anisotropic etching. Espe-
Figure 4.9: a) SEM micrographs of butt-coupled interfaces and electric field from the 2D FDTD simulations of these butt coupled interfaces with severe bending (top) and without bending (bottom). (b) Intensity transmission and reflection for the two structures shown in (a).
4.4. Semiconductor Etching for a Butt Coupling Process

Especially etching perpendicular to the substrate surface to obtain vertical side-walls, can be easily performed [136]. Therefore we used a RIE etch process for material unselective laser rib processing. On the other hand, dry-etching techniques cannot provide atomically smooth epi-ready surfaces and their use must be avoided for the regrowth preparation or a wet etching step has to follow before regrowth.

The second kind of etching techniques relies on chemical solutions for wet etching, which can themselves be subdivided into two categories. The first category is the isotropic, so-called diffusion-limited etching. For diffusion-limited etching the diffusive transport of the etchants to or away from the surface of the etched material limits the etch rate. All wet-etching solutions are a priori diffusion-limited until they reach a material surface or crystal plane, with low or nearly zero etch rate for the particular etchant. Under this condition the etching process is called reaction-controlled and is material selective. This is the second category of wet-etchants. The use of etch stop layers which differ in the material composition from the etched material provides reaction-limited etching and hence a well-defined crystal plane for further MOVPE regrowth.

4.4.1 Etching of an Angled Interface

In Sec. 4.3, we have demonstrated that an angled butt-coupled interface is mandatory in terms of reduced reflections. We describe here the theoretical technological solution for obtaining the necessary interface. If this solution can be realized with chemical etchants and the relevant etching solutions are discussed in the following.

The etching of the inhomogeneous MQW-core layer and the UTC-core layer structures is demanding for both structures but identical. Therefore it is only described in detail for the MQW layer structure. To get the desired angled interface geometry several process steps are necessary. First, the MQW gain structure is grown as shown in Fig. 4.2 up to the 10nm thick n-doped InP cladding layer (layer 10). Instead of the doped InP cladding a 10nm thick Q1.1 etch stop layer, a 140nm thick sacrificial n-doped InP layer, and a 100nm thick n-doped InGaAs layer are grown on top (Fig. 4.10c). The purposes of these sacrificial layers are explained in Sec. 4.6 and the etching steps are similar applicable for the total MQW structures as shown in Fig. 4.2.

Afterwards a 450nm thick SiO₂ mask layer for etching and local regrowth is deposited by plasma enhanced chemical vapor deposition (PECVD).
The mask is then structured using a positive-tone photo resist lithography and subsequent reactive ion etching. The mask covers the MQW regions which will be the gain sections of the final MLLDs.

To obtain the desired angled interface the mask must be oriented so that the butt-coupled interfaces lay along the (110) crystal plane \cite{137} as illustrated in Fig. 4.11. The total mask coverage of the wafer is just a few percent and so we can neglect selective-area growth effects for most part of the wafer during the following local regrowths. This is important for the core layer stacks, because their exact thicknesses and material compositions determine the electrical and optical properties of the designed sections. After mask deposition and patterning the wafer is ready for a series of selective and unselective wet-etch steps. These are schematically explained in Fig. 4.10.

First, a selective etch of the top InGaAs layer is performed to get a reliable and reproducible mask under etch. At this stage of fabrication the mask undercut can easily be inspected with optical microscopy. Afterwards the underlying InP layer is etched selectively ending up with a 40° angled surface, determined by the crystal plane for the used HCl-based etchant \cite{138}.

Subsequently the quantum well layers are non-selectively etched away. This etch step will end in the lower InP etch-buffer layer, which buffers etch depth variations. Ideally this etching step will have the same crystal orientation behavior as the InP selective etch. Thus, the initially defined SiO$_2$ mask under-etch will remain constant and the ramped surface will be preserved. The curved bottom surface in Fig. 4.10d illustrates the diffusion-limited behavior of this etch step.

In a final step the lower InP buffer layer is etched selectively to the etch-stop layer (Fig. 4.10e). This procedure creates a well determined topology and an epi-ready crystalline surface for the following MOVPE regrowth step. In the next sections we will identify the best suited etchants for the fabrication of the angled interface.

### 4.4.2 Material-Selective Wet Chemical Etching

For the selective InP etching a HCl-based etching solution as described in \cite{138} was utilized. Since concentrated HCl has very high etch rates of 250nm/s, it was diluted with de-ionized water at a ratio of HCl:H$_2$O=4:1 volume parts and etching was performed at 0°C. By etching with an ice-water bath cooling we can avoid etch speed variations due to temperature
4.4. Semiconductor Etching for a Butt Coupling Process

7. 100nm InGaAs mask under etch layer
6. 140nm InP etch stop and clean up layer for further regrowths
5. 8nm Q1.1 etch stop for laser rib etching
4. 50nm InP optical cladding layer
3. MQW SCH layer structure = layer 6-9 in Fig. 4.2

2. 490nm InP etch buffer layer
1. 8nm Q1.1 etch stop = layer 4 in Fig. 4.2

(a) MQW layer structure

(b) selective mask under etch
(c) selective InP etch
(d) unselective etch of the MQW layers
(n) InP selective etch

Figure 4.10: Schematic illustration of the etching procedure needed to create a well defined tilted interface for low optical reflections.
Figure 4.11: Correlation of the mask orientation and the resulting etching characteristics.

Differences in the lab. The dilution and the low temperature results in etch rates of 2nm/s and typical etching durations of 1-5min for 100-500nm layer thicknesses. For such etching durations we can neglect wetting and handling times during processing.

The underlying chemical process is the dissolution of InP into indium chloride and phosphine.

\[
InP + 3HCl \rightarrow InCl_3 + PH_3
\]

Due to the crystal-orientation dependence of the HCl-based etchants [137] the mask orientation must be chosen carefully to obtain the desired etching profiles. For the process used in this thesis two directions are important as indicated in Fig. 4.11.

In the (110) plane almost vertical side-walls can be etched. This etching behavior is used to etch well-defined laser rib structures down to an underlying etch stop layer. However perpendicular to the (110) plane we get 40° angled surfaces corresponding to an intermediate surface between the (111) and (211) crystal planes. This crystal plane is composed of In-atoms only and is inherently stable because of the anisotropic bonding structure of the zinc-blende crystal [29].

On the other hand, a large lateral etching rate is obtained in the (010) direction. Therefore, to avoid mask under etching of the rib waveguides...
in a latter step the design of the SiO$_2$ etching mask has to consider this orientation-dependent etch rate as shown in Fig. 4.12. At the mask edges along the (010) direction the masked area is extended to avoid etching into the final rib-waveguide region.

The selectivity of HCl against any kind of InGaAsP composition is reported [137] to be infinite because quaternary material etchants require oxidants in the etching solution. Indeed, a 5 minutes long etch of an 8nm thick Q1.1 layer results in no measurable etching rate.

As a second material-selective etchant sulfuric acid based solutions are used to remove InGaAs and InGaAsP composites selectively to InP. Sulfuric acid can only dissolve oxidized semiconductor material. Therefore a mixture of H$_2$SO$_4$:H$_2$O$_2$:H$_2$O=3:1:1 is required, whereby H$_2$O$_2$ oxidizes the semiconductor and subsequently the oxides are dissolved by sulfuric acid. To keep the etching conditions reproducible we also performed this step at 0°C.

The etch rate depends on the bandgap of the used InGaAsP material and decreases logarithmically with increasing bandgap from InGaAs to InP [29]. Thus the etching selectivity depends also on the used material. For the process presented in this thesis we only had to etch Q1.3 selectively to InP. The selectivity for these two materials is 100, i.e., no noticeable etching of the InP material is expected.
4.4.3 Material-Unselective Wet Etching

In order to etch layer stacks with inhomogeneous compositions, such as the quantum wells embedded into a SCH structure or the UTC light-guiding layers, a material unselective etchant has to be used. For these etching steps not only the etching non-uniformity over the wafer but also the etch-rate differences far away and in the vicinity of masked regions have to be considered. The situation and resulting etching profile is schematically presented in Fig. 4.13.

The etching differences are due to the local depletion of reactive etchants in the solution. The etching-speed variations can be quantified by the ratio $SD = \frac{b}{a}$ of the etching rates near the mask $b$ and far away from the masked area $a$ (see Fig. 4.13). This etching behavior can be reduced by stirring the wafer in the solution. The minimal thickness of the InP etch-buffer layer below the inhomogeneous layer stacks is determined by the ratio $SD$. For an unselective etch depth $l$ the buffer layer has therefore to be $l_{th} = SD \cdot l$ thick, neglecting any additional etching inhomogeneities over the processed wafer.

To etch an angled interface into the inhomogeneous layers, the ideal etch solution has to be material unselective and crystal orientation selective, similar to HCl-based etchants for InP. Whereas [29] used a solution containing HBr for this critical step, [28] used a solution based on acetic acid and hydrochloric acid often called a KKI-etch.

Since our demands for the interface reflections and losses in a MLLD...
4.4. Semiconductor Etching for a Butt Coupling Process

are higher than for any devices processed by [29, 28] we investigated the possible etching solutions for this etch step in detail. Clawson presented a comprehensive summary of all reported wet etching solutions for III-V semiconductor materials [139]. Tab. 4.4 summarizes all non-selective etching solutions relevant for the materials used for this thesis. Each solution is assigned by a short, concise name used in the remaining of this chapter.

<table>
<thead>
<tr>
<th>etchant</th>
<th>dedicated name</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃COOH:HBr:K₂Cr₂O₇=1:1:1</td>
<td>BCK</td>
</tr>
<tr>
<td>CH₃COOH:HBr:K₂Cr₂O₇=1:1:3</td>
<td>BCK113</td>
</tr>
<tr>
<td>HCl:HNO₃=1:1</td>
<td>CN</td>
</tr>
<tr>
<td>HBr:H₂O₂:H₂O</td>
<td>BHOH</td>
</tr>
<tr>
<td>HCl:H₃PO₄:H₂O₂</td>
<td>CPH</td>
</tr>
<tr>
<td>CH₃COOH:HCl:H₂O₂=200:80:16</td>
<td>KKI</td>
</tr>
</tbody>
</table>

Table 4.4: Chemical formulae for material-unselective etchants and dedicated names used in this chapter.

The first three solutions in Tab. 4.4 (BCK, BCK113, and CN) were not used for butt-coupled processes so far. An experiment by directly non-selectively etching an adapted UTC structure (Fig. 4.14a) covered with a patterned SiO₂ was used for the feasibility study. The first two etching steps described in Fig. 4.10, the InGaAs and InP-selective etching steps for the definition of the mask undercut were omitted. This increases the thickness which is etched material unselectively and simplifies the interpretation of the results.

For this experiment the SiO₂ mask was etched with a hydrofluoric acid (HF) solution resulting in frayed and thinned mask borders. However, this mask border does not influence the vertical etching behavior.

With this experiment we can directly answer the following questions regarding the requirements introduced in Sec. 4.4.1, without resorting to a time-consuming butt-coupling experiment including regrowth:

- Is the etching rate appropriate for a manual and reproducible handling?
- Is the etchant material un-selective?
- Is the mask under-etch negligible as desired?
• Does the crystal axis dependency of the etch rate allow us to etch the desired angled interface?

• Does the \(SD\) value allow for a thin buffer layer?

Fig. 4.14 depicts the SEM micrographs of the cleaved vertical structures for the different etching solutions. To characterize the etch results we measured the etch-rate, the \(SD\)-parameter, and the \(SiO_2\)-mask under etch (Tab. 4.5). The mask under etch ratio is determined as the ratio of the mask under etch over the deepest vertical etch near the mask.

<table>
<thead>
<tr>
<th>etchant</th>
<th>etch rate [nm/s]</th>
<th>(SD)</th>
<th>under etch [(\mu m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCK</td>
<td>30</td>
<td>4</td>
<td>1.18 (1)</td>
</tr>
<tr>
<td>BCK113</td>
<td>20</td>
<td>1.4</td>
<td>2.4 (2)</td>
</tr>
<tr>
<td>CN</td>
<td>12</td>
<td>1.34</td>
<td>0.9 (1)</td>
</tr>
</tbody>
</table>

Table 4.5: Etching parameters for the BCK, BCK113 and CH etchants

The BCK etch results in a smooth surface with no noticeable material selectivity. Also the etched angled facet looks promising to be used for angled interfaces. Unfortunately the \(SD\) value is very high as well as the etching rate. Also the mask under-etch is undesirable for our etching process. Since [140] reported increased etching rates by decreasing the amount of \(K_2Cr_2O_7\) in the BCK solution, we tried to lower the etching rate by increasing the volume parts of \(K_2Cr_2O_7\), resulting in the BCK113 etch. However this etchant is no longer material unselective as can be seen from the large under-etch of the InP layer in comparison to the upper InGaAs layer (Fig. 4.14c).

Finally the \(HCl:HN_3\) solution has an acceptable etching rate but a relatively high \(SD\) value and an undesirable mask underetching. In addition, two different crystal orientation dependencies for InP and quaternary material can be identified for this etchant. Hence we can exclude all three etching solutions for our butt-coupling process and focus on more conventional etchants.

For the BHOH, CPH and KKI solutions which were already used for butt-coupling processes an adapted MQW structure (Fig. 4.15a) was...
4.4. Semiconductor Etching for a Butt Coupling Process

Figure 4.14: (a) Schematic of the masked UTC structure ready for non-selective etching. (b)-(d) SEM micrographs of the cleaved cross-section of the etched UTC layer structure after non-selective etching with different solutions for 30s (b and c) and 40s (d).
prepared with a patterned RIE-etched SiO₂-mask. Furthermore the two first selective etching steps as described in Sec. 4.4.1 were performed (Fig. 4.15a) with a resulting mask under-etch of 0.94 μm.

Fig. 4.15 presents the resulting etching profiles in the (110) plane for the BHOH, CPH, and KKI solutions.

To characterize these etching processes the increase of the mask under-etch, the etching rate and the $SD$ parameter were measured and summarized in Tab. 4.6.

<table>
<thead>
<tr>
<th>etchant</th>
<th>etch rate [nm/s]</th>
<th>$SD$</th>
<th>increase of mask under-etch [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHOH</td>
<td>5</td>
<td>1.28</td>
<td>0.19</td>
</tr>
<tr>
<td>KKI</td>
<td>10</td>
<td>1.24</td>
<td>0.04</td>
</tr>
<tr>
<td>CPH</td>
<td>0.8</td>
<td>1.03</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 4.6: Etching rate, diffusion limiting characteristic $SD$ and under-etch increase for different etching solutions.

Fig. 4.15b shows a small discontinuity in the etched facet indicating a non-ideal crystal plane selectivity for the BHOH etchant. The CPH solution is material selective as is visible in the large under etch of the InGaAs layer under the mask in Fig. 4.15d. This also explains the good $SD$ value near one as the underlying InP layer behaves as an etch stop. To conclude we can adhere that the most appropriate homogeneous and flat ramp was obtained with the KKI solution. The etching rate is manageable and the $SD$ factor small enough. An additional benefit from the KKI etch is the negligible increase of 40nm of the mask under etch which is therefore mainly determined by the first selective etch step presented in Sec. 4.4.1. At this stage of the etching procedure the under-etch is easier to control. Since the underlying etched surfaces are less complex at this state of processing the undercut can be easier verified by optical microscope inspection. To summarize, the KKI etch is most appropriate to process angled interfaces for low reflectivity butt-coupled waveguide transitions.
Figure 4.15: (a) Schematic of the MQW structure before material unselective etch. (b)-(d) SEM micrographs of the cleaved cross-section of the etched MQW layer structure after non-selective etching with the corresponding solution.
4.5 Regrowth Process

In the previous sections, we have seen that an angled interface is essential for low reflections. Such an interface can be obtained by a combination of material and crystal-orientation selective and non-selective etching steps. In this section, we present the regrowth process itself. The challenges regarding wafer preparation, mask under-etch, growth pressure and growth rate inhomogeneities are addressed.

