Doctoral Thesis

Electrically and optically pumped semiconductor disk lasers - continuous-wave and modelocked

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ELECTRICALLY AND OPTICALLY PUMPED SEMICONDUCTOR DISK LASERS — CONTINUOUS-WAVE AND MODELOCKED

A dissertation submitted to
ETH ZURICH

for the degree of
Doctor of Sciences

presented by
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2011
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List of Acronyms

\[(CH_3)_2CO\] acetone
\[C_3H_8O\] isopropyl-alcohol
\[[(CH_3)_3Si]_2NH\] hexamethyldisilazane

AC autocorrelation
AFM atomic force microscope
Ag silver
Al aluminum
Al\(_2\)O\(_3\) sapphire
AlF\(_3\) aluminium fluoride
AR anti reflection
Ar argon
As arsenic
Au gold

BET band edge thermometry
Br bromine

C carbon
CBr\(_4\) carbon tetra-bromide
CCD charge-coupled device
CEO carrier envelope offset
CF\(_4\) tetrafluoromethane
CH\(_4\) methane
CHF\(_3\) trifluoromethane
Cl chlorine
CPU central processing unit
Cu copper
<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>CVD</td>
<td>chemical vapor deposition</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DBR</td>
<td>distributed Bragg-reflector</td>
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<tr>
<td>DNQ</td>
<td>diazonaphthoquinone</td>
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<td>EL</td>
<td>electroluminescence</td>
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<td>EP</td>
<td>electrically pumped</td>
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<td>Er</td>
<td>erbium</td>
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<td>ETH</td>
<td>Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology)</td>
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<td>F</td>
<td>fluorine</td>
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<td>FCA</td>
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<td>fast Fourier transformation</td>
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<td>FS</td>
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<td>Ga</td>
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<td>group delay dispersion</td>
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<td>GTI</td>
<td>Gires Tournois interferometer</td>
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<td>H</td>
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<td>H₂O₂</td>
<td>hydrogen peroxide</td>
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<td>He</td>
<td>helium</td>
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<td>HF</td>
<td>hydrofluoric</td>
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<td>HR</td>
<td>high reflector</td>
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<tr>
<td>IA</td>
<td>induced absorption</td>
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<tr>
<td>ICP</td>
<td>inductively-coupled plasma</td>
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<td>In</td>
<td>indium</td>
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<tr>
<td>IV</td>
<td>current-voltage</td>
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<tr>
<td>LASER</td>
<td>light amplification by stimulated emission of radiation</td>
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<td>LED</td>
<td>light emitting diode</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>LF</td>
<td>low frequency</td>
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<td>light-current-voltage</td>
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<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
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<tr>
<td>MIXSEL</td>
<td>modelocked integrated external-cavity surface-emitting laser</td>
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<td>MOCVD</td>
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<td>OC</td>
<td>output coupler</td>
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<tr>
<td>OCT</td>
<td>optical coherence tomography</td>
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<td>OMVPE</td>
<td>organo-metallic vapour phase epitaxy</td>
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<td>OP</td>
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<td>OSA</td>
<td>optical spectrum analyzer</td>
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<td>P</td>
<td>phosphorus</td>
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<td>PECVD</td>
<td>plasma-enhanced chemical vapor deposition</td>
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<td>PL</td>
<td>photoluminescence</td>
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<td>PR</td>
<td>partial reflector</td>
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<td>Pt</td>
<td>platinum</td>
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<td>quantum-dot</td>
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<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RHEED</td>
<td>reflective high-energy electron-diffraction</td>
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<tr>
<td>RIE</td>
<td>reactive ion etching</td>
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ROC  radius of curvature
RPM  revolutions per minute
RTA  rapid thermal annealing

Sb  antimonite
sccm  standard cubic centimeter: $1 \text{cm}^2 \text{s}^{-1}$
at $0 \, ^\circ \text{C}$ and 1013.25 hPa
SEM  scanning electron microscope
SESAM  semiconductor saturable absorber mirror
SF$_6$  sulfur hexafluoride
SHG  second harmonic generation
Si  silicon
SiH$_4$  silane
Si$_N$$_x$  silicon nitride
SiO$_x$  silicon oxide
SiO$_x$N$_y$  silicon oxide nitride
Sn  tin
SPM  self-phase modulation
SSL  solid state laser
STEM  scanning transmission electron microscopy

TBP  time bandwidth product
TEM$_{00}$  fundamental transverse mode
Ti  titanium
TOD  third order dispersion
TPA  two-photon absorption

UV  ultra-violet

VCSEL  vertical cavity surface-emitting laser
VECSEL  vertical external-cavity surface-emitting laser

W  tungsten
WL  wetting layer

Yt  ytterbium
List of Symbols

\( A \) 1/e beam area \([m^2]\)
\( a \) lattice constant \([m]\)
\( \alpha \) empirical linewidth enhancement factor
\( \alpha_{\text{absorber}} \) empirical linewidth enhancement factor for the absorber
\( \alpha_{\text{gain}} \) empirical linewidth enhancement factor for gain
\( A_r \) relative amplitude of slow (\( \tau_s \)) and fast (\( \tau_f \)) time-components for relaxation

\( \beta_{\text{TPA}} \) two-photon absorption coefficient \([mW^{-1}]\)

\( c \) speed of light: \( 3 \times 10^8 \text{ m s}^{-1} \)

\( d \) thickness \([m]\)
\( D_2 \) group delay dispersion \([s^2]\)
\( d_b \) 1/e beam diameter \([m]\)
\( d_c \) top contact width \([m]\)
\( \Delta D \) growth error \([\%]\)
\( \Delta g \) gain change \([m^{-1}]\)
\( \Delta \lambda \) FWHM spectral bandwidth \([m]\)
\( \Delta \nu \) longitudinal mode spacing \([s^{-1}]\)
\( \Delta \varphi \) temporal phase change \([\text{rad}]\)
\( \Delta R \) modulation depth \( (R_{\text{nl}} - R_{\text{lin}}) \)
\( \Delta R_{\text{ns}} \) non-saturable losses \( (1 - R_{\text{nl}}) \)
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<td>differential resistance at threshold</td>
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<td>$\Delta T$</td>
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<td>$\Delta t$</td>
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<td>$\Delta z$</td>
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<td>$F_{peak}$</td>
<td>peak pulse fluence</td>
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<td>$f_{rep}$</td>
<td>repetition rate</td>
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<td>revolutions per minute</td>
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<td>$F_{sat}$</td>
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<td>$G$</td>
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<td>$\Gamma$</td>
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<td>$[A]$</td>
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<td>$I_{th}$</td>
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<td>$k_0$</td>
<td>vacuum wavenumber</td>
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<tr>
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<td>cavity length</td>
<td>[m]</td>
</tr>
<tr>
<td>$l$</td>
<td>loss</td>
<td>[%]</td>
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<tr>
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<td>wavelength</td>
<td>[m]</td>
</tr>
<tr>
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<td>beam quality factor</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>carrier density</td>
<td>[m$^{-3}$]</td>
</tr>
<tr>
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<td>refractive index</td>
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</tr>
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<tr>
<td>$N_d$</td>
<td>donator density</td>
<td>[m$^{-3}$]</td>
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<tr>
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<tr>
<td>$N_p$</td>
<td>number of photons</td>
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<td>number of QWs</td>
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<td>photon frequency</td>
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<td>angular reference frequency</td>
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<td>power</td>
<td>[W]</td>
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<td>[bar]</td>
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<td>average power</td>
<td>[W]</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>mass flux</td>
<td>[kg m$^{-2}$ s$^{-1}$]</td>
</tr>
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<td>[rad]</td>
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<td>spectral phase</td>
<td>[rad]</td>
</tr>
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<td>$P_{\text{peak}}$</td>
<td>pulse peak power</td>
<td>[W]</td>
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<td>$P_{\text{pump}}$</td>
<td>pump power</td>
<td>[W]</td>
</tr>
<tr>
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<td>elementary charge</td>
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<tr>
<td>$R$</td>
<td>reflectivity</td>
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<td>1/e beam radius</td>
<td>[m]</td>
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<td>$R_b$</td>
<td>bottom contact radius</td>
<td>[m]</td>
</tr>
<tr>
<td>$r^c$</td>
<td>complex amplitude reflectivity</td>
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<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>etch rate</td>
<td>[m s$^{-1}$]</td>
</tr>
</tbody>
</table>
List of Symbols

\( R_{\text{lin}} \) linear reflectivity
\( R_m \) AR mesa radius \([\text{m}]\)
\( R_{\text{nl}} \) nonlinear reflectivity
\( r_{\text{ROC}} \) radius of curvature \([\text{m}]\)
\( R_t \) top contact radius \([\text{m}]\)
\( R_{\text{th}} \) thermal resistance \([\text{KW}^{-1}]\)

\( S \) spectral power density \([\text{W Hz}^{-1}]\)
\( s \) saturation parameter \( (\frac{F_p}{F_{\text{sat}}}) \)
\( \text{sech}^2 \) secans hyperperbolicus squared \( \left( \frac{1}{\cosh^2} \right) \)
\( \Sigma \) attenuation \([\text{dB}]\)

\( T \) transmission
\( t \) time \([\text{s}]\)
\( \tau \) 1/e relaxation time constant \([\text{s}]\)
\( \tau_f \) 1/e relaxation time constant of the fast component \([\text{s}]\)
\( \tau_p \) FWHM pulse duration \([\text{s}]\)
\( \tau_s \) 1/e relaxation time constant of the slow component \([\text{s}]\)
\( t_d \) time delay between pump pulse and probe pulse \([\text{s}]\)
\( T_g \) group delay \([\text{s}]\)
\( \theta \) angle \([\degree]\)
\( T_s \) temperature \([\degree\text{C}]\)

\( w \) 1/e\(^2\) beam waist radius \([\text{m}]\)
\( w_{\text{flat}} \) flat-top beam waist radius \([\text{m}]\)

\( \Xi \) quantum efficiency

\( z \) position \([\text{m}]\)
List of Journal Papers


List of Conference Papers


sorber mirrors (QD-SESAMs). In *Proceedings Advanced Solid-State Photonics, Denver, USA*, 2009.


Abstract

In this thesis we focus on two main experimental results, and we comment on the fabrication and characterization techniques required to enable these. We present the steps leading to the demonstration of high power femtosecond pulse generation using optically pumped SESAM-modelocked VECSELs. We achieved an average output power of more than 1 W with 784-fs pulses. The second experimental topic deals with the first steps required to extend the demonstrated performances to an electrical pumped VECSEL structure. We present various characterizations of the devices and CW power of up to 120 mW.

The necessary steps that enabled us to advance into the femtosecond regime are manifold. In our study of the influence of the intra-cavity GDD on the pulse duration of modelocked VECSELs, we experimentally confirmed that quasi-soliton modelocking is the responsible pulse shaping mechanism in the few picosecond range. In order to carry out such an experimental study, we developed a versatile design for a dispersive mirror, based on a hybrid semiconductor/dielectric material system where the GDD is set by the deposition of a single dielectric layer of defined thickness, enabling access to positive and negative GDD values in the order of $10^4$ fs$^2$ for a single reflection. By means of these dispersive mirrors we were able to alter the intra-cavity GDD of a SESAM-modelocked VECSEL and we identified an optimal operation range for the generation of the shortest pulses of low and positive values for the intra-cavity GDD. Inspired by these findings, we started to investigate low-GDD AR sections. The employment of hybrid semiconductor/dielectric multilayer structures for our VECSELs resulted in a reduction of their structural GDD of about a factor of 1000 over a wavelength range of several tens of nanometers. We used such AR sections on VECSELs with QD and QW based active regions, which were specifically designed for the generation of ultrashort pulses. These structures
were optimized for a large spectral width by employing a chirped positioning scheme of the active layers. These steps, in combination with an optimized heat management, made the demonstration of high power femtosecond pulses from a VECSEL possible.

Despite these demonstrated achievements of modelocked optically pumped VECSELS, these devices are not yet compatible with the packaging requirements necessary for industrial applications. Therefore, the development of an electrical pumping scheme is very important. For electrical pumping of VECSELS, the design of the gain element has to meet many additional and partly oppositional conditions. In order for current to flow through the structure, the presence of doping in the semiconductor structure and contacts on the device are vital. However, these requirements are accompanied by detrimental influences on the output power and the pump profile of the devices. The doping, on the one hand, provides electrical conductivity, but, on the other hand, it results in higher optical losses caused by TPA. Increasing the doping level leads to more optical losses and lowering it results in more pronounced electrical heating, both deteriorating the output performance of the device. Therefore, it is essential to analyze the critical balance between these conflicting optical and electrical properties. In order to overcome the increased losses through TPA, we implemented an intermediate DBR for gain enhancement. Another challenge is to achieve a Gaussian or at least uniform carrier injection profile in the active region, comparable to optically pumped VECSELS, where it can be controlled by the pump laser beam profile. This challenge is caused by the intrinsic ring shape of one electrode and sets a limit on the power scalability and the beam quality, however, we were able to relax these limitations by using a p-doped bottom DBR in combination with a small bottom disk contact and a current spreading layer. We obtained good power scalability and an excellent carrier injection profile in the active region, and we demonstrated more than 100 mW for several samples. In a study of the beam quality of electrically pumped VECSELS, we identified that a combination of high output power and good beam quality is only possible if an optimum reflectivity value of the intermediate DBR is found.

The presented results on modelocked optically pumped VECSELS are very promising for a vertical integration of the absorber in the VECSEL structure, and we envision several watts of output power with pulses shorter than 500 fs from a MIXSEL structure. In the field of modelocked electrically pumped VECSELS, 200 mW with pulses shorter than 10 ps seem to be feasible in the near future.
Kurzfassung

In dieser Doktorarbeit werden zwei experimentelle Resultate vorgestellt und die dafür nötigen Herstellungsverfahren und Charakterisierungs-techniken vorgestellt. Die erforderlichen Schritte werden erläutert, die zum Erreichen von Hochleistungspulsen im Femtosekundenbereich mit SESAM modengekoppelten optisch gepumpten VECSELn geführt haben. Es wurde eine mittlere Leistung von über 1 W mit 784-fs Pulsen gemessen. Das zweite Thema dieser Arbeit behandelt die ersten Schritte, die für eine Ausweitung der demonstrierten Leistungen auf elektrisch gepumpte VECSEL Strukturen nötig sind. Es werden diverse Charakterisierungen der Proben und Dauerstrichleistungen bis zu 120 mW erörtert.

Um in das Feld der Femtosekunden vorzustossen, waren eine Vielzahl Untersuchungen nötig. In einer experimentellen Studie über den Einfluss von Kavitätsdispersion auf die Pulsdauer modengekoppelter VECSEL war es uns möglich Quasisolitonenmodenkopplung als den verantwortlichen Mechanismus für die Pulsbildung im niedrigen Pikosekundenbereich zu bestätigen. Um diese Studie durchführen zu können, sind vielseitige dispersive Spiegel auf Basis von Halbleitermaterialien und Dielektrika entwickelt worden, für welche der Wert der Dispersion durch die spezifische Dicke einer einzelnen dielektrischen Lage definiert ist, und mit denen positive und negative Dispersionswerte in der Größenordnung von $10^4\text{ fs}^2$ mit einer einzigen Reflektion erreicht werden können. Mit Hilfe dieser dispersiven Spiegel konnten die Kavitätsdispersion von SESAM modengekoppelten VECSELn geändert werden und es konnte ein optimaler Arbeitsbereich der Dispersion für die Erzeugung der kürzesten Pulse von niedrigen positiven Werten bestimmt werden. Aufgrund dieser Erkenntnisse wurden Antireflexschichten mit niedriger Dispersion untersucht. Das Aufbringen von kombinierten Vielschichtsystemen bestehend aus Halbleitermaterial und Dielektrika auf unsere VECSEL führte zur Reduktion der strukturellen Dispersion die-

gangsleistung nur für einen optimalen Wert für die Reflektivität des Zwischenspiegels mit guter Strahlqualität kombiniert werden kann.

Die erreichten Resultate modengekoppelter optisch gepumpter VECSEL sind vielversprechend für eine vertikale Integration des Absorbers in die VECSEL Struktur, und mehrere Watt mit Pulsen kürzer als 500 fs sind absehbar von einer MIXSEL Struktur. Von modengekoppelten elektrisch gepumpten VECSELn sind 200 mW mit Pulsedauern kürzer als 10 ps zu erwarten.
Chapter 1

Introduction

Back in 1960, in the year of the first demonstration of light amplification by stimulated emission of radiation [1], lasers were described as a solution looking for a problem. In all likelihood, during that time, only few people knew about lasers. But those who did, most likely knew the physics behind it. This situation has changed dramatically.

Today, most common people know about lasers, or at least about the word laser. But although people are aware of lasers, the meaning of this abbreviation, what it actually stands for, or how lasers really work is often unknown.

The reason for this lack of knowledge is that nowadays, lasers have indeed become a solution to a vast number of problems and they have become an established technology in our everyday life. They have penetrated our social environment at a level such that they are not perceived anymore as a sophisticated technology. Apart from the "obvious" laser applications that most people are aware of, such as laser-guided missiles, laser printers and laser pointers, or as special effects in science fiction movies or laser shows, their real potential often remains unnoticed.

In this thesis, we present lasers that are usually not very prominent on this "obvious" level, but already have, and most likely will have much stronger, influence on our everyday life without most people even knowing of their existence. This is due to their small size, their cost-efficient and simple fabrication possibility, their versatility and of course their excellent performance.

The lasers that are described in this thesis have applications in many fields of research and industry. The most prominent research fields
are medicine, where they are used in ophthalmology, multi-photon microscopy or optical coherence tomography (OCT), and in spectroscopy, in which these lasers provide a cost-efficient alternative to expensive broadband laser sources. In the multimedia sector, these lasers could be used in miniature laser projectors using nonlinear frequency conversion, and in the field of fiber-telecommunication, they are an excellent source of ultrashort pulses at gigahertz repetition rates. Another interesting application is in the computer industry. With the trend of going to multi-core central processing units (CPUs), the individual cores need to be synchronized and be able to communicate with each other with high data throughput and at a low error rate. This can be achieved using optical clocking and optical interconnects, for which our lasers are very well suited.

In this thesis, we present our results on modelocked of optically pumped vertical external-cavity surface-emitting lasers (VECSELs), and we discuss the necessary steps we took to obtain the first femtosecond VECSEL exceeding 1 W of average output power. Moreover, we introduce a design for electrically pumped VECSELs suitable for modelocking, and we present initial continuous wave (CW) results\(^1\).

Since VECSELs are lasers based on semiconductor materials, they naturally inherit their properties. These materials can be produced with excellent purity and usually in large volume single crystals. The combination of the microscopic size of semiconductor devices and the well-established wafer processing technology enables the fabrication of such devices in very large quantities and with excellent yield. This makes them a prime example for cost-efficient mass production.

Of course, the industrial success of these materials is also connected to their physical properties. The band structure of these materials can be adjusted by using mixed crystal systems. In the field of semiconductor lasers, this allows the possibility to almost arbitrarily tailor the emission wavelength of the laser. In Table \ref{tab:1}, we show an overview of the wavelength versatility for VECSELs in CW operation, where a large wavelength range from 390 nm to 2.3 µm was demonstrated.

In comparison to most other semiconductor lasers, where usually an edge-emitting geometry is used, for VECSELs, the laser radiation is emitted perpendicular to the semiconductor surface and an additional external output coupler (OC) is used. This has three major consequences:

\(^1\)Parts of the demonstrated results discussed in this thesis can be found in the publications listed in the List of Journal Papers (page xxi) and the List of Conference Papers (page xxiii).
Table 1.1: Overview of optically pumped VECSELs. Using mixed crystals, the band gap can be tailored almost arbitrarily, enabling access to a very large wavelength range.

1. The interaction length of the laser light with the semiconductor material is relatively short with usually only a few micrometers. This leads to
   - reduced gain compared to edge emitters, where the interaction length is significantly larger,
   - a relatively low possible transmission of the OC, and
   - better noise performance [9].

2. The extension of the cavity by using an external OC allows for
   - external laser mode control,
   - excellent beam quality, and
   - employment of additional intra-cavity elements, such as
     - semiconductor saturable absorber mirrors (SESAMs) for modelocking,
     - etalons for wavelength tunability, and
     - nonlinear elements for frequency conversion.

3. The heat flow in the gain structure becomes one-dimensional and is directed perpendicular to the semiconductor surface, resulting in
   - superb heat removal and
   - power scalability.

By taking advantage of these properties, excellent beam quality was demonstrated at high output power levels. At a laser wavelength of 960 nm and in fundamental transverse mode, 20 W were achieved with
good efficiency [10]. Another impressive result was reported in Reference [11], where multi-mode operation with an output power of 40.7 W, and with a beam quality factor $M^2$ of 1.5, an output power of 23.8 W, was demonstrated. Also at longer wavelengths high power operation was demonstrated at 11 W with an unspecified beam quality [12]. The demonstrated high efficiencies of these high power CWs results make these devices also attractive for brightness conversion, since these lasers are usually pumped with multi-mode laser diodes.

These excellent performance demonstrations were also extended to modelocked VECSELs [13]. For modelocking a VECSEL, SESAMs [14] are the most obvious choice. They have a similar structural design, consist of the same materials and they are fabricated using the same growth and fabrication processes. After the first demonstration of a modelocked VECSEL [15], where 22 ps pulses were generated at a repetition rate of 4.4 GHz and an average output power of 21.6 mW, plenty of progress was made in the field of modelocked VECSELs. As in this first milestone, VECSEL structures based on quantum-wells (QWs) were used with QW-SESAMs to further increase the output power to 2.1 W in pulses of 4.7 ps duration [16].

Using QW-SESAMs based on the optical Stark effect or on surface recombinations effects allowed for the generation of significantly shorter pulses. Fundamental modelocking with a pulse duration of down to 107 fs was demonstrated [17]. The shortest pulses that have been reported from modelocked VECSELs had a duration of 60 fs [18]. Due to gain saturation during these experiments, the pulses were generated in trains of these ultrashort pulses. Nevertheless, this demonstrates that modelocked VECSELs have the potential for stable operation beyond 100 fs.

All aforementioned results were obtained in the wavelength region around 1 µm, modelocked femtosecond VECSELs are not limited to this area. Recently, using InGaSb based QWs for both the VECSEL and the SESAM, ultrashort pulses of 384 fs duration were demonstrated with an average output power of 25 mW at 1.96 µm [19].

Also in terms of the repetition rate of modelocked VECSELs, several improvements were reported. Using QWs for both the gain and the absorber, 10 GHz were demonstrated [20], but due to the reduced saturation of the absorber at these high repetition rates and thus low pulse energies, a further increase of the repetition was not possible. The employment of quantum-dots (QDs) for the absorber overcame this issue by reducing the saturation fluence of the SESAM, and a modelocked VEC-
SEL with 50 GHz was demonstrated [21]. This development brought the possible integration of the absorber section in the VECSEL gain structure within reach.

This integration concept is referred to as the modelocked integrated external-cavity surface-emitting laser (MIXSEL). The first results, where 40 mW in 35-ps pulses [22] and, at cryogenic temperatures, 185 mW in 32-ps pulses [23] were demonstrated, were limited by poor thermal properties of the heat sink and a resonant structure design. Further improvement of the QDs [24] resulted in an anti-resonant MIXSEL, with which an average output power of 6.4 W was achieved [25]. This is the highest output power for any modelocked semiconductor laser today.

A key element for this achievement was the improvement of the properties of the QDs. In comparison to QWs, QD-based absorbers have an additional degree of freedom, the density of the QDs. It can be used to engineer the saturation parameters of the absorber [26, 27]. But also on the temporal relaxation of QD-based SESAMs excellent results were achieved. Modelocking experiments of a QW-VECSEL with a QD-SESAM yielded 870 fs.

QDs were also successfully employed as an active material for modelocked VECSELs, where their inhomogeneously broadened gain [28] should provide a larger bandwidth. Initial modelocking experiments were published with an average output power of 27.4 mW in 18-ps pulses [29]. This result was improved with an optimized gain structure design and superior heat management and pulses with a duration of 784 fs were generated at an output power of 1.05 W [30]. This is the first demonstration of femtosecond pulses from VECSELs where 1 W of average output power is exceeded, and it is discussed in detail in this thesis.

Although modelocked VECSELs have achieved excellent results, their impact in industry is still rather limited. The reason is the requirement for optical pumping. This imposes a significant increase of the packaging efforts. Electrical pumping of VECSELs seems to be a solution to this problem, however, many alterations to an optically pumped design have to be made to realize this endeavor. A large section of this thesis discusses this in detail, focusing on electrically pumped VECSELs that are designed for modelocking.

The field of electrically pumped VECSELs is still rather young and there are only a small number of publications. Already in 2003, the NECSEL was presented by Novalux, Inc. [31]. At a wavelength of 980 nm, this device achieved impressive CW performance levels with a multi-mode output power of 1 W and 500 mW in fundamental transverse mode op-
eration. Unfortunately, not much information is known about the layer
design, the doping levels or the growth conditions, because these devices
were fabricated under company confidentiality. Another company, OS-
RAM GmbH, also investigated electrically pumped VECSELs [32]. Their
approach was not to pump the active layers directly, but to incorpo-
rate electrically-driven lateral optical pumping. They were able to obtain
650 mW of output power at a wavelength of 1000 nm from their devices.
Also in a different wavelength range, electrically pumped VECSELs were
demonstrated. An InP-based design with an emission wavelength of
1.55 µm achieved 0.3 mW [33].

In contrast to these three results, the design we present in this the-
sis is explicitly designed for modelocking. This development is not fin-
ished, and at the moment, we can demonstrate CW-operation with up to
120 mW [34].

This thesis is organized as follows: Chapter 2 discusses techniques
which are mostly necessary for the advanced fabrication scheme of our
electrically pumped VECSELs, such as

• semiconductor growth,

• wet and dry etching techniques, and

• photolithography technology.

We devote Chapter 3 to explain a series of important sophisticated
characterization methods for our CW and modelocked lasers. Among
the most important techniques are

• non-linear reflectivity,

• pump-pump probe measurements,

• measurement of group delay dispersion (GDD), and

• pulse propagation simulations.

Chapter 4 discusses our development of two different hybrid semi-
conductor/dielectric multilayer designs. The first is a versatile dispersive
mirror where the GDD can be accurately controlled by deposition of a
single dielectric layer. The accessible range for the GDD roughly ex-
tends from negative to positive values of $10^4$ fs$^2$. The second multilayer
design is used to reduce the structural GDD of our semiconductor struc-
tures. We achieve a reduction to values between 0 fs$^2$ and 10 fs$^2$ over a
wavelength range of more than 30 nm, which is an improvement of three orders of magnitude.

In Chapter 5, we present the modelocking experiments of our optically pumped VECSELs. First, we discuss the dependence of the pulse duration on the intra-cavity GDD of modelocked VECSELs. With this study, we showed experimentally that quasi-soliton modelocking is the responsible modelocking mechanism for pulse generation in the few picosecond regime. We used these finding to improve our VECSEL structures, and we demonstrated the first high power femtosecond pulses generated from a VECSEL. At the end of Chapter 5, we summarize our experiments and give an outlook on future modelocking performance and potential frequency comb applications.

