Thesis for the degree of doctor of philosophy

Dilute Nitride Lasers and Spectrally Engineered Semiconductor Laser Resonators

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Department of Microtechnology and Nanoscience – MC2
Chalmers University of Technology
Göteborg, Sweden, 2011
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Front cover illustration: A scanning electron microscope image of a laser with a spectrally engineered Fabry-Perot resonator designed for two-color emission. Read more about it in chapter 5.

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Dilute Nitride Lasers and Spectrally Engineered
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Abstract
The first part of this thesis deals with long wavelength (1.2-1.3 µm) InGaAs(N) multiple quantum-well (QW) lasers grown on GaAs, with the aim of understanding and improving their threshold and temperature characteristics. The epitaxial material is grown by molecular beam epitaxy (MBE). By optimizing MBE growth conditions we have obtained record low values for the threshold current density of 107 and 133 A/cm²/QW for triple QW 1.2 µm InGaAs and 1.3 µm GaInNAs lasers, respectively. A thorough investigation of the temperature dependence of the threshold current for ridge waveguide GaInNAs double QW lasers is presented. The good temperature stability of GaInNAs lasers is usually attributed to a large conduction band offset as well as strong defect recombination. This work, however, reveals that their good temperature stability also to a large extent arises from a significant and only weakly temperature dependent lateral diffusion current, which is not an effect intrinsic to GaInNAs but rather related to the geometry of the laser resonator.

The second part explores a concept used to engineer the spectral properties of a semiconductor Fabry-Perot (FP) laser resonator. A wavelength dependent resonator loss is obtained by introducing perturbations of the effective mode index at key positions along the length of the FP resonator. In a spectrally engineered FP resonator (SE-FPR) this is used to lower the resonator loss for selected longitudinal modes which thereby require less gain for lasing. Previous treatments of SE-FPRs generally relied on an approximation valid for a weakly perturbed resonator. This work extends the treatment to also include strongly perturbed SE-FPRs. The design and fabrication of SE-FPRs supporting either one or two selected modes are investigated. For a strongly perturbed SE-FPR a very large reduction of the resonator loss can be obtained for the selected modes, with the main feedback still provided by the end facets. Fabrication tolerances are, however, strict; in particular the positioning of the perturbations with respect to the end facets is critical.

Keywords: Semiconductor lasers, InGaAs, GaInNAs, GaAs, multiple quantum wells, molecular beam epitaxy, ambipolar diffusion, temperature dependence, characteristic temperature, threshold current, dilute nitrides, spectral engineering, transfer matrix method, Fabry-Perot resonator, single mode laser, two-color laser
List of papers

This thesis is based on the following appended papers:


Publications by the author related to the thesis:


[II] S. M. Wang, H. Zhao, G. Adolfsson, Y. Q. Wei, J. S. Gustavsson, M. Sadeghi, and A. Larsson, "Dilute nitrides and 1.3 $\mu$m GaInNAs/GaAs quantum well lasers on GaAs," Presented at the Workshop on recent advances in low dimensional structures and devices (WRA-LDSD), Nottingham, UK, April 2008 (invited paper)


Preface

This thesis consists of two parts. The main part is the appended papers which include all simulation and experimental results from my work on this, in my opinion, exciting research topic. The second part is the introductory text preceding the papers which aims at providing both a motivation to the work performed as well as a theoretical foundation sufficient to fully comprehend the obtained results. The theoretical background includes some basic laser theory which, presumably, many readers are familiar with. The reason why this was included was thus not to teach laser theory, but rather to have a more complete picture of the thesis topic. For the same reason a few sections of laser history was also included. Laser history is a tricky thing and statements of the type "the first..." represent merely my understanding of how things have evolved. I have marked some references in the reference list that I consider to have been important during the development of the laser. These may be labeled "classical papers", if you wish.

If the seemingly impossible has occurred, which I sincerely hope, i.e. that you, the reader, is not an examiner, supervisor, member of the examination committee or faculty opponent of this work, I recommend that you read, or at least briefly browse through, the theoretical background prior to reading the other parts of the thesis. If you on the other hand consider yourself to be family/non-colleague-friend of the author, I guess that some of the footnotes may be of (some) interest, as well as being easy to understand, together with section 1.1 which introduces a few applications of photonics.

Acknowledgment

During my work with this thesis I have received help from many persons to whom I would like to express my gratitude.

First of all I want to express my deepest gratitude to Prof. Anders Larsson for giving me the opportunity to work in this exciting field. I have had the benefit of having three excellent supervisors in Anders Larsson, Shumin Wang and Jörgen Bengtsson and I would like to thank them all for their encouragement and insightful guidance, as well as for always being available for discussions. I am in particular greatly indebted to Jörgen Bengtsson who, apart from being one of my PhD supervisors, also has been somewhat of an informal advisor ever since my first encounter with photonics as an undergraduate student. His never-ending-patience
and pedagogically explanations to all my questions have been invaluable. I have also enjoyed all our non-photonics related discussions, ranging from cycling issues to the latest episode of the Midsomer Murders.

A warm thanks goes to my predecessor YongQiang Wei, both for his excellent work that paved the way for my research on dilute nitride lasers, as well as for sharing his semiconductor laser fabrication skills. Thank you Asa Haglund for always providing help with a big smile and in particular for all help with the electron-beam processing that enabled the fabrication of the two-color lasers. A special thanks goes to Mahdad Sadeghi for patiently growing all the epitaxial material and for having the ability to always cheer me up. I have spent a significant amount of time in the cleanroom and would like to thank the people of the Nanofabrication Laboratory for their excellent work that keeps the lab running. I have especially received a lot of good advice from Mats Hagberg who kindly has shared his immense processing knowledge. Zhonghe Lai is acknowledged for providing all the photomasks that I have used in my lithography processing. I would also like to thank all my co-authors for their contributions to the papers that this thesis is based upon. Ivar Tångring and QingXiang Zhao are acknowledged for their help and assistance regarding the use of the photoluminescence lab. Huan Zhao for our collaboration with the dilute nitride research. Carl-Magnus Kihlman for his skills in the workshop which has helped me perform many of my experiments. Jeanette Träff for being the best administrator one can imagine and for many enjoyable discussions regarding, for example, Gotland-vacations. I would also like to thank Magnus Karlsson and Pontus Johannisson for their help and guidance during my master thesis work, which really got me interested in continuing with PhD studies. Thanks also to Sheila Galt for letting me be in charge of her laser show during the science festival a couple of times. It was a great deal of fun!

I have the great fortune of working in an exciting and inspiring environment and for this I would like to direct a thanks to all past and present staff members at the Photonics laboratory. Many thanks to my fellow PhD students for all fun distractions both during and after working hours. I look forward to future movie nights with exciting themes, although I believe that the bikini-sci-fi theme will be difficult to beat. Thank you Ben for introducing the concept of courage drinking, it has been most helpful this winter! Thank you Calle Be, Rambo, Yuxin, Huan and Petter for making the trips to conferences and summerschools such nice memories.

I am deeply grateful to all friends and family who has reminded me about the world outside the office. I would like to direct a special thanks to Marie. If you had not convinced me that photonics was the field that I wanted to study, during that third year of our undergraduate studies, this thesis would never have been written. Thank you Filip and Anna for all the fun times we have had over the years and Martin for all those e-mail discussions regarding all nonessentials in life. Thank you, my fellow squash players Svante, David and Calle Be for many tough and long games at the squash court. During recent years I have had the great pleasure of escaping work and Gothenburg to spend time in both Abisko and Gotland. Thank you Dagrun and Staffan for all the nice vacations.
I have spent quite a lot of time in writing this thesis and many persons have cheered on me during this time. Thank you very much Lotta, Anna, Helena, Ida and all the rest, without your cheering it would not have been possible to finish it!

I would especially like to thank my parents Jonny and Mona and my sister Malin for always believing in me, in whatever I have chosen to do. Without your love and support I would not have come this far! Jag vill också tacka min mormor Ulla som brukade imponera med sina kunskaper om pi, och därmed uppmuntrade mitt matematikintresse (mormor, kika på sidan 16).

Finally I would like to thank my wife Ida for all her love. You are and will always be the mango of my life. Tôi yêu bạn.

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Göran Adolfsson

Göteborg
January 2011
List of acronyms

ATM  Asynchronous transfer mode
BA   Broad area
BAC  Band anticrossing
CD   Compact disc
CW   Continuous wave
DBR  Distributed Bragg reflector
DFB  Distributed feedback
DQW  Double quantum well
DVD  Digital versatile disc
DWELL Dot-in-a-well
EEL  Edge emitting laser
FP   Fabry-Perot
FPL  Fabry-Perot laser
FTTH Fiber-to-the-home
GB   Gigabyte
HP   Hakki-Paoli
HR   High reflectivity
IP   Internet protocol
LAN  Local area network
LASER Light amplification by stimulated emission of radiation
LED  Light emitting diode
MASER Microwave amplification by stimulated emission of radiation
MB   Megabyte
MBE  Molecular beam epitaxy
MOCVD Metal-organic chemical vapor deposition
MQW  Multiple quantum well
PL   Photoluminescence
QD   Quantum dot
QW   Quantum well
RF   Radio-frequency
RWG  Ridge waveguide
<table>
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<tr>
<td>SCH</td>
<td>Separate confinement heterostructure</td>
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<tr>
<td>SDH</td>
<td>Synchronous digital hierarchy</td>
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<td>SE-FPL</td>
<td>Spectrally engineered Fabry-Perot laser</td>
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<tr>
<td>SE-FPR</td>
<td>Spectrally engineered Fabry-Perot resonator</td>
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<tr>
<td>SMSR</td>
<td>Side-mode-suppression ratio</td>
</tr>
<tr>
<td>SNOM</td>
<td>Scanning near-field optical microscopy</td>
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<td>SONET</td>
<td>Synchronous optical network</td>
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<td>SQW</td>
<td>Single quantum well</td>
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<td>THz</td>
<td>Terahertz</td>
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<td>TMM</td>
<td>Transfer matrix method</td>
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"Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation, and amplification, and most importantly, its utilization for the benefit of mankind."

Pierre Aigrain, 1967
1 Introduction

1.1 Photonics applications

Ever since the invention of the laser, research and development in photonics have had an increasing impact on our society, and today photons are ubiquitously working for us in subtle as well as obvious ways. The versatility of light is reflected by the diversity of areas utilizing photonics with applications ranging from innovative and energy saving lighting systems to treatment and diagnosis in medical fields. Recent experiments have demonstrated that lasers even may be used to locally control the weather [3–5]. We continuously encounter photonics in our everyday life. On our way to the supermarket we are guided in traffic by color signals from light emitting diodes (LEDs) and at the supermarket lasers in bar-code scanners register the different groceries we buy. When it comes to information storage technology, focused light is today used to read and store data in different forms of optical memories like CD, DVD and Blu-Ray discs. The amount of data that can be stored is related to the wavelength of the light. By developing lasers emitting at shorter wavelengths the storage capacity has been increased from 650 MB on a CD, using a 780 nm wavelength laser, to 25 GB on a Blu-ray disc, using a 405 nm wavelength laser. Although the capacity could be increased by reducing the wavelength further, the next generation of optical storage discs will most likely exploit some of the unique properties associated with laser light, combined with nano technology, to read and write information in multiple dimensions. Devices capable of storing data in both three [6] as well as five dimensions [7] have e.g. already been demonstrated. Such multi-dimensional discs can have a storage capacity about 10000

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1 LASER is an acronym for Light Amplification by Stimulated Emission of Radiation
2 It is estimated that by 2015 solid state lighting, such as light-emitting diodes, could reduce the global amount of electricity used for lighting by 50% [1]
3 An example is the ability to diagnose diseases by analyzing the gas molecules in a patient’s breath using laser spectroscopy [2].
4 In the future, lasers are e.g. envisioned to be used to stimulate the formation of rain clouds in drought-stricken areas, or to guide lightning along a laser beam to create a safer environment for airplanes at airports.
5 The current discs only utilize 2 dimensions (the area of the disc).
times larger than a DVD, and are expected to emerge on the market within 5-10 years [8].

Ironically, despite the significant impact light has on our society most technologies that utilize photonics are invisible to us. This may come about either because the light emitting component emits in the infrared portion of the electromagnetic spectrum – as e.g. the light source used in a remote control – or because the light emitter is implicitly used, as the semiconductor laser that emits the (infrared) light used to transmit digital ones and zeros from, e.g., an iPhone to an Internet-connected computer, in order to update the current Facebook status of the iPhone user. The last example illustrates the dramatic change in our ways of communicating that rapidly has emerged during the last two decades. This is also the perhaps most noteworthy manifestation of how photonics have influenced our lives. Instantaneous and worldwide communication is today customary through the use of Internet as well as cellular phones connected through wireless communication networks. Today, almost all communication networks around the world are using optical technologies to transmit information in some part of the network. In an optical communication channel an electrical signal is first converted to the optical domain by a transmitter, and the ones and zeros carrying the information are subsequently sent in the form of light pulses through a very thin (a few µm core radius) light-weight fiber, made of glass or plastic, in which they are guided by total internal reflection. One of the main advantages of using fiber optical systems compared to their copper-wire based counterparts is the immense amount of information one can transmit. This is attributed to the extremely high frequency of the light and the tremendous amount of bandwidth provided by the optical fiber (> 30 THz). As a result of the inventions of the semiconductor laser [9–12], the low-loss optical fiber [13, 14] and the fiber-amplifier [15] it is possible to transmit light, utilizing a sizeable fraction of the available fiber bandwidth, over long distances (10’s of km) before the signal needs to be detected or regenerated. In addition, the propagation of light in optical fibers is not as susceptible to external electro-magnetic field disturbances as electrical transmission wires are.

As the information available on the Internet is increasing at a rapid pace\textsuperscript{6} there is a need to develop new photonics technologies that can meet an increasing demand for quicker access to the available information, requested by an increasing number of users. Although optical component technologies capable of transmitting information at faster bit rates are needed, a major concern is also the increasing power consumption, as well as increasing cost, that an expansion of communication system capacity is associated with. Future optical components must thus not only have an improved functionality but also perform the tasks required by them both at a lower power consumption and at a lower cost, compared to existing components [16]. The work presented in Papers A-D in this thesis touches upon this issue.

\textsuperscript{6}The entire information that can be accessed on the Internet today is estimated to be \sim 500 billion gigabytes, which corresponds to approximately two top-of-the-range iPods for every person on the planet [16]. An interesting remark is that Google has indexed about 0.004\% of this information [17].
as will be described later in this introduction.