4.5.1 Wafer preparation

To obtain high quality regrown layers, the wafer has to provide a very clean and crystallographically well-defined surfaces. The etching procedure described in Sec. 4.4.1 is sufficient to provide a suitable wafer surface if the wafer is rinsed after the last step at least 15 min with de-ionized water and dried on an eccentric spinner. Nevertheless for regrowth without a sacrificial clean-up layer the following two-steps cleaning procedure is mandatory: (i) 30 sec long dip in concentrated sulfuric acid (ii) at least 10 min rinse in de-ionized water.

Dirty wafer surfaces due to photo-resist or etchant residuals, result in a regrowth with an amorphous layer structure especially for quaternary material. The InP growth compensates the inhomogeneities after a growth thickness of 200 nm. This was confirmed by EPIRAS [141] measurements during regrowth (Fig. 4.16). For the EPIRAS measurements a laser beam was focused onto the wafer surface and its backscattered reflection was measured and analyzed.

Fig. 4.16 presents the reflectance signal for a clean and a contaminated wafer surface during the regrowth of the p-doped cladding layer which consists of a 1300 nm thick InP layer and the contact layer stack as shown in Fig. 4.2 and Fig. 4.3. The growth of the InP layer starts after ca. 500 seconds and shows up as interference fringes in the EPIRAS signal for the clean wafer. On the contrary for the dirty wafer the reflectance signal collapses to zero indicating a very rough and hence amorphous surface, which heavily scatters the incident EPIRAS light into all directions. After a growth time of additionally 1000s the signal has fully recovered and the signals for the following layers show the expected interference fringes.
4.5. Regrowth Process

Figure 4.16: The reflectance signal of an EPIRAS detector for a p-doped cladding regrowth on a (a) clean and (b) not sufficiently clean patterned wafer.

Nevertheless the optical inspection with a microscope reveals growth disturbances as is shown in Fig. 4.17.

An other problem is the cleanliness of the SiO$_2$ mask. Remaining dust or dirt catalyze the growth of up to 10µm high local semiconductor crystallites. These crystallites can be removed with an additional etch step as long as they are not too close to the mask borders [28]. For crystallite removal the photo-resist covering the non SiO$_2$ masked areas has to overlap with the SiO$_2$ mask. Therefore also the crystallites at the
SiO₂ mask borders are covered and are protected during etching.

4.5.2 Local Regrowth Process Parameter

Challenge of Enhanced Local Growth Rates at Mask Borders

It is well known from selective-area growth processes that the global and local dimensions of the mask pattern have an impact on the growth properties. For the butt-coupled regrowth process, however, the total mask coverage of the wafer is only a few percent and so we can neglect selective-area growth effects for the most part of the wafer. This is particularly important for the MQW and UTC light-guiding layers because the thicknesses and material compositions determine critically the electrical and optical properties of the design.

At the mask edges on the other hand, these growth effects alter the material homogeneity and designed structure. The diffusion of the growth species over the masked areas results in a material piling at the mask border as shown in Fig. 4.18. If this material piling is severe the regrown layer stack can overshoot the SiO₂-mask.

![Figure 4.18: (a) an ideal regrowth with a planar interface and (b) a non-ideal regrowth with material piling resulting in non-planarity.](image)

To obtain a planar regrown surface at the interfaces we investigated the influence of the mask under-etch and the MOVPE chamber pressure on the material growth rates far away and in the vicinity of masked
4.5. Regrowth Process

Figure 4.19: Schematic drawing of a etched MQW layer structure with SiO$_2$ etching and regrowth mask, indicating the important regrowth parameter: mask under-etch and MOVPE pressure. The growth rate at the mask edge is denoted as $R_1$, the reference growth rate 2mm away from masked areas as $R_0$.

Mask Under-Etch

In contrast to selective-area growth the butt coupling process offers an additional parameter to reduce material piling: the under-etch of the mask. From the point of view of the regrowth this mask under-etch can be seen as a mask overhang, so we will refer to it in the following as the mask overhang $L_{over}$. Fig. 4.19 illustrates the important parameters for a regrowth at the interface to an etched MQW layer stack.

To compare different experiments with different total layer stack thicknesses the growth rate $R_1$ at the mask border is normalized to the nominal growth rate $R_0$ 2mm away from the masked areas. It is commonly assumed that at a distance of 2mm any local border effects can be neglected for MOVPE growth [142]. The growth rate far from masked areas is of course the intentionally grown layer thickness.

Since on the angled surface (IJI plane) the growth of InP is strongly inhibited and the growth of quaternary material is nearly zero [29, 143], due to a low atomic sticking coefficient, we can neglect the influence on the potential material piling of the growth on the angled interface. The material piling is mainly caused by the growth rate $R_1$. Hence $R_1$ and $R_0$ are sufficient to characterize the growth behavior at the mask border. Fig. 4.20 presents the growth overshoot at a growth pressure of 160mbar for different mask overhangs for the regrowth of passive waveguide stacks.
as shown in Fig. 4.4 butt-coupled to a MQW and UTC layer stacks respectively.

Figure 4.20: Material piling for different mask overhangs for a MOVPE chamber growth pressure of 160mbar.
4.5. Regrowth Process

In contrast to the results given in [29] we could not observe the vanishing of the overshoot for large $L_{over}$. Even worse, for $L_{over} > 1.6 \mu m$ the material piling reaches the mask edge before the space under the mask is filled completely which leaves a hole under the mask (Fig. 4.21). This hole will lead to internal reflections and severe optical losses in the waveguide.

**MOVPE chamber Pressure**

The main difference of the regrowth process presented in this work in comparison to the process reported by Brenner [29] is the MOVPE chamber pressure. They used a reactor with a smaller volume and could therefore limit the growth pressure to 20 mbar. With these conditions they could grow homogeneous and planar interfaces even for very thick layer stacks with an optimized mask overhang. However the minimum achievable chamber pressure for our MOVPE system is 30 mbar. Therefore we investigated the regrowth of passive-
waveguide layer stacks as shown in Fig. 4.4 on MQW layer stacks and compared them with the results for 160 mbar which is the standard growth pressure for our system. Fig. 4.22 summarizes the results for 160 mbar and 30 mbar growth pressures.

![Image](image-url)

Figure 4.22: Material piling for 30 mbar and 160 mbar chamber pressure as a function of mask overhang.

Also for 30 mbar the material piling $R_1/R_0$ decreases continuously with increasing $L_{over}$ (Fig. 4.19). For a $L_{over} > 2 \mu m$ we get a ratio of 1 at 30 mbar chamber pressure. However also here the material does not fill the area under the mask completely. The remaining hole may result in increased optical reflections and losses.

In order to explain the growth rate dependence on the pressure we applied a theory developed by T. Fujii et al. [144] which describes the growth rate for selective-area growth. This theory is based on a two-dimensional description of the growth-species diffusion on the mask and the epi-layer surface.

For our regrowth geometry the distance between the individual devices and hence the open width between masked areas is much larger than the expected diffusion length $L_D$ of the growth species. As explained in [144] the growth rate $R(x)$ at the distance $x$ from the mask border can
then be described with the following function:

\[
\frac{R(x)}{R_0} = \frac{R_i - R_0}{R_0} \exp \left( -\frac{x}{L_D} \right) + 1
\]

(4.3)

The diffusion length \( L_D \) on the semiconductor epi-layers can be fitted to the measurements as shown in Fig. 4.23 for both chamber pressures, 30 and 160 mbar.

Figure 4.23: Lateral growth enhancement for 30mbar and 160mbar with fitting by Eq. 4.3.

The growth rates \( \frac{R(x)}{R_0} \) near the mask \((x < 10\mu m)\) were measured from SEM micrographs whereas for \( x > 10\mu m \) a stylus force tool (alpha-step) was used. This can explain the slight mismatch in the two data-sets at \( x = 10\mu m \).

First of all we can conclude from Fig. 4.23 that the material piling effect is negligible at distances to the mask greater than 40\( \mu m \). So to measure \( R_0 \) at a distance of 2\( \mu m \) is a posteriori verified.

The absolute growth enhancement decreases with decreasing chamber pressure. This is confirmed by experiments for selective area growth [145].

Fitting equation (4.3) to the measurements as shown in Fig. 4.23 results in diffusion lengths of 3.6\( \mu m \) and 5.3\( \mu m \) for 30mbar and 160 mbar respectively.

On the other hand the reported diffusion lengths for the selective-area growth technique [145] have an opposite correlation to the pressure and are much larger (75\( \mu m \) and 25\( \mu m \) for 30mbar and 100 mbar, respectively). Whereas the overall much smaller diffusion length for our butt-
coupled regrowth process can be caused by the mask overhang, which creates a discontinuity for the migrating species, the difference in the correlation to the pressure remains unclear. Unfortunately the details of the growth conditions are not reported in [145] and therefore we can not compare these parameters. It must however, be borne in mind that the MOVPE growth process is a complex thermodynamical and chemical reaction far away from thermodynamical equilibrium. No quantitative model to describe the crystal formation for patterned substrates was presented so far.

Nevertheless, we attempt at giving a qualitative explanation for the observed behavior of the material piling for different chamber pressure. For this, we refer to the ideal gas theory. In this theory the density of molecules \( n_v \) is proportional to pressure \( P \):

\[
n_v = \frac{N_A}{RT} P.
\]  

(4.4)

where \( N_A \) is Avogadro's number, \( T \) the temperature and \( R \) the universal gas constant. Therefore five times more growth specimen are available for 160mbar chamber pressure per volume than for 30mbar pressure. Since the diffusion lengths are more or less equal for both pressures, the species of the same volume above the mask can diffuse to the mask border and influence the material piling. Therefore we will expect five times more material at the mask border for 160mbar than for 30mbar. The total material piling can be measured as the area under the curves of Fig. 4.23 above the \( \frac{D}{P} \) = 1 line. This procedure results in a measured material piling ratio \( MPR \) of 3.6 between 160mbar and 30 mbar chamber pressure. From ideal gas theory we expect five times more growth specimen per volume for 160mbar compared to 30mbar:

\[
\frac{n_v^{160\text{mbar}}}{n_v^{30\text{mbar}}} \approx 5
\]

(4.5)

Assuming that the volume which is relevant for the material piling is determined by the diffusion length \( Dl \) on the \( \text{SiO}_2 \) mask we get for the material piling ratio:

\[
MPR = \frac{Dl^{160\text{mbar}}}{Dl^{30\text{mbar}}} \frac{n_v^{160\text{mbar}}}{n_v^{30\text{mbar}}}
\]

(4.6)

With Eq. 4.5 we can calculate a diffusion length ratio of \( \frac{Dl^{160\text{mbar}}}{Dl^{30\text{mbar}}} \approx 0.7 \). Thus the expected inverse correlation of the diffusion length to the cham-
4.5. Regrowth Process

Her pressure is recovered. Therefore we can assume that the diffusion length on the semiconductor epi-layers is mainly caused by the complex three dimensional surface topology. Nevertheless we can conclude that the higher availability of growth specimen for higher pressures can explain the larger material pilling at higher pressure.

This tendency is further supported by the growth results of metal-organic molecular beam epitaxy (MOMBE) or chemical beam epitaxy (CBE) techniques operating with UHV chamber pressures. The UHV-condition result in a very low density of growth species above the mask and hence no observable material piling. These growth methods demonstrated already the total absence of growth enhancement at mask borders [146, 147]. Thus, low pressure growth is advantageous for butt-coupled regrowth processes.

The benefits of using a low regrowth chamber pressure in terms of material piling are obvious. Unfortunately the growth conditions for quaternary layers change dramatically at 30mbar chamber pressure in our reactor between structured substrates and blank ones. In fact, the quaternary layers growth is disturbed if we grow thicker than 400nm as can be seen in Fig. 4.24. Quaternary material is more sensitive to the exact material composition and growth species delivery. Therefore it is more complex to find the required growth parameters. The local specimen concentration seems to be more sensitive to different substrate surface topologies for lower pressure.
Figure 4.24: SEM micrograph of a regrown passive-waveguide structure at 30mbar MOVPE chamber pressure. The etch stop was enhanced with a white line to underline the start of the regrowth. The disturbance in the quaternary layers is clearly visible. The irregularities in the top Q1.3 layer is due to the applied x-y etch to uncover the layer structure for SEM inspection.

From selective area growth experiments it is known that not only the growth rate changes for masked areas but also the composition of the grown material [148]. From the presented experiments we conclude that this effect is more severe for lower pressure in our reactor.

Conclusion for Regrowth Process
To summarize we have identified the following important influences on the regrowth process:

- Material piling at the mask border can heavily disturb the waveguide alignment and the planarity of the wafer surface. The latter will prohibit the required accuracy in the following photolithography processing steps.

- Mask under-etch is important and can partially suppress the material piling. However for thick layer stacks at standard 160mbar chamber pressure even a large overhang does not prevent pile-up. In addition a hole occurs under the mask because the material piling closes the volume before it is filled completely.
Figure 4.25: **Split-Growth concept**: the three layer stacks for the gain, absorber and passive-waveguide sections. The horizontal thick line indicates the split of the regrowth process into two main parts: the core layers growths and the cladding layers growths. In addition the arrow depicts the etch-depth of the rib for the vertical light confinement.
• In addition the growth chamber pressure has a strong impact on the growth conditions and a lower pressure at 30mbar will be advantageous.

• But: quaternary layers do not grow on structured wafers in the required quality at 30mbar in our MOVPE system.

**Final Split-Growth Regrowth Procedure** To take advantage of the improved growth conditions at 30mbar we decided to grow the thick binary InP layers on masked substrates (indicated in Fig. 4.25) at 30mbar and all other layers at 160mbar. However this procedure is still not sufficient to prevent a mask overshoot completely. Non-planar surfaces will inhibit the further rib-waveguide processing steps which rely on precise contact mask lithography. Therefore to lower the absolute growth overshoot we split up the epitaxy into two main sequences as indicated by the thick horizontal line in Fig. 4.25. Thus only a reduced-thickness layer stack is grown at each step.

In a first step, the core layer structures are grown and in a second step the thick doped and undoped upper cladding layers for the optical confinement are added. The overall epitaxial process thus consists finally of five growth steps: 1st MQW-gain core, 2nd UTC-absorber core, 3rd passive WG core, 4th undoped upper cladding, and 5th doped cladding. As we will show in the next section, this will reduce the unevenness of the final surface from one to two micro meters to an acceptable level below 200nm.

Also the etching procedure will benefit from this split-growth concept as explained in Sec. 4.6.2.

On the other hand the demands for the processing especially on the cleanliness in an university laboratory are pushed to the limit.

### 4.6 MLLD Butt Coupling Process

So far we have shown that the main challenge for the butt-coupling process is the prevention of the material piling at the mask borders. Thus we have to split up the growth into the core layer growth sequence and the subsequent addition of the cladding layers. In the following,
we present the details of the process and further considerations for the design of the final device geometry are given.

### 4.6.1 Device Geometries

The lithography mask design incorporates different lateral ordering of the gain, absorber and passive waveguide structures with different lengths to investigate the influence of several device geometries. Furthermore, it was not clear at the beginning, to which level the loss and the reflections can be reduced at the interfaces.

MLLDs were designed for 80GHz, 40GHz and 10GHz repetition rates corresponding to total cavity-lengths of 0.5mm, 1mm and 4mm respectively. The absorber sections were varied with length of 30µm, 70µm, and 100µm. In fact, we have demonstrated that the saturation energy of the absorber is influenced by the detuning of its band edge with respect to the peak emission wavelength of the MQWs [94]. Therefore we can compensate for the uncertainties in the grown material by choosing the appropriate absorber length. The gain sections had lengths of 300µm, 500µm, and 1000µm to investigate the influence of noise due to spontaneous emission and self phase modulation as well as the saturation energy as explained in Chap. 3.