Chapter 6 deals with an electrical pumping scheme for VECSELs suitable for modelocking. We introduce and describe our design in detail and discuss challenges of electrical pumping in general. Furthermore, we present the fabrication scheme, CW results and the characterization of the beam quality and the injection profile. At the end of this chapter, we summarize the achieved results and give an outlook on general improvements and future modelocking experiments. Our findings suggest that the most significant challenges have been overcome and that this technology has high potential for industrial applications.
Chapter 2

Fabrication Techniques

The step from a technology based on macroscopic elements to micro and nanostructures has been one of the most important scientific and industrial advancement of the 20th century. Without this, computers would not exist the way we know them today. Because of the microscopic size of the devices that can be produced using micro and nanostructure technologies, the number of devices that are fabricated at the same time can be orders of magnitude higher than for standard methods. This gave rise to mass production capabilities and it is therefore intensely used in industry.

The necessary elements that needed to be developed to realize working micro and nanostructures are manifold and there are many key elements that made this possible. The combination of a better understanding of semiconductor physics, accurate growth of low-defect semiconductor materials, doping control, availability of ultra-pure source materials, techniques for pattern transfer such as spinning and development of photo resists, masking materials, short wavelength photolithography and selective etching, soldering and bonding techniques, cleaning procedures, surface treatment and many more led to this new era of micro and nanotechnology. Some of these aspects will be discussed in this chapter, focusing on the necessary steps for the fabrication of optically and electrically pumped VECSELs.

We have the opportunity to have access to state-of-the art semiconductor growth facilities and almost every highly advanced semiconductor fabrication technology. This is possible because of the FIRST clean

\(^1\)frontiers in research: time and space (FIRST)
room facility. Almost all of the described procedures of this chapter can be performed there.

## 2.1 Semiconductor Growth

Since usually our VECSELs and SESAMs operate at a wavelength of about 1 µm, the GaAs and AlAs-based material system is ideally suited as foundation. The involved materials are either group III, like aluminum (Al) and gallium (Ga), or group V materials, like arsenic (As). Both materials, GaAs and AlAs, form zinc blende structures and the lattice constant of the two materials is even so similar (see Table 2.1), that Ga and Al can be substituted by each other with almost no resulting stress in the crystal structure. The obtained AlGaAs can be realized for all values of \( x \in [0, 1] \) with the stoichiometric formula \( \text{Al}_x\text{Ga}_{1-x}\text{As} \).

Despite the strong similarities of the AlAs and the GaAs crystals, their chemical behavior (see Chapter 2.2.2) and physical properties differ significantly. Due to the difference in band gap energy of 0.7 eV, a significant refractive index step between the two materials is obtained (see Table 2.1), resulting in a strong Fresnel reflection at the interface between these two materials. Therefore, the semiconductor material system based on AlAs and GaAs is very well suited for optical multilayer devices such as distributed Bragg-reflectors (DBRs) or anti reflection (AR) sections.

<table>
<thead>
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<th>parameter</th>
<th>GaAs</th>
<th>AlAs</th>
<th>InAs</th>
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<td>refractive index ( n ) (at 1 µm)</td>
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<td>2.96</td>
<td>absorption</td>
</tr>
<tr>
<td>lattice constant ( a ) [Å]</td>
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<td>5.65</td>
<td>6.04</td>
</tr>
<tr>
<td>band gap energy ( E_g ) [eV]</td>
<td>1.42</td>
<td>2.12</td>
<td>0.354</td>
</tr>
<tr>
<td>band gap absorption edge ( \lambda ) [nm]</td>
<td>875</td>
<td>585</td>
<td>3500</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of some of the material properties of the semiconductor materials we used for our VECSELs and SESAMs.

Since the band gaps of AlAs and GaAs are both too high (see Table 2.1) in order to obtain gain at a wavelength of around 1 µm, we have to incorporate another material. We use indium (In) for this purpose which in our case is substituted for Ga and results in an InGaAs crystal with the stoichiometric formula \( \text{In}_x\text{Ga}_{1-x}\text{As} \). The band gap of binary InAs is low enough, so that for ternary InGaAs, in theory, gain can be achieved between the band gaps of both binary base crystals, GaAs and InAs. According to Table 2.1, this is a range from 875 nm to 3.5 µm.
However, due to the large difference of the lattice constants of InAs (see Table 2.1) with respect to AlAs or GaAs, an InAs layer that is deposited on AlAs or GaAs receives a significant level of stress. Usually, stable QWs made of InGaAs with a stoichiometric formula \( \text{In}_x \text{Ga}_{1-x} \text{As} \) are only obtained for \( x \leq 0.13 \). If the In content is increased beyond 13\%, the layer starts to be torn apart after a few mono layers due to intrinsic stress from the lattice mismatch. However, this can be used as an advantage.

By intentionally increasing the In content over this threshold, a very thin layer of InGaAs is deposited on the previous GaAs or AlAs which is still lattice matched, but under tremendous stress. This thin layer is usually referred to as wetting layer (WL). Once this WL becomes too thick, it breaks apart and small InGaAs islands are built. These QDs are referred to as self-assembled QDs, and this growth method for of QDs is called Stranski-Krastanov growth [35].

Although it might be possible to grow a QW with stress, its lifetime might be strongly reduced because of the stress. In order to release the stress, strain-compensation layers can be grown. These are usually located around the QW and, for our VECSEL structures, they consist of GaAsP.

For the semiconductor growth, all our structures are grown on GaAs wafers, usually with a thickness of 650 nm.

### 2.1.1 Molecular Beam Epitaxy

The growth of semiconductor materials using molecular beam epitaxy (MBE) involves several atomic or molecular beams of the source materials which are directed towards the sample. A necessary requirement for this is a very good vacuum of about \( 10^{-9} \text{ mbar} \) during standby and about \( 10^{-6} \text{ mbar} \) for the deposition, because otherwise the material beams would be disturbed. Depending on the material to be deposited, the necessary material quality, the growth rate, an other desired parameters, the substrate temperature is usually set to a temperature between 250 °C and 650 °C. As a rule of thumb, better material quality is obtained for higher substrate temperatures, because the atoms have a higher mobility and it takes a longer for them to be incorporated in the lattice structure of the crystal. Therefore, the crystal lattice will have less defects. In case a higher defect density is desired, a lower growth temperature is chosen. This is for instance the case for SESAMs, where a higher defect density leads to a reduced relaxation time of the excited carriers (see
Chapter 2. Fabrication Techniques

Since with MBE growth, extremely good material qualities and layer thickness precision can be achieved, it has become a standard growth method for multilayer semiconductor devices. For our MBE grown semiconductor structure, we use a Veeco Gen III MBE. This machine offers a valved As cracker, two solid Al sources, two Ga cells and one In cell. For doping, sources of silicon (Si) for p-doping, and carbon tetra-bromide (CBr$_4$) for n-doping, are available. The doping levels we can achieve with our MBE are, for n-doping, from $1 \times 10^{17}$ cm$^{-3}$ to $2 \times 10^{19}$ cm$^{-3}$ and, for p-doping, from $2 \times 10^{17}$ cm$^{-3}$ to $1 \times 10^{20}$ cm$^{-3}$. These values are sufficient to realized the necessary doping levels for our electrically pumped VECSELs (see Chapter 6).

An additional epitaxy chamber is connected to our MBE, where in addition to two cells for each, Ga and Al, one cell for each phosphorus (P), In, Si, and antimonite (Sb), and a nitrogen (N) plasma source are available.

The in-situ characterization methods that are available for our MBE are a reflective high-energy electron-diffraction (RHEED) system from STAIB INSTRUMENTS, Inc., a band edge thermometry (BET) system BandiT from k-Space Associates, Inc., and an reflectance anisotropy spectroscopy (RAS) system from LayTec AG.

**BET** The BET system determines the band gap energy by measuring the wavelength-dependent black body radiation of the wafer. Since the band gap energy is strongly dependent on the temperature, BET is a very precise in-situ optical temperature measurement system and commonly used in epitaxial growth.

**RAS** In case of the RAS measurement, an anisotropic reflectance spectroscopy analysis is used to determine the growth rate and the material quality and composition.

**RHEED** For RHEED, electrons with a typical energy of about 10 keV to 50 keV are shot onto the sample at a small angle of usually around 2°. The electrons are reflected at the interfaces of the multilayer structure of the sample, and their interference pattern is recorded. This results in a characteristic diffraction pattern from which the type of crystal structure and the parameters of the lattice can be determined.
2.1.2 Metal Organic Vapor Phase Epitaxy

In contrast to MBE (see Chapter 2.1.1), the growth of crystalline materials using metalorganic vapor phase epitaxy (MOVPE)\(^2\) is not based on physical deposition but on chemical reactions. On the top surface of the sample structure, the epitaxial layers are formed by the endmost pyrolysis of the chemical reaction of the corresponding chemicals necessary for the material to be deposited. These chemicals are applied to the MOVPE reactor in gas phase at a pressure of about 2 mbar to 100 mbar, which is a much higher pressure than during MBE growth.

In comparison to MBE growth, there are some distinct differences. Since the deposition for MOVPE growth is based on chemical reactions at higher pressures, there is no need for ultra-high vacuum. Therefore, MOVPE is comparably cheap from an equipment point of view. Furthermore, the scalability of MOVPE chambers is better, since there are no directed particle beams, which limit the usable area inside the machine. Therefore, MOVPE systems are often used for industrial mass production. A disadvantage is the requirement for highly purified source materials, especially since the material efficiency is low in comparison to MBE growth. Furthermore, due to the chemical deposition scheme and the generation of chemical by-products, a relatively large number of foreign atoms, such as oxygen (O), carbon (C), and hydrogen (H), are incorporated in the crystal structure. This leads to a higher defect density and thus a generally lower purity of the deposited material.

2.2 Semiconductor Processing

This section discusses more advanced techniques for the fabrication of semiconductor devices. Although some of these methods are regarded as standard techniques, their development, characterization and adaptation was necessary to successfully fabricate our electrically pumped VECSELs (see Chapter 6).

2.2.1 Plasma Machines

The plasma machines which are introduced in this chapter all work under very similar conditions. A number of gaseous chemical species are

\(^2\)MOVPE is also known as organo-metallic vapour phase epitaxy (OMVPE) or metalorganic chemical vapor deposition (MOCVD).
applied to a plasma reactor at precisely controlled fluxes which are usually measured in sccm. For a given pressure and ambient temperature, an electric radio frequency (RF) field is used to ignite and energize a plasma inside the reactor.

In this environment, chemical and physical processes are greatly accelerated resulting in a very versatile tool in semiconductor fabrication technology. These plasma machine can be used for deposition and etching processes, and their use and modes of operation will be described in this section.

**Plasma-Enhanced Chemical Vapor Deposition**

Plasma-enhanced chemical vapor deposition (PECVD) is a commonly used process to deposit thin films onto a solid sample at a high accuracy and relatively low cost. Especially in semiconductor manufacturing, this is a common technique for the deposition of the mask material for photo lithography (see Chapter 2.2.3). But also for the deposition of optical grade layers of dielectrics, for instance for optical top coatings (see Chapter 4), this method is widely used.

The film thicknesses of these PECVD deposited layers can reach from a few nanometers to several micrometers, usually with an accuracy of better than 5% relative to the deposition thickness.

The process utilizes chemical precipitation during a chemical reaction of several gaseous species in a plasma reactor. It is usually driven by a RF generator, and in some cases by an additional low frequency (LF) generator, which supply the power to start and energize the plasma reaction.

The PECVD system that was available to us for our processes was a *Plasmalab 80 Plus PECVD* from *Oxford Instruments, Inc.* with the following technical specifications:

- deposition capability of SiNₓ, SiOₓ, and SiOₓNᵧ
- availability of SiH₄, N₂, NH₃ and N₂O as source gases for deposition
- CF₄ and O₂ for reactor cleaning
- a deposition temperature range from 120 °C to 350 °C
- RF generator at 13.56 MHz with 600 W power
- LF generator at 40 kHz with 500 W power
For the deposition of Si$_3$N$_4$ layers, the stoichiometric formula
\[
3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2 \tag{2.1}
\]
describes the chemical reaction of the source gases, silane (SiH$_4$), which is the Si source, and ammonia (NH$_3$), the source for the N. Since during this deposition process no crystalline Si$_3$N$_4$ is produced but an amorphous layer, this stoichiometrically correct notation is not fully satisfied. A better notation of the produced material is silicon nitride (SiN$_x$), where $x \approx 4/3$. Despite the stoichiometric error being smaller than 1%, this is a common notation for PECVD deposited SiN$_x$ and it will be used throughout this thesis.

The situation is similar for the deposition of silicon oxide (SiO$_x$), with $x \approx 2$, where the obtained layer is also amorphous and not a layer of crystalline SiO$_2$ (quartz). This amorphous SiO$_x$ is usually referred to a fused silica (FS). The stoichiometric error in the stoichiometric formula is again smaller than 1%. For the deposition of SiO$_x$, the source gases SiH$_4$, as a source for the Si, and nitrous oxide (N$_2$O), as a source for the O, are used, and the chemical reaction is described by
\[
\text{SiH}_4 + 2\text{N}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 + 2\text{N}_2. \tag{2.2}
\]

A typical recipe for the deposition of SiO$_x$ is given in Table 2.2.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature $T_s$ [$\degree\text{C}$]</td>
<td>300</td>
</tr>
<tr>
<td>pressure $p$ [mTorr]</td>
<td>900</td>
</tr>
<tr>
<td>SiH$_4$/N$_2$ (2.5 %) flux $\Phi$ [sccm]</td>
<td>340</td>
</tr>
<tr>
<td>N$_2$O flux $\Phi$ [sccm]</td>
<td>710</td>
</tr>
<tr>
<td>LF power $P$ [W]</td>
<td>0</td>
</tr>
<tr>
<td>RF power $P$ [W]</td>
<td>30</td>
</tr>
<tr>
<td>LF duty cycle $R_d$ [%]</td>
<td>0</td>
</tr>
<tr>
<td>RF duty cycle $R_d$ [%]</td>
<td>100</td>
</tr>
<tr>
<td>deposition rate $\rho_d$ [nm min$^{-1}$]</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Table 2.2: Our standard PECVD recipe for the deposition of SiO$_x$. We use this recipe mostly to deposit optical grade layer on semiconductor devices.

If the source gases SiH$_4$, NH$_3$ and N$_2$O are used together, an arbitrary material with the stoichiometric formula silicon oxide nitride (SiO$_x$N$_y$) can be obtained. This can be useful if a material is desired with a refractive index between that of SiN$_x$ with about 1.9, and that of SiO$_x$ with about 1.5, each at a wavelength of 1 $\mu$m.

For our semiconductor processing, we needed to deposit SiN$_x$ masking layers with thicknesses of more than 1.5 $\mu$m on GaAs samples. By
employing a standard recipe for this process, we faced adhesion problems and the SiN\textsubscript{x} layers came off from our samples. The reason was a mismatched coefficient of thermal expansion of the SiN\textsubscript{x} layer and the GaAs substrate.

If an amorphous film of SiN\textsubscript{x} is deposited on a GaAs sample, it is deposited without internal stress. Since the deposition temperature during the SiN\textsubscript{x} deposition is 300°C in our case, the deposited layer only exhibits no internal stress at this temperature. By cooling the coated sample down, for instance to room temperature, the film and the substrate will deform in different manners, resulting in stress. This stress causes a deformation of the sample, and, in case of thick films, this can cause the SiN\textsubscript{x} film to come off from the substrate. We observed this phenomenon for our thick masking layers of SiN\textsubscript{x}, which we need for the device fabrication of our electrically pumped VECSELs (see Chapter 6.2.2).

In order to obtain better adhesion properties, we optimized the thermal expansion coefficient of the SiN\textsubscript{x} layer by altering the effective excitation frequency of the plasma. Our PECVD system has two different power generator that can drive the plasma. By adapting the duty cycles of the RF generator and the LF generator independently, the thermal expansion coefficient of the deposited layer can be altered and adapted to that of the substrate.

Using the recipe listed in Table 2.3 with varying LF duty cycles, we deposited films of SiN\textsubscript{x} with a thickness of 200 nm on a 5 cm long stripe of 400 µm thick GaAs. Before and after each deposition, we measured the deflection of a laser as a function of the position at which the laser hits the stripe along its length. We did these measurements at a temperature of 25°C. After each measurement, we removed the SiN\textsubscript{x} film with hydrofluoric (HF) acid (see Chapter 2.2.2) and did the next deposition, changing the LF duty cycle.

We deposited five different 200 nm thick layers of SiN\textsubscript{x}, where we used LF duty cycles of 100 %, 66 %, 50 %, 33 % and 0 %. This is illustrated in Figure 2.1a, where blue corresponds to a duty cycle of 100 % and green to 0 %. The black curve shows the uncoated stripe.

We found out that a duty cycle of the LF generator of 25 % provided the least stress. In order to further optimize this, we deposited SiN\textsubscript{x} layers with a thickness of 1250 nm, in order to increase the deflection effect and therefore be able to determine the deflection more accurately. This time we used LF duty cycles of 33 %, 31 %, 29 % and 25 %. This is shown in Figure 2.1b, where blue corresponds to a duty cycle of 33 % and
green to 25%. The black curve again shows the uncoated GaAs stripe.

This experiment showed that the least overall stress is obtained with a LF duty cycle of 25%. Thus, the recipe listed in Table 2.3 is the recipe we used for all SiN$_x$ layers during our semiconductor processing.

Table 2.3: Our standard PECVD recipe for the deposition of SiN$_x$. This recipe was used for the application of all masking layers during the fabrication process of our electrically pumped VECSELs (see Chapter 6).

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature $T_s$ [°C]</td>
<td>300</td>
</tr>
<tr>
<td>pressure $p$ [mTorr]</td>
<td>900</td>
</tr>
<tr>
<td>SiH$_4$/N$_2$ (2.5%) flux $\Phi$ [sccm]</td>
<td>400</td>
</tr>
<tr>
<td>NH$_3$ flux $\Phi$ [sccm]</td>
<td>30</td>
</tr>
<tr>
<td>LF power $P$ [W]</td>
<td>20</td>
</tr>
<tr>
<td>RF power $P$ [W]</td>
<td>20</td>
</tr>
<tr>
<td>LF duty cycle $R_d$ [%]</td>
<td>25</td>
</tr>
<tr>
<td>RF duty cycle $R_d$ [%]</td>
<td>100</td>
</tr>
<tr>
<td>deposition rate $\rho_d$ [nm min$^{-1}$]</td>
<td>20.2</td>
</tr>
</tbody>
</table>

After we found the optimal LF duty cycle for the deposition of stressless SiN$_x$, we wanted to know if there was simply no stress at room temperature, or also at our estimated operating temperature of our devices, which is around 100°C. In order to determine this, we made deflection measurements for different ambient temperatures of a GaAs stripe with a 1250-nm thick SiN$_x$ film that was deposited with the newly found LF duty cycle of 25%. These measurements are shown in Figure 2.2. The black curve shows the uncoated stripe at 25°C. We made measurements of the coated strip at 25°C (blue), 50°C, 75°C, 100°C and 125°C (green).

For all measurements, the deflection is comparable with the intrin-
sic deflection of the uncoated stripe. Therefore, we basically eliminated temperature-dependent deformation of the stripe. This means that using the recipe listed in Table 2.3 on a GaAs substrate results in a stressless layer of SiN$_x$.

**Reactive Ion-Etching**

Just like PECVD has become a common technique in modern semiconductor processing, so has reactive ion etching (RIE). In fact, these two techniques usually go together, since they are used to deposit the mask material using PECVD and, after structuring using photo lithography (see Chapter 2.2.3), the mask material is etched using RIE.

The RIE reactor works very similar to the PECVD reactor (see Chapter 2.2.1). The only difference between the two machines is the used chemistry. If source gases are chosen where no precipitation of a species occurs during the chemical reaction, as for the PECVD processes, ions or radicals are produced in the plasma reaction, and the surrounding materials can be etched if appropriate source gases are chosen. Depending on the type of product, ion or radical, thus depending on the used source gas, the etching behavior can differ considerable.

If source gases such as N$_2$ or argon (Ar) are used, which are both chemically inert under the conditions in the RIE reactor, the gas is only ionized in the plasma. Therefore, plenty of free electrons are present in the reactor, which eventually hit the sidewalls, the top of the chamber and the sample tray. Since the sample tray is not grounded, as opposed to the other parts of the reactor chamber, a negative charge builds up on the sample side, resulting in voltages of usually a few 100 V. This leads to an attractive potential for the positive ions which are thus accelerated towards the sample. Because of the usually low pressure during such an etching process (see Table 2.4), the average free path length of an ion is very large and it can therefore pick up a lot of inertia. If the ion
then hits the sample, it causes surface damage and a part of the sample is removed. This kind of material ablation through ion bombardment is also called sputtering or physical etching. For this method the etch profile is usually v-shaped and there is no under etch.

If a species are used that incorporate fluorine (F) or O, the etching process changes considerable. The etching process is not anymore driven by ions impacting on the sample surface, but by chemical reactions of radicals. Examples of a F based wet etch processes for etching SiN$_x$ and SiO$_x$ are given in Equations 2.3 and 2.4, respectively. The reaction runs very similar for this dry etching technique with a F-based source gas, the difference is that instead of the water-soluble H$_2$SiF$_6$, gaseous and stable SiF$_4$ is produced. This process is greatly accelerated because of the gaseous species exist in their radical form. The etch profile is mostly isotropic, resulting in round etch shapes with usually a strong under etch.

If source gases for physical and chemical etching are combined, it is possible to obtain perfectly rectangular etch profiles. The side walls can be tuned to be very straight and smooth. The smoothness can easily reach optical quality making these etching techniques a key component for the fabrication of integrated optical circuits.

The RIE system that was available to us for our processes was a Plasmalab 8o Plus RIE from Oxford Instruments, Inc. We used this RIE system only for etching of dielectrics, for which the most important technical specifications are:

- etching capability of SiN$_x$, SiO$_x$, and SiO$_x$N$_y$
- available working gases are N$_2$, CHF$_3$, CF$_4$, SF$_6$, O$_2$ and Ar
- etching temperature 18 °C
- RF generator at 13.56 MHz with 500 W power

We used the RIE system mostly to transfer photo resist patterns, which we obtained from photo lithography (see Chapter 2.2.3) to a solid mask made of a layer of SiN$_x$. For this purpose, it is required to not only know the etch rate of the SiN$_x$ for a given RIE recipe, but also for the photo resist. If this is not known and a too thin layer of photo resist is used, the etching process could completely remove the photo resist. If this happened, the underlying structure would be etched which is usually not wanted. Therefore, we also estimated the etch rate of photo resist of our SiN$_x$ etching recipe we used on the RIE system. This recipe, together with typical etch rates, is given in Table 2.4.
### Inductively-Coupled Plasma Etching

The method of inductively-coupled plasma (ICP) etching is, in principle, equal to RIE etching. The difference is that in addition to the standard RF generator, an ICP system is equipped with another high power generator. This ICP generator is usually capable to produce several kilowatts of power. This enables to etch semiconductor structures with a significantly higher etch rate than RIE alone. It is possible to etch several micrometers of semiconductor material within a few minutes.

The ICP etching system we use for our processing was a *Plasmalab System 180 ICP* from *Oxford Instruments, Inc*. The technical specifications of the machine are:

- etching capability of dielectrics III/V semiconductors
- available working gases are CH\textsubscript{4}, H\textsubscript{2}, Cl\textsubscript{2}, CF\textsubscript{4}, SF\textsubscript{6}, O\textsubscript{2}, Ar, and N\textsubscript{2}
- capability for liquid N\textsubscript{2} cooling
- etching temperature from −150 °C to 400 °C
- RF generator at 13.56 MHz with 500 W power
- ICP generator at 13.56 MHz with 3 kW power

We used the machine for all our high precision etching processes of semiconductors. We etched GaAs, AlAs and AlGaAs-based multilayer structures using a patterned layer of SiN\textsubscript{x} as a mask. The patterns were made by photo lithography (see Chapter 2.2.3) of a PECVD-deposited SiN\textsubscript{x} layer on the sample, together with an etching step using RIE.

The chemical reaction for our Cl-based recipe can be described as follows [36]. In the plasma, chlorine (Cl) radicals are produced which are

<table>
<thead>
<tr>
<th>parameter</th>
<th>SiN\textsubscript{x}</th>
<th>SiO\textsubscript{x}</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature $T_s$ [°C]</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>pressure $p$ [mTorr]</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>power $P$ [W]</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>CHF\textsubscript{3} flux $\Phi$ [sccm]</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>O\textsubscript{2} flux $\Phi$ [sccm]</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Ar flux $\Phi$ [sccm]</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>etch rate $\rho_e$ [nm min\textsuperscript{−1}]</td>
<td>164</td>
<td>21.2</td>
</tr>
<tr>
<td>photo resist etch rate $\rho_e$ [nm min\textsuperscript{−1}]</td>
<td>37.1</td>
<td>n. a.</td>
</tr>
</tbody>
</table>

Table 2.4: Typical RIE recipe for the etching of SiN\textsubscript{x} and SiO\textsubscript{x}.
adsorbed by Ga or Al on the substrate. Due to the large electro negativity of Cl, all other remaining bonds of the corresponding Ga or Al atom are weakened. This leads to a relatively easy removal of the chlorinated Ga or Al by thermal vibrations or sputtering. For this reason, we employ Ar in our ICP recipe (see Table 2.5).

Since our fabrication scheme required two different semiconductor etch accuracies, we developed two ICP etch recipes, one with a fast and one with a slow etch rate. They are both listed in Table 2.5 together with the etch rates for the semiconductor and the masking material.

<table>
<thead>
<tr>
<th>parameter</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature $T_s$ [°C]</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>pressure $p$ [mTorr]</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>RIE power $P$ [W]</td>
<td>160</td>
<td>60</td>
</tr>
<tr>
<td>ICP power $P$ [W]</td>
<td>600</td>
<td>350</td>
</tr>
<tr>
<td>Ar flux $\Phi$ [sccm]</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>$\text{Cl}_2$ flux $\Phi$ [sccm]</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>etch rate $\rho_e$ [µm min$^{-1}$]</td>
<td>2.49</td>
<td>0.58</td>
</tr>
<tr>
<td>SiN$_x$ etch rate $\rho_e$ [nm min$^{-1}$]</td>
<td>180</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2.5: Typical ICP etch recipe for the etching of GaAs, AlAs and AlGaAs-based semiconductor multilayer structure. We typically used SiN$_x$ as a masking material.

### 2.2.2 Wet-Etching

Since dry-etching techniques such as ICP etching do not offer sufficient selectivity in comparison to wet-etching, we rely on a wet-chemical procedure for the removal of SiO$_x$, SiN$_x$, and for GaAs substrate removal. For the GaAs etch, a good selectivity is required to obtain optical grade surface roughnesses. Wet-etching recipes and the etching mechanisms are presented in this section.

#### SiO$_x$ and SiN$_x$ Etching

In order to etch SiN$_x$ layers, which we use as masking material during ICP etching in the fabrication of our electrically pumped VECSELs (see Chapter 6), we employ a HF acid solution. The general chemical reaction of this etch is described by

$$\text{Si}_3\text{N}_4 + 18\text{HF} \rightarrow 2(\text{NH}_4)_2\text{SiF}_6 + \text{H}_2\text{SiF}_6.$$  (2.3)
The chemical reaction for the etching of SiO\textsubscript{x} works very similar, and the reaction equation for this process is given by

\[ \text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{H}_2\text{O}. \]  \hspace{1cm} (2.4)

In both of these chemical reaction, similar complexes are built, which are \((\text{NH}_4)_2\text{SiF}_6\) for Equations 2.3, and \(\text{H}_2\text{SiF}_6\) for Equation 2.4. These complexes are both soluble in water, in which these complexes solve according to

\[ (\text{NH}_4)_2\text{SiF}_6 \rightleftharpoons [2 \left( \text{NH}_4\right)_{(aq)}^+][\text{SiF}_6]_{(aq)}^{2-}, \]  \hspace{1cm} (2.5)

and

\[ \text{H}_2\text{SiF}_6 \rightleftharpoons [2 \text{H}^+_{(aq)}][\text{SiF}_6]_{(aq)}^{2-}. \]  \hspace{1cm} (2.6)

**Etching of GaAs, AlGaAs and AlAs**

In the fabrication scheme of our electrically pumped VECSELs, we make use of the flip-chip bonding technique. This involves the thinning of the substrate of a grown structure and subsequent wet-chemical complete removal of it. Therefore, an etching technique is necessary that efficiently etches the GaAs substrate, but stops on an etch stop layer \[37\]. This etch stop layer then has to be remove in an additional etching step.