Looking beyond information and communication technologies there are several emerging applications in e.g. manufacturing and medical fields that will require lasers offering new functionalities. Lasers are expected to improve solar cell efficiency (by using laser based processing technologies in the manufacturing of photovoltaic components), as well as aid in the early detection of diseases by enabling new and safer medical imaging methods [16]. Many applications will require lasers emitting at currently unaccessible wavelengths, with a prime example being lasers emitting so called terahertz (THz) radiation. THz radiation may be used for imaging in both medical and security applications with an advantage that it is much safer than X-rays but still can penetrate non-metallic coverings. The work in Papers E-F investigates concepts for tailoring the spectral characteristics of a semiconductor laser, which may be used to generate THz radiation.

1.2 Motivation for this work

Dilute nitride lasers

The transmitter is a key component in a fiber optical network and generically incorporates a semiconductor laser as the light emitter. One of the most important characteristics of the laser is its operating wavelength which needs to be matched with the specifications of the optical fiber. The quality of a light-signal sent through an optical fiber will inevitably deteriorate due to e.g. losses and chromatic dispersion (time stretching of pulses) and the effect of these phenomena is typically dependent on the frequency (wavelength) of the light. A vast majority of fiber-optical communication systems employ glass fibers, made of SiO$_2$, that are characterized by minimum dispersion and attenuation wavelengths of 1.3 $\mu$m and 1.55 $\mu$m, respectively$^7$ [18]. Semiconductor lasers used as transmitters in these systems are therefore typically designed to lase at one of these wavelengths in order to mitigate transmission impairments. This reduces system cost and complexity by diminishing the number of signal-quality improving components needed along the link, such as amplifiers or regenerators. The wavelength of choice depends on the transmission length of the system. For long-reach systems ($> 40$ km) it is more important to minimize losses and these systems thus provide the market for 1.55 $\mu$m semiconductor lasers. In medium-reach systems ($< 40$ km) the situation is the opposite, with dispersion effects being more significant, and 1.3 $\mu$m lasers are typically deployed. In short-reach systems (100’s of meters) one generally uses lasers emitting at around 850 nm. Optical fibers are deployed worldwide in large backbone networks connecting continents, countries and cities, and are thus constituting the core of the world’s communication system. The capacity of these core networks have experienced an extraordinary increase during the past decade and today 1-Tb/s systems are ready for commercialization [19] while in research

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$^7$These are commonly referred to as the telecommunication wavelengths.
laboratories state-of-the-art systems with bitrates of up to 69.1 Tb/s have been demonstrated\(^8\) [20]. In parallel with this development there has been a substantial increase in demand for increased bandwidth at the user end, as new multimedia services like video-on-demand, voice-over-IP, high-definition-TV etc. have begun to expand into our homes. It is expected that each user will require an individual bandwidth of more than 30 Mb/s in the near future [21], and within the European Union each user should have access to 1 Mb/s [16] today and 1 Gb/s in a longer perspective [22]. Unfortunately, the access-networks that are currently bridging the users and the core networks are based on copper-wires that are beginning to reach their bandwidth limitations. In order to solve this so-called "last-mile-bottleneck-problem" new access-network technologies needs to be implemented. One of the most promising is the fiber-to-the-home (FTTH) solution where optical fibers are installed all the way to the users [23]. This solution is however costly and in order to facilitate a widespread implementation of FTTH networks there is a strong need for developing cheap and fast semiconductor lasers emitting at 1.3 \(\mu\)m. Since FTTH presumably is the only solution that can meet the the expected bandwidth requirements on future access-networks it will inevitably provide the main future application for 1.3 \(\mu\)m lasers. It should however be mentioned that such lasers also have a future in other access-network topologies, such as e.g. wireless access through radio-over-fiber systems. As a reference for the reader Fig. 1.1 displays a schematic picture of various fiber optical communication networks at different levels, from the long reach core networks all the way down to the access-networks at the user end and local area networks at enterprises.

Today semiconductor quantum well (QW) lasers based on the InGaAsP/InP and InGaAlAs/InP material systems are extensively used as transmitters in most optical 1.3 and 1.55 \(\mu\)m communication systems. This is due to historical reasons since InP-based lasers emitting near 1.3 \(\mu\)m were the first ones to be installed in

\(^8\)This corresponds to more than 2000 DVDs per second!
commercial fiber optical systems at the beginning of the 1980s [18]. At that time there was no suitable GaAs-based material system available that could reach the 1.3–1.6 µm wavelength region (although GaAs-technology was more mature than its InP-counterpart). Research focus therefore switched from GaAs-substrates to InP-substrates and the quaternary InGaAsP compound, which was a perfect candidate since it had a narrow bandgap corresponding to the desired wavelength region and also could be grown with high quality due to its lattice-match with InP. This resulted in a rapid technological development of long wavelength InP-based lasers [24]. Nevertheless, there are several drawbacks associated with the InP material system. The relatively small refractive index contrast between the lattice matched layers of InGaAsP/InP heterostructures makes for instance the growth of distributed Bragg reflector (DBR) mirrors impractical, which severely complicates the fabrication of InP-based vertical-cavity surface-emitting lasers (VCSELs) [25]. This is rather unfortunate since the VCSEL has several beneficial properties such as low unit cost (related to on-wafer testing and screening), efficient light coupling to optical fibers (due to a low-divergent, circular beam), high modulation speed as well as low threshold current and power consumption [26], which have made VCSELs very successful in 850 nm applications and would be attractive to exploit also at 1.3 µm. A perhaps even larger disadvantage with InP-based materials is the small conduction band offset between InGaAsP and InP which facilitates thermally induced leakage of electrons over the heterostructure barriers and thereby increases the threshold current with temperature. An increase of the threshold current, $I_{th}$, will deteriorate the laser performance with e.g. a decrease of output power and modulation bandwidth. To solve this problem InGaAlAs/InP lasers are today used since the conduction band offset is larger compared to InGaAsP/InP. However, the thermal performance is still not good enough and it is therefore necessary to actively cool InP-based lasers during operation. In addition to increasing system complexity such active cooling circuitry consumes unnecessary power and is also very costly, which severely hampers the possibility of using InP-based lasers in future access-networks. In order to overcome these problems much research effort has during the last decade been aimed at exploring the possibilities of long wavelength emission on GaAs-substrates, thus switching back the focus from InP to GaAs-based lasers. GaAs-substrates are cheaper, larger and more robust, compared to InP-substrates, and also provide larger refractive index contrast which enables growth of highly reflective DBRs for VCSEL fabrication. The conduction band offset is furthermore larger for GaAs material systems, resulting in a strong electron confinement which profoundly improves the temperature stability of the lasers. The improved temperature performance opens up for uncooled operation of transmitters which would provide a significant improvement of cost- and power efficiency.

In order to reach long wavelength emission on GaAs-substrates, several novel gain materials have been suggested from which three main approaches can be identified: highly strained type-II band alignment GaAsSb QWs [27], self-organized In(Ga)As quantum dots (QD) [28] and GaInNAs QWs [29]. A promising candidate
has been the GaInNAs approach, where a small percentage of the As atoms in conventional InGaAs QWs is replaced with N atoms\(^9\). The incorporation of nitrogen gives rise to a bandgap bowing effect [30] that extends the emission wavelength beyond the maximum achievable (critical thickness limited) wavelength (\(\sim 1.25 \mu\text{m}\)) for strained InGaAs QWs [31–33]. Since the first proposal in 1996 by Kondow et al. [29], the development of \(\sim 1.3 \mu\text{m}\) edge-emitting GaInNAs lasers has been rapid and today uncooled operation up to 110 °C at bitrates of 2.5 and 10 Gb/s has been demonstrated using double QW (DQW) GaInNAs/GaAs lasers [34, 35]. Further performance improvements are however expected since the predicted temperature stability of this material system has only been achieved for limited temperature regions (\(T < 60 - 90 °\text{C}\)) and certain device structures. The modulation bandwidth of GaInNAs QW lasers has additionally been reported to be limited by thermal effects related to an increase of threshold current and/or reduction of differential gain with temperature [36]. Since the dynamic performance is of decisive importance for communication applications this emphasizes the significance of reducing the temperature dependence of the threshold current, \(I_{\text{th}}\). Besides having a weakly temperature dependent \(I_{\text{th}}\) it is also preferred to use multiple QWs (MQW) in the active region in order to obtain a good dynamic performance through improved differential gain. The work on dilute nitride QW lasers presented in this thesis has been an extension of previous research done in our group, which resulted in the development of high performance DQW GaInNAs lasers emitting at 1.28 \(\mu\text{m}\). In this thesis the emission wavelength is extended to 1.3 \(\mu\text{m}\), using three QWs in the active region for a higher differential gain (Papers A-B). Furthermore, an analysis of the temperature dependence of the threshold current is performed on our high quality DQW GaInNAs lasers (Papers C-D). The good temperature stability of GaInNAs lasers is usually attributed to a large conduction band offset as well as large amounts of defect recombination. This investigation, however, reveals that their good temperature stability also to a large extent arises from a significant and only weakly temperature dependent lateral diffusion current, which is not an effect intrinsic to GaInNAs but rather related to the geometry of the laser resonator.

### Spectrally engineered laser resonators

Conventional Fabry-Perot (FP) lasers inherently oscillate in several longitudinal modes simultaneously which is undesirable in many applications. Semiconductor lasers used as transmitters in fiber optical networks are e.g. required to emit predominantly in a single longitudinal mode since dispersion effects in the optical fiber otherwise deteriorate the transmitted signal. The enormous potential of optical communication technologies has led to large research efforts being invested in developing semiconductor single mode lasers. Longitudinal mode selection is typically achieved by designing the laser resonator to provide a wavelength selective feedback. Examples of developed single mode resonators include distributed feedback (DFB) [37,38], DBR [39] and coupled-cavity lasers [40–42]. The perhaps

\(^9\)These lasers are therefore commonly referred to as dilute nitride lasers.
most successful and familiar approach is the DFB laser which is used as the light source in most transmitters employed in 1.55 $\mu$m fiber optical systems today. In a DFB laser a periodic variation of the refractive index is introduced along the length of the resonator. The index grating provides a significantly enhanced feedback for a single longitudinal mode due to its very narrow reflectance spectrum. Another approach for obtaining mode selective feedback in FP lasers was initiated in 1990 when it was demonstrated that the introduction of a small number of refractive index perturbations along the waveguide in an FP laser had a significant influence on the lasing spectrum [43, 44]. This was shortly afterwards followed by demonstrations of single mode lasers based on FP ridge waveguide lasers with a few index perturbations introduced in the resonator by etching grooves on top of the ridge [45–48]. The technique was subsequently extended with a theory that made it possible to design these lasers with a pre-determined frequency selective feedback [49–52]. These spectrally engineered FP resonators (SE-FPR) differ from a DFB laser in that they require a significant reflection from the end facets of the resonator; the introduced pattern of index perturbations only provides a small, wavelength dependent, change of the resonator loss of the FP laser. The possibilities in spectral engineering offered by resonators of this type are, interestingly, not limited to the design of single mode lasers but can also be used to design more advanced resonators where the resonator loss is e.g. lowered for several selected modes. In particular it has been demonstrated that these resonators can be used to achieve simultaneous oscillation of two selected longitudinal modes [53]. Such so-called two-color lasers are of considerable interest in the optical generation of THz radiation. THz radiation is loosely defined as electromagnetic radiation with a frequency in the range 0.3-10 THz, and has during the last two decades been recognized to have several unique properties that make it very useful in a diverse range of imaging and spectroscopy applications. Examples include non-invasive tomography, semiconductor material characterization and detection of illegal or hazardous objects, such as drugs and explosives, to name a few [54–61]. Unfortunately THz radiation is very difficult to produce and the key hindrance for most terahertz technologies today is the lack of convenient high quality sources [62]. A possible way of producing THz radiation at room temperature is by photomixing two optical frequencies with a difference frequency in the THz-range. Such optical-to-THz converters typically employ two semiconductor laser sources that emit at slightly different wavelengths, with the difference frequency of the two wavelengths being the desired THz frequency. When the beams from the two laser sources are spatially overlapped and sent onto a nonlinear mixing device, such as a photoconductive antenna, the THz difference frequency is generated in a process referred to as nonlinear difference frequency generation [63]. For efficient THz generation the two mixed laser sources should have a narrow linewidth and sufficient wavelength stability with respect to each other [64]. From this aspect it is a clear advantage to generate the two optical frequencies in the same resonator. The feasibility of this was e.g. demonstrated in [65] where THz generation was generated by photomixing the output from a spectrally engineered FP laser designed for two-color lasing.
Previous treatments of spectrally engineered FP resonators have generally relied on an approximation assuming a weakly perturbed resonator which imposes limits on the number of index perturbations and thereby also limits the flexibility in engineering the resonator loss. This thesis investigates the possibilities offered by SE-FPRs by extending the treatment to also allow for strongly perturbed resonators (Paper E). For example, the design of SE-FPRs where either one or two modes are preferentially selected is investigated. It is found that very large reductions of the resonator loss can be obtained for selected modes, with the main feedback still provided by from the end facets. The fabrication tolerances are also investigated and lasers with SE-FPRs designed for single mode and two-color emission are realized (Paper F).

1.3 Organization of the thesis

The theoretical background for the thesis is covered in chapter 2. The work related to Papers A-D is covered in chapters 3 and 4 while the work related to Papers E-F is presented in chapter 5 and to some extent in chapter 6. The methods used for laser fabrication and characterization are given in chapter 6, followed by a summary of the appended papers in chapter 7.
2 Theoretical background

2.1 The LASER

As described in the previous chapter lasers are without doubt an integral part of our lives today, and new applications exploiting the extraordinary properties associated with laser light are continuously emerging. This section covers the basic operation and properties of a laser and also includes a brief historical perspective on laser development.

2.1.1 Einstein paved the way

Many scientists have throughout history made great efforts in attempting to elucidate the nature of light [66]. As a result of these efforts we today know that light can be understood as an electromagnetic wave that carries its energy in the form of a stream of energy quanta known as photons.\(^1\) A fundamental characteristic of any electromagnetic wave is its oscillating frequency \(\nu\) which determines both the wavelength \(\lambda = c/\nu\), where \(c\) is the speed of light, of the wave as well as the energy \(E_{\text{ph}}\) of a photon, increasing linearly with frequency according to \(E_{\text{ph}} = h\nu\), where \(h\) is the Planck constant. The wavelength of a light wave is typically defined to lie in the range from the ultraviolet (\(\lambda \sim 10\) nm) to the far infrared (\(\lambda \sim 100\) \(\mu\)m) portion of the electromagnetic spectrum, thus extending way beyond the narrow range of visible wavelengths that our eyes can detect (400 nm \(\lesssim\) \(\lambda\) \(\lesssim\) 700 nm).