The different lateral ordering of the three structures (see Chap. 2) motivated us to develop a new regrowth scheme with totally five growth steps as already mentioned in the last section. The process described in [28] uses always a passive waveguide section between different active sections. In contrast, our process was developed to support both, three-sections MLLDs and two-sections MLLDs (absorber and gain sections only) on one wafer. The latter design is especially useful for MLLDs with 40GHz and 80 GHz repetition rates because the overall device length will not necessarily require the integration of an additional passive-waveguide section.

In addition to the MLLDs several test devices were processed on all wafers. To characterize the gain sections, normal edge-emitting Fabry-Perot lasers with lengths of 500µm, 1000µm, and 1500µm were fabricated with rib width of 2.5µm (Chap. 3).

To test the UTC-absorber performance with pump-probe and absorption measurements [94] 10, 15, 30, 50, 70, 100, 150, and 200µm long absorber sections were embedded in passive waveguide sections. The output facet reflectivities are reduced by tilting the rib waveguide to the cleaved facet. The embedding of the absorber into passive waveguides
ensures that the sub-300μm long sections can be characterized because they are too short to be directly cleaved and handled after processing. The reflectivity and losses of the internal interfaces were investigated by measuring the residual optical spectrum ripples of 300μm, and 500μm long gain sections embedded in passive waveguide sections (Sec. 4.7). These devices have also tilted output facets.

4.6.2 MOVPE Layer Growth on the Substrate

To successfully split up the growth process into five steps several additional layers for etch stops and clean-up and different etching procedure are necessary and will be described in the following. All layers were grown lattice-matched on a n-doped (n=3·10^{18} cm^{-3}) InP substrate with a diameter of two inches. The substrate has a single-sided, epi-ready polished surface with a (001) crystal orientation.

To get a general idea of the total growth and regrowth process, Fig. 4.26 summarizes the necessary etch and growth steps for the definition of the final MQW, absorber and waveguide sections on the wafer. In the following we will discuss the individual steps in more detail. The shown schematics of the layer topologies are rough estimations based on the experience with SEM micrograph inspections.

Since of its potentially high sensitivity to non-planar surfaces we first grow the MQW gain material core layer stack (Fig. 4.25). The photoluminescence emission peak wavelength of the quantum wells is intentionally red-shifted by 30nm to compensate for group V element inter-diffusion and a resulting blue shift during the subsequent growth steps (Chap. 3).

**MQW Core Layer Stack**

To adapt the MQW-layer stack to the split-growth procedure, we stop the growth of the p-doped optical cladding after 40nm (layer 12 in Fig. 4.27) and add a 10nm thick Q1.1 etch-stop layer for the following clean-up layer and the rib-waveguide formation as shown in Fig. 4.27. The following 140nm thick InP layer is needed as a clean-up layer for the last p-doped optical cladding growth (Fig. 4.26 l)) and to planarize the MQW-stack to the height of the following core layer stacks. Furthermore it serves as the etch-stop of the clean-up for the undoped cladding growth (Fig. 4.26 i)). The final 100nm-thick InGaAs layer is used to define the mask under-etch as described in Sec. 4.4.1. In addition it will be
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Figure 4.26: Overview of the process flow for the layer definition.
g) 3rd growth WG layer

h) SiO₂ removal

i) 4th growth undoped cladding

j) SiO₂ deposition

k) wet etching

l) 5th growth p-doped cladding

Figure 4.26: Overview of the process flow for the layer definition (cont'd).
4.6. MLLD Butt Coupling Process

Figure 4.27: Core layers of the MQW structure grown onto the blank wafer.

used as a clean-up layer for the undoped cladding growth (Fig. 4.26 i)).

The laser gain sections are then masked with a 400nm-thick SiO₂ layer for partial etching of the MQW-stack and selective-area regrowth of the UTC-absorber core layers. Fig. 4.28 schematically shows the etched gain material down to the upper etch stop layer for the core layer regrowth. The etching was performed as described in Sec. 4.4.1 to get the desired ramped interface.

**UTC Core-Layer Stack**

The core UTC layer stack is then grown on the upper etch stop layer of the MQW structure as shown in Fig. 4.29 and Fig. 4.26 d). Here we can use the 40nm thick mode-centering layer (layer 6 in Fig. 4.29) also as an etch stop for the clean-up layer prior to the final p-doped cladding growth and the rib-waveguide etch. Therefore only two additional non-intentionally doped layers are required for the following etching and growth procedure. These layers have the same functionality as the InP and InGaAs top layers for the MQW structure, namely as clean-up layers prior to the regrowth of the p-doped and undoped cladings, respectively.
Figure 4.28: MQW core layer stack with SiO$_2$-mask after mask patterning and wet chemical etching. The base-line represents layer 4 from Fig. 4.27

Prior to the second regrowth, all active sections (UTC-absorber and gain) are covered with a SiO$_2$ mask. As shown in Fig. 4.30 and Fig. 4.31 the masked areas on top of the MQW layers are designed to be smaller than the previous masked regions in order to remove any remaining inhomogeneity at the UTC-MQW interfaces when a gain-passive waveguide interface is required.

The absorber remove etching process is similar to the gain-section etch and will result in the structure schematically shown in Fig. 4.26 f) and Fig. 4.32.

Nevertheless this second etching step is a potential source of failure as the material topology of the UTC regrowth can prohibit the removal of the UTC structure as is demonstrated in Fig. 4.32 and Fig. 4.33. Indeed, if the material piling at the mask borders results in very thick Q (Fig. 4.31) layers of the regrown UTC structure, the heterogeneous active layers of the UTC structure can not be etched completely with the material unselective etch (Fig. 4.29). Hence the residuals of the Q layer in Fig. 4.31 will act as an etch stops for the last selective InP etch as is shown in Fig. 4.32 and Fig. 4.33 a). The remaining mesas will furthermore disturb the subsequently grown waveguide core layers, resulting in high optical losses at these waveguide disruptions.

From the perspective of etching, the InP buffer layer must be as thick as possible to tolerate any etching rate differences. In contrast to this requirement the perspective of growth requires a thin InP buffer-layer to maintain the absolute material piling during regrowth of the UTC-absorber small.

Given these two contradictory requirements, we have to optimize carefully the thickness of the etch-buffer layers. Considering Fig. 4.32, it is evident that the subsequent MQW-passive waveguide interface is the
### 4.6. MLLD Butt Coupling Process

#### UTC Core Layer Stack

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>430 nm InP</td>
<td>Si $2 \times 10^{19}$ etch buffer</td>
</tr>
<tr>
<td>2.</td>
<td>170 nm Q1.3</td>
<td>nid</td>
</tr>
<tr>
<td>3.</td>
<td>10 nm Q1.53</td>
<td>Zn $1.3 \times 10^{18}$</td>
</tr>
<tr>
<td>4.</td>
<td>40 nm Q1.53</td>
<td>Zn $2 \times 10^{17}$ mode centering and etch stop</td>
</tr>
<tr>
<td>5.</td>
<td>110 nm InP</td>
<td>Zn $1.3 \times 10^{18}$</td>
</tr>
<tr>
<td>6.</td>
<td>40 nm Q1.3</td>
<td>nid etch stop and clean up</td>
</tr>
<tr>
<td>7.</td>
<td>120 nm InP</td>
<td>nid under etch and clean up</td>
</tr>
<tr>
<td>8.</td>
<td>100 nm InGaAs</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.29: Core layers of the UTC structure regrown onto the etch-stop layer of the MQW-stack as depicted in Fig. 4.25.

Figure 4.30: Top view micrograph of the masked wafer before etching for the second regrowth of the waveguide core layers. Left: passive-waveguide/gain section interface, right: gain-absorber and absorber/passive-waveguide interface. The final device interfaces are pointed out. (WG=waveguide)
Figure 4.31: Schematic of a cross-section of the layer structure after mask processing for the waveguide core layer regrowth.

Figure 4.32: Schematic of a cross-section of the layer structure after etching of the UTC-and MQW stacks selectively. A UTC residual remains due to incomplete removal of the quaternary layers during the unselective etch step.
4.6. MLLD Butt Coupling Process

Figure 4.33: SEM micrograph of a UTC-MQW interface after etching of the UTC stack for the waveguide core layer regrowth. (a): incompletely removed UTC layers due to material piling at the former MQW-UTC interface corresponding to Fig. 4.32, (b): fully removed UTC layers. The inset shows the damaged upper etch stop layer due to a too long etching time for the selective InP buffer removal etch.
most challenging one. The material unselective etch has to remove a thickness equal to the complete thickness of the MQW layer stack down to the InP buffer, because the second UTC layer (Q1.3) grows under the mask up to the top level of the MQW stack during the UTC growth (Fig. 4.29).

Assuming the worst case that the crystal facet orientation of the UTC quaternary layers under the mask overhang prohibit the etch of this growth artifact during the first two selective etches as is indicated in Fig. 4.32, we have to etch unselectively 550 nm deep (arrow in Fig. 4.29). Therefore, subtracting this etch depth for the regions where the two upper layers were removed selectively (see Fig. 4.32), we have already etched 240 nm deep in the InP buffer layer under the MQW SCH layers and 150 nm deep in the InP buffer layer of the UTC layer stack. For the following KKI etch we had determined an etch profile parameter of $SD=1.24$. This adds an additional 150 nm to the etch depth near the mask. Accounting for additional etch variation of 100 nm as was observed for a quarter wafer, the etch-buffer layer thickness for the MQW layer stack has to be at least 490 nm thick. The buffer layer of the UTC need not to be as thick as the core layers because they are thicker themselves. Its thickness is determined from optical mode-match considerations as is explained in Sec. 4.2.2.

The described problem would be even more severe if we regrow each structure in one step as presented in Sec. 4.2 as originally intended. Since the quaternary layers of the UTC structure will grow in this case up to the InGaAs contact layers as shown in Fig. 4.34 the InP etch-buffer layer has to be as thick as the arrows in Fig. 4.34, thus the buffer thickness shown in Fig. 4.34(b) would be not sufficient. This would result in severe core layer up-bending as discussed in Sec. 4.3 resulting in the collateral losses and reflections. Thus this problem was the main reason to split up the regrowth process into the core layer structuring and the subsequent cladding growths.

Waveguide Core Layer Stack

After this most demanding etch process the light-guiding layers of the passive waveguide consisting of a 300 nm-thick InP lower cladding and a 570 nm-thick InGaAsP core are grown as shown schematically in Fig. 4.35. On top of these layers we grow a 30 nm thick InP layer and a 90 nm thick InGaAs layer. The latter is used as a clean-up layer for the following growth step. The 30 nm InP layer remains as part of the optical InP cladding.
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Figure 4.34: Schematic of the UTC-MQW interface, which has to be removed for the WG-MQW interface: a) for the split-growth procedure (5 growth steps) and b) for the case of a simple three growth steps process.

As can be seen in Fig. 4.36 the little grooves visible in the inset of the SEM micrographs of Fig. 4.33b are completely planarized during this regrowth and no light scattering is expected.

Subsequently the SiO$_2$ mask is removed with a 5% HF solution and the InGaAs undoped top layers are selectively etched down to the underlying InP layers. This etch step yields an epi-ready surface and also planarizes the topological interface perturbations as can be seen in Fig. 4.37.

Undoped Cladding Layers

The undoped cladding layers are grown onto the whole mask-less two inch wafer (Fig. 4.37 and Fig. 4.26). These layers consist of a 1300nm thick InP layer and a 100nm thick Q1.3 layer. The latter is used to define the mask overhang for the following etching process and as an etch-stop for further processing. This growth step also planarizes the unevenness at the core-layer interfaces.

The last regrowth step for the p-doped cladding layers above the electronically active core layer sections (UTC-absorber and MQW-gain) differs conceptually from the regrowth steps so far. To avoid huge masked areas on the wafer and hence selective area growth effects, only small areas at the cladding interfaces are covered with a SiO$_2$ mask as shown in Fig. 4.38. For electrical isolation of the reversed-biased UTC-absorber section and the forward biased MQW-gain sections a 6μm wide stripe of undoped material is left between these structures (Fig. 4.39). It also serves as a protection of the core layer interface for the following etch
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WG core layer stack

4. 90nm InGaAs nid
3. 30nm InP nid
2. 570nm Q1.3 nid
1. 300nm InP nid

Figure 4.35: Schematic view of a cross-section of the layer structure after growth of the waveguide core layers.

Figure 4.36: Top-view micrograph of a wafer section with masked MQW area and regrown waveguide core layers. The growth artifacts at the horizontal mask borders are far away from future devices and will not disturb their performance.
4.6. MLLD Butt Coupling Process

**Figure 4.37**: Schematic of a cross section of the layer structure after growth of the waveguide undoped cladding layers. Furthermore the mask and the photo-resist for the subsequent etching steps are added.

**Figure 4.38**: Top view micrographs of the structured mask for the etching and regrowth of the doped cladding.
undoped cladding

Figure 4.39: Schematic view of a cross section of the layer structure after etching of the un-doped cladding.

processes.

For the selective etch of the Q1.3 layer all passive waveguide section are additionally covered with photo-resist overlapping with the SiO₂ mask (Fig. 4.37). Afterwards the photo-resist is cleared away and the second selective etch removes the InP layers above the active sections. Thus results in a structure depicted in Fig. 4.39.

Doped Cladding Layers

The p-doped upper optical cladding consists of a 1300nm thick InP layer, a band gap grading of 15nm thick Q1.1 and 15nm thick Q1.3 layers and a 170nm thick highly doped InGaAs contact layer. This layer stack is grown on top of the active layers but also the unmasked regions above the undoped cladding of the passive-waveguide sections (Fig. 4.40 not shown in Fig. 4.26). The doped cladding has to be removed later on above the undoped cladding to get a planar wafer surface for the following device processing. To this end the active sections are covered with photo-resist and the layers on top of the passive sections can be removed selectively as is demonstrated in the two micrographs of Fig. 4.41.

After the removal of the SiO₂ mask the wafer is ready for device processing (Fig. 4.42). The schematic represents all possible interfaces, to demonstrate the fabrication of devices with different section configurations. For instance if the structure is cleaved in the center of the MQW layer stack, we have on the left-hand side a MLLD with an absorber, passive waveguide, and gain section geometry and on the right-hand side a
Figure 4.40: Schematic view of a cross-section of the layer structure after growth of the doped-cladding layers.
Figure 4.41: Top: SEM micrographs of the cross-section of the wafer after growth of the doped cladding. The mask border and the interface of the undoped and doped cladding are highlighted with white lines. Bottom: top-view SEM micrograph after removal of the doped cladding above the passive waveguide sections before stripping the photo-resist.
MLLD consisting of a gain section and an absorber section. If the structure is cleaved in the WG region, on the right-hand side there will be a MLLD with an absorber, gain, and passive waveguide geometry (from right to left) and on the left side one half of an UTC test structure (UTC embedded in passive waveguides).

The following SEM micrographs (Fig. 4.43a-c) of the processed interfaces demonstrate the good crystallographic quality of the regrowth process. The overview cross-section is shown as cleaved, to demonstrate the crystallographic homogeneity. For the close-up cross sections the material was selectively etched with a X-Y-etch [28]. The X-Y-etch has an increasing etch-rate for increases Ga and As concentration in the material. InP is inert with regard to the X-Y-etch. Therefore the etch provides a material dependent surface profile which is then visible in the SEM micrographs. Also the crystallographic orientation determines the etching rates. This leads to holes and irregularities at the X-Y-etched butt-coupled interfaces as mainly seen in Fig. 4.43b) and c).

The MQW-UTC interface shows the largest bend-up of the light guiding layers, due to the thickest InP-buffer layer. However it is much less bent than the structure investigated in Sec.4.3 and we expect reflections in the order of $10^{-5}$ and low losses at the interfaces. The InP buffer layer for the WG regrowth is thinner and the core layer alignment is as perfect
as Fig. 4.9a) bottom which will result in reflections below $10^{-5}$ and negligible losses. The residual irregularities on the wafer surface are far away from the mode-profiles as shown in Fig. 4.5. Thus no additional losses must be considered as will be seen in the last section of this chapter.