Because of the quite large difference between the reduction potentials of Ga and Al (see Equations 2.7 and 2.8, and Table 2.6), these two elements show significantly different chemical properties.

The reduction potentials required for the reduction of Ga and Al, which are described by

\[ \text{Ga}^{3+}_{(aq)} + 3\text{e}^{-} \rightarrow \text{Ga}_{(s)} \]  \hspace{1cm} (2.7)

and

\[ \text{Al}^{3+}_{(aq)} + 3\text{e}^{-} \rightarrow \text{Al}_{(s)} \]  \hspace{1cm} (2.8)

are listed in Table 2.6. These reduction potentials are very important to obtain material selectivity for certain etchants.

<table>
<thead>
<tr>
<th>parameter</th>
<th>Ga</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_0) [V]</td>
<td>-0.56</td>
<td>-1.66</td>
</tr>
</tbody>
</table>

The etching of AlAs layers or AlGaAs layers with a high Al content
works by using a HF acid solution. The Al is oxidized and sapphire (Al$_2$O$_3$) is produced. This reacts with the HF acid according to

$$\text{Al}_2\text{O}_3 + 6 \text{HF} \rightarrow 3 \text{H}_2\text{O} + 2 \text{AlF}_3.$$  (2.9)

Although the solubility of aluminium fluoride (AlF$_3$) is not very large, it is allows for sufficient material transport, enabling a reasonable etch rate in the order of a few hundred nanometers per minute. This etch rate is of course dependent on the Al content of the layer to be etched.

Due to the reduced reduction potential of Ga in comparison to Al, Ga is not oxidized by a HF acid solution and thus does not become soluble. Thus, HF acid etches AlGaAs but not GaAs, making it an excellent selective etchant for AlGaAs layers.

In order to obtain an etchant with the opposite selectivity, we use a solution based on H$_2$O$_2$/NH$_3$/citric acid. In a first step, Ga is oxidized by the hydrogen peroxide (H$_2$O$_2$) component, which is a very strong oxidizing agent and thus capable of oxidizing Ga. This leads to a solubility of the oxidized Ga in the solution. Finally, the NH$_3$ is necessary to obtain selectivity towards AlGaAs. Once the samples has been etched down to the AlGaAs etch stop, Al is also oxidized by H$_2$O$_2$ and Al$_2$O$_3$ is produced. However, Al$_2$O$_3$ is not soluble in alkaline solutions. Thus, by increasing the pH value of the solution by means of adding NH$_3$, selectivity towards Al is obtained, making AlGaAs an excellent etch stop for this process [38]. We obtained good etching results and good selectivity for such a solution with a pH value of about 8.

2.2.3 Photo Lithography

Photo lithography is a crucial technique in today's semiconductor device fabrication. It is used to transfer geometric structures from a mask to a sample by selectively removing parts of the sample material. A typical photo lithography includes these step:

- cleaning of the sample
- spinning of photo resist on the sample
- exposure the sample
- development of the exposed photo resist
- etching (see Chapters 2.2.1 and 2.2.2)
Chapter 2. Fabrication Techniques

- removal of the photo resist

The most important steps, and the chemical mechanisms of photo lithography and development of positive and negative photo resists are explained in this chapter. A detailed overview of our photo lithography procedures is given in Table 2.7.

**Photo Lithography Technology**

Photo resists are photo-sensitive chemical species which change their solubility with respect to a certain solvent dramatically once they have been exposed to ultra-violet (UV) radiation.

There are two different types of photo resists: positive and negative photo resists. If positive photo resist is exposed to UV light, it becomes soluble in its designated solvent, whereas the change in solubility is opposite for negative photo resist. Another important difference between these two kinds of photo resist is their adhesion to typical semiconductor substrate materials such as SiN, SiO, GaAs, Si and InP. Negative photo resist has a very good adhesion for the mentioned materials, however, it is not the case for positive photo resist. Because of the insufficient adhesion properties of positive photo resist, usually an adhesion promoter is required, in order for the film of photo resist to remain on the sample after application. A standard adhesion promoter which we also use in our fabrication scheme is hexamethyldisilazane ((CH₃)₃Si₂NH).

Photo resists are usually applied to a sample by spin coating. After the photo resist has been applied to the sample, the sample is spun rapidly. Since the photo resist moves considerably faster on the top of the liquid photo resist layer compared to the bottom, only a thin layer of photo resists remains on the sample and the most part is ejected to the side. The remaining film of photo resist has a very homogeneous thickness accuracy over the sample, usually in the few nanometers range. The resulting layer thickness strongly depends on the spinning speed and the viscosity of the photo resist. After spinning of the photo resist, the sample is usually heated so that the layer of photo resist can harden. This step is called soft baking.

After this, the sample and the mask are carefully aligned and the sample is exposed to UV radiation. After a certain amount energy has been deposited in the photo resist, the sample is developed using a photo resist specific developer. During this step, in case of positive photo resist (in case of negative photo resist), the exposed sections of the sample (the not exposed sections of the sample) are removed by the developer,
leaving the pattern of the mask (leaving the negative pattern of the mask) as standing features of photo resist.

After another step of heating, which is referred to as hard baking, the photo resist pattern can now be transferred to the underlying structure. This is either done by dry etching (see Chapter 2.2.1) or by wet etching (see Chapter 2.2.2).

The last step is to remove the leftover photo resist, in our case, using acetone ((CH₃)₂CO), isopropyl-alcohol (C₃H₈O) and water.

**Photo Resist Chemistry**

In this section, the photo chemical reactions of different photo resist are discussed. A more detailed analysis of the chemical processes can be found in References [39, 40].

The chemical composition of typical photo resists is usually a resin and a photo-sensitive chemical compound. In our case, most of the photo resists we use rely on a **novolak**-based resin. The base molecule of novolak is shown in Figure 2.3.

![Figure 2.3: Base molecular structure of novolak. With increasing $i$, the novolak chain length is altered, which significantly changes the properties of the photo resist.](image)

This base molecule consist of a single 6-fold aromatic ring (benzene) with an OH and a methyl group (CH₃) on opposite sides, and it forms molecular chains according to Figure 2.3. The length of the chains significantly influences the properties of the photo resist in terms of thermal stability and viscosity. Furthermore, a shorter chain length increases the adhesion properties to the substrate. Typical lengths are eight to 20 monomeric units (i.e. $i \in [8, 20]$), according to Figure 2.3.

In case of the photo-sensitive chemical compound, it of course depends on the type of photo resist. For positive photo resist, diazonaphthoquinone (DNQ) is a widely used compound that is mixed with the novolak resin in a high dilution. The DNQ molecule and the chemical reaction for exposure and development is illustrated in Figure 2.4.

![Figure 2.4: The DNQ molecule and the chemical reaction for exposure and development.](image)

For this molecule, the nitrous bond is the photo-sensitive part of the molecule. Only a specific energy spectrum $E = h\nu$ can be absorbed by this bond, however, due to the dislocation of the valence electrons of the benzene ring, the wavelength-dependent absorptivity of the nitrous...
bond can be tuned by the $\text{SO}_3\text{R}$ part, where the rest R is an aryl group which defines the absorption septrum of the photo resist. After the exposure, the molecule undergoes the so-called Wolff rearrangement, where the 6-fold aromatic ring collapses to a 5-fold ring.

The development is done by applying an alkaline solution to this compound, where the newly formed ketone group is turned into a carboxylic group. This increases the solubility of the compound in water by several orders of magnitude, providing the desired effect, where the exposed part can be removed from the sample.

In case of negative photo resist, the photo-sensitive reaction works by cross-linking a reactive polymer, which is induced by the photosensitive agent. For bisazide polyisoprene resists, a cross-link between the molecules is built after exposure, resulting in an insoluble compound. This is illustrated in Figure 2.5.

The photo-sensitive parts of the molecule (R) are the $\text{N}_3$ bonds which split up and build bonds to neighboring molecules of the same type (see Figure 2.4). This lead to a strongly inhibited solubility of the compound.
Our Photo Lithography Procedures

In order to apply photo resist to our samples, we use an SM 180 BM spinner from Sawatec AG. The spinning speed for our photo resists is in the few thousand revolutions per minute (RPM) range. For mask alignment, we use a mask aligner from SÜSS MicroTec AG, an MA6 with a 405-nm UV lamp for exposure.

We use AZ 1505, AZ 1518 and AZ 4560 positive photo resists and the corresponding developer, AZ 400k. All these products are commercially available from Microchemicals GmbH. Our negative photo resist is Ma-N 1440, which is developed with Ma-D 332s, both from micro resist technology GmbH.

Details on spinning, exposure, hard and soft baking, and development are given in Table 2.7.

<table>
<thead>
<tr>
<th>parameter</th>
<th>AZ 1505</th>
<th>AZ 1518</th>
<th>AZ 9260</th>
<th>Ma-N 1440</th>
</tr>
</thead>
<tbody>
<tr>
<td>spinning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>speed $f_{\text{rot}}$ [rpm]</td>
<td>4000</td>
<td>3000</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>spin up time $t$ [s]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>time $t$ [s]</td>
<td>30</td>
<td>40</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>soft baking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature $T_s$ [°C]</td>
<td>95</td>
<td>95</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>time $t$ [s]</td>
<td>120</td>
<td>120</td>
<td>165</td>
<td>180</td>
</tr>
<tr>
<td>exposure at 405 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radiant exposure $H$ [mJ cm$^{-2}$]</td>
<td>100</td>
<td>140</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>development</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>developer time $t$ [s]</td>
<td>AZ 400k</td>
<td>AZ 400k</td>
<td>AZ 400k</td>
<td>Ma-D 332s</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>40</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>hard baking</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature $T_s$ [°C]</td>
<td>95</td>
<td>95</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>time $t$ [s]</td>
<td>120</td>
<td>120</td>
<td>–</td>
<td>120</td>
</tr>
<tr>
<td>obtained layer thickness $d$ [µm]</td>
<td>0.6</td>
<td>1.8</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2.7: Overview of different parameters for spinning, exposure, soft and hard baking, and development for the photo resists we used for our device fabrication.
Chapter 3

Characterization Methods and Simulation

Wherever accurate thin layer growth is required or wanted, precise characterization of the grown structure is necessary. Because the layer thicknesses are usually smaller than optical wavelengths, standard optical microscopy, for instance, is not a possible method to determine thicknesses. It is possible to characterize thicknesses using scanning electron microscope (SEM) or scanning transmission electron microscopy (STEM), but these methods require careful and time-consuming sample preparation. Instead, since interference effects are very pronounced for such structures with layer thicknesses smaller than optical wavelengths, one can determine the thickness by methods such as ellipsometry, in case of single or few grown layers, or reflectivity measurements for multilayer structures. Since we use structures with large number of layers, we typically use the latter approach. It is discussed in Chapter 3.1.1.

In order to determine more immanent device specific parameters for SESAMs or VECSELs, more advanced techniques are usually necessary. This is the case for instance for the saturation fluence of the absorber or the gain, the structural GDD of multilayer devices, or all temporally varying parameters such as relaxation time constants. These operation parameters can be obtained by measuring macroscopic characteristics using a nonlinear reflectivity setup, a Fourier transformation (FT) of an interferometric cross-correlation and a time-resolved differential-reflectivity measurement, respectively. These methods will be explained in detail in Chapters 3.1.2, 3.1.4, and 3.1.3.
Furthermore, an indirect method for characterization in almost all fields of physics is simulation. We use well-established techniques for the calculation of multilayer device properties and for the cavity geometries. Furthermore, we perform pulse propagation simulations to which we feed back our experimental data. These simulations will be introduced in Chapter 3.2.

### 3.1 Optical Characterization

#### 3.1.1 Reflectivity Measurement

For the structural analysis of epitaxially grown layers, precise measurements of the wavelength-dependent reflectivity are essential. Due to interference effects, such multilayer structures usually exhibit strong oscillations in reflectivity as a function of the wavelength (see Figure 3.1a). Fitting the simulated reflectivity of the structure to these measurements of the reflectivity usually yield a very accurate value for the growth errors of the structure. The calculated theoretical reflectivity is obtained by using an implementation of a transfer matrix algorithm according to Chapter 3.2.1.

Assuming that the growth rate of a certain material under the same growth conditions remains the same during the entire growth of the semiconductor structure, the amount of fit parameters can be reduced to one for each material. This fit parameter is a factor that is multiplied to the thickness of the corresponding material.

For a standard DBR, which usually consists of two materials, this results in only two degrees of freedom and usually a good fit is obtained. In Figure 3.1, a reflectivity curve of a DBR centered around 960 nm consisting of quarter wave pairs of GaAs and AlAs is shown. We normalized these measurements to a maximum DBR reflectivity of 100 %, because the absolute accuracy of our photo spectrometer is in the few percent range.

The measured data and the smoothed measured data are the curves in blue and green, respectively. Plotted in black and red are the simulated reflectivity curves without growth errors (black curve) and a least-squares fit of the reflectivity to the design, assuming a constant growth error for each material (red curve). The growth errors of this specific device for the individual materials are listed in Table 3.1.

In Figure 3.1b, the measured reflectivity in the stop band of the DBR is not flat. This is due to a not perfectly aligned reflectivity measurement...
Figure 3.1: Measured (blue), smoothed measured (green), calculated (black) and fitted (red) reflectivity of a DBR with a design wavelength of 960 nm. The reflectivity measurement of the DBR is not flat in the stop band because the reflection accessory of our photo-spectrometer was not perfectly aligned. Furthermore, we normalized the measurement because the measurement equipment can only provide an absolute accuracy of a few percent. The growth errors that were calculated from these curves are given in Table 3.1.

accessory with which the measurements were performed in a spectro-photometer$^1$.

Table 3.1: Overview of the growth errors of a DBR. The growth errors were determined by comparison of the measured reflectivity with the simulated one. The corresponding measurements are shown in Figure 3.1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>GaAs</th>
<th>AlAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>growth error $\Delta D$ [%]</td>
<td>1.00</td>
<td>0.86</td>
</tr>
</tbody>
</table>

With this comparison of measured and simulated reflectivity even complicated epitaxial layer structures can be accurately characterized and the growth errors can be determined. Even if the structure undergoes regrowth, this method is very successful if the characterization is performed in between the growth runs and a new characterization with new fit parameters is used. Thus, the thicknesses of the layers to be newly grown can even be adapted to possible growth errors of former growth runs. This method has been applied extensively in the fabrication of all our semiconductor structures, especially for the dispersive mirrors which were used in our study of the influence of GDD on the pulse duration of modelocked VECSELs (see Chapter 5.1).

$^1$We used a Varian Cary 5E spectro-photometer for these measurements.
3.1.2 Nonlinear Reflectivity Measurement

SESAM Reflectivity

Due to the saturation of the absorber of a SESAM, its reflectivity depends on the incident pulse fluence. With increasing pulse fluence the absorber saturates more strongly, leading to a higher reflectivity. For a flat-top shaped spatial beam profile, the fitting function

\[ R(F_p) = R_{nl} \frac{F_{sat}}{F_p} \log \left( 1 + \frac{R_{lin}}{R_{nl}} \left( e^{F_p/F_{sat}} - 1 \right) \right) e^{-F_p/F_2}, \]  \hspace{1cm} (3.1)

describes this reflectivity \( R \) of a SESAM as a function of the incident pulse fluence \( F_p \) [41]. The parameter \( F_2 \) is the induced absorption (IA) coefficient and it can be interpreted as the curvature of the rollover and is taken into account as an additional parameter in the reflectivity function for the fitting procedure. For negligible influence of IA, the parameters \( R_{lin} \) and \( R_{nl} \) in Equation 3.1 describe the reflectivities in the cases of minimal \( (F_p = 0) \) and maximal \( (F_p \to \infty) \) incident pulse fluence, and they are referred to as the linear and nonlinear reflectivities, respectively. The parameter \( F_{sat} \) is the saturation fluence at which an approximate reflectivity increase of \( 1/e \) times the modulation depth \( \Delta R \) of the unsaturated absorber is obtained. The modulation depth \( \Delta R \) with

\[ \Delta R = R_{nl} - R_{lin} \]  \hspace{1cm} (3.2)

is the highest possible change in reflectivity and the non-saturable loss \( \Delta R_{ns} \) is the amount of permanent loss of the device, given by

\[ \Delta R_{ns} = 1 - R_{nl}. \]  \hspace{1cm} (3.3)

Induced Absorption

The effect of IA, which is taken care of in Equation 3.1 by \( F_2 \), lowers the reflectivity of the SESAM for very high pulse fluences. The main contribution to this effect is two-photon absorption (TPA), especially in case of pulses shorter than 1 ps [42, 43]. This effect can be the limiting factor for high-power operation of modelocked lasers [44] and seems to be the most important damage mechanism for SESAMs today. It is independent of the absorber if thin QWs are used, since most of the IA results from TPA from the material with the highest TPA-coefficient. The reason is the pronounced dependence of \( \beta_{TPA} \) on the band gap. In the
wavelength range around 1 µm, GaAs has largest contribution to IA with \( \beta_{\text{TPA}} = 20 \text{ cm GW}^{-1} \), whereas the influence of AlAs is negligible [45, 46]. Because of the GaAs content, IA can therefore also occur in standard GaAs/AlAs-based DBRs which do not contain any absorber material. More information can be found in Reference [44].

The \( F_2 \) parameter of a multilayer structure is given by

\[
F_2 = \tau_p \left( 0.585 \int \beta_{\text{TPA}} (z) n^2 (z) |\mathcal{E} (z)|^4 \, dz \right)^{-1}, \quad (3.4)
\]

where \( \tau_p \) is the pulse duration, \( \beta_{\text{TPA}} \) the TPA coefficient, \( n \) the refractive index, \( \mathcal{E} \) the electric field, and \( z \) the position within the structure. The \( z \)-dependence of these parameters results from the multilayer structure over which has to be integrated. Except for the electric field \( \mathcal{E} \), the used parameters are constant for a given material and they are thus described by step functions in Equation 3.4.

**Correction for a Gaussian Spatial Beam Profile**

For our lasers, the transversal beam profile has a Gaussian shape. Therefore, we need to adapt Equation 3.1 accordingly. If we consider a flat-top beam, the profile is a sharp cylinder with radius \( w_{\text{flat}} \) and the fluence \( F \) as a function of the radius \( r \) is constant over the entire profile. Therefore, the fluence \( F \) is equal to the pulse fluence \( F_p \), with

\[
F = F_p. \quad (3.5)
\]

For a Gaussian beam, however, the fluence \( F \) is given by

\[
F (r) = F_{\text{peak}} e^{-2r^2 / w^2}, \quad (3.6)
\]

where the parameter \( w \) is defined as the \( 1/e^2 \) radius and \( F_{\text{peak}} \) is the peak fluence in the center of the beam. These definitions lead to the fact that the definition of the pulse fluence

\[
F_p^{\text{Gauss}} = \frac{E_p}{\pi w^2} = \frac{E_p}{\pi w_{\text{flat}}^2} = F_p^{\text{flat}} \quad (3.7)
\]

holds for both a Gaussian beam (Gauss) and also for a flat-top beam (flat).

Whereas the peak fluence of a flat-top beam is equal to the pulse
fluence

\[ F_{\text{flat}} = F_{\text{peak}}, \quad (3.8) \]

a Gaussian beam exhibits a different energy distribution. The energy in the wings of the Gaussian is relatively low and the pulse fluence \( F_{\text{Gauss}} \) is given by

\[ F_{\text{Gauss}} = \frac{F_{\text{peak}}}{2}. \quad (3.9) \]

Thus, the center of the beam can saturate the absorber significantly faster.

By integration of Equation 3.1 over the beam profile [41] and a number of substitutions and simplifications, we obtain

\[ R_{\text{Gauss}}(F_p) = \frac{1}{2F_p} \int_0^{2F_p} R(F) \, dF, \quad (3.10) \]

of which only numerical solutions can be computed. We used this correction for the characterization of our SESAMs.

**Experimental Setup**

The experimental setup consists of a high precision nonlinear reflectivity measurement system, which is described in detail in Reference [47], and a commercial modelocked Ti-doped Al\(_2\)O\(_3\) laser. Typical experimental parameters for the measurement setup are listed in Table 3.2.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement laser</td>
<td></td>
</tr>
<tr>
<td>average power (P_{\text{avg}}) [W]</td>
<td>1</td>
</tr>
<tr>
<td>repetition rate (f_{\text{rep}}) [MHz]</td>
<td>80</td>
</tr>
<tr>
<td>pulse duration (\tau_p) [fs]</td>
<td>180</td>
</tr>
<tr>
<td>center wavelength (\lambda) [nm]</td>
<td>965</td>
</tr>
<tr>
<td>setup</td>
<td></td>
</tr>
<tr>
<td>beam diameter (d_b) [(\mu)m]</td>
<td>15.0</td>
</tr>
<tr>
<td>attenuation (\Sigma) [dB]</td>
<td>44.3</td>
</tr>
<tr>
<td>minimum fluence (F_p) [(\mu)J cm(^{-2})]</td>
<td>0.1</td>
</tr>
<tr>
<td>maximum fluence (F_p) [mJ cm(^{-2})]</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.2: Experimental parameters of the measurement setup.

We use a variable attenuation stage which enables us to access a pulse fluence range of more than four orders of magnitude. We use a high reflector (HR) with a specified reflectivity of 99.98 % at 960 nm for the
reflectivity calibration. After the measurement, a least squares fit procedure to Equation 3.1 yields the saturation parameters of the SESAM.

Figure 3.2: Nonlinear reflectivity of a SESAM. The blue dots are the measurement, the red lines are the fit where IA is taken into account (solid) and where it is not (dashed). The thin black lines indicate the values for the saturation fluence \( F_{\text{sat}} \) and the linear and nonlinear reflectivities \( R_{\text{lin}} \) and \( R_{\text{nl}} \). The fit values are listed in Table 3.3.

A typical measurement and the fits of the reflectivity of a SESAM as a function of the incident pulse fluence are shown in Figure 3.2. The measurement is plotted as blue points and the fits to this data are shown as a red lines. For the solid red line, the effect of IA is taken into account and for the dashed red line it is not \( (F_2 \rightarrow 0) \). The thin black lines indicate the values for the saturation fluence \( F_{\text{sat}} \) (vertical line) and the linear \( (R_{\text{lin}}) \) and nonlinear reflectivities \( (R_{\text{nl}}) \) of this sample (horizontal lines).

The obtained fit parameters from the SESAM measurement shown in Figure 3.2 are listed in Table 3.3.

Table 3.3: Saturation parameters of the SESAM measured in Figure 3.2. The fit values were obtained by fitting according to Equation 3.1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>saturation fluence ( F_{\text{sat}} ) [( \mu \text{J cm}^{-2} )]</td>
<td>3.8</td>
</tr>
<tr>
<td>modulation depth ( \Delta R ) [%]</td>
<td>1.2</td>
</tr>
<tr>
<td>IA coefficient ( F_2 ) [mJ cm(^{-2})]</td>
<td>24.7</td>
</tr>
</tbody>
</table>

3.1.3 Time-Resolved Differential Reflectivity

As opposed to modelocked ion-doped solid state lasers (SSLs), which usually generate solitons, SESAM-modelocked VECSELs operate in the quasi-soliton regime [48] (see Chapter 5.1). Therefore, the temporal relaxation of the SESAM plays a crucial part in the minimum achievable pulse duration. In order to obtain the shortest pulses, the relaxation time constant needs to be as low as possible. It is thus important to measure this parameter for SESAM-modelocked VECSELs. This can be done using a time-resolved differential reflectivity measurement setup\(^2\).

Our setup is driven by a commercial modelocked Ti:Al\(_2\)O\(_3\) laser. The laser parameters are given in Table 3.4.

\(^2\)This is also known as pump-probe measurement.
Table 3.4: Laser parameter for our commercial Ti:Al₂O₃ laser we used for the pump-probe measurements.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>average power $P_{avg}$ [W]</td>
<td>1</td>
</tr>
<tr>
<td>repetition rate $f_{rep}$ [MHz]</td>
<td>80</td>
</tr>
<tr>
<td>pulse duration $\tau_p$ [fs]</td>
<td>180</td>
</tr>
<tr>
<td>center wavelength $\lambda$ [nm]</td>
<td>965</td>
</tr>
</tbody>
</table>

For the measurement, the input beam is split in two beams, the pump beam and the probe beam, with an intensity ratio of at least ten to one, so that only the pump beam can saturate the sample. The probe beam is directed through a variable delay stage and spatially overlapped with the pump beam on the sample. As a function of the time delay $t_d$ between the two beams, the reflectivity of the probe beam on the sample is measured.

In case of a perfect temporal overlap, the pump has saturated the sample to a certain degree, which is dependent on the incident pump fluence, and the probe pulse is reflected. The amplitude of the measured reflected probe signal is now reduced, if a temporal delay is introduced between the pump and the probe beam. This results from carrier relaxations of the excited carriers that have been generated by the pump beam and leads to a reduced reflectivity for the probe beam.

In case of QD-SESAMs, this decay occurs on two different time scales. Therefore, the relaxation dynamics of QD-SESAMs can be described by a double exponential of the form

$$\Delta R (\Delta t) = A_r e^{-\Delta t/\tau_s} + (1 - A_r) e^{-\Delta t/\tau_f}, \quad (3.11)$$

where $\tau_s$ and $\tau_f$ are the slow and fast time components of the relaxation and $\Delta t$ the time delay between the pump and the probe beams. $A_r$ describes the relative contribution of the slow components to the reflectivity change.

The fast recovery, described by $\tau_f$, is due to transitions within the dots [49, 50, 51], and the slow recovery, which is determined by $\tau_s$, results from carrier recombinations [52, 53].

In Figure 3.3, a typical data trace of a pump probe measurement is shown. The blue dots are the data and a fit to the data according to Equation 3.11 is plotted in red. The corresponding fit values to the measurement are listed in Table 3.5. Our measured values seem to be in good agreement with the relaxation times other groups measured for self-assembled QDs [54].
3.1.4 Measurement of the Group Delay Dispersion

From theoretical considerations [55] as well as from experimental studies [48] it could be shown that the optimization of the cavity GDD is crucial to obtain short pulses from SESAM-modelocked VECSELs. In this section only the experimental GDD measurement setup will be shown, however, an extensive study of the influence of GDD on the pulse duration will be presented in Chapter 5.1.

General Considerations

The GDD $D_2$ as a function of the angular frequency $\omega$ is defined as

$$D_2 (\omega) = \frac{\partial T_g}{\partial \omega} = \frac{\partial^2 \phi}{\partial \omega^2}, \quad (3.12)$$

where $T_g$ is the group delay and $\phi$ the spectral phase. Therefore, in order to measure GDD as a function of the wavelength, the wavelength dependent phase has to be measured, and by building the numerical derivative the GDD is obtained. Unfortunately, there is no direct method to measure the spectral phase.