One of the many great scientific achievements of the 20th century was the development of a theory for how light interacts with matter, and in particular how photons have the ability to stimulate emission of identical photons from excited atoms – a process which constitutes an essential building block of a laser. The theory of stimulated emission was first discussed by Albert Einstein in a paper from

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\(^1\)The concept of energy quanta for light was introduced by A. Einstein 1905 [67] but the term \textit{photon} was not introduced until 1927 by G. N. Lewis [68]. Although doubts of the existence of photons do exist [69], the wave-particle duality is today widely accepted. As Richard Feynman once supposedly said before giving a lecture on quantum electrodynamics: "I hope you can accept Nature as She is – absurd".
1917 in which he proposed three different processes by which atoms interact with radiation: absorption, spontaneous emission and stimulated emission [70]. During absorption a photon is annihilated and its energy is transferred to the absorbing material by raising a bound electron from a lower energy state to a higher energy state, thus creating an excited atom. The energy difference between the two electron states must be identical to the photon energy in order for energy to be conserved. The opposite process can occur if an electron occupies a higher energy state. The electron will sooner or later drop to a lower energy state and may release its energy by emitting a photon with an energy identical to the energy difference between the two states. Einstein realized that the electron can either make the transition spontaneously after some random amount of time (typically on the order of nanoseconds) or it can be stimulated to make the transition by the mere presence of a photon. He referred to these two different processes as spontaneous and stimulated emission, respectively. Due to the random nature of the spontaneous emission process a spontaneously emitted photon has a random polarization, phase and propagation direction, causing the emitted light to be incoherent (unpredictable). Incoherent light sources are typically used for illumination or signaling purposes and familiar everyday examples are the sun, incandescent light bulbs and LEDs. The randomness associated with a spontaneously emitted photon stands in stark contrast to a photon emitted through stimulated emission which is completely identical, in terms of frequency, phase, polarization and propagation direction, to the photon that provided the stimulus. Radiation originating from stimulated emission is therefore highly coherent (predictable) and monochromatic (contains only a single frequency), and these unique properties make laser light so useful.

From the above discussion it is clear that a single frequency light beam incident on a collection of atoms, e.g. a gas or a solid-state material, will either be absorbed or amplified by stimulated emission if the energy of the incident photons is large enough to induce a transition in energy for an electron. In his paper Einstein showed that the probability of absorption is identical to the probability of stimulated emission of an excited atom, which means that it is only the initial state of the atoms that determines whether the light beam is absorbed or amplified. For a medium in thermal equilibrium a majority of the atoms are in their ground state and a light beam propagating through the medium will thus experience net absorption and have its intensity reduced. If however a majority of the atoms are excited, a situation referred to as population inversion, the light beam will instead experience net gain and its intensity will be amplified during propagation. The change in intensity $I$ as a function of distance $z$ is given by $I(z) = I_0 \exp(gz)$, where $I_0$ and $g$ denote the initial intensity and material gain, respectively. A medium with a population inversion (a gain medium) can be created by supplying energy to it in a process called pumping, which for example can be done optically, using a high energy light source, or electrically, by injecting an electrical current through the medium.
2.1.2 How it works

A laser is constructed by placing a gain medium inside an optical resonator (also called a cavity), which in the simplest case consists of two plane-parallel mirrors separated by a distance that is typically much longer than the wavelength of the laser light. This resonator configuration resembles that of a regular Fabry-Perot interferometer and is therefore referred to as an FP resonator. The purpose of the resonator mirrors is to provide optical feedback by reflecting photons generated in the gain medium back into the resonator where they can stimulate emission of new photons. As a beam of light is propagating back and forth between the mirrors it is thus coherently amplified by the gain medium (provided that the latter is continuously pumped since stimulated emission otherwise rapidly would reduce the population inversion until eventually it is lost, and the gain medium provides net absorption). If the amplification is high enough such that it compensates for all losses experienced by the light beam during a round trip in the resonator, a standing light wave is sustained between the mirrors, and the system – comprising the gain medium and the resonator – operates as a laser. The useful laser beam is obtained as the light transmitted through either one or both of the resonator mirrors, which typically are designed to be slightly transparent. The resonator loss that needs to be overcome by the gain in order to achieve lasing includes internal optical loss during propagation inside the resonator – caused e.g. by light absorption and scattering – as well as the useful laser light that is coupled out from the mirrors, referred to as mirror loss. The amount of gain needed for this is referred to as threshold gain. A generic laser is displayed in Fig. 2.1, illustrating the above mentioned concepts.

2.1.3 The early days

Achieving oscillating waves of stimulated emission inside a resonator was first demonstrated at microwave frequencies by Gordon et al. in 1954, who used excited ammonia molecules as the gain medium in a maser³ that produced coherent output at 24 GHz [73]. The success with the maser triggered a lot of interest in extending the concept to optical frequencies, for which one of the problems considered was to find a suitable resonator for the much shorter wavelength radiation. The problem was that any resonator of reasonable size had dimensions much larger than the wavelength of the radiation and consequently supported a vast number of modes. The total amount of pump power required to sustain stimulated emission of a few wanted modes was therefore expected to be unreasonably high, since a very

²Perot used the spelling Pérot in scientific publications but according to the French civil registry his family name was Perot, without accent [71]. Despite the importance of the FP resonator (basically all lasers are based on FP resonators in various forms) the work and lives of Fabry and Perot are generally not well known to the average laser researcher. The curious researcher is therefore encouraged to read the paper in reference [72].

³MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation.
Figure 2.1: Schematic of a generic laser comprising a pumped gain medium inside an optical FP resonator defined by two partially reflective plane-parallel mirrors separated by a distance $L$. The resonator length is typically much larger than the wavelength of the laser light, i.e. $L \gg \lambda$.

large portion of the pump power would be lost to unwanted spontaneous emission (at microwave frequencies this was not an issue since only a few modes exist in a typical maser resonator) [74]. The problem was solved towards the end of the 1950s when suggestions of using a resonator with two plane-parallel mirrors to provide feedback were made (independently) by A. M. Prokhorov [75], R. H. Dicke [76] and G. Gould, as well as A. Schawlow and C. Townes who 1958 published a detailed proposal for what they referred to as an optical maser [74]. In their paper they concluded that an FP resonator would effectively suppress most of the spontaneous emission by providing a significantly enhanced feedback to modes propagating in a direction perpendicular to the mirrors. By using a proper separation and size of the mirrors Schawlow and Townes showed that the directional feedback would make it possible to sustain stimulated emission of many modes simultaneously in a laser, with a reasonable amount of pump power. The first laser utilizing an FP resonator was realized two years later in 1960 by T. Maiman who used a 2 cm long ruby crystal as both gain medium and resonator [78–80]. Maiman pumped the crystal with intense light pulses from a flashlamp and used its end facets as mirrors (coated with highly reflective silver) to obtain monochromatic and coherent output at $\lambda = 693.3$ nm. The intense pulses of red light emitted by the first ruby lasers immediately found an application and was used in the first laser eye surgery performed on a human as early as 1961 [77].

\[4\] Gordon Gould coined the word *laser* in a notebook notarized on November 13, 1957 [77].

\[5\] A laser was still expected to oscillate in a far many more modes than a maser.

\[6\] Maiman initially measured the output power in "gillettes", the number of razor blades that the laser pulses could burn a hole through [77].
The progress in laser development was rapid during the years following the birth of the ruby laser. Lasers capable of emitting continuous wave (CW) radiation were soon demonstrated [81] and the wavelength region covered by lasers was extended from visible to infrared wavelengths using a large variety of optical gain media. Gas lasers, solid-state lasers and semiconductor lasers are some examples of groups of lasers that branched out from the original concept (classified according to their optical gain medium). Among these, semiconductor lasers quickly emerged as a very promising class of lasers owing to several attractive properties, such as e.g. a very high optical gain and a high efficiency (a semiconductor laser typically has an efficiency >30% which can be compared to typical efficiencies of a few percent associated with gas and solid-state lasers). The large achievable optical gain enables a very small device size (a semiconductor laser can be made smaller by a factor of several thousand compared to a gas laser that produces the same output power), which renders the semiconductor laser a very compact and efficient light source that can be fabricated at large quantities at a low cost. Semiconductor lasers can additionally be tailored to achieve emission at in principle any wavelength over a wide spectral range, as will be further discussed in the next section which aims at describing the properties of semiconductor lasers in more detail.

2.2 Semiconductor lasers

Semiconductor lasers are typically fabricated from compound semiconductors found in the third and fifth column in the periodic table, referred to as III-V compounds. Research in light emission properties of III-V compounds dates back to 1955, when the first observation of light emission from GaAs, GaSb and InP upon current injection was made [82]. The possibility of achieving light amplification by stimulated emission in semiconductors was subsequently discussed by e.g. Basov et al. [84, 85], Dumke [86] and Bernard and Duraffourg who in 1961 presented a quantitative description of the requirements for lasing in semiconductors [87].

Experimental progress was however slow with the early work on light emission from semiconductors being plagued by very poor radiative efficiencies. This issue was however resolved in 1962 when highly efficient recombination radiation from a GaAs $p$-$n$-junction was demonstrated ($p$-$n$-junctions had not been considered earlier) [88]. This demonstration really paved the way for the semiconductor laser development and later that year four research groups demonstrated the first semiconductor lasers, based on $p$-$n$-junctions in GaAs [9,10,12] and GaAsP [11] crystals. These early semiconductor lasers were homojunction devices that operated only under pulsed conditions at very high current densities ($50 - 100$ kA/cm$^2$) and consequently suffered from extremely poor lifetimes (on the order of minutes). Much research effort was therefore directed towards improving laser characteristics, with a major breakthrough being the proposal by Kroemer [89] of using heterostructure
junctions to confine injected carriers. The introduction of the so called double heterostructure laser increased the efficiency substantially and eventually led to the first lasers operating under CW conditions at room temperature in 1970 [91,92]. Device lifetime was subsequently increased to > 100 years in 1978 which really turned the semiconductor laser into a device suitable for applications [93]. Comprehensive research has since then been invested in semiconductor laser development and, as mentioned, this has resulted in a large variety of lasers with different functionalities that have found their use in many different applications.

After this very brief historical review the remaining parts of this chapter will provide a short description of basic properties and physics of semiconductor lasers that are relevant for the work presented in this thesis.

2.2.1 Basic properties

Bandstructure

As a manifestation of the crystalline nature of semiconductors the energy levels that electrons can occupy form energy bands with very densely spaced states, as opposed to the discrete energy levels of atoms in e.g. gas lasers. In all semiconductors there exists a range of energies where there are no electronic states and this region is referred to as the bandgap $E_g$ of the material. In a semiconductor laser the electron transitions associated with the fundamental emission and absorption processes occur between the energy bands directly below and above $E_g$, referred to as the valence and conduction bands, respectively. The operating wavelength of a semiconductor laser is therefore essentially determined by the bandgap through the relation $E_g = h \frac{c}{\lambda}$, where $c$ is the speed of light.

The valence band is completely occupied at a temperature $T = 0$ K. When the temperature increases, or energy is supplied to the material in some other way, electrons may gain enough energy to make a transition across the bandgap and occupy a state in the conduction band. This leaves a vacancy in the valence band referred to as a hole. Holes in the valence band can contribute to conduction, just as electrons in the conduction band, and may therefore be treated as positive charge carriers. An electron in the conduction band can make a transition to fill an empty state in the valence band in a process referred to as electron-hole recombination. The recombination can either be radiative, in which a photon is produced, or non-radiative, in which phonons (lattice vibrations) are generated and the energy lost by the electron is released as heat. The electronic states in a semiconductor are described by its bandstructure, which expresses the electron energy $E$ as a function of its wave vector $k$. A simplified model of the bandstructure, valid for small $k$-values, assumes a parabolic dependence of band energy on electron wave vector according to $E(k) = \frac{\hbar^2 k^2}{2m^*}$, where $m^*$ denotes the effective mass of the carrier in the considered energy band (electron or hole). In

\footnote{Alferov also came up with the idea of heterostructures independently from Kroemer and both of them were later awarded the Nobel prize in physics for their discoveries [90]}
many cases it is sufficient to consider a three band model in which one conduction band and two valence bands (the heavy hole band and the light hole band) are included. This is illustrated in Fig. 2.2 where it can be seen that the conduction band minima (at \( k = 0 \)) has been drawn to coincide with the valence band maxima in \( k \)-space. This is referred to as a direct bandgap, otherwise the material is said to exhibit an indirect bandgap. Materials with an indirect bandgap exhibit a very low radiative efficiency while materials of direct bandgap can have a very high radiative efficiency, which is related to constraints of energy and momentum conservation of the photon and electron involved in a transition. For this reason semiconductor lasers are always made of direct bandgap materials\(^9\). A more detailed description of the bandstructure in semiconductors is given in reference [95].

\( ^9 \)It may be noted that semiconductor lasers recently have been developed using Ge, which has an indirect bandgap, as gain material. In this case the Ge bandstructure was however modified to obtain a direct bandgap lasing transition [94].