### 4.6.3 Device Processing

In the previous section, the complex regrowth process for the monolithic integration of dissimilar structures for absorber, gain and passive waveguide sections was presented. In this section, the device processing is
Figure 4.43: SEM micrographs of the interfaces of a processed 2-inch Wafer (cont'd).
Figure 4.43. SEM micrographs of the interfaces of a processed 2-inch Wafer (cont'd).
explained. Several etch, metalization and passivation steps are required to obtain the designed rib-waveguide structure. The whole process consists of 14 photo-lithographic masks and the full processing requires two months work in the clean-room.

The device processing sequence is similar to the one described in [57] and [28] and summarized in Fig. 4.46. The details of used photo-resist, exposure time for photo-lithography, RIE etch process recipes, and further parameters are given in the appendix (App. B).

Fig. 4.47 shows a not-to-scale three-dimensional view of a processed MLLD with an absorber, gain, and passive-waveguide geometry. This device corresponds to the vertical cross view shown in Fig. 4.42 observed from right to left up to the passive waveguide section. The n- and p-contacts provide at their ends a 50Ω co-planar waveguide for high frequency contacting. The dotted lines at the front n-contact indicate the extension of the n-contacts behind the passivation down to the n-doped substrate.

P-Contact
To avoid further oxidation and contamination of the highly-doped top InGaAs contact layer the first process step is the evaporation of the p-contact metalization for the gain and absorber sections (Fig. 4.46 a) and b)). The metalization consists of a layer stack of 5nm Pt, 15nm Ti, 40nm Pt, 100nm Au, and 10nm Ti and provides an ohmic contact with a resistance of 1-10⁻⁶Ωcm² (in good agreement with literature[149]).

Subsequently the metalization is annealed at 390°C for 30 seconds with a rapid thermal annealer under nitrogen atmosphere at a pressure of 2mbar. Although this annealing step did not improve the contact resistance [150], it improves the adhesion between the metal layers and the semiconductor. This is necessary to avoid tearing away the metalization during later removal of the rib-SiO₂-mask with a HF-solution.

Fig. 4.48 shows a top-view micrograph of the processed p-contact for a MLLD structure with absorber, gain, and passive waveguide (WG) geometry. The UTC absorber and the MQW gain are separated by a 6μm wide undoped-cladding structure.

Rib Mask
The next process step is the deposition and patterning of a 200nm-thick
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- **a)** P-contact after photolithography & evaporation
- **b)** P-contact after liftoff & RTA
- **c)** SiO$_2$ deposition by PECVD
- **d)** Photolithography & SiO$_2$ dry etching
- **e)** InGaAsP etching (CH$_4$/H, RIE)
- **f)** Polymer etching (O, RIE)

Figure 4.11: Process flow for device structuring for the MQW-cross section. Doped semiconductor material is not marked as in Fig. 4.26.
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Figure 4.45: Process flow for device structuring for the MQW-cross section. Doped semiconductor material is not marked as in Fig. 4.26 (cont'd).
Figure 4.46: Process flow for device structuring for the MQW-cross section. Doped semiconductor material is not marked as in Fig. 4.26 (cont'd).
4.6. MLLD Butt Coupling Process

Figure 4.47: 3D schematic view of a MLLD with absorber, gain, and passive waveguide sections.

Figure 4.48: Top view micrograph of a partly processed MLLD. From left to right: passive-waveguide (WG), MQW gain and UTC absorber with the p-contact metalization on top of the active structures.
SiO₂ mask for the following rib-processing steps (Fig. 4.46c to e)). Since the mask has an overlay tolerance of 250nm against the p-contact metalization, careful alignment is critical to assure the correct alignment over the whole two inch wafer.

To ensure the adhesion of the photo-resist to the SiO₂-mask deposited with PECVD a 2nm thick Ti layer is evaporated on top of it. In addition, this Ti-layer reduces the optical contrast difference between the p-contact metalization and the surrounding epi-layers. This homogeneity improves the lithography resolution by assuring a homogeneous illumination. This is also the reason for using a Ti-layer as the final metal for the p-contact stack. The top Ti-layer will be removed during the subsequent SiO₂ removal with hydrofluoric acid.

The SiO₂ layer is then structured with standard photo-lithography and subsequent RIE dry-etching process. As shown in Fig. 4.49, a diamond-shaped structure protects the interfaces of the core layers. Without this special geometry, the high crystallographic inhomogeneity at the interfaces would induce a uncontrollable under-etch into the optical guiding layers during the following etching processes [28] as is demonstrated in Fig. 4.49 and Fig. 4.50.
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The diamond shape does induce neglectable changes in the mode shape. Even an abrupt rib width change to the maximal diamond width will induce losses of less than 1% form the mode-overlap and effective refractive index changes which lead to reflection below 10⁻⁶. In Sec. 4.7 we discuss the losses and reflections due to the accidentally removal of the rib under the diamond structure due to long wet etching times.

**Rib Etching**

The laser-rib formation process is split into three parts [57]. In a first step, the rib is etched by a material unselective RIE process using a H₂:CH₄ gas mixture down to a depth of 1.3μm. When measuring the etch depth a plastic deposition on top of the masked areas of 10% of the etch depth has to be considered which is usual for methan based RIE processing.

After removing the plastic with an O₂ RIE process, the active regions (gain and absorber) are covered with photo-resist using optical lithography. Since the passive waveguide rib has to be etched down to 100nm into the Q1.3 material, the material unselectively RIE dry-etch process
has to be used to provide perpendicular side walls. The etch into the quaternary layer will improve the mode guiding for bended rib waveguides [151]. These bended rib-structures are necessary to guide the light into angled rib structures which results in reduced reflection at tilted out-coupling facets [151].

Due to the refractive-index differences of InP and Q1.3, we can use the apparent interference fringes visible by the naked eye as an end point detection for this etch process. Owing to the high absorptivity of InP in the visible-spectrum region only first and second order interference fringes are visible at the end of the etch-process. The second order fringes correspond to a rest thickness of the InP layer on top of the light-guiding Q1.3 layer of 196nm [29]. By using small etch-depth steps and visual inspection after each step, we can double check the profile etch-depth measurements with the appearance and disappearance of these interference fringes.

After a O₂-RIE step for removing the plastic layer due to the RIE etch and the photo-resist mask, a new lithography step covers the passive-waveguide regions (Fig. 4.51) with a new layer of photo-resist. The mask openings are widened to ensure a better wetting of the regions to be etched. The rib fabrication for the active regions is then completed with a material selective HCl based wet etch (Sec. 4.4.3). The InGaAs contact layer serves as an etch stop to prevent mask under etching. Furthermore the crystal orientation chosen for the rib waveguides results in smooth, nearly 90° tilted rib side-walls [138]. The first RIE based rib etch process is needed to keep the etching time of the wet-etch process short. Otherwise the risk of etching into the crystallographic inhomogeneous core layer interfaces is increased dramatically.

On the other hand only the wet etch process assures a well defined rib height over the whole 2-inch wafer due to etch-stop layers. This is especially important for the active sections to avoid loss currents due to electronic surface states.

N-Contact
To contact the absorber structures with a high-frequency coplanar waveguide probe, the n-contact has to be extended to the top side of the wafer. Therefore 1.2μm deep holes are RIE-etched on both sides of the laser rib into the highly n-doped substrate (Fig. 4.52) patterned by a lithography
4.6. MLLD Butt Coupling Process

Figure 4.51: Top-view micrograph of a MQW WG interface. Passive waveguide structures are already dry etched and covered with photoresist. The horizontal artifacts are due to high etching rates and deep etching at the mask borders during the regrowth process because of high etching rates for this crystallographic orientation.

process and photo-resist mask.

Afterwards a metalization layer stack consisting of a 30nm thick Ti, 40 nm thick Pt, and 100nm thick Au layer is deposited by e-gun evaporation and a standard lift off process. Annealing at 300°C for 30 sec guarantees a good adhesion between the metal and the semiconductor and provides contact resistances in the order of 10^-6Ωcm² which allows us to neglect this contact resistance in the overall resistance of the active sections of several Ohms.

Pad-Contact

For passivation, the wafer is spin coated with a 6μm thick Pyralin layer. The Pyralin is hard baked at 320°C and afterwards thinned by O₂-RIE so that a 500nm-thick Pyralin cover remains on top of the rib structures. Thereafter the p-contacts and n-contacts are re-opened by O₂ RIE for the final pad metalization by e-gun evaporation. This thick metalization consists of a 25μm thick Cr and a 1200μm thick Au layer.

Fig.4.53 shows the cleaving channel between a 40GHz MLLDs (left) and
1 Chapter 4. Multiple Structure Integration Process

Figure 4.52: Top-view micrograph of the wafer after n-contact fabrication. The cleaving channels mark the output facets of a 40GHz MLLD chip with four lasers with different absorber gain waveguide geometries. The 30µm long UTC absorber sections are too short to be clearly discerned.

a 10GHz MLLD (right) after this process step. In the center the UTC absorber structures are separated by this cleaving channel. There are two types of co-planar feed lines differing in the width of the central p-contact. The smaller 60µm wide ones are designed to match the 50Ω line impedance of the high frequency probes to drive the absorber with a 40GHz modulation. The 100µm wide ones can be contacted with standard DC-probes.

Back Side Metalization
Finally, the wafer is thinned down by lapping to a thickness of 120µm. An anneal etch with BCK removes remaining scratches so that the backside metalization consisting of a 30nm Ti, 40nm Pt and 100nm thick Au layer provides good contact. The backside metalization is needed as an n-contact for the rapid Fabry-Pérot laser diode bar testing and presents a reliable electrical ground for the co-planar lines. In a final step, the wafer is scribed and the lasers are cleaved and soldered on copper mounts.
4.7 Optical Characterization of the Butt-Coupled Interface

In the previous sections, the complete MLLD process with 5 growth steps and 14 lithographic fabrication steps was presented. In this section, we discuss the characterization of the process, especially with respect to the reflections and losses at the butt-coupled interfaces. To characterize the internal interfaces with regard to reflection and loss, special test devices were processed on each wafer. They consist of 300 and 500 μm-long gain sections embedded into passive waveguides. Fig. 4.54 shows a top-view micrograph of such a device. The out-coupling rib waveguides were tilted by 7° with regard to the cleaved facet to decrease the output facet reflection below $10^{-6}$ [29].

4.7.1 Optical Interface Losses

Since the simulations of the reflections and losses of the interfaces show no wavelength dependence, the total device losses were measured at a wavelength of 1.630μm where both the passive waveguide and the gain sections are transparent. To decouple the loss due to internal interfaces from the waveguide and fiber-to-chip coupling losses, the same measurements were performed also for devices without a gain section. Taking into account the differences in waveguide losses of 16cm$^{-1}$ (Chap. 3)
Figure 4.54: Top-view micrograph of a test device. 500μm and 300μm contacted long gain sections are embedded into passive waveguide sections. The rib waveguide is tilted by 7° at the out-coupling facet to reduce the reflections.

and 5cm⁻¹ [31] for the gain and passive waveguide sections, respectively. We extracted for butt-coupled interfaces with a strong up-bending of the light guiding layers a loss per interface of 3.5dB, which is in excellent agreement with our simulation results (Fig. 4.8b). For well-aligned interfaces as shown in Fig. 4.43 a loss of (1.3±1)dB per interface was extracted. This value is 0.7dB higher than expected from the simulations but still in good agreement regarding the measurement accuracy.

4.7.2 Interface Reflections

The reflectivity of the internal interfaces can be extracted from Haki-Paoli gain measurements (Chap. 3). Once again we have to determine the residual ripples in the gain spectrum as shown in Fig. 4.55 and the measurement technique do not differ from those presented in Chap. 3. If the reflections at the cleaved facets can be neglected, the residual ripples in the output spectrum of our test devices are due to the internal reflections $R_{int}$ at the butt-coupled interfaces. This assumption can be counter-checked by the peak to peak distance of the ripples which is
4.7. Optical Characterization of the Butt-Coupled Interface

![Figure 4.55: Optical spectra measured for test-devices with miss-aligned core layers and well aligned core layers.](image)

Determined by the internal cavity length. Hence, we can characterize internal reflections down to a value of $10^{-6}$ the value of the external tilted facet reflections. Since from the perspective of the gain section both interfaces have the same geometry we can assume that the reflections at both butt-coupled interfaces are equal. Thus the reflectivity can be calculated from the peak-to-valley ratio $V$ of the spectral ripples with the following equation:

$$V = \left( \frac{1 + RG}{1 - RG} \right)^2$$

(4.7)

where $G$ is the total chip gain. The chip gain is known from the investigations presented in Chap. 3.

For well-aligned core-layer structures (Fig. 4.9a), bottom) we could not resolve any residual ripples in the spectrum. The measurement accuracy of 0.05dB corresponds to an upper limit of the internal reflection of $R_{int} < 10^{-3}$.

On the other hand, the crosses in Fig. 4.56 present the residual ripple gain amplitude as a function of gain for several test devices with miss-aligned core layers (Fig. 4.9a) top). The solid lines are calculated from Eq. 4.7 for reflection parameter values $R_{int}$ of $10^{-2}$, $5-10^{-3}$ and $10^{-3}$.

From these measurements we can deduce an internal reflection coeffi-
Figure 4.56: Ripple amplitude of the gain spectrum measured for test-devices (crosses) with miss-aligned core layers. The solid lines are calculated with equation 4.7 for the indicated Reflection values.

icient between $10^{-2}$ and $10^{-3}$ for strongly miss-aligned devices. These values are an order of magnitude higher than predicted for miss-aligned interfaces by the 2D FDTD simulations (Fig. 4.9).

The highest value close to 1% can be explained by an interruption in the rib-waveguide below the diamond shaped rib-mask section (Sec. 4.6.3) as can be seen in Fig. 4.57. This interruption was caused by a defect in the rib-etching mask which is due to the non-planarity of the wafer for a non-optimized regrowth process. The photo-resist on top of the highest growth overshoots due to material piling during regrowth attaches to the mask during contact lithography and is afterwards removed with the mask. This could not be prevented by using adhesion prohibitors.

Another explanation can be a lateral underetch due to the inhomogeneously crystall orientation at the interface as is explained in Sec. 4.6.3. This can be prevented by a shorter an optimized wet etching step for the rib etching process sequence.

The investigation of this kind of defects in the rib reveals an unexpected characteristic of the loss and the reflection coefficient. As the device under test we choose a MQW-SCH structure covered with a 1300nm thick InP cladding (Fig. 4.58). We compared the optical mode overlap and the effective refractive index of a defect free rib-waveguide with a rib-
4.7. Optical Characterization of the Butt-Coupled Interface

Figure 4.57: SEM micrograph of a ready process waveguide-MQW interface. The rib was etched because of mask loss during processing.

Figure 4.58: Schematic cross view of the MQW-rib structure with original rib height and etched rib height (dotted line).
waveguide with reduced rib height representing a defect as in Fig. 4.58. The loss and reflections for different etch depths into the rib waveguide were calculated with the mode-overlap and the effective-indices, respectively. The results are summarized in Fig. 4.59.

The loss increases dramatically at an etch depth of 1 µm, whereas the reflection stays below $10^{-5}$ until the etch depth reaches the light guiding layers (MQW-SCH layers). As an explanation we can assume that the losses are mainly due to coupling into non-guided modes, whereas the reflection requires the back coupling into the guided modes of the waveguide. Thus as a conclusion the loss is more sensitive to the rib thickness variation than the reflections. For the situation shown in Fig. 4.57 the undesired etch reaches the light guiding core layers and hence we expect high losses and high reflectivities. On the other hand, a high loss not necessarily includes high reflections for this kind of defect.

### 4.8 Conclusion

The butt-coupling process is the most flexible monolithic integration scheme for the independent design of mode-locked laser diode elements. Indeed, a fast absorber structure can be designed independently from the gain section to fulfill optimally the requirements for short pulses in
4.8. Conclusion

A MLLD. Mode matching for low losses between different structures is achievable, so that the interface losses will be mainly determined by the regrowth overshoot and defects.

To realize low reflections at the butt-coupled interfaces an angled geometry is necessary, which can be achieved with a well-defined sequence of wet-etching steps presented in Sec. 4.4.1.