We use a measurement technique which is based on white-light interferometry, using the FT of an interferometric cross correlation [56] and it will be described in the next section. The derivation of the numerical calculations used in this method can be found in Reference [57] and the
simulation of the GDD as a function of the wavelength has been done using a transfer matrix algorithm (see Chapter 3.2.1).

**Measurement Setup and Calculation**

A schematic overview of the setup we use for the measurements is given in Figure 3.4. It is driven by two different light sources that are fed collinearly into a Michelson interferometer. The first light source is a broadband super luminescent light emitting diode (LED) with an emission spectrum centered around 973 nm and a full width at half maximum (FWHM) bandwidth of 38 nm. The second light source is a standard HeNe laser with an emission wavelength of 632.8 nm.

![Schematic overview of the GDD measurement setup.](image)

Figure 3.4: Schematic overview of the GDD measurement setup. The beams from the two different light sources, indicated as red and blue beams, are guided through the Michelson interferometer where the reference mirror is shaken. While the beam are collinear, the beam are plotted in magenta. The beam are separated and independently measured with corresponding photo detectors.

The sample is placed in the sample arm of the interferometer and the reference mirror is shaken at approximately 10 Hz. The resulting time dependent interference patterns from both light sources are measured separately with two different photo diodes. We analyze the signal of the photo diode of the HeNe laser and measure the time delay $\Delta t$ between
two adjacent peaks. Since the change in signal amplitude is caused by the shaker, the temporal difference $\Delta t$ of the two adjacent peaks corresponds to a length change $\Delta z$ between the two arms of the interferometer of one full wavelength. Thus, we obtain a precise conversion that translates the temporal difference $\Delta t$ between to adjacent signal peak into a spatial amplitude $\Delta z$. Like this, the actual delay of each sample point of the recorded trace for the signal from the LED can be determined, and by interpolation, its signal interferogram can be extracted using evenly spaced points for the position delay. The parameter $\Delta z$ can therefore be used to calculate the integrated intensity $I_{\text{int}}$ of the sample by using

$$I_{\text{int}} (\Delta z) \propto \text{Re} \left\{ \int_{-\infty}^{\infty} S (\omega) r_{\text{ref}}^c | r_{\text{sa}}^c | e^{i \phi_{\text{ref}} (\omega) - \phi_{\text{ref}} (\omega)} e^{i \omega \Delta z} d\omega \right\}, \quad (3.13)$$

where $S$ is the spectral power density of the LED, and $r_i^c$, with $r_i^c = \left| r_i^c \right| e^{i \phi_i}$, the complex amplitude reflectivity of the reference and sample arms ($i = \{ \text{ref, sa} \}$). The parameters $\omega$ and $c$ are the angular frequency and the speed of light. After the FT of Equation 3.13 we can extract the spectral phase $\phi$ as a function of the angular frequency $\omega$ from

$$I_{\text{int}} \left( \frac{\omega}{c} \right) = \text{FT} \left\{ I_{\text{int}} (\Delta z) \right\}. \quad (3.14)$$

This phase can be written as

$$\phi (\omega) = \phi_{\text{sa}} (\omega) - \phi_{\text{ref}} (\omega) = \phi_d (\omega) + \phi_{\text{cal}} (\omega) - \phi_{\text{ref}} (\omega), \quad (3.15)$$

where $\phi_{\text{cal}}$ is the phase shift from additional elements within the sample arms and $\phi_d$ the phase shift of the device that we want to measure.

The phase shift $\phi_d$ can now be measured through calibration. By making measurements with and without the device, all phase shifts from other components can be canceled out if the two measurements are subtracted. Therefore, the GDD $D_2$ as a function of the angular frequency $\omega$ can be determined by numerical derivation of Equation 3.15 using discrete FT sampling frequencies with a spacing $\delta \omega$ by

$$D_2 (\omega) = \frac{\phi (\omega + \delta \omega) - 2 \phi (\omega) + \phi (\omega - \delta \omega)}{\delta \omega^2}. \quad (3.16)$$
Typical Measurement Results

A typical measurement of a Gires Tournois interferometer (GTI) (see Chapter 4.1.2) where such a technique was used is shown in Figure 3.5. In this case we used our own GTI design according to Figure 4.3 (see Chapter 4.1.2). Plotted in blue are the measurement points, the solid blue line is a spline fit, and the solid red line is a simulated GDD curve for this multilayer structure design (see Chapter 3.2.1 for details on the simulation).

Figure 3.5: GDD of a dispersive mirror with a FS layer thickness of 285 nm according to the design shown in Figure 4.3 as a function of the wavelength (see Chapter 4.1.2 for details). The dots are the measurement, the solid blue line is a spline fit and the solid red line a simulated curve for this multilayer design. The simulation was made using a transfer matrix algorithm (see Chapter 3.2.1).

3.2 Simulation

3.2.1 Multilayer Structure and Cavity Simulations

The semiconductor multilayer structures we use for our experiments consist of a little less than 100 layers in case of simple SESAMs, or even more than 400 in case of our electrically pumped VECSELs. In order to calculate optical properties like reflectivity or structural GDD as a function of the wavelength for such devices, we employ the well-known transfer matrix algorithm [58]. The only required input parameters for this method are the wavelength-dependent complex refractive indexes of all materials involved and the thicknesses of all layers. We use an implementation of the transfer matrix algorithm which is based on Matlab. Since this is a standard method and commonly used for the simulation of multilayer structures, we will not discuss this topic in detail here.

Another standard procedure is the simulation of laser cavities. The cavity plays an important role since cavity parameters such as the length of the cavity define the spot sizes and thus have a significant influence of the output power and the beam quality of the laser. Since for our
laser cavities, the intra-cavity beam is usually very well described by a Gaussian beam, we can make use of the ABCD matrix formalism for the propagation of Gaussian beams [59].

3.2.2 Simulation of the Pulse Propagation Modelocked VECSELs

We can simulate the propagation of a pulse within a VECSEL cavity by implementing numerical iterations of a circulating pulse inside an artificial cavity, similar to Reference [55]. Within a cavity round trip the pulse interacts with the cavity elements such as gain, absorber, OC, etalon, losses and cavity GDD. These elements are represented by operators either in the time or frequency domain. The slowly varying envelope approximation is used to describe the temporal evolution of the pulse shape and fast Fourier transformation (FFT) converts the pulse between the time domain and the frequency domain. The effects our simulation takes into account are schematically shown in Figure 3.6.

![Figure 3.6: Schematic overview of our pulse buildup simulation model. While a pulse circulates in a modeled cavity, it takes into account the effect of saturable gain, saturable absorption, noise, losses, SPM, gain filtering, GDD and an intra-cavity etalon.](image)

The gain filter simulates the optical gain with respect to the center wavelength and the bandwidth. It is a normalized parabolic function that is applied in the frequency domain. The filtering effect of the etalon is also applied in the frequency domain by using the standard Fabry-Perot formula for transmission as a function of the wavelength, the etalon thickness and the rotation angle. We use this etalon to obtain wavelength selectivity, just like we do in the actual experiment. Since, usually, the bandwidth of the etalon is smaller than the gain bandwidth, this is an effective method to set the wavelength, not only in the real experiment but also in the simulation.

Effects of dynamic saturation of the gain and the absorber are described in the time domain (the variables are functions of the time $t$)

3.2. Simulation
using the differential equation

\[
\frac{dg(t)}{dt} = \frac{g_0 - g(t)}{\tau} - \frac{g(t) P(t)}{E_{\text{sat}}},
\]

(3.17)

where \( g \) is the wavelength-independent gain, \( g_0 \) the small signal gain, \( \tau \) the recombination time, \( P \) the instantaneous power and \( E_{\text{sat}} \) the saturation energy. For the gain, we use a positive small signal gain \( g_0 > 0 \), while for the saturable absorber we use a negative approximated value of \( g_0 = -\Delta R/2 \), with \( \Delta R \) the modulation depth of the SESAM (see Chapter 3.1.2).

By Kramers-Kronig relations, the saturation of the gain and the absorber implies a change of the real part of the refractive index which results in a nonlinear phase change. The relation between the temporal change of the gain \( \Delta g \), i.e. the saturation, and the temporal phase change \( \Delta \phi \) is given by

\[
\Delta \phi(t) = -\frac{\alpha}{2} \Delta g(t),
\]

(3.18)

where \( \alpha \) is the empiric linewidth enhancement factor [60]. The values we use in our simulation were \( \alpha_{\text{absorber}} = 2 \) and \( \alpha_{\text{gain}} = 3 \).

All simulated phase shifts of a SESAM (green), a VECSEL (magenta) and the sum of both (magenta) are plotted in Figure 3.7 together with the simulated phase shift of normal self-phase modulation (SPM) (black) and the temporal incident pulse intensity (blue). The phase shifts are plotted against the left \( y \)-axis, whereas the pulse envelope is plotted against the blue right \( y \)-axis.

Due to the extremely short interaction length, SPM play an insignificant role for modelocked VECSELs. However, our simulation model can also be used for bulk lasers or with intra-cavity elements where the influence of SPM becomes important. Our algorithm applies the effect of
SPM in the time domain by using

$$\varphi (t) = k_0 n_2 I_p (t),$$  \hspace{1cm} (3.19)

with $k_0$ is the wave number in vacuum, $n_2$ the nonlinear refractive index, $I_p$ the pulse intensity and $\varphi$ the temporal phase.

The GDD is included in the model by applying

$$\phi (\omega) = \frac{1}{2} D_2 (\omega - \omega_0)^2$$  \hspace{1cm} (3.20)

in the frequency domain, where $\phi$ is the spectral phase, $\omega$ and $\omega_0$ the angular frequency and angular reference frequency, respectively, and $D_2$ the GDD. During the simulations we maintain a constant GDD value over the full optical pulse spectrum.

With this model we can simulate the pulse buildup from a 10-pW noise floor which is illustrated in Figure 3.8. The detailed simulation parameters we used for that pulse buildup calculation are given in Table 3.6.

Figure 3.8: Pulse buildup from noise floor, assuming 10 pW noise power. The pulse is stable after about $10^4$ round trips. All parameters we used for the simulation are listed in Table 3.6 together with the details on the stable pulse. The inset in the top right is the same data in a 3-dimensional view.

The simulation of a pulse buildup from noise is possible, however,
we usually initialized the simulations already with a sech$^2$ pulse shape. This significantly decreases the number of iterations for a stable solution, reducing the simulation time by about a factor of three to five. Yet, only the calculation time changes and we have never observed any differences in the pulse shape if we compared a stable pulse that was initialized from noise with a stable pulse which was initialized from a sech$^2$ pulse shape.

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Table 3.6: Listed in this table are results for the stable pulse and the values we used as startup parameters during the pulse buildup simulation which is shown in Figure 3.8.
Chapter 4

Development of Novel Dispersive Mirrors and Low-GDD Top Coatings

In this chapter, we present two different hybrid semiconductor/dielectric multilayer designs which both have a strong influence on the structural GDD.

The first design is for a novel type of GTI. It allows for the cost-efficient fabrication of a dispersive element with a precise value for the GDD. The amount of GDD is controlled by deposition of a dielectric material on top of the MBE-grown base structure. The thickness of the deposited layer defines the GDD of the device, and by fabricating samples with different dielectric layer thicknesses, we obtained a set of dispersive mirrors, ranging from GDD values of $-7000\,\text{fs}^2$ to $9000\,\text{fs}^2$. With these devices, we were able to investigate the influence of intra-cavity GDD on the pulse duration of modelocked VECSELs (see Chapter 5.1). We found that low positive values result in the shortest pulse durations.

These findings led us to develop multilayer designs which we could use on top of our VECSELs and SESAMs, again based on semiconductor and dielectric materials, which resulted in low and flat structural GDD. These designs were obtained using a computer-aided optimization algorithm.
4.1 Dispersive Mirrors

Since VECSELs with standard anti-resonant design exhibit GDD values in the order of several thousand $\text{fs}^2$, in order to perform the study of the influence of GDD on the pulse duration of SESAM-modelocked VECSELs (see Chapter 5.1), we needed to find a way to change the GDD within a VECSEL cavity by large amounts. Since commercial GTIs were not an option, first, because of the limited amount of GDD of usually less than $10^3\text{fs}^2$, and second, because of the cost and availability to acquire a set of GTIs with a large span in GDD, we developed our own versatile design for a dispersive mirror.

4.1.1 Standard GTI design

In order to experimentally control the GDD of a pulsed laser, dispersive mirrors, such as GTIs [61], are commonly used. A standard GTI-design consists of a HR and a partial reflector (PR) section, which are separated by a spacer layer with thickness $d$. This is illustrated in Figure 4.1.

![Figure 4.1: Basic principle of a GTI, consisting of a HR, a spacer layer and a PR. The incident light usually impinges perpendicular to the surface. The wavelength-dependent GDD is obtained through the resulting phase shift after the reflections at the two interfaces and their interference.](image)

For such a device, an incoming beam is typically sent at nearly perpendicular incidence onto the PR. The transmitted light that enters the spacer layer will be reflected by the HR, which ideally has a reflectivity of 100%. In case of no losses, the GTI will reflect everything but with a wavelength-dependent phase shift resulting in either positive or negative GDD for a given wavelength. The amount of GDD depends on the wavelength, the reflectivity of the PR, the spacer material and the spacer thickness.

4.1.2 Our GTI Design

We developed a new versatile design for dispersive mirror by using a standard GTI design as a starting point. In Figure 4.2, we show the calculated dispersion for a GTI consisting of a standard HR section, which
was realized with a GaAs/AlAs DBR, and the Fresnel reflection of the spacer/air interface as PR section. We chose two different spacer materials, GaAs and FS, and plotted the resulting GDD as a function of the spacer thickness for a wavelength of 960 nm for both materials. The blue curve corresponds to a GaAs spacer and the green to a spacer made of FS. For the GaAs spacer, we can obtain large values for the GDD, however it would require very precise layer thickness control. For example, for a device design value of $4500 \text{ fs}^2$, which would be at the steep slope part in the rightmost peak of the blue curve in Figure 4.2, a difference in spacer thickness of 1 nm would correspond to an error in GDD of about $223 \text{ fs}^2$. Since we are interested in accuracies of less than $100 \text{ fs}^2$, we would have to achieve a sub-nanometer accuracy for the thickness of the GaAs layer. This accuracy, however, is difficult to achieve with todays fabrication techniques. Another aspect of the steep slope is the significant amount of third order dispersion (TOD), i.e. the change of the GDD. Although TOD does not play a significant role for picosecond pulses, it is still worth reducing it, because the GDD variation around a given wavelength will be smaller. A last disadvantage of using GaAs as a spacer material is that if GTIs with different amounts of GDD are required, a new growth run has to be made for each dispersive mirror device, making this approach very costly.

In comparison, FS as a spacer material provides a much smoother GDD dependence on the spacer thickness. This is shown as a green curve in Figure 4.2. In addition, FS can easily be deposited on multiple semiconductor samples with different and accurately controllable thicknesses using PECVD (see Chapter 2.2.1). The only drawback is the limited amount of GDD that we can obtain for typical layer thicknesses below 1 µm of FS.

Since neither FS nor GaAs could provide the required dispersion properties when used as spacer material, we developed a hybrid design for our dispersive mirror devices, which benefits from the advantages of

![Figure 4.2: Comparison of the GDD of a GaAs (blue) and a FS spacer (green) for a standard GTI-design according to Figure 4.1.](image-url)
both materials. This design is shown in Figure 4.3.

Figure 4.3: Our dispersive mirror design, consisting of a GaAs/AlAs DBR as the HR, the top FS/air interface as the PR and the spacer layer formed by a GaAs layer, the AR section and the FS layer. The GaAs layer was chosen to be 3.1 µm thick whereas the FS layer thickness was varied to adjust the final dispersion of the dispersive mirror device. The AR section is required to minimize reflections between the GaAs/FS interface.

Its main part consists of a bottom AlAs/GaAs DBR and a thick GaAs layer with \( d_{\text{GaAs}} = 3.1 \text{µm} \) (see Figure 4.3), which can provide a very large amount of dispersion in the order of \(10^4 \text{fs}^2\). For the fine adjustment of the final GDD of the device, we insert an AR section on the top and add an additional layer of FS. The thickness of this FS layer \( d_{\text{FS}} \) needs to be chosen appropriately in order to obtain the desired value for the GDD of the final dispersive mirror. The GDD of our dispersive mirror design as a function of the FS layer thickness is plotted in Figure 4.4 for a wavelength of 960 nm.

A necessary requirement of our design is the AR section, which consists of a 10-layer GaAs/AlAs layer system to reduce internal reflections between the 3.1-µm thick GaAs layer and the FS layer to less than 0.1 % for the entire wavelength range from 950 nm to 970 nm. This is needed to eliminate the etalon effect which would arise from the reflection of the interface between GaAs and FS. Because of the strong refractive index difference for the two materials at our design wavelength of 960 nm, 3.54 for GaAs and 1.45 for FS, this reflection would be very strong, making this AR section a crucial part of the design.
4.1.3 GDD of our GTIs

With this novel GTI design we could produce a set of different dispersive mirrors with GDD values ranging from $-7000 \text{fs}^2$ to $9000 \text{fs}^2$ for a single reflection. The GDD curves for some of the fabricated devices are plotted in Figure 4.5 as a function of the wavelength. The measurement data is plotted as dots and a corresponding spline interpolation is plotted as a solid line for each of the dispersive mirrors. The measurement was done using white-light interferometry which is described in detail in Chapter 3.1.4. Figure 3.5 in Chapter 3.1.4 shows the comparison between the measurement, its spline fit and the theoretical GDD curve for a FS layer-thickness of 285 nm. The theoretical curve was obtained using the transfer matrix algorithm which is described in Chapter 3.2.1.

![Figure 4.5: Wavelength-dependent GDD of some of our GTIs according to the design shown in Figure 4.3. In the wavelength range between 955 nm and 960 nm we have a collection of dispersive mirror which are very well distributed in the GDD range between $-7 \times 10^3 \text{fs}^2$ and up to almost $10^4 \text{fs}^2$.](image)

4.1.4 Growth of the Devices

We grew the semiconductor part of the structure, consisting of the DBR, the 3.1-µm thick GaAs spacer, and the ten-layer GaAs/AlAs AR section (see Figure 4.3), using MBE (see Chapter 2.1.1) on a 650-µm GaAs wafer.
After cleaving the wafer into square pieces with 3 mm edge length, we added the FS coatings using PECVD (see Chapter 2.2.1) with different thicknesses to obtain a set of dispersive mirrors. The thicknesses of the FS layers on the individual samples ranged from 80 nm to 350 nm which correspond to GDD values between $-7000 \, \text{fs}^2$ and $9000 \, \text{fs}^2$. This is illustrated in Figure 4.4, an overview of the wavelength-dependent GDD of some of our dispersive mirrors is given in Figure 4.5.

### 4.2 Low GDD Top Coating

As we will demonstrate experimentally in Chapters 5.1, low and flat intra-cavity GDD is a key to achieve ultrashort laser pulses with SESAM-modelocked VECSELs. Inspired by these results we started to investigate AR coatings that exhibit flat and low GDD. Their application to our VECSEL and SESAM structures allowed us to achieve record-high output power in the femtosecond regime (see Chapter 5.3). These coating will be described in the section.

#### 4.2.1 Design of the Top Coating

We simulated the GDD of a VECSEL with and without an AR coating that is build up of 12 AlAs/Al$_{0.2}$Ga$_{0.8}$As layers, a GaAs cap layer, and an additional layer of FS on the top. In our simulation model, which is based the transfer matrix algorithm that is described in Chapter 3.2.1, we added a Monte Carlo procedure that altered the layer thicknesses of all layers of the AR section and calculated the obtained GDD. Using an additional least squares algorithm we then optimized the best 10 results from the Monte Carlo procedure. An important part of the design of our AR section is the last FS layer [62] without which the improvement in GDD would have been less pronounced.

#### 4.2.2 Comparison of Structures with and without the Top Coating

Using this hybrid semiconductor/dielectric AR coating allowed us to achieve GDD values of less than $\pm 10 \, \text{fs}^2$ over a wavelength range of more than 30 nm around a central wavelength of 960 nm. This is an improvement in GDD of about a factor of 1000 compared to the same VECSEL structure without such an AR section.
The simulated GDD curves of the VECSEL with and without the AR section as a function of the wavelength are plotted in Figure 4.6a. In blue and green are the GDD of the VECSEL structure without and with the AR coating, respectively. Since the GDD is extremely low with this new coating, the GDD curve with AR section is plotted again in black where it was multiplied by a factor of 1000.

![Graph](image)

(a) AR influence on GDD for a VECSEL  
(b) FS layer influence on GDD for a SESAM

Figure 4.6: Difference in GDD with and without AR-coating. (a) shows the GDD of a VECSEL without AR section in blue, with AR section in green, and again with AR section in black, but here multiplied by a factor of 1000 for better visibility. (b) shows the GDD of a SESAM with a single layer of FS as AR section (green) and without this layer (blue).

We also tried to improve the GDD of SESAMs that had been grown already. Therefore, we compare the GDD between a standard resonant design and the same structure with an additional quarter wave layer of FS on top. In this case we could obtain an improvement in GDD of about a factor of 10. The corresponding plot can be found in Figure 4.6b, where the blue curve corresponds to the original structure, and the green curve to the same structure where an additional layer of FS.

In both cases, for the VECSEL and for the SESAM, we obtained a large improvement in GDD (see Figure 4.6). Each time the FS layer was deposited using PECVD (see Chapter 2.2.1).

The full multilayer structure, including the corresponding AR section, of the VECSEL and the SESAM of which the GDD is given in Figure 4.6 can be found in Figure 5.14a for the VECSEL, and in Figure 5.15b for the SESAM. Both of these structures were used to achieve the first femtosecond pulses with more than 1W of output power generated by a SESAM-modelocked VECSEL. This is discussed in Chapter 5.3.

4.2. Low GDD Top Coating
Chapter 4. GTIs and Top Coatings

4.2. Low GDD Top Coating
Chapter 5

Modelocked Optically Pumped VECSELs

In the first demonstration of a fundamentally modelocked VECSEL [15], 22-ps pulses were generated at a repetition rate of 4.4 GHz and an average output power of 21.6 mW. This result could be improved in all aspects (an overview is given in Figure 5.1 and Table 5.1). Shorter pulses were generated with pulse durations down to 107 fs [17], the output power was increased to 6.4 W using the MIXSEL geometry [25], and the repetition rate was increased to 50 GHz [21]. The successful combination of one of the three parameters, however, could not be reported until recently, where the first femtosecond generation from a VECSEL was demonstrated with an average output power of more than 1 W [30]. We will discuss this result in detail in this chapter.

In this chapter, we discuss all necessary steps we took to realize this novel result. We present the study of the influence of the intracavity GDD on the pulse duration of SESAM-modelocked VECSELs [48], high power femtosecond modelocking from a QD-based VECSEL, and initial modelocking results from a low-GDD QW-VECSEL. At the end of the chapter, we compare the modelocking performances of the two VECSELs and give an outlook on possible future improvements.
Figure 5.1: Overview of published results on fundamentally-modelocked optically pumped VECSELs. Highlighted in green are VECSELs based on QW-layers for gain, in red are VECSELs based on QDs, and in blue are MIXSELs. The numbers on the colored dots correspond to the numbers in Table 5.1, where the details of the individual results are given.

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<td>5.4</td>
<td>[30]</td>
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</table>

Table 5.1: Overview of published results on fundamentally-modelocked optically pumped VECSELs. The numbers correspond to the numbers in Figure 5.1.
5.1 Study of the Influence of Group-Delay Dispersion on the Pulse Duration

This study of the influence of the intra-cavity GDD on the pulse duration was published in Reference [48].

5.1.1 Experimental Laser Setup

For our experiment, we used a standard z-shaped cavity (see Figure 5.2) with an OC, an optically pumped QW-VECSEL gain structure, one of the dispersive mirrors that are introduced in Chapter 4.1.2, a QD-SESAM and a 20-µm thick etalon for wavelength tunability. In order to change the overall GDD of the laser cavity, we simply replace the dispersive element by another dispersive device from our set of dispersive mirrors (see Chapter 4.1). Thus, the total intra-cavity GDD can be changed without changing the emission wavelength which is controlled by the 20-µm thick FS etalon.

Figure 5.2: Schematic overview of the cavity we used for the study of the influence of GDD on the pulse duration of SESAM-modelocked VECSELs. The lengths are drawn to scale. In order to change the overall GDD of the cavity, we exchanged the GTI (see Chapter 4.1). We paid great attention that the cavity remained the same when we changed the GTI.

The QW-VECSEL was grown in the FIRST clean room facility at ETH Zurich using MOVPE (see Chapter 2.1.2) with a design similar to Reference [16]. The VECSEL contains an AlAs/Al$_{0.2}$Ga$_{0.8}$As DBR which reflects both the laser and the pump wavelength using a super lattice mirror structure design. The calculated reflectivity for the laser wavelength at 10° angle of incidence is higher than 99.95 % and for the pump radiation at an angle of incidence of 45° it is larger than 99.5 %. The active region of the VECSEL consists of seven InGaAs QWs with a thickness of 5 nm, placed at the anti-nodes of the standing wave pattern of the electric field inside the VECSEL structure. The QWs are separated...
by GaAs spacer layers which also serve as absorbing medium for the pump radiation. From these spacer layers the excited carriers can drift into the QWs. On top of the active region there is an AR section which controls the field enhancement in the gain region.

Self-starting and reliable modelocking is achieved with a QD-SESAM with moderate saturation fluence [27]. It consists of an AlAs/GaAs DBR, a single InAs QD saturable absorber layer which is centered at a maximum of the standing wave pattern of the electric field and several AlAs/GaAs layers on top of the structure to control the field enhancement. The SESAM was grown using MBE at the FIRST clean room facility at ETH Zurich and it has a resonant design similar to the one described in Reference [69]. We measured its nonlinear reflectivity at a wavelength of 956 nm using the measurement setup described in detail in Chapter 3.1.2. The measured saturation fluence is 4.2 µJ cm$^{-2}$, the modulation depth 1.3 %, and the non-saturable losses are smaller than 1 %.

Due to the resonant design, both the modulation depth and the saturation fluence are wavelength dependent. With increasing wavelength, the saturation fluence increases and the modulation depth decreases. This is illustrated in Figure 5.3, where the measured linear reflectivity of the used SESAM (blue dots) is shown with a spline fit (red line) as a function of the wavelength. The stop band of the device shown in Figure 5.3a exhibits a dip which results from absorption in the absorber section. In principle, the measured wavelength-dependent amplitude of this dip corresponds to the modulation depth $\Delta R$ of the SESAM (see Chapter 3.1.2), which also is a function of the wavelength in case of a resonant structure. However, since the measurement in Figure 5.3 was not made with a high-precision nonlinear reflectivity setup (see Chapter 3.1.2), these measurements can only qualitatively illustrate this dependence.

With the used laser cavity setup (see Figure 5.2), we obtained a laser mode radius of about 90 µm on the VECSEL and about 45 µm on the SESAM. The VECSEL gain structure was pumped optically using an 808 nm diode laser at a pumping angle of about 45°. The OC had a radius of curvature (ROC) of 38 mm and a reflectivity of 99.3 % . The temperature of the VECSEL heat sink was set to 5°C. The typical output power was about 30 mW for all GDD dependent measurements. The parameters for the cavity and the SESAM are summarized in Table 5.2.