**Active region design**

The gain region in a semiconductor laser, also called the active region, consists of an intrinsic, smaller bandgap semiconductor layer embedded between \( p- \) and \( n- \) doped materials of higher bandgap. This forms a \textit{pin}-doped double heterostructure that effectively confines both carriers and photons; carriers are confined due to the conduction and valence band offsets between the active (intrinsic) region and the surrounding barriers, while photons are confined due to a higher real part of the
Figure 2.3: Simplified bandgap structure for a separate confinement heterostructure laser with a QW active region. The overlap between the optical mode and the active region is indicated with the shaded grey area. The increase in bandgap energy due to quantization is also shown.

refractive index for the active region. If the thickness of the active region is made much smaller than the de Broglie wavelength of an electron, in practice $\lesssim 20$ nm, the motion of electrons will be restricted along this dimension. This creates a potential well where carriers are confined in a very narrow region – known as a quantum well – with the depth of the QW depending on the band offsets between the well and the surrounding barriers. The depth of the QW is usually given as the conduction band offset, which is defined as $Q_c = \Delta E_c / \Delta E_g$ where $\Delta E_c$ is the QW depth and $\Delta E_g$ is the difference in bandgap between the QW and the surrounding barriers. The restriction in carrier movement results in a quantization of the energy levels according to $E_n = E_n + \hbar^2 k_{||}^2 / 2m^*$, where $k_{||}$ is the electron wave vector in the direction parallel to the QW and the quantization energy is approximately$^{10}$ given by $E_n = \pi^2 \hbar^2 l^2 / 2m^* L^2$, where $l \in \mathbb{N}$ and $L$ denotes the width (thickness) of the QW. The energy quantization effectively increases the bandgap of the QW, such that it is defined by the difference in energy between the first quantized state in the conduction band and the corresponding state in the valence band. Since $E_n$ depends on the width of the QW one can thus to some degree tailor the emission wavelength of the active region simply by changing its thickness. As an additional advantage the quantization effects also modify the density of states such that the total number of states is lower compared to a bulk semiconductor, which makes it easier to achieve a population inversion. Since a quantum well is too thin to

$^{10}$This expression for $E_n$ is found by solving the Schrödinger equation for an electron in an infinitely deep potential well. In reality, the well depth is finite and the quantization energies become somewhat lower. [95]
provide efficient photon confinement QW structures are usually embedded between materials of even larger bandgap, thus creating a double heterostructure inside another double heterostructure. In this case the QW structure confines the carriers while the surrounding barriers provide the photon confinement. This is referred to as a separate-confinement heterostructure (SCH) and has the advantage that carriers are confined where the optical field has its maximum (see Fig. 2.3), which translates into a very efficient stimulated emission process that reduces the amount of injected current needed to achieve lasing. By incorporating strain in the QW layer further enhancements in laser performance can be achieved, which will be discussed in section 2.2.3. Due to the many advantages, QWs have since their first realization [96, 97] evolved to be one of the most commonly used active gain materials in semiconductor lasers today.

Optical gain

By forward biasing the pin-junction carriers will diffuse towards the junction and accumulate in the active region where the excess carriers can recombine. In order to achieve gain the injection level must be high enough to create a population inversion. The condition for this to happen can be derived by considering the occupation probability of energy states in the conduction and valence band. This is given by a Fermi-Dirac distribution [98,99]

\[ f_{c(v)}(E) = \frac{1}{1 + \exp \frac{E-E_{F_{c(v)}}}{k_B T}}, \]  

(2.1)

where \( E_{F_{c(v)}} \) denotes the quasi Fermi level for the conduction (valence) band, defined as \( f_{c(v)}(E_{F_{c(v)}}) = 0.5 \) and \( k_B \) is the Boltzmann constant. When population inversion occurs the probability to find an electron at a conduction band state is higher than the probability to find it at a valence band state, which is expressed simply as \( f_c > f_v \). By using Eq. (2.1) this leads to the so called Bernard-Duraffourg condition for achieving population inversion [87]

\[ E_g < E_{ph} < E_{F_c} - E_{F_v}. \]  

(2.2)

The separation between the quasi Fermi levels is controlled by injecting excess carriers into the active region, and increases with carrier density \( n \). By injecting carriers such that the quasi Fermi levels are separated by the bandgap energy, transparency is reached and the injected carrier density is referred to as the transparency carrier density \( n_{tr} \). With a further increase in \( n \), the material will provide optical gain for photon energies according to the Bernard-Duraffourg condition. The bandwidth over which optical gain is achieved thus increases with carrier density, simply because more states are populated at higher energy. The maximum material gain also increases with \( n \) and for QWs the increase is typically modeled to be sublinear, according to

\[ g = g_0 \ln \frac{n}{n_{tr}}, \]  

(2.3)
Figure 2.4: Calculated material gain dispersion as a function of carrier density for an InGaAs/GaAs QW (a) and the corresponding peak material gain (b). The gain curves were calculated using the model described in [100]. The parameters $g_0$ and $n_{tr}$ were found by a best fit to the maximum gain of these curves.

where $g_0$ is a material gain coefficient [100]. This is illustrated in Fig. 2.4 which shows calculated material gain dispersion curves as a function of carrier density for an InGaAs/GaAs QW.

Threshold gain

At lasing threshold the round trip gain experienced by a light wave exactly balances the total resonator loss, $\alpha$, which includes the internal optical loss and the out coupling loss through the resonator mirrors (mirror loss). Since the active region in a semiconductor laser is very thin, only a fraction of the optical mode intensity will experience gain, as illustrated in Fig. 2.3. This is accounted for by a confinement factor $\Gamma$ which is defined as the overlap of the optical field distribution with the active region. The threshold gain is then given by

$$\Gamma g_{th} \triangleq g_{\text{modal},th} = \alpha, \quad (2.4)$$

where $g_{\text{modal},th}$ is referred to as the threshold modal gain.

2.2.2 Carrier transport and recombination

When carriers are injected in a semiconductor laser they will be transported from the injection contacts to the active region where they can recombine. The natures of the transport and recombination mechanisms are of importance for the device performance and will therefore be described in this section.
Carrier transport

Transport of carriers in a specific direction requires the existence of either an electric field, which causes a drift current where electrons and holes move in different directions (with electrons moving in the direction opposite to the field), or a concentration gradient which gives rise to a diffusion current with carriers moving from a region of high concentration to a region of lower concentration. The total current in a semiconductor under the influence of both drift and diffusion is given by the current density equation

\[ J_{\text{total}} = J_e + J_h, \]

where the current density of electrons is given by

\[ J_e = qn \mu_e E + qD_e \nabla n, \]

and the current density of holes is given by

\[ J_h = qp \mu_h E - qD_h \nabla p. \]

Here \( n, p, \mu \) and \( D \) denote the electron and hole concentration, mobility and diffusion coefficient, respectively, and the electric field is represented by \( E \). The mobility is related to the velocity of the carriers and is a measure of how easily the carriers can move in the material under an electric field of moderate strength. The motion of carriers is restricted by carrier scattering caused by e.g. charged impurities, lattice vibrations and lattice defects. In a material of good quality carrier scattering is reduced which increases the mobility. The mobility is related to the diffusion coefficient through the Einstein relation,

\[ \frac{D}{\mu} = \frac{k_B T}{q}, \]

which holds for both electrons and holes.

When electrons and holes are injected uniformly in the active region they will diffuse laterally along the active layer. This transport is typically described as ambipolar diffusion, which is a purely diffusive process in which electrons and holes are transported in pairs with an ambipolar diffusion coefficient given by

\[ D_a = \frac{2D_e D_h}{D_e + D_h}. \]

Equation (2.9) assumes charge neutrality \( (n = p) \), which usually is the case for the active region in semiconductor lasers, and is easily obtained from Eq. (2.5)–(2.8) by using that \( J_{\text{total}} = 0 \) for ambipolar diffusion.

Recombination processes

Carriers in the active region can recombine either spontaneously or through stimulated emission. While stimulated recombination by definition is a radiative process,
Figure 2.5: Different radiative and non-radiative recombination processes in a direct bandgap semiconductor. (a) Spontaneous emission (b) Stimulated emission (c) Defect recombination via deep levels. (d) An Auger recombination process in which two electrons in the conduction band collide. The collision knocks one electron down to the valence band and the other to a higher energy state in the conduction band. The high-energy electron eventually thermalizes back down to the bottom of the conduction band and produces heat.

Spontaneous recombination processes can be either radiative or non-radiative. The total spontaneous recombination rate $R_{sp}$ can therefore naturally be written as

$$R_{sp} = R_{\text{radiative}} + R_{\text{non-radiative}}.$$  \hspace{1cm} (2.10)

Spontaneous emission occurs when a recombining electron-hole pair emits a photon. Due to the involvement of two carriers the radiative recombination rate is proportional to the excess carrier densities of both electrons and holes

$$R_{\text{radiative}} = B n^2,$$  \hspace{1cm} (2.11)

where $B$ is the radiative, also called bi-molecular, recombination coefficient and charge neutrality has been assumed. The value of $B$ depends on the band structure with typical values being on the order of $\sim 10^{-10}$ cm$^3$s$^{-1}$. The non-radiative recombination rate is given by

$$R_{\text{non-radiative}} = A n + C n^3,$$  \hspace{1cm} (2.12)

which highlights the fact that there are two types of non-radiative recombination processes. The first one involves only one carrier and is related to recombination at defects, impurities, surfaces and interfaces. Defects introduced to a crystal through either impurities or dislocations create electronic states within the bandgap where they act as trapping centers for carriers. The theory for recombination through such deep levels, which was developed by Shockley, Read and Hall [101,102], shows that the recombination rate is proportional to the excess carrier density. A surface
acts as a huge lattice defect and creates a high density of non-radiative recombi-
nation states within the bandgap that reduces the carrier concentration close to
the surface. Recombination at surfaces and interfaces is also proportional to the
carrier density and one usually accounts for all the above mentioned non-radiative
recombination processes through a single defect recombination coefficient, denoted
by $A$. The value of $A$ is highly dependent on the quality of the material and can
be in the range $\sim 10^7 - 10^9 \text{ s}^{-1}$. The second type of non-radiative recombina-
tion is called Auger recombination. This is a three carrier process which makes
it proportional to the cube of the excess carrier density, with the proportionality
constant denoted $C$. This constant is called the Auger recombination coefficient
and its value is, just as $B$, dependent on the band structure with typical values in
the range $\sim 10^{-30} - 10^{-29} \text{ cm}^3\text{s}^{-1}$. In an Auger process [103] the excess energy
released through an electron-hole pair recombination is transferred to either a free
electron in the conduction band or a free hole in the valence band. These carriers
are subsequently raised to a higher energy level where they will lose the energy by
multiple phonon emission, which generates heat. Auger recombination increases
rapidly with both temperature and decreasing bandgap and is therefore one of the
most significant processes that deteriorate device performance at high temperatures
for long wavelength ($\lambda > 1.3 \mu\text{m}$) lasers. Figure 2.5 illustrates some of the radiative
and non-radiative recombination processes that can occur in a semiconductor.

In general, all of the recombination coefficients will depend on temperature.
The Auger recombination coefficient is usually the most temperature sensitive co-
efficient and increase exponentially with temperature for bulk material with low
bandgap. However, for QW material $C$ has a weaker temperature dependence and
increases linearly or superlinearly [104]. The $A$ and $B$ coefficients typically exhibit
a much weaker temperature dependence with $B$ typically decreasing with temper-

ature for most common gain materials [105], while $A$ slightly increases ($A$ may in
some cases even be virtually independent on temperature).

2.2.3 Gain materials

In order to identify the active gain materials that can be used for achieving emission
at a particular wavelength one needs to know two basic properties of the material;
the bandgap energy and the lattice constant. For efficient radiative recombination
the material must be of direct bandgap and have a lattice constant similar to the
substrate it is grown upon, at the wanted transition energy. The lattice matching
constraint stems from the fact that a large mismatch between the substrate and
the layered material may result in a significant amount of lattice defects. Since
this severely reduces the radiative recombination efficiency the relative difference
in lattice constant is typically required to be less than 0.1% [106]

$$\frac{\Delta a}{a_0} = \left|\frac{a - a_0}{a_0}\right| < 10^{-3},$$

(2.13)
Figure 2.6: Relation between bandgap energy and lattice constant for some of the ordinary III-V semiconductors. All material parameters are taken from [108, 109] except for GaInNAs which is merely schematically drawn, along with the indicated region of pseudomorphic growth. The two arrows illustrate the process of growing GaInNAs by first incorporating as much In as possible in an InGaAs QW and subsequently adding N to further reduce the bandgap.

where $a_0 (a)$ denotes the lattice constant of the substrate (grown material) and $\Delta a = a - a_0$ is the lattice mismatch. The amount of lattice defects that is generated is dependent on the thickness of the grown material and it is in fact possible to grow very thin films with a larger lattice mismatch than the one given by Eq. (2.13). A relative lattice mismatch of a few percent can be accommodated up to a certain critical thickness $h_c$, which typically is a few hundred Ångström. Above $h_c$, the accumulated strain energy is released through misfit dislocations and the material generally becomes useless for device applications [107]. The critical thickness is dependent upon the amount of lattice mismatch and decreases with increasing $\Delta a$. For thicknesses below $h_c$, the film becomes elastically deformed to fit the lattice constant of the substrate, which introduces strain in the material. The strain can either be tensile or compressive depending on whether the lattice constant of the grown film is expanded or compressed in the plane perpendicular to the growth direction, respectively. Compressive strain increases the bandgap and lifts the valence band degeneracy such that only heavy holes take part in band-to-band recombination, while tensile strain has the opposite effect [100]. The ability to grow defect-free thin layers with strain is called pseudomorphic growth and is very attractive since it, to some extent, relaxes the restriction of lattice matching and enables new emission wavelengths to be reached. In addition, introducing strain in the active region is...
advantageous in terms of device performance [110,111], which has made strained QWs the active gain region of choice in most semiconductor lasers today. Thanks to a reduced effective hole mass, strained QW lasers exhibit for example lower transparency carrier density and significantly higher differential gain, \(dg/dn\), compared to unstrained devices [100,111]. Both the reduction of \(n_{tr}\) and the improvement of \(dg/dn\) can be as large as a factor of 2 [100]. As a result, strained QWs are more efficient (due to a reduced non-radiative recombination caused by the lower \(n_{tr}\)) and can be modulated at higher speed (due to the increased \(dg/dn\)).

With advances in epitaxial growth techniques such as MBE\(^{11}\) and MOVCD\(^{12}\), the extra degree of freedom in bandgap engineering\(^{13}\) enabled by pseudomorphic growth has become feasible to employ. This has for example opened up the possibility of achieving 1.3 \(\mu\)m emission from active gain materials grown on GaAs substrates, which traditionally has been difficult because of a lack of lattice matched semiconductors to GaAs for wavelengths \(\gtrsim 1 \mu\)m. This is illustrated in Fig. 2.6 which shows the relations between the bandgap energy, the emission wavelength and the lattice constant for the III-V semiconductor compounds relevant for 1.3 \(\mu\)m emission. The potential candidates are found at the intersections of the dashed horizontal line with the solid lines representing different direct bandgap semiconductor alloys. Figure 2.6 shows that lattice matched growth for 1.3 \(\mu\)m emission can be achieved with InGaAsP grown on InP. For growth on GaAs one is in principle restricted to using pseudomorphic growth to reach 1.3 \(\mu\)m and the possible semiconductors are GaAsSb, InGaAs and GaInNAs. The first part of this thesis deals with GaInNAs QW lasers and this material system will be described in more detail in the next chapter.