Interface losses and reflections are very sensitive to growth overshoot at the boundary between the different MLLD sections, due to material piling at the growth-mask borders. To avoid the material piling, a low pressure chamber reactor (P<30mbar) or even a MOMB.E or CBE growth device is favorable. A low chamber pressure lowers the design restrictions of the buffer layers and will result in a higher device yield. In addition the mask under etch must be optimized for the regrowth steps to avoid material piling or void formation under the mask overhang.

In order to overcome the total material piling at the mask borders we subdivided the growth steps of the three structures into five single growth steps. This growth splitting between the core layers and the waveguide cladding layers is also necessary for the proposed etching procedure for the integration of three different structures in any lateral configuration. This results in a MLLD process which needs seventeen masks, four metalization layers and a total processing time of two to three months.

With this process a interface with the desired reflection below $10^{-5}$ and losses of 1.5dB per interface was demonstrated successfully.
Chapter 5

Characterization of Mode-Locked Laser Diodes

5.1 Introduction

In Chap. 2 we showed, that for future optical networks a fast absorber is mandatory in MLLDs for sub-ps pulse generation for data bit rates per channel above 160GHz. In contrast to the conventionally used reversed-biased gain section as the saturable absorber structure we have developed an optimized UTC-absorber structure which is designed for fast relaxation and extraction of the photo-generated electrons. Furthermore the slow hole drift and diffusion constants are circumvented by a p-doping of the absorption layers which will result in a fast absorber recovery.

In the previous chapters the technology for monolithic integration of three vertical layer structures for gain, absorber and passive waveguide sections were presented. We have demonstrated theoretically and experimentally, that the internal interface reflections coefficient $R_{int}$ can and must be as low as $10^{-5}$ which should allow single pulse MLLD output without satellite pulses.

In this chapter we present the characterization of the fabricated monolithically integrated MLLDs whose performance can be described by several features. The length of the cavity $L_{can}$ and the refractive index of
the used material define the repetition rate $f_{rep}$ of the out-coupled pulse train. The individual pulses have a characteristic pulse width $\tau$, peak power $P_{peak}$ and spectral width $\Delta \lambda$ determined by the gain and absorber dynamics.

To demonstrate the quality of the developed integration process we focus our attention on the pulse width $\tau$ and the behavior of the pulse shape regarding to internal reflections $R_{int}$ at the butt coupled interfaces. We will show in the following, that sub-ps pulses can be generated with the integration of the fast UTC-absorber.

Due to the higher than expected interface losses, the MLLD gain sections need to be 1mm long to provide enough gain to reach lasing threshold. Therefore we can study the different arrangements of absorber gain and passive waveguide sections only for the 4mm-long MLLDs with a repetition rate of $f_{rep}=10\text{GHz}$. On the other hand the higher pumping current also increases the saturation energy of the gain section as explained in Chap. 3. Even though this will increase noise effects due to an increased generation of spontaneous emission, this will as a benefit also increase the ratio between the saturation energy of the gain and the absorber which is advantageous for mode-locking.

On the other hand, the impact of the internal reflections on the laser performance is studied for 40GHz MLLDs without passive waveguide sections. Since these MLLDs include only one single absorber-gain interface inside the laser cavity the problem is better isolated and tractable. All presented MLLD results were obtained in the hybrid mode-locking regime, where the absorber section was reversed-biased between -0V and -3V and driven by a 10GHz or 42GHz modulation with a power of up to 20dBm, respectively. It turns out that the cavity length of 1mm and the beforehand unknown exact effective refractive index of the whole cavity corresponds to a repetition rate of 42GHz, slightly higher than the 40GHz design goal. Tab. 5.1 summarizes the investigated laser structure and the extracted parameters.
The pulse width investigations were performed with 1mm long MLLDs with $f_{rep} = 42$GHz.

### 5.2 Pulse-Width Measurements

In general conventional semiconductor MLLDs without fast absorbers produces optical pulses with a width in the range of 1 to 10ps. The characterization of such short optical pulses cannot be performed with photo diodes or streak cameras to get a direct image of the temporal pulse-intensity profile. To measure optical pulse widths in the ps to fs range a second-order autocorrelation based upon second-harmonic generation or two photon absorption (TPA) has to be used [152]. From this measurement we get an indirect always symmetrical image of the intensity profile. Assuming a specific pulse shape (commonly Gaussian) the real pulse width can be estimated from the temporal width of the autocorrelation signal.

The second-order autocorrelation signal of the electric field $E(t) = E(t) \exp[i(\omega t + \Phi(t))]$ is written as:

$$I(\tau) = \left| \int [E(t) \exp[i(\omega t + \Phi(t))] + E(t+\tau) \exp[i(\omega(t+\tau) + \Phi(t+\tau))]]^2 dt \right|^4$$

in which $E(t)$ is the amplitude and $\Phi(t)$ is the phase of the field.

If the autocorrelation signal is traced with interferometric accuracy the interference fringes due to the underlying carrier frequency $\omega$ can be resolved. From Eq. 5.1 we recognize that one characteristic of the second-order interferometric autocorrelation is a peak-to-background ratio of 8:1 (Fig. 5.1). The details of this so called interferometric autocorrelation can be used to fit also the chirp of the pulse to the measured
Chapter 5. Characterization of Mode-Locked Laser Diodes

signal. Chirp will show up in the autocorrelation trace as side-shoulders without interference fringes. Chirp leads to a higher time-bandwidth product and is hence undesired for optical network pulse sources.

The low average output power (1-10mW) and the high repetition rates of MLLDs results in a relatively low peak power. This is disadvantageous for the detection scheme because commonly used second-order generation provides only a low sensitivity in our wavelength range. Therefore measurement times of several hours are required to obtain a good signal to noise ratio [57].

J.M. Roth and co-workers [153] proposed an autocorrelation set-up using a single photon counter based on a silicon avalanche photo-diode as a two-photon detector. They demonstrated autocorrelation measurements of 10GHz pulse trains with an average power of a few μW and a single pulse width of 2ps. We rebuild their set-up and could measure autocorrelations with a significant increase in signal to noise ratio in comparison to our previous home build autocorrelator based on second harmonic generation. Thus the measurement time is decreased from several hours down to a few minutes.

Fig. 5.2 presents a schematic of the autocorrelator used for the measurements presented in this chapter. In principle the setup consists of a
Michelson interferometer, where the length of one arm can be varied. After collimating the highly divergent beam emitted from the MLLD into a parallel beam, the optical pulses are split into two identical components by the beam splitter. One half of the pulse is delayed with respect to the other half by changing the length of one interferometer arm. Both parts are then recombined at the beam splitter and focused onto the photon counting module (Perkin-Elmer SPM-AQR-16) photo-diode with a beam diameter of 10μm. This module creates a standardized TTL pulse for each detected photon.

Since silicon is transparent at the wavelength of 1550nm generated by our MLLDs TPA is required to generate an electron hole pair in the APD which results in one TTL pulse. Therefore the receiver response count-rate is quadratic with respect to the incoming intensity resulting in the desired second-order autocorrelation signal. However for the low peak powers of our MLLDs the receiver response is not purely quadratic due to light absorption of donor levels and defects in the detector [64]. This results in a lower peak-to-background ratio of the autocorrelation signal than the ideal 1:8 ratio and can be taken into
Chapter 5. Characterization of Mode-Locked Laser Diodes

account for the signal by adding a linear term to Eq. 5.1 [45].

\[ I(t) = \alpha \int |E(t - \tau) + E(t)|^2 d\tau + \beta \int |E(t - \tau) + E(t)|^4 d\tau \]  

(5.2)

The parameters \( \alpha \) and \( \beta \) are used to fit the calculation to the measured autocorrelation. For our measurements we found good fitting for \( \alpha = 1 \) and \( \beta = 1 \) to 2. Further details on the measurement set-up characteristics can be found in [31].

5.3 10GHz MLLDs

In the following we present the PI-threshold current and pulse characteristics for a 4mm long MLLD with a repetition rate of 10GHz. The gain sections are 1000\( \mu \)m and the absorber sections 70\( \mu \)m long, resulting in mode-locking with low satellite pulse intensity. For these lasers we investigate the impact of different arrangements for the gain, absorber and passive-waveguide sections on the laser performance. We designed a MLLD chip with 4 lasers realizing the two possible section configurations gain/waveguide/absorber and waveguide/gain/absorber as shown in Fig. 5.3 to extract the UTC-MQW interface losses. The thin horizontal lines in Fig. 5.3 represent the passive rib-waveguides. The light out-coupling cleaved facets are on the left- and right-hand sides of the micrograph. The two inner MLLDs on the chip have a direct interface between the absorber and gain sections and are electrically separated by a short \( \approx 6\mu \)m wide undoped cladding section (Chap. 4), whereas for the outer two devices the two active sections are separated by the long passive waveguide section.

As displayed in Fig. 5.4, the devices with gain and absorber sections separated by a long passive waveguide section show lower losses resulting in a lower threshold laser current than devices with adjacent gain and absorber sections. This difference in threshold current of \( \Delta I_{th} \approx 60mA \) can be explained by the more complex structure of the cladding layers in the latter case. Indeed, for the waveguide/gain/absorber geometry the upper cladding contains one additional interface, which is due to the \( 6\mu \)m wide undoped cladding stripe required to isolate the two active sections electronically (Fig. 4.43).

To extract the interface losses out of the light-current characteristic the waveguide loss term \( \alpha_{W} \) in the equation for the threshold current (Eq. 3.23) has to be analyzed in detail. To account for the mismatch
between cavity length $L_{\text{cav}}$ and gain section length $L_{\text{gain}}$ Eq. 3.23 has to be slightly modified as follows [104]:

$$I_{\text{th}} = \frac{qBN_T^2}{\eta_i \exp\left(\frac{2L_{\text{cav}}(\alpha_W + \alpha_M)}{L_{\text{gain}}\Gamma g_0}\right)}$$ (5.3)

where $q$ is the elementary charge, $B$ the bimolecular recombination factor, $N_T$ the transparency current density, $\eta_i$ the internal quantum efficiency, $\alpha_M$ the mirror losses at the facets, $\Gamma$ the optical confinement factor and $g_0$ the fitting parameter for the two-parameters gain fit performed in Chap. 3. Solving Eq. 5.3 for the total waveguide losses $\alpha_W$ one gets:

$$\alpha_W = \frac{\Gamma L_{\text{gain}}g_0}{2L_{\text{cav}}} \ln\left(\frac{\eta_i I_{\text{th}}}{qVN_T^2}\right)$$ (5.4)

$\alpha_W$ can be decomposed into the waveguide losses in the gain section $\alpha_W^{\text{gain}}$, the waveguide losses in the passive section $\alpha_W^{\text{passive}}$, the unsaturated modal losses in the absorber $\alpha_{\text{abs}}$ and the interface losses $\alpha_I$.

$$\alpha_WL_{\text{cav}} = \alpha_W^{\text{gain}}L_{\text{gain}} + \alpha_W^{\text{passive}}L_{\text{passive}} + \alpha_{\text{abs}}L_{\text{abs}} + \alpha_I$$ (5.5)

The total waveguide loss $\alpha_w$ can be determined from the threshold current with Eq. 5.4. The passive-waveguide active section interface losses $\alpha_I$ for the geometries with only passive-waveguide active interfaces are known from the measurements presented in Sec. 4.7 to be 1.5 dB. Taking into account for the waveguide losses of 16 cm$^{-1}$ and 5 cm$^{-1}$ for the gain and passive waveguide sections, respectively, the remaining unknown in

Figure 5.3: Top view micrograph of a $L_{\text{cav}} = 4 \text{mm}$ long 10 GHz laser diode chip with four MLLDs of different geometry
Chapter 5. Characterization of Mode-Locked Laser Diodes

Figure 5.4: Light-current characteristic for all four MLLDs shown in Fig. 5.3 with a) separated gain and absorber section (outer geometry) and b) adjacent gain and absorber section (inner geometry).

Eq. 5.5, the modal absorption losses $\alpha_{abs}$ of the absorber are determined to be $(540\pm10) \text{cm}^{-1}$. This value differs by a factor of two compared to the spectral absorption measurements presented in [94] and Fig. 5.11. The measurements in [94] where calibrated with the transparent wavelengths regime to zero absorption. Therefore wavelength independent losses are not included in these measurements but are included here. From this result the interface losses of the direct absorber-gain interface can be extracted from the threshold current of the adjacent gain/absorber geometry to be $15\pm2 \text{dB}$. This value is an overestimation of the real value mainly due to the omission of the Auger recombination rate $CN^2$, which is important at high pumping rates. Thus the $CN^3$ term has to be subtracted from the $BN^2$-term in Eq. 5.4 leading to a non-unique solution for $\alpha_W$.

Considering the interface analysis of the previous chapter such high losses for well-aligned core layers can only be explained by defects in the rib waveguide as shown in Fig. 4.57. The geometry with adjacent absorber/gain sections is more sensitive to this failure because of the more complex cladding layer structure as shown in Fig. 5.5 (Sec. 4.6.3).
5.3. 10GHz MLLDs

Figure 5.5: SEM micrograph side view of ready processes MLLDs. The Pyralin passivation was removed with a oxygen RIE etching. On top the MQW - UTC interface is shown and on bottom the perfect passive waveguide - MQW interface. Due to the additional electronical isolation with an undoped cladding the MQW-UTC interface is more complex.

It can be concluded that the interface losses for the gain-absorber interface are much higher than for the passive-waveguide active-sections interface.
From the spectral modulation as shown in Fig. 5.6 we can also estimate
a non-negligible reflection at the interfaces.

Figure 5.6: Spectrum of a 10GHz MLLD with passive-waveguide/gain/absorber geometry. The over modulation is due to internal reflections at the interfaces.

This reflection will lead to secondary pulses as shown in the autocorrelation trace of Fig. 5.7.
Figure 5.7: Autocorrelation signal of a 10 GHz MLLD. Due to internal reflection the MLLD works in the compound-cavity mode-locking regime (see Sec. 5.5) resulting in multiple pulse formation.

How this modulation of the spectral laser modes is related to the value of internal reflection will be discussed in the next section for a 1mm long laser with $f_{rep}=42$ GHz without a passive waveguide section. So only one interface has to be considered allowing a simpler and.

5.4 42GHz MLLDs

In this section we represent results from 1mm long MLLDs with a repetition rate around 42GHz. The results demonstrates the achievable performance in terms of pulse width due to the incorporation of a fast absorber structure. Moreover the effect of the internal reflections on the pulse shape and their analysis are presented. We also compare devices from two different runs with miss- and well-aligned core layers (see Sec. 4.3). We designed 30µm and 70µm-long absorber sections to optimize the absorption strength for different material compositions [31]. The corresponding gain sections are 970µm and 930µm long. No passive waveguide section is present in these lasers, although the two active sections are electrically isolated by the adjunction of a 6µm-long undoped cladding section at the gain/absorber interface (Fig. 5.5 upper case). A top-view
Chapter 5. Characterization of Mode-Locked Laser Diodes

A micrograph of a chip with 4 MLLDs with 70μm long absorber sections is shown in Fig. 5.8.

The light-current characteristics, as shown in Fig. 5.9 for devices with well-aligned core layers, confirm the high losses at the absorber gain section interface of 15dB.

Nevertheless this high loss does not necessarily imply a high interface reflection, which would lead to parasitic satellite pulses. To quantitatively determine the amount of internal reflections, the output spectra below threshold have to be investigated.

The modulation of laser diode spectral modes was first used to localize internal defects [154] using the Fourier transform of the spectrum. Lambkin and co-workers [155] presented a detailed analysis of the Fourier transform and could extract the reflection coefficient by comparing the amplitude of the different spectral components. Since our laser diodes are more complex due to internal absorber and gain sections this method can unfortunately not be applied for our spectra.