Figure 5.4 shows the measurement data of the result with (a) the optical spectrum, (b) the RF spectrum and (c) the autocorrelation (AC) trace.
Figure 5.3: Linear reflectivity of the used SESAM as a function of the wavelength. The blue dots show the measurement and the red line a spline fit of the data. (a) stop band of the SESAM. The gray box indicates the wavelength range the SESAM was used in. A zoomed view of this box is shown in (b).

<table>
<thead>
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<td>modulation depth $\Delta R$ [%]</td>
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<td>non-saturable losses $\Delta R_{\text{ns}}$ [%]</td>
<td>&lt; 1</td>
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<td>cavity parameters</td>
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<tr>
<td>average output power $P_{\text{avg}}$ [mW]</td>
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<tr>
<td>repetition rate $f_{\text{rep}}$ [GHz]</td>
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<td>OC transmission $T$ [%]</td>
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<tr>
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<td>pump wavelength $\lambda$ [nm]</td>
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<td>pump angle $\theta$ [°]</td>
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<td>heat sink temperature $T_{\text{s}}$ [°C]</td>
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</table>

Table 5.2: Overview of the cavity parameters during the GDD study.
These measurements show the shortest pulse duration of 1.52 ps that we achieved during this study. This was achieved with 30 mW of average output power, at a repetition rate of 4.2 GHz and with a positive total intra-cavity GDD of 5300 fs$^2$. The FWHM spectral width of the pulses was 0.86 nm centered around 953.5 nm, resulting in a time bandwidth product (TBP) of 0.43 which is 1.35 times the transform limit of an ideal sech$^2$ soliton pulse shape. The experimental results are summarized in Table 5.3.

![Image](image_url)

**Figure 5.4**: Pulse characterization traces of the results where the shortest pulses of 1.52 ps where achieved. (a) shows the optical spectrum, (b) the RF spectrum and (c) the AC trace (blue) with a sech$^2$-fit (red). Details on this result are listed in Table 5.3.

<table>
<thead>
<tr>
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<td>average output power $P_{\text{avg}}$ [mW]</td>
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<tr>
<td>repetition rate $f_{\text{rep}}$ [GHz]</td>
<td>4.2</td>
</tr>
<tr>
<td>center wavelength $\lambda$ [nm]</td>
<td>953.5</td>
</tr>
<tr>
<td>spectral width $\Delta \lambda$ [nm]</td>
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</tr>
<tr>
<td>intra-cavity GDD $D_2$ [fs$^2$]</td>
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</tr>
<tr>
<td>TBP (multiples of sech$^2$)</td>
<td>1.35</td>
</tr>
</tbody>
</table>
5.1.2 GDD-Dependence on the Pulse Duration

Both VECSELs and SESAMs exhibit a significant amount of GDD, usually in the range of \( \pm 10^4 \text{ fs}^2 \), which strongly depends on the operation wavelength. The typical MBE growth accuracy leads to a relatively large uncertainty, and measurements of the real GDD are needed. Therefore, we first measured the wavelength-dependent GDD of the VECSEL, the SESAM and all fabricated dispersive mirrors with our GDD measurement setup which is described in detail in Chapter 3.1.4.

An example of the obtained GDD curves for the entire cavity, as well as the individual cavity elements for one specific cavity setup, is given in Figure 5.5. The GDD \( D_2 \) of the entire cavity was determined using

\[
D_2^{\text{cavity}} = 2 \cdot D_2^{\text{VECSEL}} + 2 \cdot D_2^{\text{GTI}} + D_2^{\text{SESAM}},
\]  

(5.1)

because the laser cavity beam has two passes over the VECSEL and the GTI and only one pass over the SESAM per cavity round trip (see Figure 5.2). Plotted in blue, green, magenta and red are the GDD of the VECSEL, the SESAM, one of our GTIs, and the total intra-cavity GDD according to Equation 5.1, respectively. The dots are the measurements and the solid lines are spline fits.

![Figure 5.5: Measurements (dots) and a spline fit (solid lines) of the GDD as a function of the wavelength for all cavity elements. Plotted in blue is the VECSEL, the SESAM is shown in green and one of our dispersive elements is drawn in magenta.](image-url)
For every dispersive mirror we changed the center wavelength of the laser emission using the etalon, tuning the wavelength between 950 nm and 960 nm in increments of 0.5 nm. We determined the optical spectrum, the RF spectrum, and the AC trace using a standard second harmonic generation (SHG) autocorrelator. We took special care during those measurements not to alter other parameters, such as the repetition rate or the pump power, to ensure that only the total intra-cavity GDD dependence was investigated. Therefore, we can determine the pulse duration as a function of the total intra-cavity GDD for any given emission wavelength from these measurements because every dispersive mirror has a different GDD. The GDD of the dispersive mirrors we used can be found in Figure 4.5.

Figure 5.6 shows the measured pulse duration given as a function of the total intra-cavity GDD for several different laser wavelengths, where dark blue corresponds to 953 nm and, in increments of 0.5 nm, dark red corresponds to 958 nm.

Figure 5.6: Pulse duration as a function of the GDD for several different wavelength from 953.0 nm (dark blue) to 958.0 nm (dark red), in increments of 0.5 nm. Dots are the measurement and solid lines are spline fits as a guide to the eye. We see a clear difference between the positive and the negative GDD regime. For positive GDD, the pulse duration change is much less pronounced for the individual GDD values. The wavelength dependence between the difference curves is due to the resonant SESAM, resulting in wavelength-dependent SESAM parameters. However, for all measurements done for each curve, those parameters are the same.

5.1. Influence of GDD
We can clearly see that the pulse duration strongly depends on the amount of total intra-cavity GDD. For positive GDD values the pulse duration becomes shorter compared to negative GDD values. The minimum duration is observed at low positive values between 0 fs\(^2\) and 6000 fs\(^2\). The pulse duration for a given value of intra-cavity GDD depends strongly on the operation wavelength, which is mainly due to the resonant SESAM design, which introduces a significant wavelength dependent modulation depth and saturation fluence. This effect, however, is much more pronounced in the negative GDD regime compared to the positive, which is clearly visible in Figure 5.6.

In comparison to our experimental results our simulations (see Chapter 3.2.2) give a good qualitative agreement which is illustrated in Figure 5.7. For the simulation parameters we used the experimental values which are summarized in Table 5.2. Some parameters of the gain we could not measure were assumed and are listed in Table 5.4. However, according to our simulations (see Chapter 3.2.2) these assumed parameters only have a small influence on the pulse duration.

### Table 5.4: In addition to experimental parameters (see Table 5.2), we used the following parameters of the gain for the simulation which is shown in Figure 5.7. According to our simulations, these parameters, however, have a small influence on the pulse duration.

<table>
<thead>
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</tr>
<tr>
<td>relaxation time (\tau) [ns]</td>
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</tr>
<tr>
<td>saturation fluence (F_{\text{sat}}) [(\mu)J cm(^{-2})]</td>
<td>500</td>
</tr>
<tr>
<td>linewidth enhancement factor (\alpha)</td>
<td>3</td>
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<tr>
<td>small signal gain (g_0) [%]</td>
<td>2</td>
</tr>
</tbody>
</table>

In Figure 5.7, the measurement results for an emission wavelength of 957 nm are shown together with the corresponding simulation. We clearly see that positive GDD values are favored over negative ones to achieve short pulse durations. This also verifies that the presumed modelocking mechanism for SESAM-modelocked VECSEL is indeed very well described by the quasi-soliton modelocking model [55].

![Figure 5.7: Pulse duration as a function of the GDD for an emission wavelength of 956 nm. We used the experimental parameters listed in Table 5.2 and the values listed in Table 5.4 for the simulation.](image)
5.1.3 Quasi-Soliton Modelocking

In the theory of soliton modelocking, SPM, which is given by Equation 3.19, and negative GDD are balanced to form soliton pulses with sech\(^2\)-shaped temporal profile (for details see Chapter 3.2.2). This theory is very well understood and applies to most soliton-modelocked ion-doped SSLs [70, 71]. This is the case, because for normal dispersion materials, the nonlinear refractive index \(n_2\) is positive and thus stable soliton formation requires negative GDD. In the femtosecond to few picosecond domain this pulse formation process becomes dominant and the SESAM only starts and stabilizes this pulse formation process. This even relaxes the requirements on the SESAM parameters.

On the other hand, passive modelocking at GHz repetition rates typically has negligible SPM and therefore soliton modelocking becomes less effective at these high pulse duty cycles and correspondingly lower peak powers. This is usually true for SESAM-modelocked VECSELs. Moreover, in contrast to ion-doped SSLs, semiconductor lasers such as VECSELs exhibit strong dynamic gain saturation (see Chapter 3.2.2), which, by Kramers-Kronig relations results in a nonlinear phase shift. This behavior is illustrated in Figure 3.7.

The combination of both the nonlinear phase shift introduced by the dynamic gain saturation and the fast absorber saturation leads to a similar effect as SPM (see Figure 3.7) but with a negative \(n_2\) (see Equation 3.19). Therefore, this modelocking regime in VECSELs is referred to as quasi-soliton modelocking [55]. In this modelocking mechanism, the mathematical analogy to the soliton modelocking model is the interplay of a nonlinear phase shift with positive intra-cavity GDD which becomes the dominant pulse forming mechanism. Thus, this nonlinear phase shift is not based on SPM but is induced by significant VECSEL gain and SESAM saturation.

A theoretical study of quasi-soliton modelocking has been made [55], however, only a qualitative experimental agreement could be found, since various important parameters were changed simultaneously during the experiments. We explored this modelocking regime with the study of the influence of GDD on the pulse duration in this chapter and compared our experimental finding with the quasi-soliton theory.

Both experimentally and in our simulations we obtained an asymmetric curve for the pulse duration as a function of the GDD, where positive GDD values are better suited for the generation of short pulses (see Figure 5.7). As one might expect, if saturation effects are neglected,
the curve becomes perfectly symmetric which also was reproduced using our theoretical model (see Chapter 3.2.2).

5.2 Modelocked Quantum-Well VECSELs

Since we were trying to achieve sub-femtosecond operation with our SESAM modelocked VECSELs, we investigated in QW-based gain material and also QD-based gain material. The QDs will be discussed in detail in Chapter 5.3, the QWs in this chapter.

5.2.1 QW-VECSEL Design and Fabrication

The QW-VECSEL gain structure (see Figure 5.8) we used for the experiments was grown by MBE (see Chapter 2.1.1) on a 650-nm GaAs substrate in the FIRST clean room facility at ETH Zurich. It consists of two DBRs based on pairs of quarter wave layers of AlAs and AlGaAs. We use Al_{0.2}Ga_{0.8}As instead of GaAs, although the refractive index contrast and therefore the reflectivity per DBR-pair is lower in comparison, in order to circumvent unwanted pump absorption in these DBRs.

The 15-pair DBR on the bottom of the structure was optimized to reflect the pump light at a wavelength of 808 nm with a theoretical pump reflectivity more than 99% at an incident pump angle of 45°, and the second 30-pair DBR to reflect the laser light at around 960 nm with a theoretical reflectivity more than 99.9% at around 10°. We use an Al_{0.2}Ga_{0.8}As spacer layer between the two DBRs of which we adjust the thickness and therefore shift the standing wave pattern of the electric field of the pump without influencing that of the laser. With this approach we can use this layer to optimize the structure for a maximum pump absorption in the active region where we achieve more than 95% of absorbed pump light.

After the two DBRs, the active region is grown. It is mostly made up of GaAs, that serves as absorbing material for the pump radiation,
in which seven InGaAs QWs are embedded. These QWs are distributed within the active region according to the standing wave pattern of the electric field of the laser. However, the positions of the individual QWs are all optimized for slightly different laser wavelengths, resulting in a chirped positioning scheme of the active QWs. The wavelengths we optimized the positions for are, in increments of 1.66 nm, 952 nm to 962 nm, with a design laser wavelength of 957 nm. The QW optimized for 952 nm is the one closest to the DBRs and the other QWs were added subsequently with the mentioned linearly increasing optimization wavelengths.

After the active region we directly grew the semiconductor part of our AR section and deposited a quarter wave layer of FS using PECVD (see Chapter 2.2.1) to complete the AR section. The top coating was necessary to reduce the GDD of the VECSEL and it was crucial to achieving these demonstrated results. Details on the AR section can be found in Chapter 4.2.

The full structure design of this QW-VECSEL can be found in Figure 5.8. In Figure 5.9, the simulated standing wave pattern is shown as a red line together with the refractive index profile in different colors for the different materials. Drawn in black are QWs, GaAs is blue, AlAs is green, FS is pink and AlGaAs is grey.

Unfortunately, the last QW, the one with the largest distance to the DBRs, was placed incorrectly while it was designed. This is visible in Figure 5.9 in the active region. It is not close to the anti-node of the standing wave pattern of the laser field, and it will therefore not contribute to the gain.

On the contrary, since this QW has to be pumped until transparency is reached, this misplacement will result in a slight decrease of the overall efficiency. Nevertheless, we obtained good results from this sample.

In order to obtain high average output power levels, it is crucial to
optimize the thermal management [13]. Therefore, we used the thinned QW-VECSEL structure on a copper (Cu) heat sink [72]. This so-called flip-chip bonding is done by starting the structure growth from the GaAs wafer with an $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}$ etch stop layer and then the actual QW-VECSEL structure is grown in reverse order. After that, the wafer can be cleaved, metalized and soldered to the Cu heat sink and the substrate can be removed by selectively etching the GaAs substrate using a citric acid hydrogen peroxide solution (see Chapter 2.2.2).

In this way, a significant improvement of the thermal conductivity of the substrate to about $400 \text{W K}^{-1} \text{m}^{-1}$ can be achieved, in comparison to the thermal conductivity of GaAs which is about $46 \text{W K}^{-1} \text{m}^{-1}$ [73, 74, 75, 76].

## 5.2.2 QD-SESAM Design and Fabrication

The QD-SESAM was grown by MBE (see Chapter 2.1.1) on a GaAs substrate in the FIRST clean room facility at ETH Zurich. The structure was directly grown on the 650-µm thick GaAs substrate and directly used like this, without thinning the substrate.

The resonant QD-SESAM has a 30-pair DBR made of quarter wave pairs of AlAs and GaAs. The absorber section consists of a single InAs QD-layer embedded in GaAs. The QDs were grown using the Stranski-Krastanov growth method for self-assembled QDs.

The full structure design of this QD-SESAM can be found in Figure 5.10a. Figure 5.10b shows the simulated standing wave pattern in red and the refractive index profile in different colors for the different materials. Layers of GaAs are drawn in blue, AlAs is green, and QWs are black.

Using a nonlinear reflectivity measurement setup according to Chapter 3.1.2, we determined the modulation depth of this SESAM with 3.5%, non-saturable losses of smaller than 0.5% and a saturation fluence of 1.5 $\mu$J cm$^{-2}$. Pump-probe measurements of this samples resulted in a fast relaxation time component for this SESAM of about 500 fs (see Chapter 3.1.3 for more details).

## 5.2.3 Cavity Design

For the experiments we used a simple v-shaped laser cavity which is shown in Figure 5.11. The half opening angle of the laser with respect to the surface normal of the QW-VECSEL was about $10^\circ$. We used an
Figure 5.10: Semiconductor structure design of our QD-SESAM. Blue corresponds to layers of GaAs, green to AlAs and black is the QD-layer. (a) Schematic overview of the QD-SESAM structure. It was used directly on the substrate without thinning. (b) Plotted as a function of the device thickness are in colors, the refractive indexes $n$ of the layer materials, and in red the normalized field intensity $|E|^2$. Visible from left to right are the last few layers of the AlAs/GaAs DBR and the absorber region with the InAs QD-layer.

OC with a transmission of 0.5% and a ROC of 200 mm. We applied the pump light under an angle of 45° to the QD-VECSEL in a pump spot radius of about 150 µm.

Figure 5.11: Schematic overview of the QW-VECSEL cavity. The cavity consist of the OC, the QW-gain structure and the QD-SESAM. The pump light is applied to the VECSEL at an angle of 45°. The results are given in Table 5.5 and the measurement data is shown in Figure 5.12.

The distance between the SESAM and the VECSEL was chosen to be about 5 mm which resulted in almost identical laser mode radii on the SESAM and the VECSEL. We refer to this geometry as one-to-one modelocking [24] which is very well suited for further integration within a MIXSEL structure. According to our cavity simulations (see Chapter 3.2.1), the laser mode radii on the QW-VECSEL and on the QD-SESAM were about 148 µm.

### 5.2.4 Experimental Results

In the described cavity configuration we obtained a repetition rate of 5.4 GHz which corresponds to a cavity length of 27.8 mm. With a pump
power of about 7.0 W we could generate 553-fs pulses at an average output power of 40 mW. The measured spectral width of the pulses was 2.6 nm, centered at around 971 nm. This corresponds to a TBP of 0.47, or 1.5 times the transform limit of a sech²-pulse.

During this experiment we had to cool the heat sink to about −20 °C. The pulse fluence on the QD-SESAM amounted to 2.2 µJ cm⁻².

An overview of this and more data is listed in Table 5.5. The measurement traces of the optical spectrum (a), the RF spectrum (b) and the AC (c) for the shortest pulses we achieved are shown in Figure 5.12.

Figure 5.12: Measurements traces of the femtosecond result from the QW-VECSEL. (a) Optical spectrum with a center wavelength of 971 nm and a spectral width of 2.6 nm. (b) RF spectrum with a repetition rate of 5.4 GHz, a resolution bandwidth of 10 kHz and a span of 1 MHz. (c) Measurement (blue) and sech²-fit (red) AC trace showing a pulse duration of 553 fs. More details are presented in Table 5.5.

5.3 Modelocked Quantum-Dot VECSELs

5.3.1 QD-VECSEL Design

The QD-VECSEL gain structure (see Figure 5.13) we used for the experiments was grown by MBE (see Chapter 2.1.1) on a 450-nm GaAs substrate at Innolume GmbH. It consists of two DBRs based on pairs of quarter wave layers of AlAs and AlGaAs. We use Al₀.₂Ga₀.₈As instead of
Table 5.5: Overview of the results for the shortest pulses for the QW-VECSEL.

<table>
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<td>repetition rate $f_{rep}$ [GHz]</td>
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<td>center wavelength $\lambda$ [nm]</td>
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<td>spectral width $\Delta \lambda$ [nm]</td>
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<td>TBP</td>
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<td>TBP (multiples of sech$^2$)</td>
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<tr>
<td>SESAM parameters</td>
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<td>saturation fluence $F_{sat}$ [\mu J cm$^{-2}$]</td>
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<td>modulation depth $\Delta R$ [%]</td>
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</tr>
<tr>
<td>cavity half opening angle $\theta$ [°]</td>
<td>10</td>
</tr>
<tr>
<td>OC transmission $T$ [%]</td>
<td>0.5</td>
</tr>
<tr>
<td>OC ROC $r_{ROC}$ [mm]</td>
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</tr>
<tr>
<td>pump power $P_{pump}$ [W]</td>
<td>7.0</td>
</tr>
<tr>
<td>pump wavelength $\lambda$ [nm]</td>
<td>808</td>
</tr>
<tr>
<td>pump mode radius $r$ [\mu m]</td>
<td>150</td>
</tr>
<tr>
<td>pump angle $\theta$ [°]</td>
<td>45</td>
</tr>
<tr>
<td>heat sink temperature $T_s$ [°C]</td>
<td>-20</td>
</tr>
</tbody>
</table>
GaAs, although the refractive index contrast and therefore the reflectivity per DBR-pair is lower in comparison, in order to circumvent unwanted pump absorption in these DBRs.

Figure 5.13: Schematic overview of the QD-VECSEL structure. After growth the substrate thinned and the sample was soldered to a CVD diamond heat sink. The QD-VECSEL consist of two DBRs, one for the pump and one for the laser, an active region with seven groups of nine InAs QD-layers which were grown using the Stranski-Krastanov growth method, and a hybrid semiconductor/FS AR section (see Chapter 4.2).

The 15-pair DBR on the bottom of the structure was optimized to reflect the pump light at a wavelength of 808 nm (theoretical pump reflectivity more than 99 %), and the second 30-pair DBR to reflect the laser light at around 960 nm (theoretical reflectivity more than 99.9 %). We use an Al$_{0.2}$Ga$_{0.8}$As spacer layer between the two DBRs of which we adjust the thickness and therefore shift the standing wave pattern of the electric field of the pump without influencing that of the laser. With this approach we can use this layer to optimize the structure for a maximum pump absorption in the active region where we achieve more than 95 % of absorbed pump light.

After the two DBRs, the active region is grown. It mostly consists of GaAs, that serves as absorbing material for the pump radiation, in which seven groups of nine InAs QD-layers each are embedded. The QD-gain layers were grown using the Stranski-Krastanov growth method for self-assembled QDs. These groups of QD-layers are distributed within the active region according to the standing wave pattern of the electric field of the laser. However, the positions of the individual groups are all optimized for slightly different laser wavelengths, resulting in a chirped positioning scheme of the active QD-layers. The wavelengths we optimized the positions for are, in increments of 1.5 nm, 955.5 nm to 964.5 nm, with a design laser wavelength of 960 nm. In an additional step of optimization we calculated the spatially-resolved pump absorption in the active region and superimposed it with the chirped positioning of the groups of QD-layers. This results in a design of the active region where the specific group of QD-layers optimized for the designed center laser wavelength of 960 nm is optimally placed at the position in the active region.
which exhibits the highest pump absorption. Consecutively, the other QD-layer groups are optimally positioned at anti-nodes of the corresponding chirped laser wavelength, placing a QD-layer group with an optimization wavelength closer to the design wavelength in an area with higher pump absorption.

After the active region we directly grew the semiconductor part of our AR section and deposited a quarter wave layer of FS using PECVD (see Chapter 2.2.1) to complete the AR section. The top coating was necessary to reduce the GDD of the VECSEL and it was crucial to achieve the demonstrated results. Details on the AR section can be found in Chapter 4.2.

The full structure design of this QD-VECSEL can be found in Figure 5.13. Figure 5.14a shows the simulated standing wave pattern in red together with the refractive index profile in different colors for the different materials. Layers of GaAs are drawn in blue, AlAs in green, AlGaAs in gray, FS in pink and the QD-layers are black. A magnified view is given in Figure 5.14b, where the rightmost group of QD-layers from Figure 5.14a is shown.

![Index profile of the QD-VECSEL](image1)

(a) Index profile of the QD-VECSEL

![QD-VECSEL gain layers](image2)

(b) QD-VECSEL gain layers

Figure 5.14: Semiconductor structure design of our QD-VECSEL. Plotted as a function of the device thickness are in colors, the refractive index \( n \) of the materials, and in red the normalized field intensity \( \| E \|^2 \). Blue corresponds to GaAs, green to AlAs, gray to AlGaAs, pink to FS and the QD-layers are drawn in black. (a) From left to right the last few layers of the AlAs/GaAs DBR, the active region and the multilayer top coating according to Chapter 4.2. (b) Magnified view of the rightmost group of QD-layers from (a).

### 5.3.2 Fabrication of the QD-VECSEL

In order to obtain high average output power levels, it is crucial to optimize the thermal management [13]. Therefore, we used the thinned QD-
VECSEL structure on a chemical vapor deposition (CVD) diamond of 450-nm thickness \([72]\). This so-called flip-chip bonding is done by starting the structure growth from the GaAs wafer with an \(\text{Al}_{0.85}\text{Ga}_{0.15}\text{As} \) etch stop layer and then the actual QD-VECSEL structure is grown in reverse order. After that, the wafer can be cleaved, metalized and soldered to the CVD diamond and the substrate can be removed by selectively etching the GaAs substrate using a citric acid hydrogen peroxide solution (see Chapter \(2.2.2\)).

In this way, an optimal thermal conductivity of the heat sink of about \(1800 \text{W K}^{-1} \text{m}^{-1}\) can be reached \([77]\), which is a significant improvement over other standard heat sink materials such as Cu with \(400 \text{W K}^{-1} \text{m}^{-1}\) or GaAs with \(46 \text{W K}^{-1} \text{m}^{-1}\) \([73, 74, 75, 76]\).

### 5.3.3 QD-SESAM Design and Fabrication

The QD-SESAM was grown by MBE (see Chapter \(2.1.1\)) on a GaAs substrate in the FIRST clean room facility at ETH Zurich. The structure was directly grown on the 650-µm thick GaAs substrate and directly used like this, without thinning the substrate.

The anti-resonant QD-SESAM has a 30-pair DBR made of quarter wave pairs of AlAs and GaAs. The absorber section consists of a single InAs QD-layer embedded in GaAs. The semiconductor part of the structure is finished resonantly but there is an additional quarter wave layer of PECVD-deposited (see Chapter \(2.2.1\)) FS on top, which results in an anti-resonant QD-SESAM design. This top coating was necessary to reduce the GDD of the SESAM and it was an important part in achieving the demonstrated results. Details on this single layer AR section can be found in Chapter \(4.2\).

Pump-probe and nonlinear reflectivity measurements of this specific SESAM can be found in Figures \(3.3\) and \(3.2\), and the corresponding measurement parameters are listed in Tables \(3.5\) and \(3.3\), respectively.

The full structure design of this QD-SESAM can be found in Figure \(5.15a\). In Figure \(5.15b\), the simulated standing wave pattern is shown in red together with the refractive index profile in different colors for the different materials. Layers of GaAs are drawn in blue, AlAs in green, FS in pink and the QD-layers are black.
5.3.4 Cavity Design

For the experiments we used a simple v-shaped laser cavity which is shown in Figure 5.16. The half opening angle of the laser with respect to the surface normal of the QD-VECSEL was about 10°. We used an OC with a transmission of 2.5% and a ROC of 100 mm. We applied the pump light perpendicular to the QD-VECSEL in a pump spot radius of about 110 µm. The distance between the QD-SESAM and the QD-VECSEL was adjusted to about 3 mm. In this configuration we obtained close to identical mode sizes on both the SESAM and the VECSEL gain structure. We refer to this geometry as one-to-one modelocking [24] which is very well suited for further integration within a MIXSEL structure. According to our cavity simulations (see Chapter 3.2.1), the laser mode radii on the QD-VECSEL and on the QD-SESAM were 115 µm for the 5.4 GHz cavity and 119 µm for the 4.5 GHz cavity.

Figure 5.16: Schematic overview of the QD-VECSEL cavity. The cavity consist of the OC the QD-gain structure and the QD-SESAM. The pump light is applied perpendicular to the VECSEL. The results are given in Table 5.6 and the measurement data is shown in Figures 5.17 and 5.18.
5.3.5 Shortest Pulses from the QD-VECSEL

The cavity configuration with 4.5 GHz corresponds to a cavity length of 33.6 mm. With a pump power of about 3.2 W we could generate 416-fs pulses at an average output power of 143 mW. The measured spectral width of the pulses was 2.7 nm, centered at around 960 nm. This corresponds to a TBP of 0.36, or 1.13 times the transform limit of a sech^2-pulse. During this experiment we had to cool the heat sink to about −24 °C. The pulse fluence on the QD-SESAM amounted to 3.1 µJ cm\(^{-2}\).

An overview of this and more data is listed in Table 5.6. The measurement traces of the optical spectrum (a), the RF spectrum (b) and the AC (c) for the shortest pulses we achieved are shown in Figure 5.17.