2.2.4 Resonators

The main purpose of a resonator is to provide optical feedback and to define the optical mode(s), thereby also controlling the beam characteristics, such as e.g. the shape of the emitted beam. In all resonators two groups of modes exist. Longitudinal modes have the same transverse field distribution but a different integer number of half wavelengths along the propagation axis. For each longitudinal mode there is also a set of transverse modes that have different transverse field distributions. A laser resonator is usually designed to provide some sort of mode selective feedback and wave guiding. Many different types of laser resonators have been developed and they are usually divided into two groups; resonators for edge-emitting lasers (EELs) and resonators for surface emitting lasers, depending on whether the light wave propagates parallel or perpendicular to the active region, respectively. This thesis deals with edge-emitting lasers and this section introduces three of the most common types.

\(^{11}\)Molecular Beam Epitaxy

\(^{12}\)Metal-Organic Chemical Vapor Deposition

\(^{13}\)Tailoring the emission wavelength of a laser by growing suitable heterostructures is called bandgap engineering.
The simplest semiconductor EEL is based on an FP resonator and is hence referred to as an FP laser. The FP resonator is typically defined by cleaving the semiconductor crystal along specific atomic planes and the mirrors are thus formed by the semiconductor-air interface. The power reflectivity of such a mirror is given as a Fresnel reflectivity

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

where $n$ is the refractive index experienced by the optical mode inside the resonator. For a GaAs-air interface $R \approx 30\%$ although the reflectivity can be changed by applying a coating on the mirror. The reflectivity of the cleaved mirrors is nearly wavelength independent which tends to make FP lasers lase at multiple longitudinal modes, since many modes fit within the material gain bandwidth and the gain difference between neighboring modes is too small to provide sufficient mode selection.

Carrier injection is performed through a stripe metal contact$^{14}$ deposited on the top of a ridge, as illustrated in Fig. 2.7. The purpose of the ridge is to provide lateral waveguiding by introducing a lateral index-discontinuity. FP lasers can be classified according to the width of the ridge. Lasers with a fairly wide ridge, typically larger than 20 µm, are commonly referred to as broad area (BA) lasers. In addition to supporting several longitudinal modes BA lasers also support many transverse modes. Since this deteriorates the laser beam quality BA lasers are typically only used for assessing material quality. By making the laser ridge very narrow (a few µm) one can force the laser to support only one transverse mode and such lasers are usually referred to as ridge waveguide (RWG) lasers.

In addition to single transverse mode operation many applications also require that the laser emits in a single longitudinal mode. Several resonators have been developed to achieve this and two examples are the DFB and DBR resonators [37–39],

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$^{14}$The stripe geometry contact was proposed by Dyment in 1967 in order to improve the laser beam quality [112].
Figure 2.8: Schematic drawing of DFB (a) and DBR (b) resonators.

illustrated in Fig. 2.8. In a DFB laser the feedback is provided by a grating incorporated along the waveguide. The grating, which consists of a periodic variation of the refractive index, has a very narrow reflectance spectrum which results in single longitudinal mode oscillation. A DBR laser is a variation on the DFB resonator where the gain section is spatially separated from the feedback grating. A DBR laser can therefore be viewed as a conventional FP laser with the cleaved FP mirrors replaced by wavelength selective grating reflectors.

2.2.5 Threshold current

An extremely important parameter of a semiconductor laser is the threshold current $I_{th}$ which represents the injection current needed to achieve lasing. The threshold current can be calculated from a rate equation for the injected carriers

$$\frac{dn}{dt} = \eta_i I_{inj} - R_{sp} - R_{st} - R_{leak},$$  \hspace{1cm} (2.15)

where $\eta_i$, $I_{inj}$, $V$, $R_{st}$ and $R_{leak}$ denote the internal quantum efficiency, injection current, active region volume, stimulated emission rate and carrier leakage rate, respectively. The internal quantum efficiency represents the fraction of the injected carriers that reaches the active region, which is defined as the region where recombining carriers contribute to useful laser gain. Carrier leakage represents carriers that escape the active region and recombines elsewhere. By considering the steady-state ($dn/dt = 0$) solution of (2.15) at threshold we can neglect stimulated emission and obtain

$$I_{th} = \frac{qV}{\eta_i} \left[ An_{th} + B n_{th}^2 + C n_{th}^3 \right] + I_{leak},$$  \hspace{1cm} (2.16)

where $n_{th}$ is the threshold carrier density and $R_{sp}$ has been expressed using Eq. (2.11)-(2.12). For a QW active region $n_{th}$ is found from Eq. (2.3) and Eq. (2.4)

$$n_{th} = n_{tr} \exp \frac{\alpha}{\Gamma g}. $$  \hspace{1cm} (2.17)

Equations (2.16)-(2.17) show that it is desirable to have high internal quantum efficiency and a large confinement factor, while internal and mirror losses, the active
region volume as well as the transparency carrier density and leakage current should be minimized. Note that (2.16) only is valid for the case of a single QW (SQW) in the active region. If multiple QWs are used both $V$ and $\Gamma$ should be multiplied with the number of QWs used.

A common measure of laser material quality is the threshold current density, $J_{\text{th}}$, defined as

$$J_{\text{th}} = \frac{I_{\text{th}}}{wL},$$

(2.18)

where $w$ and $L$ denote the width and length of the laser, respectively. Although a low $J_{\text{th}}$ is indicative of good laser material quality, care must be taken when calculating $J_{\text{th}}$ for narrow lasers, since leakage currents can significantly enhance the effective width of such laser due to lateral diffusion of injected carriers. For this reason $J_{\text{th}}$ is typically evaluated for lasers with a large resonator width ($\gtrsim 50 \ \mu m$) for which diffusion effects are negligible. An FP laser that is $w = 100 \ \mu m$ wide and $L = 1000 \ \mu m$ long should have a $J_{\text{th}}$ on the order of $100 - 200 \ \text{A/cm}^2$, if the material quality is good (for the InGaAs(N)/GaAs material systems).

Most of the parameters in (2.16) are dependent on temperature in an undesirable way such that $I_{\text{th}}$ typically increases with temperature. In order to describe the temperature dependence of $I_{\text{th}}$ properly one would need information on the temperature dependence of each parameter. Since one usually do not have this information at hand it is common to account for all temperature dependencies in a simple model that assumes an exponential increase of $I_{\text{th}}$ with temperature, such that

$$\frac{1}{I_{\text{th}}} \frac{dI_{\text{th}}}{dT} = \frac{1}{T_0}$$

(2.19)

where $T_0$ is the characteristic temperature. Although this merely is an empirical relation it has been shown through many experiments that it approximates the $I_{\text{th}} - T$ characteristics quite well. According to the above definition, $T_0$ represents the temperature increase at which the threshold current has increased by approximately 2.7 times and it is thus desirable to have a $T_0$ as large as possible. For InP-based lasers $T_0$ typically is around 60-80 K while GaAs-based lasers typically exhibit $T_0$-values around 100 K. The value of $T_0$ depends on the recombination process that dominates at threshold in a given temperature region. For an ideal laser, in which only radiative recombination is contributing to the threshold current, it has been shown that $T_0$ would be equal to the physical temperature (thus, about 300 K at room temperature) while any non-radiative contributions would cause a reduction of $T_0$ [114]. If Auger recombination is dominating it has for example been shown that a maximum value of $T_0 \approx 100 \ \text{K}$ can be achieved [115].

\[15\] This was originally proposed by Pankove in 1968 [113].
3 Dilute nitride lasers

This chapter describes my work on dilute nitride quantum well lasers, thus covering the material presented in Papers A-D. A short summary of the unique electronic properties associated with dilute nitride alloys is first given, followed by a description of some of the issues related to MBE growth of these alloys. In particular, the techniques we have utilized to achieve high quality growth of GaInNAs multiple quantum wells are described, as well as the results from a detailed study of the threshold current stability against temperature variations for GaInNAs QW lasers.

3.1 Electronic properties

3.1.1 Band structure

One prominent feature seen in Fig. 2.6 is the fact that the bandgap generally increases when the lattice constant decreases. This is true for all III-V compounds displayed in the figure with one exception; the nitrogen containing semiconductor compounds GaNAs and GaInNAs, for which the bandgap bowing is negative (for small N concentrations). This was experimentally observed for the first time by Weyers et al. in a paper from 1992 [116] in which they reported a rapidly decreasing bandgap of GaNAs by adding a small amount of N\(^1\). The bandgap bowing in any ternary compound can be represented by \[ E_{g}^{A_{x}B_1-x} = xE_{g}^{A} + (1-x)E_{g}^{B} - bx(1-x), \] (3.1)

where the bowing parameter \(b\) typically is a constant for most compounds. However, for GaN\(_x\)As\(_{1-x}\) it has been shown that \(b\) initially decreases exponentially for low N concentrations (causing a negative bandgap bowing) and eventually becomes constant for high N-concentrations, for which the bandgap bowing is positive. This dependence of \(b\) on N-concentration can be described by \[ b(x) = b_0 + b_1e^{-x/x_1} + b_2e^{-x/x_2}, \] (3.2)

\(^1\)Baillargeon et al. also reported the same phenomenon for GaNP in 1992 [117].
Figure 3.1: Schematic illustration of the effects of BAC on the conduction band structure in a dilute nitride alloy. The solid $E^{\pm}$ lines are subbands resulting from the BAC interaction between the localized N-states at level $E_N$, and the unperturbed conduction band $E_c$. For real calculations of the band structure see e.g. [120,121].

where $b_0, b_1, b_2, x_1$ and $x_2$ are constants. The anomalous bandgap bowing described by Eqs. (3.1)-(3.2) is related to specific properties of the nitrogen atom, which has a very small atomic radius and a very high electronegativity$^2$ compared to the other III-V elements. If there is a large difference in electronegativity between host and impurity atoms, the incorporation of the impurity will give rise to localized levels close to the conduction band edge [119]. Shan et al. have shown that when a small concentration of N is added to the ternary InGaAs compound, N-states at a highly localized energy level will interact strongly with the conduction band and as a result split the InGaAs conduction band into two subbands [30]. This phenomenon is referred to as band anticrossing (BAC) and will result in a reduction of the fundamental bandgap energy, as illustrated in Fig. 3.1 which shows a schematic $E(k)$-plot for a dilute nitride alloy. The bandgap energy reduction is astonishingly rapid with a typical value of $\sim 0.1$ eV/% for N-concentrations $x \lesssim 1.5$ % [116]. As a result it is possible to reach emission at the important telecommunication wavelengths (1.3 $\mu$m and 1.55 $\mu$m) by adding just a few percent nitrogen to InGaAs grown on GaAs.

The BAC model predicts that the incorporation of N mainly affects the conduction band and only has a negligible effect on the valence band. Studies have shown that the resulting band alignment is ordinary type-I with a large conduction band offset between GaInNAs and GaAs of $Q_c \sim 0.8$ [122–125]. For comparison, the conduction band offset between InGaAsP and InP is about 0.4 [126] (for In-

$^2$The electronegativity is a measure of the tendency of an atom to form a bonding pair of electrons.
GaAlAs/InP it is $\sim 0.7$ [127]). A large conduction band offset results in a more efficient electron confinement and improved device performance at elevated temperatures. Dilute nitride QW lasers are thus expected to have a better thermal performance compared to InP-based QW lasers.

### 3.1.2 Electron effective mass

The BAC model further foresees an increased electron effective mass $m_e^*$ with increasing N-concentration and experimental results indeed confirm this [122, 124, 125, 128–130]. The increase of $m_e^*$ for GaInNAs compared to InGaAs has e.g. been observed to be $\gtrsim 30\%$ [125, 130]. A larger $m_e^*$ suggests an improved radiative efficiency in the same way as the strain-induced reduction of effective hole mass mentioned earlier in section 2.2.3, thus adding more incentive for considering dilute nitride QWs as active gain medium in lasers. The above described BAC model is usually referred to as the two-level BAC model since it only considers the interaction between the conduction band edge and N-states at a single localized energy level. For this reason it only provides a simplified explanation of the effects caused by nitrogen incorporation and it particularly fails in predicting the composition dependence of the electron effective mass [121]. Agreement between predicted and measured $m_e^*$ values have for example only been obtained at very low N concentrations ($x < 0.05\%$) for GaInNAs alloys [121,125]. In [125], the following empirical estimate of $m_e^*$ was obtained for GaInNAs QWs with In-concentrations of $\sim 30\% - 40\%

$$m_e^* = (0.072 + 0.011x) m_0, \quad (3.3)$$

where $m_0$ denotes the electron mass and $x \lesssim 5\%$. Equation (3.3) is useful for cases when a quick estimate of $m_e^*$ is needed. In order to obtain a more correct description of the conduction band structure, O’Reilly et al. refined the two-level BAC model by considering a range of N-related defect levels (arising due to the formation of nitrogen complexes) [121,131]. In this model the increase in $m_e^*$ is quantitatively predicted and explained by a hybridization of the conduction band edge and nitrogen states close to the band edge. However, as pointed out in [131] the simple two-level BAC model still provides a good qualitative description of most electronic properties of dilute nitride alloys, in particular the composition, pressure and temperature dependence of the bandgap energy.

### 3.1.3 Electron mobility

The dependence of electron mobility $\mu$ on N-concentration and temperature has been examined by Fahy and O’Reilly for dilute GaN$_x$As$_{1-x}$ alloys [132]. They linked the N-concentration dependence of the conduction band energy to the mobility according to

$$\mu^{-1} = \frac{\sqrt{3m_e^* k_B T}}{q} \pi \left( \frac{m_e^*}{2\pi\hbar^2} \right) \left[ \frac{dE_c}{dx} \right]^2 a_o^3 x, \quad (3.4)$$
where $E_c$, $q$ and $a_0$ denote conduction band energy, elementary charge and GaAs lattice constant, respectively, and demonstrated that a strong scattering due to N atoms significantly limits the room temperature mobility to values of about $1000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ in these alloys, for $x \sim 0.01 - 0.02$. Equation (3.4) was derived within the framework of the two-level BAC model but has been shown to give $\mu$-values within 10% of those obtained when also considering effects caused by the formation of nitrogen complexes [133].

3.2 Material growth considerations

It is in general very challenging to grow GaInNAs QWs with good crystalline quality. One of the difficulties is related to the existence of a miscibility gap due to the different basic crystal structures of the constituent alloys and their regions of growth compatibility; InGaAs is a cubic crystal grown at low temperatures while InGaN is a hexagonal crystal grown at high temperatures. As a consequence the GaInNAs material will break up into microscopic regions of InGaAs and InGaN with an increase of either N-concentration or temperature, which constraints the growth temperature $T_g$ to lower temperatures [126]. The low $T_g$ makes growth by MOCVD challenging and therefore MBE is commonly employed for growing GaInNAs, with $T_g$ typically being in the range 420-450 °C [126].