Instead of fitting the Fourier components of the spectra, we directly fit the main characteristics of transmission spectrum for Fabry-Perot cavi-

Figure 5.8: Top-view micrograph of a 1mm long MLLD, with 4 devices. Each MLLD consists of a 70μm long absorber section and a 930μm long gain section.
Figure 5.9: Light-current characteristic for MLLDs which a 30μm long absorber section and 970μm long gain section.

ties with a net modal gain $g(\lambda)$ comprising all wavelength independent losses and absorption $\alpha(\lambda)$.

A 42GHz laser diode can be modeled by two cavities separated by the internal reflection $r_{\text{int}}$ as shown in Fig. 5.10. The absorber sub-cavity can be described by a wavelength-dependent reflectivity $r_{\text{abs}}(\lambda)$ and transmission $t_{\text{abs}}(\lambda)$ [156].

$$r_{\text{abs}}(\lambda) = r_{\text{int}} + \frac{t_{\text{out}} \exp[2(i\beta - \alpha_{\text{abs}})L_{\text{abs}}]}{1 - r_{\text{int}}t_{\text{out}} \exp[2(i\beta - \alpha_{\text{abs}})L_{\text{abs}}]} \quad (5.6)$$

$$t_{\text{abs}}(\lambda) = \frac{t_{\text{out}}r_{\text{out}} \exp[i\beta L_{\text{abs}}]}{1 - r_{\text{int}}t_{\text{out}} \exp[2(i\beta - \alpha_{\text{abs}})L_{\text{abs}}]} \quad (5.7)$$
Here $\beta$ is the propagation constant and $t_{out} = \sqrt{1 - r_{out}^2}$ is the transmittivity through a cleaved facet. $\alpha_{abs}$ is also a function of $\lambda$ and can be linearly fitted in the wavelength range of the emitted light to the measurements presented in Fig. 5.11. The fitting results are summarized in the following two equations:

$$\alpha_{abs}^{\text{badly}} = 2.72 \frac{cm^{-1}}{nm} \lambda - 4262 cm^{-1}$$  \hspace{1cm} (5.8)
$$\alpha_{abs}^{\text{well}} = 3.03 \frac{cm^{-1}}{nm} \lambda - 4787 cm^{-1}$$  \hspace{1cm} (5.9)

The spectral gain dependence is described by the parabolic gain approximation.

$$g(\lambda) = g_1 + g_2(\lambda - \lambda_0)^2$$  \hspace{1cm} (5.10)

The whole laser cavity can then be described by an equivalent structure consisting of a cavity with length $L_g$ with the reflectivity at one facet described by Eq. 5.6 and at the other by $r_{out}$. Thus the transmittivity of this equivalent cavity is

$$t = \frac{E_{in}}{E_{out}} = \frac{t_{out}t_{abs}(\lambda)\exp[(i\beta + g(\lambda))L_{gain}]}{1 - r_{abs}(\lambda)r_{out}\exp[2(i\beta + g(\lambda))L_{gain}]}$$  \hspace{1cm} (5.11)
The output spectra of the MLLDs can then be fitted with $|t|^2$. Fig. 5.12 shows the measured and the calculated spectra for a 40GHz MLLD with a 30μm- and 970μm-long absorber and gain sections, respectively. Contrary to the device used at the beginning of this section for extracting the interface losses, this device suffers from badly-aligned core layers.

The fitting was performed with the following steps (see Fig. 5.12 (b)):

1. Fitting of the central modulation depth $P_{max}/P_{min}$ with the gain parameter $g_1$ to adjust the real round-trip gain.

2. Fitting of the side peaks with the gain parameter $g_2$ to adjust the spectral width of the gain.

3. Fitting of the spectral peaks $P_{peak}$ and valleys $P_{val}$ by adjusting the internal reflection $r_{int}$

The deviation from the targeted cavity optical length of the MLLD due to the uncertainties in the cleaving process and the knowledge of the effective refractive index results in a small wavelength mis-match of the neighboring spectral peaks. Nevertheless the peak to valley ratio is very sensitive to the value of $r_{int}$ and a variation of 10% results in recognizable deviations.

The resulting internal power reflection of $R_{int} = r_{int}^2 = 0.17\%$ for the MLLD with badly-aligned waveguide cores is comparable with the reflections measured for the active-passive interface of test devices from the same wafer (Chap. 4).
Figure 5.12: a) Measured output spectrum of a 1mm long MLLD with 30μm long UTC-absorber section and 970μm long gain section. b) fitting of the spectrum resulting in an internal reflection $r_{int} = 0.042$.

Fig. 5.13 presents the spectrum and the fitting for a 40GHz MLLD with well-aligned core layers and a 70μm long absorber section from an technologically optimized wafer run. Here contrary to the badly-
aligned case the fitting results in an internal reflection of $R = 2.5 \cdot 10^{-5}$, which is also in good agreement with the measurements presented in the previous chapter. This low reflection should allow for mode locking without secondary pulse formation.

Figure 5.13: a) Output spectrum of a 1mm long MLLD with 70µm long UTC-absorber section and 930µm long gain section. b) Fitting of the spectrum resulting in an internal reflection of $r_{int} = 0.005$. 
Tab. 5.2 summarizes the characteristics of the investigated interfaces for well aligned core layers (Chap. 4).

<table>
<thead>
<tr>
<th>Interface</th>
<th>$R_{\text{int}}$</th>
<th>Loss [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WG-MQW</td>
<td>$&lt;10^{-5}$</td>
<td>$\approx 1.3$</td>
</tr>
<tr>
<td>WG-UTC</td>
<td>$&lt;10^{-5}$</td>
<td>$\approx 1.3$</td>
</tr>
<tr>
<td>UTC-MQW</td>
<td>$2.5 \cdot 10^{-5}$</td>
<td>$\approx 15$</td>
</tr>
</tbody>
</table>

Table 5.2: Reflection and losses of the investigated interfaces in a butt-coupled MLLD.

The mode locking behavior with different internal reflection coefficients is described in the following section.

### 5.5 Mode locking with internal reflections

In the last sections we investigated experimentally the interface losses and reflections in MLLDs from static laser characteristics such as power-current curves and the optical spectra. Here we present the influence of the internal reflections on the mode-locking behavior of the laser in the time domain. The influence of internal reflections on the MLLD performance was first studied in external-cavity MLLDs [41]. Only recently the influence of the internal reflections on mode locking was investigated theoretically [157] and experimentally [64, 45] for monolithically integrated MLLDs. The internal reflections, which have a negative impact for fundamental mode locking were later exploited to realize MLLDs with repetition rates beyond one THz [64]. This was achieved by using the so-called compound-cavity mode locking (CCML) [45] regime based on a short internal cavity corresponding to a THz repetition rate.
Figure 5.14: (a) Autocorrelation signal and (b) spectrum for a 1mm long MLLD with 70 μm long absorber and 930μm long gain section. The gain sections was pumped with 400mA and the reverse bias for the absorber section was 3V.
The monolithic cavity gain section is subdivided into two cavities by an internal reflector. Due to the loss modulation of these sub-cavities some modes are suppressed in the overall laser cavity. This leads to repetition frequencies corresponding to multiples of the cavity length ratio \( M \) (Eq. 5.12). Yanson and co-workers [64] demonstrated that compound cavity mode-locking leads to a 2.4THz repetition rate with 0.24ps wide uniform pulses corresponding to a nearly sinusoidal pulse train shape. They also observed pulse formation with secondary pulses for internal reflection coefficients below 1% with repetition rates corresponding to the overall cavity length. To assure uniform pulse trains with high repetition rates corresponding to \( M \) the internal reflection coefficient has to be \( \approx 1\% \) and the length ratio of the two sub-cavities should be around 10.

Fig. 5.14 presents an autocorrelation trace of a 1mm long MLLD with a 70\( \mu \)m long absorber section and a 930\( \mu \)m long gain section with badly-aligned core layers due to the bending at the regrown interfaces (Sec. 4.3). Consequently we expect CCML due to the high internal reflection around 0.2%.

The CCML manifests itself as modulated peaks in the Fourier transform of the autocorrelation trace. The modulation frequencies of these peaks occur at well-defined integer multiples \( M \) of the sub-cavities length ratio:

\[
M = \frac{L_{\text{gain}}}{L_{\text{abs}}} + 1. \tag{5.12}
\]

For the presented geometry we get \( M=14 \). We observe compound cavity harmonics for our device at 0.6, 1.2, 1.8, 2.4 and 2.9 THz corresponding to \( M=14, 28, 42, 56 \) and 70 respectively. The Fourier transform of the autocorrelation trace shown in Fig. 5.15 confirms this analysis. Why our MLLDs delivers also CCML with higher harmonics remains unclear within our investigations because we could not analysis this behavior with our simulation model.

The center pulse has an extracted width of 0.7ps which confirms the expected pulse width due to the fast absorber. The determination of the time bandwidth product is not obvious, because of the amplitude modulation of the spectral modes.

In contrast to these imperfect results a mode-locked laser diode from the technologically optimized wafer with well-aligned core layers and hence a much lower internal reflection coefficient around \( 10^{-5} \) shows less modulation of the spectral modes (Fig. 5.16) even above threshold and the parasitic pulses are much lower in intensity.
Figure 5.15: Fourier transform of the envelope of the autocorrelation trace shown in Fig. 5.14a).
Figure 5.16: (a) Autocorrelation signal with 0.9ps pulse width and (b) spectrum for a 1mm long MLLD with 30 \( \mu \)m long absorber and 970\( \mu \)m long gain section. The gain sections was pumped with 240mA and the reverse bias for the absorber section was 0.4V.

From this autocorrelation trace we can extract a pulse width of 0.9ps and a time bandwidth product of 0.9 indicating a slight chirp of the pulse. The longer pulse of these lasers with respect to the center pulse of Fig. 5.14 can be explained by the lower reverse bias of -0.8V of the
absorber section. For higher reverse biases the losses increases and the
lasing threshold could not be reached anymore. Thus we could not take
advantage of the fast recovery time, which decreases considerably as
shown in Fig. 2.9 for low reverse biases.

5.6 Conclusion

For the first time a monolithically integrated mode locked laser diode
with different material for absorber and gain sections was demonstrated
to optimize the different requirements for these two laser sections.
We figured out that a fast absorber structure will lead to sub-ps output
pulse widths. The demanding butt-coupled integration process com-
pelled us to consider carefully the internal reflections at the regrown
interfaces. MLLDs are very demanding with regard to these reflections.
The interface reflection coefficients has to be as low as $10^{-5}$ to provide
single pulse mode locking. For reflection coefficients of $\approx 1\%$ so-called
compound cavity mode locking with relatively strong satellite pulses will
occur. To extract these internal reflections, we used the Fabry-Perot am-
plitude modulation of the output spectral modes below lasing threshold.
Due to the process design we used for the electrical isolation of the ad-
jacent active structures, interface losses are substantial for our MLLDs
with adjacent gain and absorber sections. A process design with passive
waveguide structures between active (MQW/UTC) sections is preferable
to reduce these losses. However for this case gain structures with higher
gain for MLLDs shorter than 1mm are required.
The pulse measurements for MLLDs are very challenging with respect
to the sensitivity of the detector because of a relatively low pulse peak
power of about $\approx 60\mu W$. We used a silicon avalanche photo-diode to
realize the required quadratic detector response by two-photon absorp-
tion. However the use of this silicon avalanche photo-diode requires to
consider an undesired linear term in the receiver response to extract the
pulse width out of the autocorrelation signal.
With this autocorrelation technique we measured pulse widths of 0.6-
0.9ps and time bandwidth products around 1 for MLLDs with quantum-
well gain sections and the fast uni-traveling carrier absorber.
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Chapter 6

Outlook

In this thesis we investigated the design, fabrication and characterization of InP-based monolithically integrated mode-locked laser diodes for sub-ps pulse generation. We demonstrated, that a fast absorber structure with recovery times of 2-3ps enables us to decrease the pulse-width below one pico-second. As a fast absorber structure, we resorted to a uni-traveling carrier structure. To overcome the opposed design goals for the MLLD gain and absorber structures, the vertical layer design of these laser sections have to be optimized independently.

Therefore only a butt-coupled regrowth process is adequate for the monolithic integration of the optimized gain and absorber. The monolithic integration is very demanding with respect to internal reflections. Theoretical and experimental investigations demonstrated, that a reflection coefficient of $10^{-5}$ at the internal interfaces is required. Interfaces with such low reflections are technologically achievable and demonstrated. Thus compound cavity mode-locking effects can be suppressed to realize single pulse output from monolithic MLLDs.

Despite the very demanding process requirements with respect to cleanliness and reproducibility, we demonstrated for the first time monolithically integrated mode locked laser diodes with different materials for the absorber and gain sections.

In the following we present possible future research goals and problems to be solved as well as possible alternatives to the presented approach.
6.1 Process Technology

The main challenge for the technological process was the etching of the angled interface required for the integration of a third structure. Since the active core layer structures have a very inhomogeneous composition, an unselective etch is required. The etch rate differences in the vicinity and far away from the masking layers impose the use of an underlying buffer layer, which on the other hand should be as thin as possible to reduce the material piling behavior during regrowth. This problem can be avoided by using a MOMBE or CBE selective area growth technique, which do not suffer from different growth rates near and far away from the masked areas.

An other possibility to reduce the material piling issue is to include a passive waveguide section between the absorber and gain sections (Fig. 6.1). For this approach the MQW-layers can be selectively etched with a sulfuric based etchant and only the regrowth of a thin layer stack is required for the UTC section as no direct MQW-UTC interface is present in the device (Fig. 6.1). After regrowth the UTC layers as well as the MQW buffer are partly removed using the etching sequence for angled interfaces presented in Chap. 4. Thus the imperfect MQW-UTC interface is removed by optimized MQW-WG and UTC-WG interfaces. Finally this process sequence results in the five growth steps presented in Fig. 6.1.

The selective etch of the MQW layers leads to an under-etch into the MQW core layers of up to 10μm resulting in a hole in the core layer.
structure. Thus the passive waveguide between MQW and UTC structures must be at least 10μm long to replace this under etched hole. An additional advantage is, that the electrical isolation between the active structures is always guaranteed.

A further process simplification would be to replace the undoped cladding with the doped cladding. Thus the 4th growth step in Fig. 6.1 can be omitted. As a worst case scenario this would increase the waveguide losses mainly due to free carrier absorption of a 1mm long MLLD from 2dB to 6dB assuming a waveguide loss of 5cm⁻¹ for a cavity with undoped cladding and of 15cm⁻¹ for a cavity with doped cladding (Chap. 4). This loss can be counteracted by high reflection coatings on the output facets. The electrical isolation can be realized by removing the highly doped InGaAs contact layers above the passive waveguide sections.

From the point of view of process complexity and cost effectiveness the best technology is one without any regrowth. This will require a material with optimal performance for the absorber and gain sections.

### 6.2 Material

As already mentioned in the Chap. 2 one promising candidate for the one-material MLLD are quantum dots (QD). They combine the ideal behavior for both absorber and gain sections with respect to a fast recovery time constant for an absorber section and a high saturation energy for a gain section. Despite of the difficulties regarding to the low gain and emission at a wavelength of 1550nm they already demonstrate short pulses (0.4ps) with relatively high output power. The material parameters such as saturation energies, line-width enhancement factors, absorption recovery time and spectral gain width are still under investigation and sometimes controversially discussed [158]. The further investigation of these materials will also improve the understanding of the MLLD behavior and reliability of the impressive results for QDs MLLDs.

An other approach for a single material MLLD was proposed by Nikolaev and Avrutin [22]. They investigated theoretically the use of quantum wells with additional electronic-potential steps or even QWs with a triangular or trapezoidal electronic-potential. This design will improve the carrier sweep out under reverse bias for the absorber while maintaining a good carrier confinement under forward bias for the gain.
If the technological problems at the interfaces between the structures can be solved to provide a reliable process with acceptable yield, further design optimizations of the gain structure can be envisaged. First of all the influence of the gain-section’s length and its influence on the saturation energy can be systematically addressed. An other possibility to influence the saturation energy is the use of mode shape adaptors. Most of the solid state mode locked lasers place the absorber section in the cavity where the optical mode is mostly confined. This confinement will increase the mode confinement factor and hence decrease the absorber saturation energy which is advantageous for mode-locking. In monolithic mode locked laser diodes this could be realized with different waveguide geometries and mode shape adaptors. For this purpose also the use of a photonic crystal waveguide to confine the light in the absorber section can be envisioned.