![Figure 5.17: Shortest pulses from the femtosecond modelocking of the QD-VECSEL. (a) Optical spectrum with a center wavelength of 961 nm and a spectral width of 2.7 nm. (b) RF spectrum with a repetition rate of 4.5 GHz, a resolution bandwidth of 100 kHz and a span of 10 MHz. (c) Measurement (blue) and sech^2-fit (red) AC trace showing a pulse duration of 416 fs. More details are presented in Table 5.6.](image)

5.3.6 High Power Modelocking

In order to increase the output power, we moved the OC closer to the QD-VECSEL to prevent over-saturation of the QD-SESAM. The cavity length was therefore adjusted to 27.6 mm, resulting in a repetition rate of 5.4 GHz. We pumped the QD-VECSEL with a power of about 11.7 W
and we could observe 784-fs pulses with an average output power of 1.05 W.

During this experiment the heat sink temperature was about $-20^\circ\text{C}$. The pulse fluence on the QD-SESAM was 17.5 $\mu\text{J cm}^{-2}$.

An overview of this data with parameters for the SESAM and the cavity setup is listed in Table 5.6. The measurement for this result is shown in Figure 5.18, showing the optical spectrum (a), the RF spectrum (b) and the AC (c).

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Signal [a. u.]</th>
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</thead>
<tbody>
<tr>
<td>966</td>
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</tr>
<tr>
<td>968</td>
<td>0.80</td>
</tr>
<tr>
<td>970</td>
<td>0.60</td>
</tr>
<tr>
<td>972</td>
<td>0.40</td>
</tr>
<tr>
<td>974</td>
<td>0.20</td>
</tr>
<tr>
<td>976</td>
<td>0.00</td>
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</table>

(a) Optical spectrum

<table>
<thead>
<tr>
<th>Offset Frequency [MHz]</th>
<th>Signal [dBc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>-60</td>
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(b) RF spectrum

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<tr>
<td>0.2</td>
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<td>0.4</td>
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</tr>
<tr>
<td>0.6</td>
<td>0.40</td>
</tr>
<tr>
<td>0.8</td>
<td>0.20</td>
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<tr>
<td>1.0</td>
<td>0.00</td>
</tr>
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</table>

(c) Intensity AC

Figure 5.18: High power results of the femtosecond modelocking of the QD-VECSEL. (a) Optical spectrum with a center wavelength of 970 nm and a spectral width of 1.7 nm. (b) RF spectrum with a repetition rate of 5.4 GHz, a resolution bandwidth of 100 kHz and a span of 10 MHz. (c) Measurement (blue) and sech$^2$-fit (red) AC trace showing a pulse duration of 784 fs. More details are presented in Table 5.6.

### 5.3.7 Overview of the Results

Table 5.6 lists all results from Chapters 5.3.5 and 5.3.6. The high power results are, to our knowledge, the only results of a femtosecond modelocked VECSEL with an output power of more than 1 W.
<table>
<thead>
<tr>
<th>parameter</th>
<th>high power</th>
<th>shortest pulses</th>
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<tbody>
<tr>
<td>pulse duration $\tau_p$ [fs]</td>
<td>784</td>
<td>416</td>
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<tr>
<td>average output power $P_{\text{avg}}$ [W]</td>
<td>1.05</td>
<td>0.143</td>
</tr>
<tr>
<td>repetition rate $f_{\text{rep}}$ [GHz]</td>
<td>5.4</td>
<td>4.5</td>
</tr>
<tr>
<td>center wavelength $\lambda$ [nm]</td>
<td>970</td>
<td>961</td>
</tr>
<tr>
<td>spectral width $\Delta \lambda$ [nm]</td>
<td>1.7</td>
<td>2.7</td>
</tr>
<tr>
<td>TBP</td>
<td>0.43</td>
<td>0.36</td>
</tr>
<tr>
<td>TBP (multiples of sech$^2$)</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### SESAM parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>high power</th>
<th>shortest pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>saturation fluence $F_{\text{sat}}$ [µJ cm$^{-2}$]</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>modulation depth $\Delta R$ [%]</td>
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<td>1.2</td>
</tr>
<tr>
<td>non-saturable losses $\Delta R_{\text{ns}}$ [%]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>fast relaxation $\tau_f$ [fs]</td>
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<td>460</td>
</tr>
<tr>
<td>slow relaxation $\tau_s$ [ps]</td>
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### Pulse parameters

<table>
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<th>shortest pulses</th>
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<tbody>
<tr>
<td>beam radius on SESAM $r$ [µm]</td>
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<td>115</td>
</tr>
<tr>
<td>beam radius on VECSEL $r$ [µm]</td>
<td>119</td>
<td>115</td>
</tr>
<tr>
<td>fluence on SESAM $F_p$ [µJ cm$^{-2}$]</td>
<td>17.5</td>
<td>3.1</td>
</tr>
<tr>
<td>fluence on VECSEL $F_p$ [µJ cm$^{-2}$]</td>
<td>17.5</td>
<td>3.1</td>
</tr>
<tr>
<td>saturation parameter $s$</td>
<td>4.6</td>
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<td>pulse energy $E_p$ [pJ]</td>
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<td>32</td>
</tr>
<tr>
<td>peak power $P_{\text{peak}}$ [W]</td>
<td>218</td>
<td>67</td>
</tr>
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</table>

### Setup parameters

<table>
<thead>
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<th>parameter</th>
<th>high power</th>
<th>shortest pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity length $L$ [mm]</td>
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<td>33.6</td>
</tr>
<tr>
<td>cavity half opening angle $\theta$ [°]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>OC transmission $T$ [%]</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>OC ROC $r_{\text{ROC}}$ [mm]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>pump power $P_{\text{pump}}$ [W]</td>
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<td>3.2</td>
</tr>
<tr>
<td>pump wavelength $\lambda$ [nm]</td>
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<td>808</td>
</tr>
<tr>
<td>pump mode radius $r$ [µm]</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>pump angle $\theta$ [°]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>heat sink temperature $T_s$ [°C]</td>
<td>−20</td>
<td>−24</td>
</tr>
</tbody>
</table>

Table 5.6: Overview of the results for the shortest pulses and the shortest pulses with more than one watt for the QD-VECSEL.
5.4 Conclusion and Outlook

In this chapter we demonstrated femtosecond pulses at unprecedented power levels from SESAM-modelocked VECSELs. We obtained a pulse duration of about 780 fs at an average output level of 1 W. This set a new milestone for femtosecond VECSELs in terms of output power (see Table 5.1).

Before we published this result [30], the highest output power in the femtosecond regime was limited to 120 mW with a pulse duration of 330 fs [67]. Except for the 45-mW result with 870-fs pulses where a QD-SESAM was used as the modelocking element [63], the femtosecond regime of ultrashort VECSELs was completely dominated by Stark-modelocked and fast saturable absorber modelocked VECSELs. In our new results, we do not rely on these modelocking techniques.

We realized these results through a number of steps, finally leading to the results that were presented in Chapter 5.3:

GDD study We made an extensive study of the influence of intra-cavity GDD on the pulse duration of SESAM-modelocked VECSELs (see Chapter 5.1).

- We developed a novel type of GTI based on a hybrid semiconductor/dielectric AR section (see Chapter 4.1), offering
  - a large range of GDD from $-7000 \text{ fs}^2$ to $9000 \text{ fs}^2$,
  - cost-efficient and accurately-controllable fabrication using PECVD (see Chapter 2.2.1).
- We could prove experimentally that the modelocking scheme of SESAM-modelocked VECSELs is the quasi-soliton pulse buildup mechanism.
  - Positive GDD is required to compensate for the phase shift which results from gain and absorber saturation.
  - This effect is similar to soliton modelocking, however the required phase shift, and thus the sign of the GDD, is opposite.
- We could observe that positive values for the GDD have a significantly reduced influence on the pulse lengthening.
  - This relaxes the demands on the growth accuracy if the devices are designed accordingly.
GDD values around $0\text{fs}^2$ result in the shortest possible pulses.

Low-GDD AR section Based on the results we obtained from the study of intra-cavity GDD, we started to investigate on ultra-low GDD coatings for our VECSELs and our SESAMs (see Chapter 4.2).

- We developed a hybrid semiconductor/dielectric top coating for SESAMs and VECSELs.
- We reduced the GDD of our VECSEL structure by a factor of 1000.

VECSEL design We designed a QD-VECSEL structure for the generation of ultrashort pulses, with

- two separate DBRs, one each for the pump and the laser, with
  - more accurately controllable standing wave pattern of the laser,
  - individual tuning of the pump absorption in the active region,
  - higher efficiency,
- an optimized active region with,
  - a chirped positioning scheme of the active layers,
  - the chirping scheme is weighted, depending on the pump absorption in the active region,
- an ultra-low GDD AR section,
- a CVD diamond heat sink.

5.4.1 QD gain vs. QW gain

Although we did laser experiments with both QD-based gain layers and QW-based gain layers, even using VECSELs with very similar structural designs (see Figures 5.8 and 5.13), we did not have enough conclusive measurement data, especially for the QW-based VECSEL, to clearly point out differences between the two. A more detailed comparison is necessary to drawn clear conclusion.
Proposed Future Measurements

Important future measurements could be the determination of the gain saturation fluence of both QW and QD-based VECSELs. Similar to QW and QD-based SESAMs, this gain saturation should alter for the two, enabling a new degree of freedom for the design of QD-VECSELs. An adapted measurement setup as described in Chapter 3.1.2 could be used.

Also the difference in relaxation time dependence between the two gain layers types could provide useful information. This part could be measured with a setup similar to the one described in Chapter 3.1.3. Since QDs should exhibit a longer relaxation time in comparison with QWs, longer cavity should be feasible without the problem of multipulsing, potentially enabling much higher pulse energies than QW-based VECSELs can achieve. This behavior also needs to be studies in a series of low repetition rate experiments, comparing QD-VECSEL and QW-VECSEL performances.

Temperature Stability

In terms of temperature stability, where QDs should be superior to QWs [78], we could already obtain initial measurement results for our structures. According to Equation 3.18, absorption leads to a phase shift, which should result in a measurable change in GDD.

For both the QD-VECSEL and the QW-VECSEL, we measured the GDD as a function of the wavelength. Although both VECSELs had a low-GDD coating (see Chapter 4.2), there was a significant peak in the GDD. It is important to note that this peak is not the intrinsic structural GDD but the obtained GDD resulting from the absorption of the measurement beam (see Chapter 3.1.4 for details on the measurement scheme). In Figure 5.19, we plotted the results for both VECSEL for heat sink temperatures of 10°C, 20°C, 25°C, 30°C, 40°C, 50°C, 60°C, and 70°C, where blue corresponds to lower temperatures and green to higher temperatures.

We can see that there is a significant shift of this GDD peak with the temperature. Since the field enhancement of both structures is almost constant over a large wavelength range, this shift results from the shift of the absorption and not from the temperature-dependent refractive index change (dn/dT) of the structure. The absorption for these VECSEL structures is given by the band gap of the active layers, i.e. the QWs and the QD-layer, respectively. However, the band gap also determines the photoluminescence (PL). Therefore, we can interpret these
measurements of the wavelength shift of the GDD as measurements of the temperature shift of the PL peak.

For a temperature increase from 10 °C to 70 °C, the wavelength shifts for the QD-VECSEL and the QW-VECSEL are 17.1 nm and 20.3 nm, respectively. Although the wavelength shift for the QDs is smaller in comparison to the QWs, a significantly smaller shift would be expected for perfect single-state QDs.

Other groups [79] have reported a difference in the temperature shift of the gain of a factor of ten between QDs and QWs. However, the characteristics of the dots in Reference [79] was quite different. They used colloidal QDs with QD sizes smaller than 10 nm and a size variation of less than 5%. These sizes are within the boundaries where high quality single-state QDs are estimated. According to Reference [80], these boundaries state upper limits for the size of the QDs of 120 Å and 200 Å for GaAs/AlGaAs and InAs/GaAs QDs, respectively.

The QDs we use, however, were grown using the Stranski-Krastanov growth method for self-assembled QDs [35]. This growth mode does not produce single-state QDs, but relatively large QDs with a size distribution and a variation of the material composition of the QDs. This, for instance, leads to inhomogeneous broadening [28].

Figure 5.20 shows atomic force microscope (AFM) images of QDs we grew with our MBE using the Stranski-Krastanov growth mode. Al-

Figure 5.19: In these measurements we show the measured GDD as a function of the wavelength for temperature of 10 °C, 20 °C, 25 °C, 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C, where blue corresponds to lower temperatures and green to higher temperatures. The measured GDD is not the structural GDD but the one resulting from the absorption of the measurement beam of the measurement setup. (a) Measurement of the QD-VECSEL with a wavelength shift of 17.1 nm. (b) Measurement of the QW-VECSEL with a wavelength shift of 20.3 nm.
though these QDs were used in a SESAM, the size distribution should be very similar to the QDs we used in the QD-VECSEL. Figure 5.20a shows an AFM image of a section with an area of 2 µm × 2 µm, and in Figure 5.20b we plot a magnified view of only 500 nm × 500 nm.

![AFM images](image)

(a) 2 µm × 2 µm  
(b) 500 nm × 500 nm

Figure 5.20: Typical AFM measurements of MBE-grown self-assembled QDs using the Stranski-Krastanov growth mode. The QD sizes are in the order of 50 nm in diameter.

We can see that the QDs are considerably larger than the aforementioned upper limit of 200 Å for single-state InAs/GaAs QDs. We believe that this is the reason for the similar temperature dependence of the QD-VECSEL to the QW-VECSEL (see Figure 5.19).

Nevertheless, these QDs constitute a key step in the development of the MIXSEL, where their low saturation fluence is essential for the vertical integration [24]. A proper development of QDs could even lead to a combination of the gain characteristic of QDs and QWs, where a QW-like high gain is combined with the inhomogeneously broadened spectral component from QDs.

### 5.4.2 Further Improvements

The limiting factor for the high power femtosecond result presented in Chapter 5.3.6 was a strong saturation of the SESAM. It was necessary to shorten the cavity length, resulting in an increased repetition rate and thus a reduced pulse energy, to obtain stable modelocking. Nevertheless, we obtained a saturation parameter $s$ of 4.6 (see Table 5.6). A first step to improve this result is to use a SESAM with a larger saturation fluence. This will enable to use higher pump powers before an over saturation
of the SESAM occurs, and will thus result in a higher average output power in the femtosecond regime. This can also be useful to only operate the SESAM at a lower saturation parameter $s$, which typically results in slightly shorter pulses.

Other possible improvement is the optimization of the GDD of the SESAM. According to Figure 5.15, the SESAM we used to achieve both the 1 W of output power in 784 fs, and also the 143 mW at 416 fs, merely had a single layer of FS as top coating. By using a similar coating to the one we used for the QD-VECSEL (see Figure 5.14a), both results could be improved and shorter pulses could be obtained.

Another important discovery was obtained during the measurements shown in Figure 5.19, where we measured the GDD of our low-GDD VECSELs. In contrast to our design of the QD-VECSEL (see Figure 4.6a), the measurement shows a peak in the GDD. Disregarding the temperature shift, the amplitude of the obtained GDD peaks is quite large. Therefore, since the measured GDD in this case is dependent on the absorption, this could lead to variations of the GDD which depend on the instantaneous operation parameters of the VECSEL. Changing the pump power, for instance, could result in a change of the GDD.

If we look at a simulation of the pulse duration as a function of the GDD in the femtosecond regime (see Figure 5.21), a change of the GDD from $0 \text{ fs}^2$ to $-200 \text{ fs}^2$ can already lead to pulses longer than 1 ps. However, the measured absolute absorption-dependent GDD is larger than these $-200 \text{ fs}^2$. Thus, it is possible that the pulse duration changes considerably with changing operation conditions.

Figure 5.21: Simulation of the pulse duration as a function of the intra-cavity GDD. We used a gain bandwidth of 60 nm, which is in good agreement with measured values [81].

This shows, that a good understanding is required to be able to circumvent these effects, or to exploit them for the generation of possibly even shorter pulses.

One potential application where this knowledge would be useful is the generation of real solitons from modelocked VECSELs. In this modelocking regime, pulse formation would not strongly depend on the used
SESAM anymore, and other known techniques for the pulse shortening are usable.

### 5.4.3 MIXSEL Integration

Since the spot sizes for both experiments, using the QW-based VECSEL and the QD-based VECSEL, the spot sizes on the gain element and the SESAM were almost identical, the integration of similar structures into a MIXSEL structure is the clear next step.

But applying a top coating according to Chapter 4.2, it should be possible to fabricate MIXSELs that support the generation of femtosecond pulses. In combination with the excellent power scaling properties that are intrinsic to the MIXSEL platform, an average output power of several watts in the femtosecond regime should be feasible. By further scaling up the pulse energy of these multi-watt femtosecond pulses by reducing the repetition rate, the generation of carrier envelope offset (CEO) stabilized frequency combs should be straight forward.

### 5.4.4 Frequency Comb Generation

The generation of frequency combs using passively modelocked femtosecond lasers provides a phase-stable link between microwave frequencies and optical frequencies [82, 83, 84]. The resulting wavelength precision can be used for applications such as metrology or spectroscopy [83, 85].

The employment of frequency combs generated by optically pumped VECSELs or MIXSELs could be very promising for such applications, because the high repetition rate of these lasers results in a higher power per mode. This is caused by the wider mode spacing $\Delta \nu$ of the longitudinal modes of the cavity, which is given by

$$\Delta \nu = \frac{c}{2L} = f_{\text{rep}}, \quad (5.2)$$

where $c$ is the speed of light, $L$ the length of the cavity and $f_{\text{rep}}$ the repetition rate.

In order to obtain a frequency comb, two main requirement have to be fulfill. They pulses of the driving modelocked laser need to have

- sufficiently high pulse peak power, and
- a sufficiently short pulse duration.
It is important to note, that both of these demands have to be met at the same time, and that an overabundance of one cannot compensate for the lack of the other.

The reason is that the high pulse peak power is necessary for the generation of the octave-spanning spectrum which is usually obtained in a highly nonlinear fiber, and the short pulses are required to sustain the coherence of this supercontinuum [86, 87].

In Reference [88], a SESAM-modelocked Er:Yt:glass laser was used for the generation of a frequency comb. It delivered 170-fs pulses at a repetition rate of 75 MHz and an average output power of 110 mW. In this work, it was shown that a CEO beat signal with a signal to noise ratio of more than 30 dB could be obtained for many different values for the pulse duration of the modelocked laser source. This is illustrated in Figure 5.22, where the CEO beat is shown for a range of pulse durations, ranging from 188 fs (dark blue) to 261 fs (dark red). The pulse duration was altered by adjusting the pump power.

These results demonstrate that a CEO beat signal with sufficient intensity for active stabilization (30 dB) can be generated even with pulses of 260 fs duration.

Figure 5.22: By varying the pump intensity (differently colored curves) the pulse duration of an Er:Yt:glass laser is changed from 188 fs (dark blue) to 261 fs (dark red). For all pulse durations a clear and stable CEO beat is visible. The rightmost peak corresponds to the repetition rate of the laser.
Such pulse durations, however, have already been achieved using optically pumped VECSELs [66, 64, 68, 18]. This means, that, in principle, frequency generation from modelocked VECSELs or MIXSELs should be possible. However, due to the limited output power of up to 25 mW in these results, the peak power was not sufficient to obtain the octave spanning spectrum. Additionally, the availability of highly nonlinear fibers in the wavelength range around 1 µm is by far not as good as for the 1.5 µm wavelength region. Nevertheless, we believe that by further improving the performance of modelocked optically pumped VECSELs we presented in this thesis, it should be possible to obtain a CEO stabilized frequency comb generated by a SESAM-modelocked VECSEL or MIXSEL. The improvement of fibers should help in this task and it will most likely further relax the constraints on the required pulse duration.
Chapter 6

Electrically Pumped VECSELs

In Chapter 5, we presented our results of SESAM-modelocked optically pumped VECSELs. We could demonstrate the first femtosecond pulses with an average output power exceeding 1 W. These novel results emphasize the potential of the external cavity in combination with the semiconductor gain material, i.e. the VECSEL geometry.

Nevertheless, a major improvement to these devices in terms of packaging effort is the realization of electrical pumping. In developing this approach, we hope to extend the success story of optically pumped modelocked VECSELs, possibly leading to an industrial adoption of this technology.

However, to realize such an endeavor, first, basic challenges of the electrical pumping scheme have to be explored, understood and finally overcome. We took the first steps already, and we will present an extensive characterization of our devices and laser results from our CW experiments.

Electrical pumping of VECSELs has been demonstrated before and we list an overview in Table 6.1. So far, mostly companies have done research on electrically pumped VECSELs [31, 32]. This again shows the strong interest in this technology. The first demonstration was realized with the NECSEL from Novalux, Inc. [31], where direct electrical pumping was used. OSRAM GmbH chose a different approach, where already known technologies from edge-emitting laser diodes and VECSELs could be combined by integrating an electrically-driven optical
pumping scheme in their design \[32\]. In contrast to these two results at an emission wavelength of around 1 µm, the feasibility of electrical pumping at 1.55 µm could also be demonstrated \[33\]. In contrast to the structure designs introduced in these results, our design was conceptualized for modelocked operation \[34\]. In our first experiments in CW operation, we obtained up to 120 mW. The corresponding measurement data for all demonstrated results is listed in Table 6.1.

<table>
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<tr>
<th>wavelength λ [nm]</th>
<th>multi-mode power $P_{\text{avg}}$ [mW]</th>
<th>TEM00 power $P_{\text{avg}}$ [mW]</th>
<th>reference</th>
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<td>500</td>
<td>[31]</td>
</tr>
<tr>
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<td>n. a.</td>
<td>[32]</td>
</tr>
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<td>n. a.</td>
<td>[33]</td>
</tr>
<tr>
<td>970</td>
<td>120</td>
<td>10</td>
<td>[34]</td>
</tr>
</tbody>
</table>

Table 6.1: Overview of published results on electrically pumped VECSELs.

In this chapter, we will present general considerations that are required for electrical pumping, the fabrication of the devices, CW results, and the characterization of beam quality, electrical properties and power scaling.

### 6.1 General Design Guidelines

Based on previously published guidelines on the design of electrically pumped VECSELs, which were identified in a collaboration \[89\], we developed a design that is specifically suitable for modelocking. Some general consideration and a detailed overview of the design will be discussed in this section.

#### 6.1.1 Balance Between Optical and Electrical Properties

One of the key requirements for an electrically pumped VECSEL is a good balance between electrical and optical properties. As opposed to optically pumped VECSELs, electrical pumping necessitates electrical current to flow through the VECSEL. This is achieved by doping the semiconductor structure, where a lower device resistance is obtained for higher doping levels. Therefore, because of lower resistive heating which results from a larger free carrier density for a highly-doped device, the temperature increase of the device is less pronounced, augmenting the performance of the device. However, an increased free carrier density
consequently increases the optical losses within such a structure due to free carrier absorption (FCA). For too high doping levels, such a device cannot operate as a laser anymore, since the equality of gain and loss is not fulfilled anymore because the losses are too high. Thus lower doping levels are necessary to reduce the optical losses which in return increases the electrical resistance and thus resistive heating. It is clear that a good balance between the oppositional optical and electrical properties has to be found.

Even if the optimal doping level has been found, due to the presence of doping in general, the total cavity losses will always be significantly higher in comparison to optically pumped VECSELs. In order to compensate for that, the gain has to be increased. In our case, we introduce an additional DBR in our structure, which results in a resonance of the standing wave pattern of the laser in the active region. Therefore, the overall gain is increased by increasing the field enhancement $\Gamma$ at the positions $z$ of the QWs. This can be described by the power reflectivity coefficient $G$ which relates the input power $P_{\text{in}}$ to the output power $P_{\text{out}}$ by

$$P_{\text{out}} = GP_{\text{in}}. \quad (6.1)$$

This power reflectivity coefficient $G$ can be expressed by

$$G (\lambda) = 1 + N_{\text{QW}} \Gamma (\lambda) g (\lambda, N) n_{\text{real}} d_{\text{QW}}, \quad (6.2)$$

where $N_{\text{QW}}$ is the number of QWs, $g$ the intrinsic QW gain, $N$ the carrier density, $d_{\text{QW}}$ the thickness of the QWs, $n_{\text{real}}$ the real part of the refractive index and $\Gamma$ can be described by

$$\Gamma = \frac{1}{N_{\text{QW}}} \sum_{QWs} |\mathcal{E}(z)|^2, \quad (6.3)$$

with $\mathcal{E}$ the electric field strength.

Another way to increase the gain is to increase the number of QWs $N_{\text{QW}}$. However, since our active region is undoped, increasing the thickness of the active region so that more QWs can be placed at anti-node positions of the standing wave pattern of the laser field results in a strong increase in electrical resistance with the thickness of the active region. Also in this case an optimum has to be found where high enough optical gain is achieved with sufficiently low electrical resistance.
6.1.2 Current Confinement

Another important feature an electrically pumped VECSEL design must exhibit is an adapted carrier injection profile in the active region. It is very beneficial if the largest pump injection occurs in the center of the device instead of at the sides. If modelocked operation is desired, the injection profile needs to be as close to a Gaussian shape as possible. Otherwise, the laser might operate in several transverse modes, prohibiting modelocked operation because of instabilities resulting from the transversal mode beating. Since the electrically pumped VECSEL should be power scalable, where the scaling of the power is achieved by scaling up the pumped area of the device, current injection with sufficient homogeneity has to be guaranteed over the entire pumped surface. Due to the physical design of the contacts, where the top contact needs to have a ring shape forming a circular aperture through which the laser light can exit the device, this turns out to be quite difficult for large device diameters.

Our goal is to modelock an electrically pumped VECSEL, and we therefore need to achieve an excellent electrical current injection in the active region. As proposed in Reference [89], we use a p-doped bottom DBR, although the mobility of holes is much lower compared to that of electrons, which unfortunately results in a significantly higher electrical resistance of this mirror. We nevertheless choose this approach, because this lower mobility also leads to nearly no lateral carrier spread of the holes. Therefore, we obtain a quasi one-dimensional flow of holes, generating an injection profile in the active region that almost mimics the shape of the bottom contact. Thus, if the bottom contact is chosen to be in the middle of the device and rather small, a good current injection can be achieved (see Reference [89]). If this approach is combined with a current spreading layer in the n-doped region, the high-mobility electrons injected from the top electrode follow the potential given by the holes, recombining with them in the active region resulting in an injection profile that should support modelocking.

To evaluate the injection profile for the two kinds of doping for the bottom mirror, we made a general comparison of the electrical properties of a p-doped and an n-doped DBR. The structure we used for these simulations consisted of a p-doped (n-doped) 30-pair bottom mirror of quarter wave layers of GaAs/AlAs with a p-doping (n-doping) level of $2 \times 10^{18}$ cm$^{-3}$, an undoped active region and an n-doped (p-doped) GaAs current spreading layer with a thickness of 2 µm and a doping level
of \(2 \times 10^{18} \text{ cm}^{-3}\). The device geometry (see also Chapter 6.2.1 for a comparison with our actual design) we used for this simulation is a bottom contact diameter of 80 µm and 300 µm for the top contact. The lateral carrier density distribution for this device is plotted in Figure 6.1a. The blue curve corresponds to a p-doped bottom DBR and the green to an n-doped DBR.

![Carrier distributions for n and p-doping](image1.png)

(a) Carrier distributions for n and p-doping

![IV-curves for n and p-doping](image2.png)

(b) IV-curves for n and p-doping

Figure 6.1: Comparison of n and p-doping for the bottom DBR for a device with a bottom contact diameter of 80 µm and 300 µm for the top contact, and a 2 µm thick current spreading layer. The p and n-doping level for the full structure and for both doping schemes is \(2 \times 10^{18} \text{ cm}^{-3}\). (a) Carrier density distribution within the device. The p-doped mirror has a significantly better current injection in the center of the device. (b) The corresponding IV curves show a reduced electrical performance of the p-doped DBR.