Another major problem is that luminescence rapidly deteriorates with increasing N-concentration [134]. One of the reasons is related to the small size of the nitrogen atoms which easily leads to incorporation at interstitial sites and deep levels that act as non-radiative recombination centers. The most widely used method to generate reactive N for MBE growth is to use a radio-frequency (RF) coupled plasma source [126, 135]. Apart from the atomic N there are unfortunately both molecular radicals and ions generated during the plasma operation. The molecular N particles are unwanted since they lower the N incorporation efficiency while the ions can cause a severe damage after being accelerated by the plasma source and subsequently impinging on the substrate. Since such ion-damage is believed to be one of the main causes for non-radiative recombination centers a technique for reducing ion-damage has been developed [136]. The technique utilizes biased deflection plates that deflect the charged particles away from the substrate (thereby lowering the ion induced damage), with improved threshold current density and photoluminescence (PL) as a result [136]. The nature of the N-bonding is also of importance for material quality and it has been suggested that N with only a weak bond to Ga-atoms leads to deep-level non-radiative recombination centers that kill luminescence [126]. Regardless of the nature of the non-radiative recombination centers it has been widely demonstrated that performing a thermal annealing of GaInNAs material greatly enhances the luminescence [137–139], albeit with an associated blue-shift of the emission wavelength. The enhancement is attributed

\begin{footnote}
3The low growth temperature is too low to achieve a reasonable cracking of the ammonia used a N source [126].
\end{footnote}
to an increased crystalline quality of the active region and the blue-shift to a re-
distribution of N atoms and clusters [126, 137, 138]. The annealing is typically
performed post growth but in-situ annealing may also be used to improve material
quality [140, 141].

Optimization of MBE growth conditions

Since both the material quality and the luminescence intensity is reduced with in-
creasing N-concentration it is desirable to minimize the amount of N in the active
region. This can be done by incorporating as much In as possible in order to extend
the wavelength long enough so that only a small amount of N is needed to lower the
bandgap and reach the 1.3 μm-region, as illustrated in Fig. 2.6. To reach 1.3 μm
one typically needs to incorporate \( \gtrsim 36\% \) indium (\( \lambda \sim 1.2 \mu m \)) and add about
1% nitrogen. Growth of highly strained InGaAs QWs is therefore an important
step in the optimization of the growth conditions for GaInNAs QWs (Paper A).
Under normal growth conditions a maximum emission wavelength of 1.1 μm is ex-
pected from InGaAs, based on calculations of critical thickness from the Matthews
and Blakeslee model [107]. The limitation is caused by strain relaxation through
either the formation of dislocations or 2D-3D growth-mode transitions (quantum
dot formation), depending on the amount of In in the film. For In-concentrations
\( \gtrsim 25\% \), 2D-3D growth-mode transitions is the major limitation while the creation
of dislocations is more crucial for lower concentrations [25]. A key to impede the
formation of QDs is to use a low growth temperature which limits the surface dif-
fusion length of adatoms. Although the critical thickness can be increased this
way the optical quality will suffer, thus creating a trade-off between long emission
wavelength and material quality.

The growth temperature is the single most important parameter determining
material quality when growing InGaAs(N) QWs and needs careful optimization.
This is illustrated in Fig. 3.2(a) which shows the dependence of PL peak intensity
on growth temperature for a triple QW (TQW) GaInNAs material grown in our
MBE system. As seen in the figure, only a slight deviation from the optimum
growth temperature results in a significant reduction in PL intensity. The growth
temperature window in which the optical quality of the material is high is thus very
narrow. A similar dependence on growth temperature applies for growing InGaAs
QWs. For GaInNAs growth there are some additional growth parameters that
need to be optimized, in order to increase the fraction of N atoms while avoiding
a degradation of optical quality. These include e.g. the RF power of the plasma
source, the N flux and the growth rate. An increase in RF power and N flux typically
reduces the PL intensity due to increased ion-damage, suggesting that they
should be kept as low as possible [142]. In order to efficiently incorporate enough
N while still using a low RF power and a low N flux, one can reduce the growth
rate [143]. By utilizing this technique it is possible to extend the wavelength to
\( \gtrsim 1.3 \mu m \) while keeping the degradation of optical quality fairly low. Examples of
typical PL spectra for InGaAs(N) QWs are shown in Fig. 3.2(b). In this case the
Figure 3.2: (a) PL peak intensity as a function of MBE growth temperature for a TQW GaInNAs/GaNAs laser material. (b) Examples of PL spectra for InGaAs(N) SQWs.

wavelength was extended from 1188 nm to 1270 nm, while the PL intensity was reduced by $\sim 40\%$. The In and N concentrations were estimated to be 38% and 0.7%, respectively.

Strain accumulation is an additional hinder for growth of high quality GaInNAs multiple QWs (MQW). Although the incorporation of N reduces the compressive strain, the material quality degrades with the associated increase of non-radiative recombination centers, as mentioned above. A trade-off thus exists between strain accumulation and N-related defects, which translates into limitations of the amounts of In and N that can be incorporated. The critical thickness can be extended by surrounding the QWs with strain-compensating GaNAs barriers. However, in this case an increase in temperature sensitivity and a reduction of differential gain are expected due to a reduced band offset caused by the incorporation of N in the barriers [144, 145], which somewhat limits the applicability of using GaNAs barriers. GaNAs barriers can also be used to extend the emission wavelength slightly since the strain compensation allows a thicker QW to be used, which lowers the quantized energy levels in the QW [144,146].

3.3 1.3 $\mu$m GaInNAs QW lasers

3.3.1 Lasers at Chalmers University of Technology

By optimizing growth conditions our group has previously grown high quality single and double QW $\sim 1.3$ $\mu$m GaInNAs laser material. Fabricated broad area lasers from these materials exhibited low threshold current densities $J_{th}/$QW $\sim 150$ Acm$^{-2}$ and high characteristic temperatures of $T_0 \sim 130$ K [147,148]. Lasers
fabricated from the DQW material were successfully modulated uncooled up to 110 °C at 2.5 and 10 Gb/s [34, 35]. Although these were very good results it was shown that the dynamic performance was limited by thermal effects which caused a reduction in e.g. differential gain. Since adding more QWs can increase the differential gain, through a lower threshold carrier density per QW, we wanted to investigate if further enhancements of the dynamic performance could be achieved by using three QWs. We first optimized growth conditions for heavily strained TQW In0.38GaAs laser material and achieved a very low threshold current density of $J_{th}/\text{QW} \sim 107 \text{ A cm}^{-2}$, for broad area lasers, at an emission wavelength of $\sim 1.2 \mu\text{m}$ [Paper A]. It’s worth mentioning that broad area lasers of this material had high $T_0$-values similar to our DQW GaInNAs lasers, which is explained by a combination of a low operating carrier density per QW and a large conduction band offset between InGaAs and GaAs (being slightly smaller than that of GaInNAs/GaAs). After this we continued to optimize growth conditions for GaInNAs TQW lasers. Growing GaInNAs QWs tends to be more difficult than InGaAs QWs and during this work we found it necessary to both insert strain compensating GaNAs barriers to cope with the large strain accumulation as well as perform an in-situ thermal annealing after the growth of each QW. After extensive optimizations we obtained TQW GaInNAs lasers emitting at $1.29 \mu\text{m}$ with a record low $J_{th}/\text{QW} \sim 130 \text{ A cm}^{-2}$ [Paper B]. A relatively low $T_0 \sim 94 \text{ K}$ was obtained, most likely related to the use of GaNAs barriers, as explained previously. The following list summarizes the techniques that have been used for growth optimization of GaInNAs QWs.

A Low growth temperature for growth of highly strained InGaAs QWs with an estimated In-content of $\sim 38\%$.
B Low growth rate for efficient N incorporation at reduced RF power and N flux.
C Strain compensating GaNAs barriers when growing multiple QWs.
D In-situ annealing after each QW when growing multiple QWs.

The dynamic performance of our TQW GaInNAs lasers was investigated in [149]. The emission wavelength of these lasers was tuned to match the zero dispersion wavelength of optical fibers at 1310 nm, by using slightly thicker GaNAs barriers compared to the structure in Paper B. The obtained modulation bandwidth was 13 GHz. This is lower than the 17 GHz previously obtained in our group using 1.28 μm DQW lasers [36], most likely because of the need to incorporate GaNAs barriers which has a negative impact on differential gain. In general, the modulation bandwidth is expected to decrease with increasing wavelength in GaInNAs QW lasers since most methods that can be used to extend the emission wavelength also are associated with a reduction of the differential gain. For example, at shorter wavelengths heavily strained QWs with large In and small N concentrations are used which yields a large differential gain. To achieve longer emission wavelengths one can e.g. increase the N-content in the QWs, which reduces the strain, or use GaNAs barriers, which lowers the conduction band offset. Both a reduction of strain and a reduction of conduction band offset lowers the differential gain [150,151].
3.3.2 Threshold current density

The $J_{th}$-values of the first 1.3 $\mu$m GaInNAs lasers were typically measured in the kA/cm$^2$ range [160–162]. These high threshold current densities were to some extent related to bad material quality associated with the nitrogen incorporation. During the past decade much research effort has been aimed at exploiting the above mentioned techniques to optimize growth conditions in order to improve device performance of 1.3 $\mu$m GaInNAs QW lasers [142, 148, 153–159, 163–174]. This has resulted in a good development of threshold characteristics, as shown in Fig. 3.3. The original kA/cm$^2$ threshold current densities have now been lowered to 178 [157] and 133 [Paper C] A/cm$^2$/QW for current state-of-the-art SQW and MQW lasers, respectively. In terms of threshold current densities the GaInNAs lasers are comparable to the other QW approaches, with values very similar to GaAsSb QWs and slightly higher than InGaAs QWs. GaInNAs lasers however outperform GaAsSb QWs in terms of temperature stability, with $T_0$-values typically larger than 100 K, and InGaAs QWs in terms of longer emission wavelengths.

These were all ridge waveguide lasers for which it is difficult to define a $J_{th}$ due to a large amount of lateral carrier diffusion. One should therefore be careful to use $J_{th}$ as a measure for these lasers.
Maximum ambient temperature, [°C]
Characteristic temperature, [K]

Measurements
Tc region

Figure 3.4: Characteristic temperature versus maximum ambient temperature under pulsed measurement conditions. [142, 153–157, 162–168, 171, 174, 176–178]

### 3.3.3 Characteristic temperature (T₀)

Dilute nitride lasers were predicted to have T₀-values in excess of 150 K [175]. However, even though a majority of the BA GaInNAs lasers reported so far exhibit fairly high T₀-values their temperature performance is far from the original prediction, as seen in Fig. 3.3. There have been demonstrations of GaInNAs lasers that do fulfill the prediction [34, 157, 162, 164, 174] but those T₀-values have only been obtained at lower temperatures (T < 70 – 90 °C) and for certain device structures. Above a certain critical temperature (T_c), a more rapid increase of the threshold current has usually been observed, with an associated substantial decrease of T₀. This trend is clearly illustrated in Fig. 3.4 which shows a plot of measured T₀-values against the maximum ambient temperature and suggests that 70 < T_c < 90 °C. A considerable amount of research has been devoted to investigate the reasons behind this, with special attention given to the temperature dependence of the different components of the threshold current [155, 179–183]. These studies have shown that the threshold current is dominated by non-radiative recombination currents at all temperatures. In particular, it has been shown, numerically and experimentally, that defect related mono-molecular recombination is dominating at lower temperatures [179–182] and it is now widely accepted that the high T₀-values obtained so far can be attributed to a weak temperature dependence of this process [179]. The reduction of T₀ at higher temperatures has been attributed to both an increased Auger recombination [179–181] and increased hole-leakage associated with a small valence band offset [155, 183]. Although the research that has been done have given interesting insights regarding the temperature dependence of I_th, the physics of the
investigated mechanisms has been fundamentally related to the active gain region, through either the band structure or the material quality, which should not have any dependence on the geometry of the laser resonator. However, there is a clear relation between $T_0$ and the width of GaInNAs QW lasers. This is illustrated in Fig. 3.5 which shows a plot of reported $T_0$-values for different laser widths for a variety of 1.3 $\mu$m GaInNAs SQW and MQW lasers. Lasers with wide resonators have been demonstrated to have $T_0$-values in the range 60-130 K while lasers with widths below $\sim$20 $\mu$m typically have $T_0$-values larger than 120 K.