As a possible drawback for these kind of waveguides the reflections between the different waveguide sections have to be analyzed and controlled carefully.

Furthermore staggered quantum wells can be designed to realize extremely broad gain spectra. The problem will be to maintain the properties of the special quantum well design under the regrowth process (see Chap. 3). It has to be investigated in detail, whether the interdiffusion can be included in the design to end up with the desired material composition and strain. For example to realize very broad gain spectra in QWs a stack of strained QWs with different widths is required. A drawback is the potential dependency of the spectral width on the pumping current because the pumping current represents also a degree of freedom which is necessary to tune the MLLD to a steady state with a short pulse output.

Poole and co-workers demonstrate broader gain spectra without a pumping current dependency by using interdiffused quantum wells [159]. But also here it is very challenging to integrate such a structure into a multi-section MLLD without severely changing its behavior due to further interdiffusion. For these structure the presented model for the QW interdiffusion during regrowth is barely adequate and a more material based description will be required.
6.3. Modeling

To further understand the complicate, non-linear, and potentially chaotic dynamics of the MLLD behavior a more advanced model is required to implement the wavelength dependent interference effects. A deeper insight of the different material effects such as fast gain recovery and complex saturation effects can only be addressed by a model based on the basic physical principals. Unfortunately this will lead to unacceptable computation times as can be seen from the following estimate. A laser model based on the fundamental physics such as carrier-carrier scattering is implemented in the Dessis software for steady state simulations. This model requires half a day computation time on a multiprocessor Linux grid for the calculation of a two dimensional optical-field semiconductor-gain interaction. For a time resolved dynamical model we can assume, that we have to repeat this calculation for every time step. To avoid numerical dispersion effects a resolution of $\Delta t$ is required. For a 1mm long MLLD we get therefore ca. 13 000 grid points corresponding to a time step of 0.775 fs. These requirements would result in infeasible computation times.

Thus we have to deal with approximations either for time or frequency domain models. One interesting solution could be the use of wavelets to combine the advantages of frequency and time-domain simulation into one single model [160].
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Appendix A

Numerical Implementation of Time Domain Model

Programming flow

For the numerical implementation of the time domain model presented in Chap. 2 the laser diode is divided in subsections with length $\Delta z$ as is shown in Fig. A.1. For each subsection $i$ we have to store the carrier number $N$, the gain compression due to carrier heating $g_T$ and the optical fields propagating in the left and the right direction $A_r$ and $A_l$, respectively. The out-coupled intensity $P_{\text{out}}$ is calculated as:

$$P_{\text{out}} = (1 - R)|A_{r,l}|^2 \quad (A.1)$$
were $R$ is the intensity reflection coefficient of the laser facet. For uncoated laser diodes the reflection coefficient for InP-based laser diodes is $R \approx 0.3$.

### A.1 Wave-Propagation

The propagation of the optical field is described by Eq. 2.10 and is for convenience repeated (Eq. A.2):

$$
\frac{\partial A}{\partial z} = (\hat{g} - \alpha_{\text{int}})A \\
+ \left(-\frac{1}{v_g} - j \frac{\Gamma}{2} \frac{\partial A}{\partial t}\right) \\
+ \left(j \frac{\beta_2}{2} - \frac{\Gamma}{4} \hat{g}'' \frac{\partial^2 A}{\partial t^2}\right)
$$

(A.2)

To solve this equation we change into a frame of reference $\tilde{z}$ moving with the group velocity $v_g$: $\tilde{z} = z - vtv_g$. Thus we get for $\tilde{A}$ [161] in the new frame of reference:

$$
\frac{1}{v_g} \frac{\partial \tilde{A}}{\partial t} = (\hat{g} - \alpha_{\text{int}})A \\
+ \left(-j \frac{\Gamma}{2} \frac{\partial \tilde{g}}{\partial \omega} \frac{\partial \tilde{A}}{\partial t}\right) \\
+ \left(j \frac{\beta_2}{2} - \frac{\Gamma}{4} \frac{\partial^2 \tilde{g}}{\partial \omega^2} \frac{\partial^2 \tilde{A}}{\partial \omega^2}\right)
$$

(A.3)

The partial derivatives $\frac{\partial \tilde{A}}{\partial \omega}$ and $\frac{\partial^2 \tilde{A}}{\partial \omega^2}$ are approximated in the following way. $\frac{\partial \tilde{A}}{\partial \omega}$ is a function of $\tilde{A}$:

$$
\frac{\partial \tilde{A}}{\partial \omega} = - \frac{\partial \tilde{A}}{\partial z} v_g + \frac{\partial \tilde{A}}{\partial t}
$$

(A.4)

The temporal evolution of $\tilde{A}$ during the time step $\Delta t$ is dominated by the gain and loss and thus $\frac{\partial \tilde{A}}{\partial t}$ can be written as:

$$
\frac{\partial \tilde{A}}{\partial t} \approx v_g (\hat{g} - \alpha_{\text{int}})\tilde{A}
$$

(A.5)
and we get:

\[
\frac{\partial A}{\partial t} \approx v_g \left( -\frac{\partial}{\partial z} + \ddot{g} - \alpha_{int} \right) \dot{A} \tag{A.6}
\]

\[
\frac{\partial^2 A}{\partial t^2} \approx v_g^2 \left( -\frac{\partial}{\partial z} + \ddot{g} - \alpha_{int} \right)^2 \ddot{A} \tag{A.7}
\]

The propagation equation can than be transformed into:

\[
\frac{1}{v_g} \frac{\partial \ddot{A}}{\partial t} = \ddot{g} \dddot{A}
\]

\[+
\quad + v_g \left( -\frac{\Gamma}{2} \frac{\partial g}{\partial \omega} \right) \left( -\frac{\partial}{\partial z} + \ddot{g} - \alpha_{int} \right) \dddot{A}
\]

\[+
\quad + v_g^2 \left( j \frac{\beta_2}{2} - \frac{\Gamma}{4} \frac{\partial^2 g}{\partial \omega^2} \right) \left( -\frac{\partial}{\partial z} + \ddot{g} - \alpha_{int} \right)^2 \dddot{A} \tag{A.8}
\]

with the complex gain/absorption for the amplifier/absorber:

\[
g' / \alpha = \frac{\Gamma}{2} (g_N (1 + j\alpha_N) + g_T (1 + j\alpha_T)) \tag{A.9}
\]

The first and second order derivatives of \( \dddot{A} \) are approximated with the two-point and three-point middle-point formula respectively:

\[
\frac{\partial \dddot{A}}{\partial z} \approx \frac{A(z + \Delta z) - A(z + \Delta z)}{2\Delta z} \tag{A.10}
\]

\[
\frac{\partial^2 \dddot{A}}{\partial z^2} \approx \frac{A(z + \Delta z) - 2A(z) + A(z + \Delta z)}{\Delta z^2} \tag{A.11}
\]

The evolution of \( \dddot{A} \) over the time \( \Delta t \) is then calculated by integrating equation A.8 with the use of Eqs. A.10, A.11 with a Runge-Kutta scheme simultaneously with the gain- and absorption-rate-equations. The neglect of the dispersion in the frame moving with the group velocity leads to errors in the order of two percent [162]. The evolution of the optical field through the cavity is realized by shifting the values \( A_{i,n} \) with \( n = r, l \) respectively to its neighboring discretization point \( i - 1 \) and \( I + 1 \) after the time step \( \Delta t \):

\[
A_r(z + \Delta z) \leftarrow A_r(z) \tag{A.12}
\]

\[
A_l(z - \Delta z) \leftarrow A_l(z) \tag{A.13}
\]
Appendix A. Numerical Implementation of Time Domain Model

At the facets the forward and backward traveling values are assigned by:

\[ A_r(z = 0, t_n) = \sqrt{R} A_f(z = 0, t_{n-1}) \]  
(A.14)
\[ A_l(z = L, t_n) = \sqrt{R} A_r(z = L, t_{n-1}) \]  
(A.15)

where \( R \) is the power reflection coefficient at the facets.

A.2 Gain and Absorption Equations

The carrier dynamics are described over the recombination coefficients \( A, B, \) and \( C, \) and the pumping current \( I \) with the following rate equation:

\[ \frac{dN}{dt} = \frac{I}{qV_{act}} - A_r N + BN^2 + CN^3 - g \frac{|A_r|^2 + |A_l|^2}{\hbar \omega_0 \sigma / T} \]  
(A.16)

where \( V_{act} \) is the active volume of the pumped gain section and \( \sigma \) the active region cross section. The gain is given by

\[ g = a(N - N_{tr}) + g_T \]  
(A.17)

The dynamics of the carrier heating gain \( g_T \) due to intra-band carrier relaxation is also described as a relaxation process with a saturation energy \( E_{sat,T} \) and a recovery time \( \tau_T. \) Thus we approximate the dynamics with the rate equation:

\[ \frac{dg_T}{dt} = -\frac{g_T}{\tau_T} - g \frac{|A_r|^2 + |A_l|^2}{E_{sat,T}} \]  
(A.18)

From Eq. A.16 we can also deduce the equation for the saturation energy \( E_{sat,N} \) as

\[ E_{sat,N} = \frac{\hbar \omega \sigma}{\Gamma a} \]  
(A.19)

For the absorber dynamics we get:

\[ \alpha = a(N - N_{tr}) + \alpha_T \]  
(A.20)

and the dynamics determined by

\[ \frac{d\alpha_{abs}}{dt} = -\frac{\alpha_{0} - \alpha_{abs}}{\tau_{abs}} - \alpha \frac{|A_r|^2 + |A_l|^2}{E_{sat,abs}} \]  
(A.21)
\[ \frac{d\alpha_T}{dt} = -\frac{\alpha_T}{\tau_{abs,T}} - \alpha \frac{|A_r|^2 + |A_l|^2}{E_{sat,T}} \]  
(A.22)
with $\alpha_{abs} = a(N_n - N_{tr})$. The external modulation voltage applied to
the absorber section was directly implemented by the modulation of $\alpha_{abs}$
[31].

The spontaneous emission $f$ is simply added to the envelope function
$A$ for each time step in each segment $\Delta z$ of the gain section following
the theory presented in [58] with the function:

$$f_{s,\text{spont}} = x_n \cdot \sqrt{\hbar \omega \Gamma_{th}} n_{sp} v_g$$

(A.23)

where $x_n$ is a pseudo random Gaussian distributed number between $-1$
and 1, $\Gamma_{th}$ the gain at threshold and $n_{sp}$ is the inversion factor at thresh¬
old. Eq. A.23 corresponds to a white Gaussian noise source.

Fig. A.2 summarizes the computation flow for the time $T = n \cdot t$.

![Figure A2: Process flow of the time domain model. The time-step $\Delta t$
is correlated with the spatial resolution $\Delta z$ as $\Delta t = \Delta z / v_g$, where $v_g$ is
the group velocity.]

The used parameters and their values are summarized in the following
### Appendix A. Numerical Implementation of Time Domain Model

Table A.1: Parameters used for the amplifier/absorber model: † calculated, * measured, § from literature, ‡ fitted or estimated.

#### Propagation

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_r^2$</td>
<td>$-1.8 \frac{cm^2}{TW}$</td>
<td>nonlinear refractive index</td>
</tr>
<tr>
<td>$\gamma^2$</td>
<td>$75 \frac{GW}{cm}$</td>
<td>TPA coefficient</td>
</tr>
</tbody>
</table>

#### Absorber

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{abs}^i$</td>
<td>0.1</td>
<td>absorber confinement factor</td>
</tr>
<tr>
<td>$\sigma_{abs}$</td>
<td>$0.125 \mu m^2$</td>
<td>absorber active region cross section</td>
</tr>
<tr>
<td>$N_{tr,abs}^*$</td>
<td>$4.5 \cdot 10^{18} \frac{1}{cm^3}$</td>
<td>transparency carrier density</td>
</tr>
<tr>
<td>$\alpha_{abs}^*$</td>
<td>$2.4 \cdot 10^{-16} \frac{cm^2}{J}$</td>
<td>differential absorption</td>
</tr>
<tr>
<td>$E_{sat,abs}^*$</td>
<td>$500 fJ$</td>
<td>Saturation energy for CH</td>
</tr>
<tr>
<td>$\tau_T$</td>
<td>1 ps</td>
<td>CH time constant</td>
</tr>
<tr>
<td>$\alpha_{int}^*$</td>
<td>$15 cm^{-1}$</td>
<td>internal loss factor</td>
</tr>
</tbody>
</table>

#### Amplifier

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{amp}^i$</td>
<td>0.06</td>
<td>amplifier confinement factor</td>
</tr>
<tr>
<td>$\sigma_{amp}^2$</td>
<td>$0.05 \mu m^2$</td>
<td>amplifier active region cross section</td>
</tr>
<tr>
<td>$\mu^1$</td>
<td>0.75</td>
<td>current efficiency</td>
</tr>
<tr>
<td>$N_{tr,amp}^*$</td>
<td>$1.9 \cdot 10^{18} \frac{1/cm^3}{cm^2}$</td>
<td>transparency carrier density</td>
</tr>
<tr>
<td>$\alpha_{amp}^*$</td>
<td>$5.34 \cdot 10^{-16} \frac{cm^2}{J}$</td>
<td>differential gain</td>
</tr>
<tr>
<td>$E_{sat,amp}^*$</td>
<td>$500 fJ$</td>
<td>Saturation energy for CH</td>
</tr>
<tr>
<td>$\tau_T$</td>
<td>1 ps</td>
<td>CH time constant</td>
</tr>
<tr>
<td>$A^6$</td>
<td>$0.5 \mu s^{-1}$</td>
<td>non-radiative carrier recombination rate</td>
</tr>
<tr>
<td>$B^6$</td>
<td>$7 \cdot 10^{-13} \frac{cm^2}{s}$</td>
<td>bimolecular recombination rate</td>
</tr>
<tr>
<td>$C^6$</td>
<td>$1.9 \cdot 10^{-26} \frac{cm^6}{s}$</td>
<td>Auger recombination rate</td>
</tr>
<tr>
<td>$\alpha_{int}^*$</td>
<td>$15 cm^{-1}$</td>
<td>internal loss factor</td>
</tr>
<tr>
<td>$g_1^*$</td>
<td>0</td>
<td>gain slope</td>
</tr>
<tr>
<td>$g_2^*$</td>
<td>$\approx -150 \frac{f s^2}{\mu m}$</td>
<td>gain dispersion</td>
</tr>
<tr>
<td>$\beta_2^*$</td>
<td>$20 \frac{ps^2}{km}$</td>
<td>group velocity dispersion</td>
</tr>
</tbody>
</table>
Appendix B

Process Sequences

B.1 Metalization

All metals were evaporated with 5Å/s in a Univex 500 machine. The alloying was done with a JIPElec JetFirst100 machine at a N$_2$ pressure of 5mbar. The heating ramp was 10°C/s.