We can clearly see that the injection profile is significantly better for a p-doped bottom DBR since it is much closer to a Gaussian shape. The small peaks at around 150 µm originate from the top contact, which has a radius of 150 µm, and the fact that the current spreading layer is only 2 µm (see the comparison for different current spreading layers in Chapter 6.2.1).

Despite the large advantages of the p-doped bottom DBR with respect to the beam profile, in terms of device resistance its performance is reduced. As expected, in comparison to an n-doped bottom mirror a higher voltage is required to obtain a given, indicating a higher electrical resistance. This is illustrated in Figure 6.1b, where the simulated current-voltage (IV) curves that correspond to the simulations of Figure 6.1a are plotted.
6.2 Our Realized EP-VECSELs

6.2.1 Design Overview

After the careful evaluation of the theoretical considerations from Chapter 6.1, we developed the design for an electrically pumped VECSEL shown in Figure 6.2. The semiconductor part of the structure consists of a p-doped DBR as the HR of the VECSEL, on top of that is the undoped active region, an n-doped intermediate DBR to increase the field enhancement in the active region, a current spreading layer to obtain a good injection profile in the active region and an AR section to reduce reflections from the semiconductor/air interface, which would introduce a strong spectral filter. The current is injected through contacts on the top and on the bottom of the device, indicated as a ring contact with a contact pad for the top, and a disk for the bottom.

In the following section we will discuss the mentioned semiconductor elements of our device from the bottom to the top according to Figure 6.2. After this, the carrier wafer, the device geometry and the fabrication scheme are introduced. In the following Figures of this section, we tried to keep a consistent color profile for the used materials and doping levels. Except for Figure 6.3, which will be described in the following section, a green color corresponds to AlAs, blue to GaAs, grey to AlGaAs and black to QWs. If the materials are doped, the color tone is lighter for p-doping and darker for n-doping.

Bottom Contact Layer and p-Doped Mirror

The p-doped DBR we implemented in our electrically pumped VECSEL design (see Figure 6.2) was grown on top of a highly p-doped contact layer made of GaAs with a doping level of $3 \times 10^{19}$ cm$^{-3}$, and it has 30 pairs of quarter wave layers of AlAs and GaAs. According to the simulated standing wave pattern of the laser field (see Chapter 3.2.1 for more information on the simulation), regions where the field enhancement of the laser is lower were doped with a higher concentration compared to where the field is higher. Starting from the bottom, we use p-doping levels $N_a$ of $(5, 4, 3, 2) \times 10^{18}$ cm$^{-3}$ for the DBR pairs 1–15, 16–20, 21–25, and 26–30, respectively. This is illustrated in Figure 6.3, where a more saturated tone of red and blue corresponds to a higher p-doping and n-doping, respectively. These different doping levels result in a lower electrical resistance of the electrically pumped VECSEL in comparison to a constant doping level of $2 \times 10^{18}$ cm$^{-3}$. The increase of the optical
Figure 6.2: Schematic overview of the design of our electrically pumped VECSEL. Starting from the bottom, the bottom disk contact (yellow) is surrounded with an isolation layer (gray), followed by the 30-pair p-doped bottom DBR, the undoped active region with two times three QWs, the 11-pair n-doped DBR, the current spreading layer, an isolation layer on top of that together with a ring electrode, and a mesa structure which is the AR section of the device. The bottom (top) contact layer which is located between the p-doped DBR and the bottom contact (between the current spreading layer and the top contact) is not shown in this figure.
losses through FCA are not significant because of the relatively low field enhancement in these higher doped regions. This means for instance that since the electrical field is quite low in the bottom part of this p-doped DBR, the higher doping does not significantly increase the overall optical losses through FCA.

Figure 6.3: Electric field pattern (red line), the doping levels (background color and notation on top) and refractive index profiles (black line) of the entire structure of the electrically pumped VECSEL. The bottom DBR is shown in red and is p-doped. Its doping profile is adapted to the field intensity within the structure, where the darker red parts have a higher p-doping level than less lighter red parts. The p-doping levels range from $5 \times 10^{18}$ cm$^{-3}$ (darkest red) to $2 \times 10^{18}$ cm$^{-3}$ (lightest red). The blue parts correspond to the n-doped section of the device. The intermediate DBR and the current spreading layer are n-doped with $2 \times 10^{18}$ cm$^{-3}$ (light blue) and the contact layer is n-doped with $5.5 \times 10^{18}$ cm$^{-3}$ (light blue). The active region and the AR section are not doped (light gray). The 100 nm thick p-doped bottom contact layer is left of the p-doped DBR and has a doping level of $3 \times 10^{19}$ cm$^{-3}$.

In addition to the different doping levels within the p-doped DBR, we wanted to improve the electrical properties of the bottom mirror further. By using a mole fraction grading between the two different materials GaAs and AlAs for the DBR, not only the resistance is further reduced, but also the thermal conductivity is increased [90]. By smoothening the valence band discontinuity at the interface of the two materials, both the phonon barrier and the electronic tunnel barrier are reduced. This leads to improved thermal and electrical properties. We realized this grading by utilizing a 16-nm thick band gap grading in five discrete Al$_x$Ga$_{1-x}$As layers of intermediate composition with $x \in \{0.19, 0.44, 0.51, 0.6, 0.81\}$.
Active Region

For our active region we use two groups of three QWs each. These QWs are 8 nm thick and consist of InGaAs. They are embedded in 10-nm thick layers of GaAs and positioned according to the standing wave pattern of the electric field of the laser. This is indicated in Figure 6.5, where on the left the p-doped bottom DBR (light colors) is illustrated, the active region (intermediate colors) with the two times three QWs, and on the right the p-doped intermediate DBR (dark colors).

Figure 6.5: Illustration of the design of our active region using the material refractive indexes $n$. The active region (intermediately colored) is sandwiched between the (lightly colored) p-doped bottom DBR and the (darkly colored) n-doped intermediate DBR (see also Figure 6.2). The active region consists of two times three InGaAs QWs. Plotted in red is the standing wave pattern of the electric field, divided by 25. The strong resonance is due to the intermediate DBR.

The active region is undoped and sandwiched between the p-doped bottom DBR and the n-doped intermediate DBR (see also Figure 6.2).

Since the electrically pumped VECSEL is designed for a center wavelength of about 965 nm and an internal operation temperature of roughly 100 °C when it is pumped at high currents, the maximum of the amplification spectrum has to be adapted to overlap with the device resonance wavelength of 965 nm at the operation temperature. To achieve this, we used a room temperature detuning of the PL peak with respect to the design wavelength of the laser of 25 nm towards shorter wavelengths. We based this values on well-known values for the temperature-dependent gain peak shift of about 0.3 nm K$^{-1}$ [91, 92]. This results in a peak of
the electroluminescence (EL) which is very close to the cavity resonance if the device is pumped electrically and the operation temperature is reached.

**n-Doped Mirror, Current Spreading Layer and Top Contact Layer**

For the n-doped DBR, as opposed to the p-doped DBR, we chose a constant doping concentration and also no AlGaAs grading between the individual layers of GaAs and AlAs. The reason is the significantly lower resistance of n-doped material in comparison to p-doped material. This was discussed in detail in Reference [89].

We chose 11 pairs of quarter wave layers of GaAs and AlAs and we n-doped it with a constant doping level $N_d$ of $2 \times 10^{18}$ cm$^{-3}$. This intermediate n-doped DBR is necessary to enhance the gain of the device and therefore compensate for the losses that result from FCA. This is explained in detail in Reference [89]. With these 11 pairs for the intermediate DBR, we achieve an internal reflectivity of about 92.5%. In Figure 6.6, we simulated the field enhancement in the active region (blue) and the reflectivity (green) of this intermediate n-doped DBR as a function of the number of GaAs/AlAs pairs. Details on the simulation can be found in Chapter 3.2.1.

Figure 6.6: As a function of the number of GaAs/AlAs pairs of the intermediate n-doped DBR, the field enhancement inside the active region and the reflectivity of this DBR are plotted in blue and green, respectively.

On top of the n-doped intermediate DBR we have a GaAs current spreading layer. It is also n-doped with a doping level of $2 \times 10^{18}$ cm$^{-3}$.

To allow for the electrons to move to the center of the device, the current spreading layer needs to have a certain thickness. Only then is it possible to obtain an injection profile similar to a Gaussian. Using our electro-opto-thermal model [89], we calculated the expected carrier density $N$ within our electrically pumped VECSELs. Figure 6.7, the simulated carrier density is plotted for current spreading layer thicknesses of 2 µm (blue), 6 µm (black) and 50 µm (green) as a function of the distance from the rotation axis of the device with a bottom (top) contact
Chapter 6. Electrically Pumped VECSELs

The diameter of 80 µm (300 µm) (see also Table 6.2).

**Figure 6.7:** The carrier density $N$ is plotted for an electrically pumped VECSEL with a bottom (top) contact diameter of 80 µm (300 µm) for current spreading layer thicknesses of 2 µm (blue), 6 µm (black) and 50 µm (green) as a function of the distance from the center of the device.

From these simulations, there still is an improvement of the injection profile for a thickness change from 2 µm to 6 µm, since the carrier density is higher at the center of the device and thus more similar to a Gaussian. Further increasing the thickness does not improve the carrier distribution anymore. We therefore chose a thickness of 6.1 µm for our current spreading layer.

On top of the current spreading layer is a highly doped contact layer to which we apply our top metalization. This layer is necessary to form an ohmic contact from the metal to the semiconductor. It consists of highly n-doped GaAs with a doping level of $5.5 \times 10^{18}$ cm$^{-3}$ and has a thickness of 150 nm.

**AR Section**

The AR section (see Figure 6.8) we use for our electrically pumped VECSEL is an undoped system of 14 layers of AlAs and GaAs. According to Figure 6.2 we etch the AR section and metalize the highly doped contact layer to obtain our top contact. After etching we protect the sidewalls of the AR mesa against oxidation by depositing a layer of SiN$_x$ (see Chapter 2.2.1). This is important since AlAs is very susceptible to the O$_2$ in air and thus, these layers can easily degrade in air. This protective layer of SiN$_x$ is also indicated in gray in Figure 6.2 surrounding the AR mesa.

The AR section is required to reduce Fresnel reflection at the interface between air and the contact layer. Because of the large refractive index step of about $\Delta n = 2.54$ between these two materials, this reflection would be very strong. We want to reduce this reflection, because otherwise a sub-cavity formed by the current spreading layer would generate a strong spectral filtering effect. The free spectral range of this sub-cavity would be 18.8 nm, which was determined using a transfer matrix
algorithm (see Chapter 3.2.1). This would deteriorate the spectral performance of our electrically pumped VECSELs.

The design of the AR section was calculated using the transfer matrix algorithm that is described in Chapter 3.2.1. We combined this method with a Monte Carlo procedure that altered the layer thicknesses of all layers of the AR section and minimized the obtained reflectivity. Using an additional least squares fit algorithm we then optimized the best ten results from the Monte Carlo procedure to obtain the design for the AR section.

**Carrier Wafer**

Since our electrically pumped VECSELs should be power scalable, we thin the substrate and solder the entire grown semiconductor structure onto a carrier wafer. We chose an alloy consisting of Cu and tungsten (W) with a weight percentage ratio of 75% W and 25% Cu. This results in a similar thermal expansion coefficient compared to that of GaAs. This is necessary because otherwise the GaAs-based electrically pumped VECSEL structure could detach from the carrier wafer during the required annealing step. This CuW carrier wafer is 300 µm thick and 25 mm in diameter.

**Device Geometries**

In order to evaluate which device geometry (see Figure 6.2), in terms of bottom and top contact radii and their ratio, is most suitable for laser operation of our electrically pumped VECSELs, we designed a mask set that supported many different variations of these parameters. These values are listed in Table 6.2 for all 61 different electrically pumped VECSEL designs. The corresponding definitions for the individual measures can be found in Figure 6.9.
Chapter 6. Electrically Pumped VECSELs

Figure 6.9: Illustrated here are the different measures we used for the fabrication of our electrically pumped VECSELs. We realized 61 different designs which are listed in Table 6.2.

<table>
<thead>
<tr>
<th>bottom contact radius $R_b$ [µm]</th>
<th>top contact radius $R_t$ [µm]</th>
<th>top contact width $d_c$ [µm]</th>
<th>AR mesa radius $R_m$ [µm]</th>
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Table 6.2: Overview of all different geometries we realized for our electrically pumped VECSELs. The corresponding measures can be found in Figure 6.9.
6.2.2 Growth and Fabrication

Our electrically pumped VECSEL structure was fully grown by MBE (see Chapter 2.1.1) in the FIRST clean room facility at ETH Zurich. It was grown in reverse order to allow for substrate removal and thus efficient heat removal. The fabrication of the semiconductor chip was also realized in the FIRST clean room facility at ETH Zurich.

Four series of 61 designs of electrically pumped VECSELs with different top and bottom contact diameters were fabricated on a $14.5 \times 12.5$ mm$^2$ chip. The individual steps necessary to fabricate these devices are explained in detail in Chapter 2.2. The fabrication scheme to obtain the device structure depicted in Figure 6.2 is as follows:

**markers** Using photo lithography, markers are defined to facilitate top and bottom alignment. The markers are dry-etched using ICP etching through the entire structure of about 14-µm thickness.

**bottom isolation** A 350-nm thick SiN$_x$ layer acts as an electrical insulator and it is deposited in a PECVD system.

**bottom contact** The openings of the bottom disk contacts are produced by photo lithography and dry-etching in a RIE system.

**bottom metalization** The full chip is coated with Ti/Pt/Au in order to form the bottom contacts.

**wafer soldering** The semiconductor chip is soldered onto a CuW carrier wafer. The soldering employs a eutectic Au/Sn alloy and is performed with a wafer bonder at a temperature of 340 °C and a pressure of 450 N cm$^{-2}$.

**lapping** The GaAs substrate is removed mechanically by lapping.

**wet etching** Using a solution based on citric acid and hydrogen peroxide, the remaining GaAs substrate is removed. An Al$_{0.85}$Ga$_{0.15}$As etch stop layer ensures a flat surface with optical grade surface roughness. The etch stop layer is removed using a HF acid solution.

**AR etch** The AR section is then etched down to the contact layer using ICP etching.

**laser separation** A dry etch step isolates the neighboring electrically pumped VECSELs electrically and physically from each other.
AR protection The chip is again covered with SiN$_x$, protecting the sidewalls of the AR mesa.

top contact The top of the AR section and the electrical contacts are opened by photo lithography and RIE etching.

top contact definition With a step of photo lithography the top contacts are defined and a lift-off layer is created.

top metalization The full semiconductor chip is metalized with a stack of Ge/Au/Ge/Au/Ni/Au.

lift-off The unused metalized areas are opened using a lift-off method in (CH$_3$)$_2$CO.

annealing The chip is annealed using rapid thermal annealing (RTA) at 400°C to form ohmic contacts between the metalization and the semiconductor contact layer.

6.3 Experimental Results

6.3.1 Resistance of the Devices

In order to evaluate the electrical properties of our electrically pumped VECSELs, it was first necessary to determine a characteristic value which allows for proper comparison of the devices. Because of the large differences of our electrically pumped VECSELs with respect to their geometric size (see Figure 6.9 and Table 6.2), the differential resistance at laser threshold $\partial R_{th}$ was chosen, since it is a comparable parameter. This is explained in Reference [89]. According to this theoretic model, the differential resistance at laser threshold should depend exponentially on the bottom contact diameter.

We could confirm this experimentally in our measurement of the current $I_{th}$ and the differential resistance $\partial R_{th}$ at laser threshold, and we found a linear dependence of the current with respect to the bottom contact diameter. In Figure 6.10 we plot this data as a function of the bottom contact diameter for the different sizes of our electrically pumped VECSELs. The measurement points are shown as blue dots together with a linear fit for the current (Figure 6.10a, red line) and an exponential fit for the differential resistance (Figure 6.10b, red line).
Figure 6.10: Electrical properties of our electrically pumped VECSELs. (a) Dependence of the current at laser threshold on the bottom contact diameter. We could observe a linear behavior. These measurements are in good agreement with the linear power scalability of our devices (see Figure 6.13 and Chapter 6.5.2). (b) Differential resistance $\partial R_{th}$ (blue dots) plotted against the bottom disk contact diameter of the individual devices. According to Reference [89], the differential resistance should have an exponential dependence on the bottom disk contact diameter which could be verified in our experiments.

6.3.2 Current Confinement

In order for the electrically pumped VECSELs to be power scalable (see also Chapter 6.1.2), the pump profile in the active region needs to scale accordingly as well. By increasing the diameter of the top contact (see Figure 6.2), the pumped area becomes bigger, but the pumping profile does not necessarily scale in the same way due to the intrinsic ring-shape contact geometry scheme that electrically pumped VECSELs adhere to. This was demonstrated in Reference [89].

We measured the current injection profile experimentally in order to be able to compare the results with the theoretical predictions. However, due to the dependence of the gain on the field enhancement (see Equation 6.2), this is not possible during laser operation, because the obtained optical power is not proportional to the carrier density in the active region. As opposed to measuring the optical power distribution from stimulated emission, spontaneous emission indeed does mirror the current density of the active region in its optical power profile.

Therefore, we imaged the EL profile of our electrically pumped VECSELs onto a charge-coupled device (CCD) camera and evaluated the signal intensity as function of the position. This data is shown in Figure 6.11, where we plot the measured EL intensity together with the simulated EL profiles for several electrically pumped VECSELs with different bottom contact diameters. We used samples with bottom contact...
diameters of 24 µm, 40 µm, 60 µm, 80 µm, 100 µm, 120 µm, 140 µm and 160 µm. For the simulation of the carrier density in the active region, we applied our coupled electro-opto-thermal model [89, 93].

![EL Intensity Profiles](image)

Figure 6.11: Measured (solid lines) and simulated (dashed lines) EL profiles of the electrically pumped VECSELs with bottom contact diameters of 24 µm, 40 µm, 60 µm, 80 µm, 100 µm, 120 µm, 140 µm and 160 µm.

From the measurements shown in Figure 6.11, we can see that the current injection resembles a Gaussian shape for bottom contact diameters up to 40 µm. With increasing size of the device to 100 µm, the EL profile becomes more and more flat-top shaped and from 120 µm on a dip in the middle of the intensity profile starts to form.

The intensity dip of the largest device, where it is the most pronounced, amounts to about 11.5%. This shows that even for the largest of our devices the active region is pumped with a reasonable current distribution. The devices with a bottom disk contact diameter of up to 100 µm seem to be best suited for fundamental transverse mode operation.

### 6.3.3 EP-VECSEL Cavity

During the laser experiments with our electrically pumped VECSELs, we used a simple straight cavity, only consisting of the electrically pumped gain chip and an OC. The cavity length was usually adjusted to just
under the ROC of the OC to obtain lasing. From that point we optimized the position of the OC for maximum power. The simple straight cavity that we used for all our experiments is depicted in Figure 6.12.

By changing the distance of the OC to the electrically pumped gain structure, the laser mode diameter is altered. If the overlap of the laser mode and the pumped area, which is given by the bottom contact diameter (see Chapter 6.1.2) is maximized, the highest laser efficiency is reached, which should result in the maximum optical output power.

For our electrically pumped VECSELs, the optimal cavity length was usually between a few 100 µm to 1 mm less than the ROC of the OC we used during the experiment. From these observations, we conclude that the thermal lensing of the gain chip is considerably smaller compared to the equivalent effective focal length \( f_1 \) of the OC with a radius \( r_{ROC} \), which is given by

\[
f_1 = \frac{1}{2} r_{ROC}
\]

This was also true for OCs with ROC of up to 100 mm, which was the largest ROC that we tested, and therefore we assume a thermal lens of larger than 100 mm or smaller than \(-100\) mm, respectively. Thus, the influence due to thermal lensing is negligible.

### 6.3.4 Laser Operation

#### Power Scaling

Since we fabricated electrically pumped VECSELs with many different geometries (see Chapter 6.2.1), we were able to study their power scalability for which we compared all devices under the same operation conditions. The parameters we used during this comparison are listed in Table 6.3.

The maximum output power we obtained for 35 different devices (see Chapter 6.2.1) is plotted in Figure 6.13 as a function of the bottom contact...
Table 6.3: Parameters used for the CW laser experiments with the electrically pumped VECSELs. The corresponding cavity is shown in Figure 6.12.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC transmission $T$ [%]</td>
<td>10</td>
</tr>
<tr>
<td>OC ROC $r_{ROC}$ [mm]</td>
<td>25</td>
</tr>
<tr>
<td>cavity length $L$ [mm]</td>
<td>24.5</td>
</tr>
<tr>
<td>heat sink temperature $T_s$ [$^\circ$C]</td>
<td>3</td>
</tr>
</tbody>
</table>

diameter. There are small differences between the individual devices with the same bottom contact diameter. The origin of this variation can most likely be found in small differences during the fabrication process. Nevertheless, we can observe a clear linear scaling behavior of the output power with the bottom contact diameter.

Figure 6.13: Output power of 35 different electrically pumped VECSELs plotted as a function of their bottom disk contact diameter. The highest obtained output power was 120 mW for a bottom disk contact diameter of 180 µm (see Figure 6.14 for the LIV curves). The cavity parameters for these measurements are given in Table 6.3. The linear fit (red line) of the measurement points (blue dots) shows a linear power scaling of the output power as a function of the bottom disk contact diameter.

**Highest Output Power**

Using an electrically pumped VECSEL with a bottom contact diameter of 180 µm and a top contact diameter of 300 µm (see Figure 6.9) we obtained the highest output power of 120 mW. The corresponding light-current-
voltage (LIV) curves for this measurement are shown in Figure 6.14 together with the quantum efficiency (see Equation 6.5), where we achieve a maximum value of about 25%. The cavity parameters for this result are listed in Table 6.3. We can see that the maximum output power is limited by the thermal rollover which come into effect at around 1 A of pump current. At the laser threshold, we obtain a differential resistance of the device of about 1.5 Ω.

![Figure 6.14: LIV curves of the electrically pumped VECSEL where the highest output power was achieved. We achieved a maximum output power of 120 mW. The cavity parameters for this measurement is given in Table 6.3. The quantum efficiency is plotted in magenta.](image)

The quantum efficiency $\Xi$ is defined as the energy ratio of the number of generated photons $N_p$ and the number of electrons $N_e$ which is necessary for the generation of these photons

$$\Xi = \frac{N_p}{N_e} = \frac{P\lambda / (hc)}{I/q}. \quad (6.5)$$

The parameters $P$, $\lambda$, $h$, $c$, $I$ and $q$ are the output power, the emission wavelength, the Planck constant, the speed of light, the pump current and the elementary electron charge, respectively.
Influence of the OC Transmission

In comparison to optically pumped VECSELs, where the OC usually has a transmittance of a few percent, the intermediate DBR of the electrically pumped VECSELs can strongly influence the value for the optimal transmittance of the OC. Since in our case this intermediate DBR already has a reflectivity of around 92.5%, and thus a transmittance $T_{DBR}$ of about 7.5%, an effective cavity round trip transmission $T_{rt}$ comparable to that of optically pumped VECSELs is obtained, if an OC transmission $T_{OC}$ in the order of about 10% is used.

Assuming an effective overall cavity transmission $T_{rt}$ of about 1.5%, an OC transmission of $T_{OC} = T_{rt} / T_{DBR}$ has to be chosen, which would be 20%. This is a considerably higher OC transmmission than usually used for optically pumped VECSELs, although the effective cavity round trip transmission is exactly the same.

However, this should be used as a guideline rather than as an exact rule, since the losses due to FCA (see Chapter 6.1.1) is not taken into account.

We evaluated the influence of the transmittance of the OC for an electrically pumped VECSEL with a bottom contact diameter of 180 µm. For a heat sink temperature of about 20°C, we measured the light-current (LI) curves for the same laser for eight different OC transmissions. This is illustrated in Figure 6.15, where we used OC transmissions of 1.5%, 2.5%, 5%, 8%, 10%, 14%, 20%, and 30%. For the lowest transmission value we use a dark blue, the highest is plotted in dark red. The optimal OC transmission seems to be between 10% and 14%.

Beam Quality

In our first fabrication of electrically pumped VECSELs, we only realized devices with eleven quarter wave pairs for the intermediate DBR, and thus an internal reflectivity of about 92.5%. As will be discussed in detail in Chapter 6.4.3, the internal reflectivity of this intermediate DBR has a strong influence on the beam quality of electrically pumped VECSELs. Since we were thus not able to make an extensive study of the matter using our own samples, here, only the result of one of our samples is shown.

Using an electrically pumped VECSEL with a bottom disk contact diameter of 80µm we obtained 30 mW of output power with a beam quality factor $M^2$ of 3.6. We achieved this result in a straight cavity with
an OC with 10% transmission and a ROC of 25 mm. With an intracavity pinhole we were able to improve the beam quality to a nearly fundamental transverse mode. However, the output power was reduced to 10 mW.

### Emission Wavelength and Internal Heating

We measured the emission spectra of all our electrically pumped VECSELs as a function of the pump current. A typical emission spectrum, in this case for the device with a bottom contact diameter of 60 µm and a top contact diameter of 200 µm, is shown in Figure 6.16. This particular spectrum was taken for a pump current of 305 mA and the optical spectrum analyzer (OSA) signal is plotted on a logarithm scale against the wavelength.

Despite the strong spectral filtering effect due to the sharp resonance peak, which is induced by the high reflectivity of the intermediate DBR (see Chapter 6.2.1), we obtain a spectral width of about 1.4 nm at a center wavelength of about 967.5 nm. In regard to future modelocking experiments, this seems to be a sufficient bandwidth to obtain pulses in the few picosecond regime. Therefore, a structure design with a reduced
number of intermediate DBR pairs should exhibit a considerably wider spectral bandwidth, possibly sufficient to support femtosecond pulses.

We also made measurements of the emission spectrum as a function of the pump current. For an electrically pumped VECSEL with a bottom (top) contact diameter of 60 µm (200 µm), these measurements are shown in Figure 6.17, where the pump current corresponds to the horizontal axis, the emission wavelength to the vertical axis, and the measured optical power in a logarithmic scale to the color bar.

Due to resistive heating, a higher pump current results in a higher absolute temperature inside the device, which in turn also influences the emission wavelength of the QWs. Therefore, a red shift of the emission wavelength is obtained as a function of the pump current. Furthermore, the spectral width is increased with increasing temperature. The change of the noise floor level at around 190 mA results from a relatively low laser signal with respect to the noise floor for low pump currents, and from the fact that for every current value the spectrum was normalized to the dBc scale individually.

Using well established values for the temperature drift of our QWs of about 0.3 nm K$^{-1}$[91, 92] and for the temperature-dependent shift of the structural gain confinement due to a refractive index change of the materials ($dn/dT$) of about 0.04 nm K$^{-1}$ [94], we can assume that the obtained wavelength shift in our electrically pumped VECSELs is mostly caused by the temperature shift of the very pronounced resonance due to the intermediate DBR (see Chapter 6.2.1).