3.3.4 Effects of carrier diffusion

Figure 3.5 suggests the existence of a process that may influence the temperature dependence of the threshold current for narrow width lasers but with little, if any, influence for lasers with a large width. In order to find the reason behind this difference one must consider what happens with injected carriers at threshold in the two different structures and try to quantify the different currents that contribute to $I_{th}$. When a current is injected some of the carriers will reach the active region and recombine spontaneously through either radiative or non-radiative recombination processes while some of the carriers will escape the active region and recombine elsewhere. The active region is defined as the region where recombining carriers contribute to useful laser gain. In practice this means that the active region will be
Figure 3.6: Illustration of the various currents in a RWG FP laser at threshold. The injection current is denoted by $I_{\text{inj}}$ while the defect, radiative and Auger recombination currents are denoted by $I_A$, $I_B$ and $I_C$, respectively. The vertical leakage current and the lateral leakage current are denoted by $I_{\text{leak,vertical}}$ and $I_{\text{leak,lateral}}$, respectively.

defined by the volume occupied by the optical mode, since the stimulated emission process requires the presence of both photons and carriers in order to create new photons. In a RWG laser carriers may escape the active region in either the vertical (transverse) or the lateral direction which makes it possible to express the leakage current in Eq. (2.16) as

$$I_{\text{leak}}(T) = I_{\text{leak,vertical}}(T) + I_{\text{leak,lateral}}(T),$$  \hspace{1cm} (3.5)

where the $I_{\text{leak,vertical}}(T)$ is associated with carriers with enough thermal energy to traverse the QWs and recombine in the confinement regions. The various current paths are illustrated in Fig. 3.6. For GaInNAs QW lasers the vertical leakage current should be very small for electrons due to the large conduction band offset. Furthermore, it has been shown that the strong electron confinement gives rise to an electrostatic attraction that increases the binding energy of holes in the QW, thereby also reducing the amount of vertical hole leakage [181]. The lateral leakage current is caused by lateral diffusion of carriers [184] which is described as ambipolar diffusion, as mentioned in section 2.2.2. Because the carrier density will vary along the active region, the spontaneous recombination rate should more accurately be written as

$$R_{sp}(x) = A n(x) + B n(x)^2 + C n(x)^3,$$  \hspace{1cm} (3.6)

where $n(x)$ explicitly denote the position dependence of the carrier density (with $x$ being the lateral coordinate). The carrier density is governed by the diffusion equation [184]

$$D_a \frac{d^2n(x)}{dx^2} - R_{sp}(x) + \frac{n_i I_{\text{inj}}(x)}{q d L} = 0,$$  \hspace{1cm} (3.7)
Figure 3.7: Calculated carrier density profiles for \( w = 100 \) \( \mu m \) and \( w = 3.4 \) \( \mu m \) wide FP lasers. Also shown is a calculated optical mode profile for a 3.4 \( \mu m \) wide GaInNAs DQW laser. The strong lateral diffusion in the narrow laser reduces the overlap between the injected carrier density and the optical mode, resulting in a significant lateral leakage current.

where \( D_a \) is given by Eq. (2.9) and \( d, L \) and \( I_{\text{inj}}(x) \) denotes the active region thickness, resonator length and the injection current per unit width, respectively. The relative amount of diffusion to the total amount of injected carriers is highly dependent on the laser width, as illustrated in Fig. 3.7 which shows a plot of \( n(x) \) obtained by solving Eq.(3.7) for both a BA (100 \( \mu m \) wide) laser and a RWG (3.4 \( \mu m \) wide) laser (with all other parameters kept the same). As seen in the figure a lateral diffusion current exists in both lasers but for the BA laser the amount of out-diffusing carriers is negligible compared to the total amount of carriers under the ridge. For the RWG laser, however, the out-diffusing carriers constitute a significant portion of all injected carriers. Also shown in the figure is a calculation of the optical mode profile for a 3.4 \( \mu m \) wide DQW GaInNAs laser. The optical mode is very well confined beneath the ridge which means that essentially all carriers that escape to regions outside the ridge edges are lost since they cannot contribute to optical gain. A lateral diffusion current thus fulfills the requirement of being a process that could influence RWG laser performance but have little effect on BA lasers. The influence of lateral diffusion on laser performance has previously been studied for several material systems [185–187] and it has particularly been shown that it may have an impact on the thermal performance of lasers [188–190]. In fact, a temperature insensitive leakage current was identified to yield high \( T_0 \)-values for InGaAsP buried heterostructure lasers already in 1982 [191].

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In Paper C the influence of lateral carrier diffusion on thermal performance of GaInNAs DQW lasers was investigated by simulating the dependence of threshold current on temperature. The simulated values of $I_{th}(T)$ were calibrated with extensive experimental $I_{th}-T$ data for 100 $\mu$m and 3.4 $\mu$m wide lasers. The results from these measurements were in agreement with the trend that wider lasers exhibit much lower $T_0$-values, with obtained $T_0$-values on the order of 100 K and 200 K for BA lasers and RWG lasers, respectively. Above a critical temperature (in the range of 80–100 °C) a substantial reduction of $T_0$ was also observed for both laser geometries, with a more pronounced reduction for lasers of shorter length. The various components of $I_{th}$ were calculated by integrating Eq. 3.7 according to

$$I_A = qdLA(T) \int_{|x|<w/2} n_{th}(x, T) dx,$$

$$I_B = qdLB(T) \int_{|x|<w/2} n_{th}^2(x, T) dx,$$

$$I_C = qdLC(T) \int_{|x|<w/2} n_{th}^3(x, T) dx,$$

$$I_{leak} = 2D_a(T)qdL \left| \frac{dn_{th}}{dx} \right|_{x=w/2},$$

where $w$ denotes the width of the active region and $n_{th}(x, T)$ is the carrier density profile at threshold obtained by solving Eq. (3.7) with $I_{inj}$ equal to the simulated $I_{th}$. The temperature dependence of the model parameters necessary for the simulations were either deduced from temperature dependent measurements on the lasers or taken from literature. The defect recombination and ambipolar diffusion coefficients were used as fitting parameters in the simulations since their values to some extent are related to the material quality. The $A$ coefficient was taken to be independent of temperature, as reported in [179]. The temperature dependence of $D_a$ can be derived by expressing Eq. (2.9) with mobilities, using Eq.(2.8), which gives

$$D_a = 2 \frac{\mu_n\mu_p}{\mu_n + \mu_p} \frac{k_B T}{q}.$$  

(3.9)

From Eqs. (3.4) and (3.9) one obtains that $D_a \propto \sqrt{T}$. Some results of the simulations are shown in Fig. 3.8 which displays the relative contributions of the various currents in Eq. (3.8) to $I_{th}$ for lasers of different lengths. As can be seen in Fig. 3.8(a) a weakly temperature dependent defect recombination current dominates $I_{th}$ at most temperatures for BA lasers, with a contribution $\gtrsim 50\%$ at all temperatures. At higher temperatures Auger recombination increases rapidly and eventually becomes comparable to the defect recombination current at threshold, which explains the reduction of $T_0$ above $T_c$. The critical temperature occurs roughly at the temperature where Auger recombination becomes much larger than
radiative recombination. More notably, however, is the significant contribution of the lateral leakage current to $I_{th}$ for the RWG lasers, as seen in Fig. 3.8(b). The leakage current contributes with as much as $\sim 40\%$ of $I_{th}$ at all temperatures and exhibits only a weak temperature dependence. As for the BA lasers there is also a significant contribution of defect recombination at all temperatures. The weakly temperature dependent defect recombination and lateral leakage currents together

Figure 3.8: Calculated relative contributions to $I_{th}$ of defect ($I_A$), radiative ($I_B$) and Auger ($I_C$) recombination currents and lateral leakage current ($I_L$). (a) 100 $\mu$m wide GaInNAs DQW lasers (b) 3.4 $\mu$m wide GaInNAs DQW lasers.
contribute to $\sim 80\%$ of the threshold current at room temperature for the RWG lasers. This emphasizes that the high $T_0$-values obtained for RWG lasers to a large extent arise from a significant and weakly temperature dependent lateral diffusion current which is not an effect intrinsic to GaInNAs but rather related to the geometry of the laser resonator.

**Determination of diffusion coefficient**

In Paper C a room temperature value of $D_a \sim 25\text{ cm}^2/\text{s}$ was obtained from simulations of $I_{th}$. In order to verify this value and directly demonstrate the presence of lateral diffusion in the RWG lasers one can measure the near-field components of the spontaneous emission profile, since this maps the lateral carrier distribution in the active region [192]. In Paper D this was done using a scanning near-field optical microscopy (SNOM) probe to collect the spontaneous emission at a sub-wavelength distance from the laser facet. The result from a room temperature SNOM measurement on a 300 $\mu$m long RWG GaInNAs laser is displayed in Fig. 3.9, together with calculated carrier density profiles for three different values of $D_a$. As seen in Fig. 3.9 a good agreement between the calculated carrier density profile and the measured spontaneous emission profile was obtained for the value of $D_a$ obtained in Paper C ($D_a \sim 25\text{ cm}^2/\text{s}$). As the figure shows, the strong lateral diffusion causes a significant amount of carriers to diffuse several micrometers outside the ridge edges.
Figure 3.9: SNOM measurement of a spontaneous emission profile for a 300 μm long and 3.4 μm wide 1.3 μm GaInNAs DQW laser (filled circles). The bias current was ∼ 0.4*Ith. Also shown are calculated carrier density profiles for three different values of ambipolar diffusion coefficient.
4 Alternative techniques for 1.3 μm emission on GaAs

This chapter briefly reviews some of the other approaches, apart from dilute nitrides, that can be used to achieve 1.3 μm emission on GaAs substrates. In particular In(Ga)As quantum dots, GaAsSb quantum wells and pseudomorphic and metamorphic InGaAs quantum wells are described. The chapter ends with a short comparison between the most promising GaAs-based approaches and conventional InGaAlAs/InP QWs.

4.1 In(Ga)As quantum dots

Quantum dots are zero dimensional structures that restrict the motion of carriers in three dimensions at distances comparable to their de Broglie wavelength (∼ 20 nm for electrons). The beneficial properties of semiconductor lasers based on QDs were first recognized by Arakawa et al. in 1982 [193] when they demonstrated a drastic increase of $T_0$ for a QD laser\(^1\) compared to a QW laser. Apart from an improved temperature performance QD lasers were envisaged to have very low threshold currents, very high differential- and material gain and reduced chirp under direct current modulation [194,195]. One of the reasons for the advantages is the increased density of states near the band edges that stems from the size-quantization. This results in a concentration of most of the injected non-equilibrium carriers in an narrow energy range near the band edges which causes a larger material gain and a reduced influence of temperature on device performance [196]. These effects increase with increasing degree of confinement and are therefore most pronounced for QD-material.

The first QD lasers were fabricated with patterning techniques and selective etching of QWs but suffered from very high threshold current densities related to bad material quality [197]. A real breakthrough in QD laser technology came with the possibility to grow self-organized QDs. When a material is pseudomorphically

\(^1\)In their work they created QD-like states by applying a magnetic field to a QW laser.
grown it may spontaneously transform into an ensemble of three-dimensional islands once the critical thickness has been exceeded. This is commonly referred to as the Stranski-Krastanov growth mode. For certain growth conditions these islands will be small ($\sim 10$ nm), have similar size and form a dense ensemble [198] that can be used as the active region in a laser by inserting it between higher-bandgap material, as illustrated in Fig. 4.1. Although self-organized growth of QDs significantly improved the device performance of QD lasers there are problems associated with the method. The size and the density of the QDs are e.g. very difficult to control. This may reduce the material gain which is proportional to the QD density and inversely proportional to the linewidth of the energy levels (QD size fluctuations broadens the linewidth) [199]. Furthermore, the (usually obtained) low QD density causes the modal gain provided by a single layer of QDs to be very low, which sets a hurdle for achieving ground state lasing. QD lasers are therefore typically fabricated with very long cavity lengths and high reflection (HR) coatings in order to reduce the mirror loss and thus lower the threshold gain. One can also increase the modal gain by stacking several QD layers on top of each other, although this is rather challenging from a growth point of view.

During the last decade there has been a considerable amount of research devoted to developing In(Ga)As/GaAs QD lasers emitting at 1.3 $\mu$m [200–218]. In order to improve the performance of the lasers a variety of different techniques have been suggested and realized, such as capping the dots with a strain-reducing InGaAs layer or placing the dot inside a quantum well, referred to as DWELL\(^2\) [25, 28, 196, 198, 200]. By exploiting these techniques the threshold current density has been drastically reduced from 270 A/cm\(^2\), at pulsed operation in the first demonstration of a 1.3 $\mu$m QD-laser [200], to a record low 17 A/cm\(^2\) under continuous wave (CW) operation [212]. In Fig. 4.2 the historical development of edge-emitting 1.3 $\mu$m In(Ga)As/GaAs QD lasers is displayed. Although extremely low threshold current densities have been demonstrated the lasers are quite sensitive to temperature, with a maximum $T_0$ of about 100 K. This has been

---

\(^2\)Acronym for dot-in-a-well.
Figure 4.2: The development of room temperature threshold current density for $\lambda \sim 1.3 \mu m$ In(Ga)As/GaAs QD lasers [200, 202, 206, 209, 212, 213, 216, 218].

shown to be related to the presence of a significant amount of non-radiative Auger recombination [219]. There have been suggestions of increasing the characteristic temperature by applying $p$-type modulation doping to the QDs [209] and $p$-doped lasers with very high (650 K) [214] or even negative [218] $T_0$ values have been demonstrated. The high $T_0$-values are however only obtained for quite low temperatures and above (typically) 330 K the $T_0$ of $p$-doped lasers drops to values similar to that of undoped devices [219]. Furthermore, the threshold currents of high-$T_0$ $p$-doped devices are in general much higher than undoped devices. It is in fact a typical characteristic of QD-lasers that high $T_0$-values are linked with high $J_{th}$-values.

### 4.2 GaAsSb quantum wells

The formation of GaAs$_{1-x}$Sb$_x$ by the addition of Sb to GaAs reduces the bandgap of GaAs with increasing Sb-concentration according to [220]

$$E_g(x) = 1.42 - 1.9x + 1.2x^2,$$

making it possible to reach 1.3 $\mu$m by adding approximately 30% Sb. The effect of the bandgap bowing described by (4.1) has been shown to be more significant for the valence band which causes the band alignment to be of (weak) type-II for the GaAs$_{1-x}$Sb$_x$/GaAs interface [221], as opposed to the type-I band alignment in conventional material systems. The difference between the two types of band alignment is illustrated in Fig. 4.3. In a type-I band alignment the electrons and
holes are confined in potential wells in the same layer. In a type-II band alignment
the band offset is negative for either the conduction band or the valence band. A
negative conduction band offset would e.g. cause the electrons to be confined in the
barrier region instead, thereby spatially separating them from the holes confined in
the potential well in the sandwiched material. This spatial separation results in a
space charge field that produces an approximately triangular QW in the conduction
band of the barrier material. The electric field will increase as the electron density
increases and thereby push the electrons towards the interface. There, the electron
density will build up until population inversion is reached and lasing can occur. The
transition is thus spatially indirect in the narrow region near the interface [221].
It should be mentioned that a weak type-I band alignment of a GaAsSb/GaAs
interface (for 30% Sb) also has been reported [222, 223]. The fact that both type-I
and type-II band alignments have been reported indicates that the conduction band
offset may be close to zero. Using the type-II GaAsSb/GaAs system to reach long
emission wavelengths was first proposed in a paper by Anan et al. in 1998, which
also included the first demonstration of a GaAsSb/GaAs EEL [224]. The active
region consisted of a SQW of GaAsSb and the laser emitted at 1.2 \( \mu \)m with a high
threshold current density \( (J_{th}) \) of 3 kA/cm\(^2\) [224]. Since then the performance of
GaAsSb SQW lasers has improved significantly, with the lowest \( J_{th}\)-values so far
being 400 (125) A/cm\(^2\)/QW for SQW (MQW) lasers emitting at 1.292 (1.28) \( \mu \)m,
respectively [225, 226]. In Fig. 4.4 the historical development of edge-emitting
GaAsSb SQW lasers, with an emission wavelength near 1.3 \( \mu \)m, is displayed. As seen
in the figure the lasers reported so far have been highly temperature sensitive, with
\( T_0 \)-values on the order of 60 K. Investigations of carrier recombination processes in
GaAsSb/GaAs SQW lasers have revealed that temperature sensitive non-radiative
(Auger) recombination accounts for \( \sim 90\% \) of \( I_{th} \) at room temperature [227, 228],
which provides an explanation to the poor temperature performance of these lasers.
The small (near zero or even negative) conduction band offset is also believed to
give rise to a significant thermally induced overflow of carriers into the barrier
region, further degrading the temperature stability of the lasers [227, 228]. The
poor temperature characteristics of GaAsSb SQW lasers needs to be improved before

Figure 4.3: Illustration of type-I (left) and type-II (right) band alignments.
Figure 4.4: The development of room temperature threshold current density per QW for \( \lambda \sim 1.3 \, \mu m \) GaAsSb/GaAs SQW and MQW lasers [27, 225, 226, 229–231]. For comparison purpose the data are for \( \sim 1000 \, \mu m \) long resonators.

this approach can be a realistic alternative to InP-based lasers.