Lift-off for p-contact

<table>
<thead>
<tr>
<th>photo-resist</th>
<th>AZ1510 = AZ1505:AZ1518=1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>spinning</td>
<td>2s @ 1000 U/min 40sec @ 5000U/min</td>
</tr>
<tr>
<td>baking</td>
<td>1min @ 110°C</td>
</tr>
<tr>
<td>relaxation</td>
<td>2h under N$_2$ atmosphere</td>
</tr>
<tr>
<td>hardening</td>
<td>40min covered with chlorobenzene</td>
</tr>
<tr>
<td>drying</td>
<td>N$_2$-pistol</td>
</tr>
<tr>
<td>exposure under mask developed</td>
<td>80mJ @ 403nm</td>
</tr>
<tr>
<td>rinsing</td>
<td>40sec in 0.8% KOH</td>
</tr>
<tr>
<td>drying</td>
<td>5min under floating H$_2$O</td>
</tr>
<tr>
<td>evaporation</td>
<td>N$_2$-pistol</td>
</tr>
<tr>
<td>lift-off</td>
<td>50Å Pt/150Å Ti/400Å Pt/1500Å Au/200Å Ti</td>
</tr>
<tr>
<td>cleaning</td>
<td>10min in acetone/isopropanol = 1:1 @ 50°C</td>
</tr>
<tr>
<td>drying</td>
<td>5min isopropanol 5min H$_2$O</td>
</tr>
<tr>
<td>alloying</td>
<td>N$_2$-pistol</td>
</tr>
<tr>
<td></td>
<td>30sec @ 370°C</td>
</tr>
</tbody>
</table>
### Lift-off for n-contact

- **photo-resist**: AZ1518
- **spinning**: 2s @ 1000 U/min 60sec @ 4000U/min
- **baking**: 1min @ 110°C
- **relaxation**: 2h under N₂ atmosphere
- **hardening**: 40min covered with chlorobenzene
- **drying**: N₂-pistol
- **exposure under mask**: 100mJ @ 403nm
- **development**: 2min 30sec in 0.8% KOH
- **rinsing**: 5min under floating H₂O
- **drying**: N₂-pistol
- **evaporation**: 300ÅTi / 400 ÅPt /1000ÅAu
- **lift-off**: 10min in acetone:isopropanol = 1:1 @ 50°C
- **cleaning**: 5min isopropanol 5min H₂O
- **drying**: N₂-pistol
- **alloying**: 30sec @ 370°C

### Lift-off for pad-contact

- **drying**: 20min @ 90°C under N₂ atmosphere
- **cooling**: 5min @ room temperature
- **photo-resist**: maN-490
- **spinning**: 10s @ 1000 U/min 60sec @ 5000U/min
- **baking**: 40min @ 90°C
- **relaxation**: 10 min under N₂ atmosphere
- **exposure under mask**: 7 cycles with 30s exposure of 7.7mW/cm²
- **development**: @ 365nm and 15s break
- **rinsing**: 2min in maD-333
- **drying**: 5min under floating H₂O
- **sputtering**: N₂-pistol
- **evaporation**: 12min Ar-ion
- **evaporation**: 250 ÅCr /12000ÅAu
- **lift-off**: 10min in acetone:isopropanol = 1:1 @ 50°C
- **cleaning**: 5min isopropanol 5min H₂O
- **drying**: N₂-pistol
### B.1. Metalization

**Backside n-contact**

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mounting</td>
<td>upside down on glass substrate with wax @ 70°C with a Logitech thin section bonding jig</td>
</tr>
<tr>
<td>Cooling</td>
<td>1h @ room temperature</td>
</tr>
<tr>
<td>Lapping</td>
<td>down to wafer thickness of 130μm</td>
</tr>
<tr>
<td>Etching</td>
<td>10min with CH₃COOH:HBr:K₂Cr₂O₇=1:1:1 @ room-temperature</td>
</tr>
<tr>
<td>Rinsing</td>
<td>5min under floating H₂O</td>
</tr>
<tr>
<td>Drying</td>
<td>N₂-pistol</td>
</tr>
<tr>
<td>Sputtering</td>
<td>12min Ar-ion</td>
</tr>
<tr>
<td>Evaporation</td>
<td>300Å Ti/400Å Pt/1000Å Au</td>
</tr>
<tr>
<td>Wax Dissolution</td>
<td>10min in Logitech wax solution @ 120°C</td>
</tr>
<tr>
<td>Cleaning</td>
<td>5min trichloroethylene / 5min acetone</td>
</tr>
<tr>
<td>Drying</td>
<td>N₂-pistol</td>
</tr>
</tbody>
</table>
B.2 RIE-etching with Oxford Plasma Lab 80

**Rib mask etching**

200nm SiO₂ mask deposition

- under-coating evaporation
- photo-resist
- spinning
- baking
- relaxation
- exposure under mask
- development
- rinsing
- drying
- mask etching
- plastic removal

<table>
<thead>
<tr>
<th>Oxford Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PECVD 80+ system</td>
</tr>
<tr>
<td>3min30s @ 900mTorr, 20W,</td>
</tr>
<tr>
<td>10s pulse time</td>
</tr>
<tr>
<td>300°C, 340sccm SiH₄</td>
</tr>
<tr>
<td>and 710sccm N₂O</td>
</tr>
<tr>
<td>20Å Ti</td>
</tr>
<tr>
<td>AZ1510</td>
</tr>
<tr>
<td>2s @ 1000U/min, 40s @ 6000U/min</td>
</tr>
<tr>
<td>1min @ 110°C</td>
</tr>
<tr>
<td>2h under N₂ atmosphere</td>
</tr>
<tr>
<td>35mJ @ 403nm</td>
</tr>
<tr>
<td>45sec in 0.8% KOH</td>
</tr>
<tr>
<td>5min under floating H₂O</td>
</tr>
<tr>
<td>N₂-pistol</td>
</tr>
<tr>
<td>15 times 30s @ 100mTorr, 175W, 18°C</td>
</tr>
<tr>
<td>61sccm Ar, 13sccm CHF₃</td>
</tr>
<tr>
<td>with 3min break @ 100mTorr, 18°C</td>
</tr>
<tr>
<td>61sccm Ar</td>
</tr>
<tr>
<td>5min @ 100mTorr, 130W,</td>
</tr>
<tr>
<td>18°C, 100sccm O₂</td>
</tr>
</tbody>
</table>

**Rib semiconductor etching**

<table>
<thead>
<tr>
<th>etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 times 10min @ 85µbar, 225W, 10°C</td>
</tr>
<tr>
<td>60sccm H₂, 12sccm CH₄, 6sccm Ar</td>
</tr>
<tr>
<td>with 3min break @ 85µbar and 12sccm Ar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>plastic removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>10min @ 100mTorr, 130W, 10°C, 100sccm O₂</td>
</tr>
</tbody>
</table>
### B.2. RIE-etching with Oxford Plasma Lab 80

#### Rib etching for passive waveguide

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>photo-resist</td>
<td>AZ1518</td>
</tr>
<tr>
<td>spinning</td>
<td>2s @ 1000 U/min 50sec @ 5000U/min</td>
</tr>
<tr>
<td>baking</td>
<td>2min @ 110°C</td>
</tr>
<tr>
<td>exposure under mask</td>
<td>100mJ @ 403nm</td>
</tr>
<tr>
<td>development</td>
<td>60sec in 0.8% KOH</td>
</tr>
<tr>
<td>rinsing</td>
<td>5min under floating H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>drying</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;-pistol</td>
</tr>
<tr>
<td>etching</td>
<td>≈3 times 10min @ 85µbar, 225W, 10°C</td>
</tr>
<tr>
<td></td>
<td>60sccm H&lt;sub&gt;2&lt;/sub&gt;, 12sccm CH&lt;sub&gt;4&lt;/sub&gt;, 6sccm Ar</td>
</tr>
<tr>
<td></td>
<td>with 3min break @ 85µbar and 12sccm Ar</td>
</tr>
<tr>
<td>plastic removal</td>
<td>5min @ 100mTorr, 130W, 10°C, 100sccm O&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>cleaning</td>
<td>5min acetone / 5min isopropanol / 5min H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>drying</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;-pistol</td>
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</tbody>
</table>

#### Etching for n-contacts

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>photo-resist</td>
<td>AZ1518</td>
</tr>
<tr>
<td>spinning</td>
<td>2s @ 1000 U/min 50sec @ 4000U/min</td>
</tr>
<tr>
<td>baking</td>
<td>2min @ 110°C</td>
</tr>
<tr>
<td>exposure under mask</td>
<td>100mJ @ 403nm</td>
</tr>
<tr>
<td>development</td>
<td>60sec in 0.8% KOH</td>
</tr>
<tr>
<td>rinsing</td>
<td>5min under floating H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>drying</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;-pistol</td>
</tr>
<tr>
<td>etching</td>
<td>≈5 times 10min @ 85µbar, 225W, 10°C</td>
</tr>
<tr>
<td></td>
<td>60sccm H&lt;sub&gt;2&lt;/sub&gt;, 12sccm CH&lt;sub&gt;4&lt;/sub&gt;, 6sccm Ar</td>
</tr>
<tr>
<td></td>
<td>with 3min break @ 85µbar and 12sccm Ar</td>
</tr>
<tr>
<td>plastic removal</td>
<td>5min @ 100mTorr, 130W, 10°C, 100sccm O&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>cleaning</td>
<td>5min acetone / 5min isopropanol / 5min H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>drying</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;-pistol</td>
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</tbody>
</table>

#### Pyralin etching for contacts and cleaving channels

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>photo-resist</td>
<td>S1828</td>
</tr>
<tr>
<td>spinning</td>
<td>2s @ 1000 U/min 60sec @ 4000U/min</td>
</tr>
<tr>
<td>baking</td>
<td>3min @ 110°C</td>
</tr>
<tr>
<td>exposure under mask</td>
<td>85mJ @ 403nm</td>
</tr>
<tr>
<td>development</td>
<td>60s in 0.8% KOH</td>
</tr>
<tr>
<td>rinsing</td>
<td>5min under floating H&lt;sub&gt;2&lt;/sub&gt;O</td>
</tr>
<tr>
<td>drying</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;-pistol</td>
</tr>
<tr>
<td>etching</td>
<td>≈5 times 10min @ 100mTorr, 130W, 10°C, 100sccm O&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>with 3min break @ 85µbar and 12sccm Ar</td>
</tr>
</tbody>
</table>
### B.3 Miscellaneous

**Wet etching of laser rib active sections**
- **oxide etching**
- **rinsing**
- **drying**
- **photo-resist**
- **spinning**
- **baking**
- **exposure under mask**
- **development**
- **etching**
- **rinsing**
- **drying**

<table>
<thead>
<tr>
<th>Step</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1min NaOH @ room temperature</td>
<td><strong>Pyralin 2560 application</strong></td>
</tr>
<tr>
<td>5min under floating H₂O</td>
<td>drying</td>
</tr>
<tr>
<td>N₂-pistol</td>
<td>cooling</td>
</tr>
<tr>
<td>AZ1518</td>
<td>spinning</td>
</tr>
<tr>
<td>2s @ 1000 U/min 60sec @ 5000U/min</td>
<td>relaxation</td>
</tr>
<tr>
<td>2min @ 110°C</td>
<td>soft bake</td>
</tr>
<tr>
<td>60sec in 0.8% KOH</td>
<td>photo-resist</td>
</tr>
<tr>
<td>5min under floating H₂O</td>
<td>spinning</td>
</tr>
<tr>
<td>≈2min 30s HCl:H₃PO₄=1:3</td>
<td>baking</td>
</tr>
<tr>
<td>@ room-temperature</td>
<td>exposure under mask</td>
</tr>
<tr>
<td>5min under floating H₂O</td>
<td>development</td>
</tr>
<tr>
<td>N₂-pistol</td>
<td>60s (for edge bead removal)</td>
</tr>
<tr>
<td>60s in 0.8% KOH</td>
<td>rinsing</td>
</tr>
<tr>
<td>5min under floating H₂O</td>
<td>drying</td>
</tr>
<tr>
<td>2min @ 100°C</td>
<td>cleaning</td>
</tr>
<tr>
<td>30min @ 100°C under N₂ atmosphere</td>
<td>drying</td>
</tr>
<tr>
<td>10min @ room temperature</td>
<td>relaxation</td>
</tr>
<tr>
<td>4s @ 500 U/min 60sec @ 5000U/min</td>
<td>cooling</td>
</tr>
<tr>
<td>15min @ room temperature</td>
<td>soft bake</td>
</tr>
<tr>
<td>20min @ 100°C</td>
<td>photo-resist</td>
</tr>
<tr>
<td>2s @ 1000 U/min 60sec @ 4000U/min</td>
<td>baking</td>
</tr>
<tr>
<td>2min @ 100°C</td>
<td>exposure under mask</td>
</tr>
<tr>
<td>60s in 0.8% KOH</td>
<td>development</td>
</tr>
<tr>
<td>5min under floating H₂O</td>
<td>rinsing</td>
</tr>
<tr>
<td>N₂-pistol</td>
<td>drying</td>
</tr>
<tr>
<td>under spinner @ 1000 U/min</td>
<td>cleaning</td>
</tr>
<tr>
<td>with butylacetate:isopropanol=4:6</td>
<td>drying</td>
</tr>
<tr>
<td>spinner @ 3000U/min</td>
<td>relaxation</td>
</tr>
<tr>
<td>24h @ room temperature in N₂ atmosphere</td>
<td>hard bake</td>
</tr>
<tr>
<td>60min @ 300°C</td>
<td></td>
</tr>
</tbody>
</table>
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Acknowledgements

First I like to thank Prof. Dr. Heinz Jäckel for his persistent support over my long work and for the possibility to make the impossible possible for real research.
Second I want to thank Prof. Dr. Marc Ilegems not only for co-examining my thesis but also for his encouraging and sympathetic statements during the project review meetings.

My further appreciations goes to all the people who contributed to the success of this project.
Prof. Dr. G. Guckos supported financially the start of my PhD and gave me the possibility to learn processing in his lab.
Riccardo Scollo was my project partner and measured all the devices I delivered even it was sometimes nearly impossible. Dr. Frank Robin acted as a matching unit and forced me to publish my results. Dr. Daniel Erny was always ready for detailed theoretical discussions and encouraged me during some hopeless periods.
The FIRST team prepared the clean-room facilities and was so kind to repair all non-working machines immediately. Especially I want to mention Dr. Emilio Gini and Martin Ebnöther who growed all suspect and non-suspect layer stacks with the MOVPE machine.
A special thanks goes to Dr. Werner Vogt. Without his deep insight in III-V technology and his support in planning, reporting and mask-design the project would not be what it is now. Another very important person for my project was Res Neiger. He constructed the most fancy probes I ever saw and interrupted his holidays to help me finishing my “golden” run.
Martin Kwakernaak gave me a not to short introduction in the MLLD process and provided a working laser model on which we could continue.
Dr. Roland Schreieck helped moving stuff around and was a conversation partner at the beginning of my work. Furthermore the Photonic Crystal and the Optical Switching groups with Robert Wueest, Glen Stark, Yuriy Fedoryshyn, Dr. Peter Cristea, and Peter Kasper enriched all the time in FIRST lab to be more fun. Especially I want to mention Patrie Strasser for his kindness to make SEM-Pictures 24 hours a day 7 days a week. Dr. Rik Harbers was my interface to the 2DFDTD simulation tool. The HBT-group with Dr. Volker Schwarz, Dr. Iwan Schnyder, and Urs Hammer shared some scientific and non-scientific problems. Dr. Valerio Laino, Dr. Friedhard Römer and Dr. Mathieu Luisier from the IIS shared with me several semester projects for students. Martin Lanz offered me the possibility to use his well equipped bonding and soldering lab. Dr. Dominique Vez provided a LabView program for the Hakki-Paoli measurement set up. The work with the semester project students was always a pleasure and contributed many interesting subjects to the progress of my work. Mr. Hediger and Mr. Vogt and their teams from the mechanical workshops of the physics and electronics department respectively were always very obliging with my quaint demands. Mr. Maag helped me with all known and unknown Mac problems and joined his detail knowledge about the ETH financial zoo. Ruth Zähringer filled out all the HR papers and was a resource for all unknown mysteries of the institute.

I am especially grateful to my wife Riki and my sons Julian, Benjamin and Valentin for their support and love and the whole mishpocha for their help.
Curriculum vitae

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1991-1992 Military Service with Big Band der Bundeswehr in Euskirchen, Germany
1992-1995 Studies in Physics at the University of Siegen, Germany
1995-1996 Studies in Physics at the University Claude Bernard Lyon, France
1996-1998 Studies in Physics at the University of Hannover, Germany Diploma Degree in Physics at the University of Hannover, Germany
1999-2000 Assistant at the Institute for mechanical systems, ETH Zurich
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