From Figure 6.17, we can extract a wavelength shift of about 5 nm for if the pump current is varied from 150 mA to 400 mA. Using only the temperature-dependent shift of the gain peak, this would correspond to a temperature increase of about 16.67 °C, which would be too little and it would not agree with our simulations (see Chapter 6.5.2 for a more detailed discussion on that matter). The temperature increase in the electrically pumped VECSEL yields about 125 °C, if a shift of the reso-
Figure 6.17: Dependence of the optical spectrum of an electrically pumped VECSEL with a bottom contact diameter of 60 µm on the pump current. Due to resistive heating, this figure also illustrates the temperature dependence of the spectrum. The pump current corresponds to the horizontal axis, the emission wavelength to the vertical axis, and the measured optical power in a logarithmic scale to the color bar. The change of the noise floor level at around 190 mA results from a relatively low laser signal with respect to the noise floor for low pump currents, and from the fact that for every current value the spectrum was normalized to the dBc scale individually.
nance peak is assumed as the main cause for this effect. This seems to be a reasonable temperature increase for these types of devices and thus the temperature increase due to the dependence of the refractive index on the temperature \(\frac{dn}{dT}\) seems to be the most likely explanation for the measured temperature increase. This is supported by the fact that the resonance in the active region due to the high reflectivity of the intermediate DBR is very strong (see field enhancement in Figure 6.5).

For the proper comparison of all our different fabricated electrically pumped VECSELs with respect to their temperature dependence on the pump power, we plotted the temperature increase \(\Delta T\) obtained from measurements similar to those shown in Figure 6.17 as a function of the current density for a number of differently sized devices. The curves, plotted in blue for smaller devices and in green for larger devices, correspond to electrically pumped VECSELs with bottom contact diameter of 24 µm, 40 µm, 60 µm, 80 µm, 100 µm, 120 µm, 140 µm, 160 µm, and 180 µm.

![Figure 6.18: Temperature increase as a function of the current density for the electrically pumped VECSELs with bottom contact diameters of 24 µm, 40 µm, 60 µm, 80 µm, 100 µm, 120 µm, 140 µm, 160 µm, and 180 µm. Smaller devices are plotted in blue, larger ones in green. The temperature increase was determined with measurements similar to Figure 6.17.](image)

We can see a clear difference between the individual devices. Smaller devices can be pumped at significantly higher current densities compared to larger devices, despite the fact that the temperature increase is the same. From this we can draw the conclusion, that in case of our electrically pumped VECSELs, we do not have power scaling with a perfectly one dimensional heat flow. This was already indicated in Figure 6.13, where we could only obtain a linear power increase as a function of the pumped area, instead of a quadratic increase. This will be discussed in more detail in Chapter 6.5.2.

### 6.4 EP-VECSELs from Philips

In addition to the electrically pumped VECSELs we fabricated ourselves, we were also able to use samples that were grown and fabricated at
Philips Technologie GmbH, U-L-M Photonics for our experiments. We had access to devices that exhibited different numbers of intermediate DBR pairs, which allowed us to study the influence of the intermediate DBR reflectivity, especially on the beam quality of the laser. Despite the slightly different device design of these electrically pumped VECSELs compared to ours, these experiments revealed insightful information on our future designs for our devices.

6.4.1 Differences to Our EP-VECSEL Design

The electrically pumped VECSELs we used during the experiments in this section had a similar design to our design which is described in Chapter 6.2.1 and illustrated in Figure 6.2. For all samples we used, the electrically pumped area had a diameter of 100 µm. The current spreading layer was thicker than in our design with values for the current spreading layer thickness between 60 µm and 80 µm. The doping level of the current spreading layer varied from $5 \times 10^{17} \text{ cm}^{-3}$ to $10^{18} \text{ cm}^{-3}$. Due to the considerably thicker current spreading layer, the effect of FCA is more pronounced and the maximum output power is reduced in comparison to our electrically pumped VECSELs.

The most important difference to our design is the number of intermediate DBR pairs. We tested devices with 9, 11 and 13 pairs for intermediate DBR. These values correspond to internal reflectivities of 90%, 82% and 71%, respectively. This allowed for the experimental study of the influence of the internal reflectivity. Since the general design is very similar to ours, the obtained relations between the internal reflectivity, the output power and achievable beam quality is comparable to our devices and we can apply the findings to improve our future device designs.

6.4.2 CW-Operation

For the evaluation of the electrical and the optical properties of the electrically pumped VECSELs from Philips we measured the LIV curves for all samples. The general properties of these devices were comparable to our samples, and only a typical set of LIV curves is plotted in Figure 6.19 together with the quantum efficiency.

The electrically pumped VECSEL we used for this measurement had an intermediate DBR with eleven pairs. We obtained an output power of
up to 40 mW with an emission spectrum centered around 977 nm and a FWHM spectral width of 0.5 nm.

The laser cavity was comparable to the one we used in the experiments for our electrically pumped VECSELs (see Figure 6.12). The only difference was the much more pronounced thermal lens we experienced with the Philips samples. The thermal lens was in the order of about 2-mm focal length. This led to a cavity length that was adjusted to a little more than the ROC of the OC. The cavity parameters are listed in Table 6.4.

Table 6.4: Parameters used for the CW laser experiments with the electrically pumped VECSELs from Philips. We used a simple straight cavity setup similar to the cavity shown in Figure 6.12.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC transmission T [%]</td>
<td>5</td>
</tr>
<tr>
<td>OC ROC $r_{ROC}$ [mm]</td>
<td>25</td>
</tr>
<tr>
<td>cavity length L [mm]</td>
<td>27</td>
</tr>
<tr>
<td>heat sink temperature $T_s$ [°C]</td>
<td>−12</td>
</tr>
</tbody>
</table>

6.4.3 Beam Quality

For the study of the beam quality as a function of the internal reflectivity of the intermediate DBR of the electrically pumped VECSELs from
Philips, we employed a simple straight cavity similar to that described in Chapter 6.4.2. We used different OCs with transmission values of 1.5%, 2.5%, 5%, and 10%, and a ROC of 15 mm or 25 mm. For all the measurements with all devices, we optimized the OC position for maximum output power and operated the sample under test at the thermal rollover where we obtained the highest output power. The heat sink temperature was set to about $-12^\circ$C, similar to the experiments discussed in Chapter 6.4.2.

In Table 6.5, the results for our beam quality measurements are listed, stating the parameters for the reflectivity of the intermediate DBR of the electrically pumped VECSEL under test, the transmission of the OC, and the measured values for the obtained output power and the beam quality factor $M^2$.

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>OC Transmission</th>
<th>Power [mW]</th>
<th>Beam Quality $M^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>2.5</td>
<td>3.1</td>
<td>11</td>
</tr>
<tr>
<td>90</td>
<td>5.0</td>
<td>22.2</td>
<td>8.8</td>
</tr>
<tr>
<td>90</td>
<td>10.0</td>
<td>34</td>
<td>2.6</td>
</tr>
<tr>
<td>82</td>
<td>2.5</td>
<td>17.3</td>
<td>1.4</td>
</tr>
<tr>
<td>82</td>
<td>5.0</td>
<td>15.1</td>
<td>1.1</td>
</tr>
<tr>
<td>82</td>
<td>10.0</td>
<td>10.6</td>
<td>1.5</td>
</tr>
<tr>
<td>71</td>
<td>1.5</td>
<td>7.5</td>
<td>1.2</td>
</tr>
<tr>
<td>71</td>
<td>2.5</td>
<td>8.2</td>
<td>1.1</td>
</tr>
<tr>
<td>71</td>
<td>5.0</td>
<td>n. a.</td>
<td>n. a.</td>
</tr>
</tbody>
</table>

Table 6.5: Overview of the results from the study of the beam quality of electrically pumped VECSELs as a function of the reflectivity of the intermediate DBR and the OC.

During these measurements we found that if we use the electrically pumped VECSEL with 90% transmission of the intermediate DBR and we increase the transmission of the OC from 2.5% to 10%, we can steadily increase both the beam quality and the output power. We could reach a value for the beam quality factor $M^2$ of 2.6 at a maximum output power of 34 mm for this device (see also Table 6.5).

In case of the electrically pumped VECSEL with a transmission value for the intermediate DBR of 82%, we obtained beam quality factors of better than 1.5 for all OCs we used, and with the OC with a transmission of 5%, we could obtain nearly fundamental transverse mode operation with an $M^2$ value of 1.1. The measurement of the beam quality factor $M^2$ is shown in Figure 6.20.

The sample with which we obtained the best beam quality was the device with an internal reflectivity of 71%. Laser operation with 5% OC
Figure 6.20: Measurement of the beam quality factor $M^2$ in both lateral direction with respect to the beam axis. The horizontal axis is plotted in blue, the vertical axis in green. This measurement belongs to the electrically pumped VECSEL with a reflectivity of the intermediate DBR of 81% and an OC transmission of 5%. See also Table 6.5.

transmission or more was not attained because of the combined effective transmission of the OC and the intermediate DBR, which was too large. However, using the other OCs with transmissions of 1.5% and 2.5%, we were able to obtain excellent beam quality with $M^2$ values of 1.2 and 1.1, respectively.

### 6.5 Conclusion and Outlook

We were able to apply an electrical pumping scheme to VECSELs and realized a semiconductor design which should support modelocking. Although modelocking experiments are not presented in this thesis, we presented excellent current injection profiles (see Chapter 6.3.2) and output power levels of more than 120 mW (see Chapter 6.3.2). These power levels were achieve in multi-mode, but our study of the beam quality (see Chapter 6.4.3) shows that high output power and good beam quality can be combined with an appropriate value for the reflectivity of the intermediate DBR. The knowledge will be applied to future structure.

Another important conclusion can be draw from publications of other groups, especially References [31, 32], where research on electrically pumped VECSELs was conducted in an industrial background. This fact alone shows the massive impact that this technology has on applications, and it is very therefore very important to further advance this technology.

Thus, in this chapter, possible ways of improvements are discussed and an outlook on the modelocking performance is given at the end.

#### 6.5.1 Simplification of the Fabrication

Due to the complex fabrication process our electrically pumped VECSELs have to undergo (see Chapter 6.2.2), the margin of error during this
fabrication scheme is relatively large. This is caused by several reasons:

**critical growth** To realize our semiconductor structure, many different properties have to be thoroughly characterized. The characterization of doping levels and doping profiles, material composition and material grading, mole fractioned materials and growth accuracies for all involved materials are among the most important components (see Chapter 6.2.2).

**limited pre-processing characterization** Since the structure is grown in reverse order, there is only a limited optical characterization potential before the structure is fabricated, and it is impossible to determine the electrical properties.

**challenging fabrication scheme** The fabrication of our samples requires a large number of highly advanced fabrication steps (see Chapter 6.2.2).

**requirement for process re-optimization** The fabrication is performed in a multi-user clean room, where reproducibility cannot be fully guaranteed. Therefore, the most critical steps usually have to be re-optimized for each fabrication run.

**many processing steps** The high number of processing steps leads to a reduction of the yield of working devices and increases the margin of error for a successful fabrication.

Most of the mentioned points are intrinsic properties of the device design, however, it is possible to reduce the number of processing steps. Therefore, the following improvements are suggested for the fabrication scheme:

- Remove the AR section mesa structure. This removes the most critical step, where the AR section has to be etched precisely down to the top contact layer (see Figure 6.2). For this step, two necessary alteration to the semiconductor structure have to be done, which further simplify the fabrication process.

  - Use an n-doping level of $2 \times 10^{18} \text{ cm}^{-3}$ for the AR section. This is required to obtain electrical conductivity of the AR section, through which the pump current now has to flow.
Move the top contact from between the current spreading layer and the AR section above the AR section. This is necessary to obtain an ohmic contact. This enables doping measurement level measurements and, in combination with an doped wafer, allows for simple electrical characterization on the unprocessed sample. This was not possible before.

- For some of the processing step listed in Chapter 6.2.2 (all photo lithographies after the laser separation), a planarization is required before the actual photo lithography can be performed. We suggest to use a thicker photo resist to avoid this additional photo lithography for each of these steps.

By incorporating the suggested steps in the processing, the fabrication scheme should be simpler and less time consuming, leading to a reduction of the error margin and a higher chance of a successful completion of the fabrication.

### 6.5.2 Power Scaling

The measurements we described in Chapter 6.3.4, where the maximum output power of all our electrically pumped VECSELs was plotted as a function of the bottom contact diameter (see Figure 6.13), clearly show that the output power of our samples does not scale quadratically with the radius of the devices, as it would be in case of truly one-dimensional heat flow through the back of the device. Thus, for our electrically pumped VECSELs, the heat flow seems to have additional components.

This was proven to be correct with the measurements shown in Figure 6.18, where, as a function of the current density inside the device, the temperature increase of several differently sized electrically pumped VECSELs is plotted. From these measurements we concluded that for the same temperature increase, smaller devices could be driven at much larger current densities in comparison to larger devices. If the heat flow were perfectly one-dimensional, the temperature increase would be directly proportional to the current density and independent of the size of the electrically pumped VECSEL.

### Device Scaling

Since the heat flow for our devices definitely seems to have a three-dimensional component, we simulated the device geometry using our
electro-opto-thermal model [89]. By scaling the device radius $R_d$ (see Figure 6.9 for the definition of $R_d$) and leaving all other geometric sizes unaltered, the temperature increase inside the device can be reduced.

For the electrically pumped VECSEL with a bottom contact diameter of 80 µm and a top contact diameter of 300 µm we altered the device size $R_d$ and simulated the lateral temperature profile (Figure 6.21a) and the maximum temperature increase in the center together with the achievable output power as a function of the pump current (Figure 6.21b). We used values of 200 µm (green), 250 µm, and 300 µm (blue) for the device radius $R_d$.

![Temperature distribution and QD-VECSEL gain layers](image)

Figure 6.21: Using a bottom (top) contact diameter of 80 µm (300 µm), we simulated both the temperature increase and the output power as a function of the pump current, only changing the device radius $R_d$. We increased the device radius using values of 200 µm (green), 250 µm and 300 µm (blue). (a) Temperature distribution within the device. (b) Temperature increase in the active region and achievable output power.

We can see that by increasing the device radius $R_d$ from 200 µm (green) to 300 µm, about 50% more pump current can be used while the same temperature increase of 75 °C is obtained inside the device. Furthermore, this leads to an increase in output power of almost 100% — From 40 mW to almost 80 mW. This shows that a considerable amount of the heat is dissipated laterally through the structure and is only then transferred to the heat sink. This design aspect of scaling the device diameter without altering the other geometric lengths of the devices will be accounted for in the next photo lithography mask set.

**Heat Sink Optimization**

Another possibility to improve the thermal properties of our electrically pumped VECSELs is to investigate possible heat sink alternatives that
exhibit higher values for the thermal conductivity. The CuW heat sink we utilize at the moment has a thermal conductivity of 200 W K\(^{-1}\) m\(^{-1}\). This is about a factor of two lower in comparison with Cu and roughly ten times lower compared to diamond.

An important prerequisite for this is a similar coefficient of thermal expansion. One possible alternative would be to use a composite Ag/diamond compound as a heat sink material. It offers a thermal expansion coefficient similar to that of GaAs and a coefficient of thermal expansion of 650 W K\(^{-1}\) m\(^{-1}\).

In order to evaluate the performance increase if such a material would be used as a heat sink, we used the electrically pumped VECSEL with a bottom contact diameter of 80 µm and measured the temperature-dependent shift of the emission spectrum and thus the temperature increase due to resistive heating (see Figure 6.17). Furthermore, we measured the laser power as a function of the pump current using an OC with 10% transmission and a heat sink temperature of 3 °C and fitted this data with our simulation of the same VECSEL using only experimental parameters. As a fit parameter we used the thermal resistance \(R_{th}\) of the CuW carrier wafer and we obtained a value of about 57 K W.

The experimental (black) and the simulated (red dashed) curves for the power as a function of the pump current are shown in Figure 6.22. Since the simulated curve was fitted to the measured curve, the overlap is very good.

By using the thermal resistance of CuW as a scale, we could implement the same simulation with a value for the thermal resistance that was adapted to that of the composite Ag/diamond. This curve is plotted in green in Figure 6.22.

We can see that by using this new heat sink material, the output power can be increased from about 65 mW to almost 170 mW, which is an increase of over 160%.
6.5.3 Optimization of the p-Doped DBR

The optimization of the p-doped DBR is closely related to Chapter 6.5.2 because its improvement results in superior electrical properties and thus usually a generally improved performance. Due to the extent of this topic, we devote a whole section to it.

Material Composition of the DBR

In comparison to an n-doped DBR, the electrical performance of the p-doped DBR is reduced due to the low mobility of the holes. Since, however, p-doping is required to obtain a good beam profile for large electrically pumped VECSELs (see Chapter 6.1.2), other ways of improvement have to be found.

A large contribution to the high resistance of the p-doped DBR originates from the interfaces of the mirror, and not only from the ohmic resistance of the doped material. These interfaces introduce discontinuities in the valence band and the Fermi levels, resulting in phonon barriers, leading to a decreased thermal conductivity, and electronic tunnel barriers, increasing the electrical resistance of the device.

These discontinuities emerge from the abrupt interfaces between the two materials the DBR is consists of. Consequently, an improvement can be achieved by smoothening those material transitions by means of gradings.

In Figure 6.23, the simulations for three different types of grading between GaAs and AlAs are compared to each other. The green curves show no grading between the materials, for the blue curves five steps of AlGaAs according to the design from Chapter 6.2.1 were simulated, and the magenta curves correspond to a linear grading. The simulated geometry was a cylindrical device of 10 µm radius where the bottom and the top contacts cover the entire bottom and top surfaces. We used GaAs and AlAs for the DBRs and a constant p-doping level of $2 \times 10^{18}$ cm$^{-3}$. The n-doped sections of the structure were doped with a doping level of $2 \times 10^{18}$ cm$^{-3}$.

For Figure 6.23a, we used a pump current of 500 mA (the rightmost point of Figure 6.23b) and we plotted the valence band edge for the first seven pairs of the p-doped DBR. The valence band discontinuities are
clearly visible for the sample with abrupt interfaces (green) and they have almost disappeared for the sample with linear grading (magenta). The band edge offset from left to right corresponds to the necessary voltage which is required to drive the current of 500 mA through the structure. The corresponding IV curves are plotted in Figure 6.23b.

As expected, the best result is obtained with the linear grading. One can clearly see that stronger valence band discontinuities result in a higher voltage necessary to drive the same current through the structure. This additional voltage is necessary to overcome these electronic tunnel barriers, which are the origin of the diode behavior which is clearly visible in Figure 6.23b at least for the sample with abrupt interfaces (green curve).

In addition to a grading between the two materials of the DBR, the valence band discontinuities can be reduced by reducing the valence band gap between the two materials, i.e. by using more similar materials. One possibility instead of using a binary system composed of GaAs and AlAs layers, is to use a ternary AlGaAs system. Despite decreasing optical properties (the refractive index difference will be reduced), this can lead to a further improvement of the electrical and the thermal properties, leading to a better overall performance of the device. However, a good balance between optical and electrical properties has to be found.
Possible Ways to Realize an Improved p-DBR

Ideally, the grading between the two materials of the p-doped DBR is smooth [101]. This is illustrated in Figure 6.23. Realizing a perfectly smooth grading, however, proves to be quite difficult if MBE growth is used. The problem is the accurate flux control of the materials. Since the grading should usually not exceed a few nanometers, the required flux change to obtain the two different DBR materials is big, and nevertheless it needs to be very precise so that a smooth grading is guaranteed. We tried to do this using our MBE (see Chapter 2.1.1), yet, the resistance of the DBR was even higher than for our DBR with five discrete grading steps (see Chapter 6.2.1). Furthermore, the growth accuracy and thus the repeatability was poor.

The reason for the bad electrical performance of this DBR seems to be an insufficient precision of the temperature controller of the Al cell of our MBE. For every temperature increase of this cell, the set temperature was exceeded, resulting in an overshoot of the Al flux of about 27% and thus a too high Al content. In a similar way we obtained a too low temperature when the temperature was decreased with a to small Al content in the grown layer. The circumstances were even worse, because the set temperature was reached only after a few oscillations around the set point. This leads to a cascade of valence band discontinuities, resulting in a reduced device performance.

This is illustrated in Figure 6.24, where we plotted the set temperature (black), the measured temperature (green) and the measured material flux (blue). We used arbitrary units and overlapped all data curves for better comparison.

Figure 6.24: Set temperature (black), measured temperature (green) and measured material flux (blue) for (a) the Ga cell and the f:mbel-lingrad-al Al cell of our MBE.
The Ga cell (Figure 6.24a) seems to be quite slow and the temperature of the cell cannot follow the set point. This could result in difficulties to obtain good growth accuracies. Yet, the material quality should not be influence by this effect and we should be able to obtain interfaces with low phonon barriers.

In contrast, the Al cell (Figure 6.24b) is very fast and the cell temperature follows the set temperature. However, at the point where the maximum temperature is reached, a large overshoot of the cell temperature is visible. Because of the high cell temperature, the effect on the material flux (blue curve) is very strong, resulting in a large peak of the Al flux.

This is the most likely reason for the unsatisfactory electrical performance of this sample. Smooth grading using MOVPE should be considerably easier to realize and it is one option to further improve the p-doped DBR of our electrically pumped VECSELs.

We also tried to realize a digital alloy \[102, 103\] using our MBE. This grading techniques relies on quick shutter control of the source cells of the MBE machine. Despite the fact the other groups \[102, 103\] were able to obtain significantly improved results for their vertical cavity surface-emitting lasers (VCSELs) using this technique, the electrical properties of our p-doped DBRs were inferior to our five step AlGaAs grading from GaAs to AlAs (see Chapter 6.2.1). We are not sure what caused the reduced electrical properties in our case, but we believe that by thorough development, this technique can significantly improve our p-doped DBR with respect to its electrical and thermal properties.

**Doping of the DBR**

Doping of the semiconductor structure is a necessary requirement for electrical pumping. This is explained in detail in Chapter 6.1. However, doping causes optical losses due to FCA (see Chapter 6.1.1). Since FCA strongly depends on the electric field strength, higher doping levels at the interfaces between the two materials of the DBR where the electric field has a node will considerably improve the resistance of the electrically pumped VECSEL. At the same time, the effect on the optical properties is negligible as the electric field strength is very close to zero in these areas.

According to Reference \[104\], one possible way to do this is to use \(\delta\)-doping. This technique, however, involves growth interruptions during the implantation of the dopant in the structure, introducing potential
defects at the abrupt regrowth interfaces.

An alternative is to use Δ-doping, where an entire layer is highly doped. We propose to use such an approach with Δ-doping levels of $5 \times 10^{18}$ cm$^{-3}$ in combination with a grading between the two materials of the p-doped DBR. In this situation, this Δ-doping has to be applied to the grading layers between the two materials of the DBR, where the standing wave pattern of the laser has a node.

This is schematically illustrated in Figure 6.25 for a p-doped DBR based on quarter wave layer of GaAs (blue) and AlAs (green), where we use five discrete steps of AlGaAs to grade from one material to the other.

Figure 6.25: Illustration of a p-doped DBR where the grading layer between the quarter wave layers of the mirror are Δ-doped at the interfaces where the standing wave pattern of the laser has a node. This should reduce the resistance of the device without compromising the optical properties due to FCA.

The color of the AlGaAs grading layers differ according to the amplitude of the electric field of the laser. Darker gray corresponds to the higher Δ-doping, the lighter gray to the standard doping level of $2 \times 10^{18}$ cm$^{-3}$.

### 6.5.4 Beam Quality

From the measurements and the discussion from Chapter 6.4.3, where we used electrically pumped VECSELs from Philips for the experiments, it is clear that the beam quality strongly depends on the internal reflectivity of the n-doped intermediate DBR. By applying this knowledge to our samples, the reflectivity of the intermediate DBR should be reduced to values between 65% and 80%.

During the experiments with the electrically pumped VECSEL from Philips with an internal reflectivity of 71%, we could still obtain laser operation with an OC transmission of 2.5%. Considering the higher losses due to FCA of the samples from Philips which result from the thicker current spreading layer, this lower limit of the intermediate DBR reflectivity of 65% seems reasonable. However, it is not necessary to minimize this reflectivity to a value where laser operation is barely achieved, only to improve the beam quality. The measurement from Chapter 6.4.3 have
shown that reasonable beam quality and output power can be obtained also with higher reflectivities of the intermediate DBR. This situation changes if the samples should be modelocked, where the total GDD value of the structure is important (see Chapter 6.5.5).

### 6.5.5 Modelocking

Two of the key requirements to obtain short pulses in modelocked operation is low GDD and a broad spectral bandwidth. In terms of the bandwidth of our electrically pumped VECSELs this requirement seems to be met, offering an approximate spectral bandwidth of more than 1 nm (see Figure 6.16). Assuming a transform limited pulse at our central wavelength of about 965 nm, the generation of pulses in the few picosecond regime should be feasible. Reducing the number of intermediate DBR pairs, the spectral filtering effect of the strong resonance in the active region should be reduced, a wider spectrum should be obtained, possibly supporting the generation of femtosecond pulses.

In regard to the structural GDD the situation does not seem to be as straightforward. The strong resonance induced by the high reflectivity of our n-doped DBR results in significant amounts of structure-intrinsic GDD. In comparison to optically pumped VECSELs (see Chapter 5), the structural GDD of electrically pumped VECSELs is at least a factor of 100 higher.

To evaluate possible future modelocking experiments, we used our electrically pumped VECSEL design (see Chapter 6.2.1) and simulated the structural GDD as a function of the wavelength for devices design with a different number of pairs for the n-doped intermediate DBR. These simulations are shown in Figure 6.6, for eight (green), nine, ten, and eleven (blue) n-doped intermediate DBR pairs.

![Figure 6.26: GDD as a function of the wavelength for eight (green), nine, ten, and eleven (blue) GaAs/AlAs pairs for the n-doped intermediate DBR. The values are given in ps$^2$ and are therefore significantly larger in comparison to optically pumped VECSELs. The GDD is significantly smaller for an eight-pair intermediate DBR.](image)

We obtained GDD values in the order of 1 ps$^2$ (i.e. $10^6$ fs$^2$) for the electrically pumped VECSEL design with 11 pairs for the intermediate...
To determine the minimum pulse duration that we could possibly achieve with such large GDD values, we employed our pulse simulation algorithm (see Chapter 3.2.2). We simulated how the pulse duration depends on the total GDD and plotted the results in Figure 6.27. We made several simulations and we altered the spectral gain bandwidth to values of 1 nm, 1.5 nm, 2 nm, and 5 nm, where smaller bandwidths are plotted in blue and larger bandwidths in green.

Taking all results from the sections of this chapter, we can conclude that an overall GDD value of about 0.1 ps$^2$ seems to be a reasonable assumption. We obtain this value if an n-doped intermediate DBR with eight pairs is chosen (see Figure 6.26). Using such a device, according to Chapter 6.4.3, the beam quality of such an electrically pumped VECSEL can be assumed to be an almost fundamental transverse mode. Due to the reduced spectral filtering effect of the lower reflectivity of the eight pair intermediate DBR in comparison to the eleven pair DBR we realized so far, the spectral gain bandwidth of 1.4 nm (see Figure 6.16) is most likely exceeded.

Assuming a spectral gain of 2 nm and an 8-pair intermediate DBR, according to Figure 6.27, a pulse duration of about 5 ps should be feasible.

Further enhancements to the structure to increase the efficiency and the output power, for instance improvements to the p-doped DBR, the heat sink material, or the lateral device size (see Chapter 6.5.2 for these points), can be added additionally to the design suggested here. With these combined improvements to the design for an electrically pumped VECSEL which is specifically suitable for modelocking, we assume that pulses shorter than 10 ps can be achieved at average power levels of 200 mW in the near future for such a device.
References


References


References