4.3 InGaAs quantum wells

Pseudomorphic growth

Due to the success of InGaAs QWs as active gain material in 980 nm applications (such as e.g. pump lasers for EDFAs), a lot of effort has been devoted to transfer the InGaAs technology to longer wavelengths via pseudomorphic growth of InGaAs QWs on GaAs substrates [31, 32, 232–238]. By optimizing the growth conditions (of most importance is the growth temperature) there have been several demonstrations of highly strained InGaAs QWs with emission wavelengths above 1.2 \( \mu m \), as shown in Fig. 4.5. The lowest \( J_{th}/QW \) obtained so far is 70 [238] and 107 A/cm\(^2\) [Paper A] for lasers grown by MOCVD and MBE, respectively. In contrast to the GaAsSb QW and In(Ga)As QD approaches, the InGaAs QW lasers demonstrated thus far exhibit a very good temperature stability with \( T_0 \)-values typically larger than 100 K. However, the lasers are highly strained and it is unlikely that it will be possible to extend the wavelength to 1.3 \( \mu m \) with maintained material quality using pseudomorphic growth.
Figure 4.5: The development of room temperature threshold current density per QW for $\lambda > 1.2 \, \mu m$ InGaAs/GaAs SQW and MQW lasers [31, 232–238]. For comparison purpose the data are for $\sim 1000 \, \mu m$ long resonators.

**Metamorphic growth**

In InGaAs/GaAs metamorphic growth a thick high In-content buffer layer of In-GaAs is grown on a GaAs substrate. Since the buffer layer is lattice mismatched and much thicker than the critical thickness it will inevitably relax through the introduction of misfit dislocations. The key in metamorphic growth is to design the buffer and optimize its growth in order to minimize the dislocation density at the top of the layer. In the ideal case one can obtain a defect free top layer with a different lattice constant than the substrate the buffer was grown upon, referred to as a virtual substrate. The wanted laser structure is subsequently grown upon this layer. Metamorphic growth is challenging and there have so far only been a few demonstrations of $1.3 \, \mu m$ InGaAs QW lasers, with typical $T_0$-values in the range 50-70 K [239–242].
Table 4.1: Comparison of laser performance between state-of-the-art InGaAlAs lasers on InP and InAs QD lasers and GaInNAs QW lasers on GaAs.

<table>
<thead>
<tr>
<th>Characteristic temperature</th>
<th>$T_0$ [K]</th>
<th>$T_0$ [K]</th>
<th>$T_0$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(20-85 °C)</td>
<td>(20-50 °C)</td>
<td>(20-80 °C)</td>
</tr>
<tr>
<td></td>
<td>97</td>
<td>420</td>
<td>163-208</td>
</tr>
<tr>
<td></td>
<td>(85-150 °C)</td>
<td>(50-100 °C)</td>
<td>(80-110 °C)</td>
</tr>
<tr>
<td>Bandwidth [GHz]</td>
<td>20 °C</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>85 °C</td>
<td>15.5</td>
<td>7.7@70 °C</td>
</tr>
<tr>
<td></td>
<td>110 °C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Un-cooled 10 Gb/s modulation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>No (Yes@100 °C)</td>
<td>Yes</td>
</tr>
<tr>
<td>Reference</td>
<td>[244]</td>
<td>[245, 246]</td>
<td>[35]</td>
</tr>
</tbody>
</table>

4.4 Dynamic performance comparison: GaAs vs. InP

When it comes to dynamic performance only InAs/GaAs QDs and GaInNAs/GaAs QWs have so far shown to be comparable to InGaAlAs/InP QW lasers for 1.3 µm applications. Table 4.1 shows a comparison of state-of-the-art performance between these three technologies. Although InGaAlAs/InP QWs and GaInNAs/GaAs QWs exhibit higher modulation bandwidths than InAs/GaAs QDs, the latter have been demonstrated to be capable of un-cooled operation at 10 Gbit/s up to 100 °C. When it comes to commercialization InGaAlAs/InP QWs is today an established material system with lasers already in use. InAs/GaAs QDs have recently been commercialized\textsuperscript{3} for 10 Gbit/s applications. Despite the promising results of GaInNAs/GaAs QWs, especially at temperatures > 85 °C where GaInNAs $T_0$-values e.g. are much higher compared to the other techniques, there are concerns regarding the reliability of lasers fabricated from the material [243], which most likely hinders GaInNAs from being a serious competitor at the moment.

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5 Spectrally engineered laser resonators

This chapter covers the work presented in Papers E-F. The concept of spectral engineering is first introduced by a discussion of longitudinal mode selection in FP lasers. The mode selection mechanism in the spectrally engineered resonators considered in this work is subsequently described in more detail. This is followed by a section that describes the design of our spectrally engineered FP resonators, with an emphasis on SE-FPRs designed to select either one or two specific longitudinal modes for lasing.

5.1 Longitudinal mode selection

The emission spectrum of any laser is determined by the combined effects of the wavelength dependence of the material gain and the spectral properties of the resonator. The mode structure of the resonator determines the possible lasing wavelengths. In a conventional FP laser (FPL) the longitudinal modes are defined by the FP mirror separation and the refractive index inside the resonator, such that the lasing wavelength for a mode is given by

$$\lambda_m = \frac{2Ln}{m}, \quad m \in \mathbb{N}, \quad (5.1)$$

where $n$, $L$ and $m$ denote the refractive index, mirror separation and mode number, respectively. The modes are separated in wavelength according to

$$\Delta \lambda = \frac{\lambda_m^2}{2Ln_g}, \quad (5.2)$$

where the group refractive index $n_g = n - \lambda dn/d\lambda$. As already mentioned, the feedback provided by the FP mirrors is identical for all longitudinal modes so that the only mode discrimination arises from the spectral dependence of gain. This is explicitly expressed in the expression for the threshold gain of a longitudinal mode,

$$g_{\text{modal,th}}(\lambda_m) = \alpha_t + \alpha_{FP}, \quad (5.3)$$
where \( \alpha_i \) and \( \alpha_{\text{FP}} \) denote the internal optical loss and mirror loss, respectively. The mirror loss is given by

\[
\alpha_{\text{FP}} = \frac{1}{2L} \ln \frac{1}{R_1 R_2},
\]

(5.4)

where \( R_1 \) and \( R_2 \) are the mirror reflectivities given by the Fresnel formula in Eq. 2.14 if the mirrors are of high quality. Since the mode spacing \( \Delta \lambda \) is very small compared to the gain bandwidth an FPL typically emits in multiple longitudinal modes.

In a laser based on a spectrally engineered FP resonator the resonator is designed to provide a wavelength dependent loss through the introduction of a set of refractive index perturbations. The threshold condition for the longitudinal modes is in this case expressed by

\[
g_{\text{modal,th}} = \alpha_i + \alpha_{\text{SE-FPR}}(\lambda_m).
\]

(5.5)

In order to create e.g. a single mode laser \( \alpha_{\text{SE-FPR}}(\lambda_m) \) is designed to provide a lower loss for one selected mode. It should be realized though that the neighboring modes will still carry some power and single mode operation is a relative definition. Mode selectivity is measured by the side-mode-suppression ratio (SMSR), which simply is the ratio of the output power in the primary lasing mode to that in the second strongest mode. The SMSR should typically be > 30 dB for a laser to qualify as a single mode laser. The SMSR increases with an increase in loss margin, which is defined as the difference in resonator loss between a selected mode and its neighboring modes [100]. For a large SMSR the reduction in resonator loss for selected modes, provided by \( \alpha_{\text{SE-FPR}}(\lambda_m) \), should thus be as large as possible.

### 5.2 The spectrally engineered FP resonator

#### 5.2.1 Geometry

The geometry of the spectrally engineered resonators considered in this work is shown in Fig. 5.1(a). The basic structure is a conventional ridge waveguide FPL with the width of the ridge varying in the longitudinal direction. The varying width changes the transverse dimensions of the waveguide and thereby also the effective index of the guided optical mode. A change in ridge width thus corresponds to a perturbation of the effective (mode) index. Any change in the transverse dimensions of the ridge waveguide is associated with a change in effective index and it is therefore also possible to realize an index perturbation by etching slots on top of the ridge, as illustrated in Fig. 5.1(b). So far all spectrally engineered FP lasers (SE-FPLs) have been fabricated using a top etch geometry [48, 53, 247–252]. The choice of using a side wall etch or a top etch will discussed more in section 5.3.3.
Figure 5.1: Schematic illustration of the geometry of a spectrally engineered FP resonator with the index perturbations realized as (a) a side wall etch of a RWG FPL and (b) a top etch of a RWG FPL.

5.2.2 How it works

The mode selective mechanism of any resonator based on a longitudinally varying effective index is interference. Whenever an optical mode propagating along the waveguide of a resonator experiences a change in effective index it will be partially reflected. The total optical field for a mode is given by the coherent sum of all partially reflected waves. For some wavelengths the partially reflected waves will be in phase and increase in amplitude through constructive interference. Modes with wavelengths close to these will thus experience an enhanced feedback, which translates into a lower resonator loss. As a well-known example, in a DFB laser where the refractive index varies binary with a period $\Lambda$, feedback is enhanced for wavelengths that fulfill the Bragg condition $\Lambda = s\lambda/2\pi$, where $s$ is an odd integer and $\pi$ is the average effective mode index. Since $\Lambda$ typically is very small ($\sim 200$ nm for $s = 1$) there will be a very large number of partial reflections along a resonator with a typical length of $\sim 300$ $\mu$m. The resulting strong feedback for modes that fulfill the Bragg condition is sufficiently large for them to reach lasing and the feedback from the cleaved end facets is not necessary. In fact, in an ideal DFB laser there should not be any feedback from the end facets. For this reason anti-reflection coatings are typically applied. In contrast to a DFB laser the operation of an SE-FPL relies on a significant feedback from the end facets and the introduced index perturbations only changes the resonator loss by some amount $\Delta \alpha(\lambda_m)$. The loss can thus be expressed as

$$\alpha_{\text{SE-FPR}}(\lambda_m) = \alpha_{\text{FP}} + \Delta \alpha(\lambda_m),$$

with the magnitude of the extra loss typically being much smaller than the mirror loss, $|\Delta \alpha|_{\text{max}} \ll \alpha_{\text{FP}}$. The spectral behaviour of $\Delta \alpha(\lambda_m)$ depends on the exact position of each index perturbation relative to the other perturbations and the end.
facets and its magnitude is related to the number of perturbations in the resonator. The more perturbations that are introduced the larger change in resonator loss can be obtained. The magnitude of each individual index perturbation is also very important in determining $\Delta \alpha (\lambda_m)$.

Since the net threshold modal gain, $g_{\text{modal, th}} - \alpha_i$, is equal to the resonator loss $\alpha_{SE\text{-FPR}}(\lambda_m)$, it is in this work referred to as the (modal) threshold gain spectrum$^1$. A plot of the threshold gain spectrum gives both the longitudinal mode wavelengths of a resonator and the modal gain required to reach threshold for each mode.

## 5.3 Resonator design

The design of an SE-FPR involves finding the segments of the resonator that should have a perturbed index in order to produce a desired threshold gain spectrum. This so called inverse problem represents the design of the longitudinal dimension of the waveguide and will be discussed in section 5.3.2. Since the effective index is determined by the transverse cross section of the waveguide, the transverse dimension of the ridge must also be designed for a desired magnitude of index perturbation. This is discussed in section 5.3.3.

Numerical methods are in general required to analyze very complicated resonator structures where multiple reflections occur along the resonator. A very successful method is the transfer matrix method (TMM) that was introduced for resonators with a complex structure by Björk and Nilsson in 1987 [253] in order to analyze e.g. DFB lasers. In this approach the amplitudes of waves propagating in the forward and backward direction of a resonator are related to each other by a transfer matrix. The beauty with the approach is that all multiple reflections occurring inside a resonator can be exactly accounted for by simple matrix multiplications of matrices that are easy to obtain/define. Since it is a one dimensional model it can be used to obtain the threshold gain spectrum of very complex resonators with a reasonable computational effort. The following section introduces a TMM model that can be used to calculate the threshold gain spectrum.

### 5.3.1 Transfer matrix model

In our TMM model the laser resonator is divided into a large number of equally long segments where each segment is taken to be uniform, i.e. have the same effective index. In most cases it is sufficient to consider a binary variation of the effective index such it is equal to either $n$ or $n + \Delta n$, corresponding to the unperturbed and perturbed effective index, respectively. The unperturbed effective index is the effective index of a FP resonator without perturbations. This is illustrated in Fig. 5.2 which shows a resonator of length $L$ that is divided into $N$ segments numbered with an index $i$. A transfer matrix $T$ is used to relate the forward- and

$^1$In the following threshold gain will refer to modal threshold gain if not stated otherwise.
Figure 5.2: A schematic illustration of a segmented FP resonator with a longitudinally varying effective index.

The backward propagating optical fields directly to the left and right side of the cavity according to

\[
\begin{pmatrix}
E_{\text{r},l} \\
E_{\text{l},l}
\end{pmatrix} = \begin{pmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{pmatrix} \begin{pmatrix}
E_{\text{r},r} \\
E_{\text{l},r}
\end{pmatrix}
\]

The optical fields in the segments are assumed to have a longitudinal propagation described by \( E \propto \exp(\pm j\beta_i z) \). The complex propagation constant is given by \( \beta_i = kn_i \), where \( k = 2\pi/\lambda \) and \( n_i = n'_i + jn''_i \) denotes the wavevector and complex effective refractive index, respectively, and \( \lambda \) denotes the vacuum wavelength of the light. With these definitions the modal gain is given by

\[
g_{\text{modal}} \triangleq \gamma = -2kn''.
\]

The modal gain is also taken to be identical in all segments. The transfer matrix of the entire resonator is now obtained by multiplying a large number of fundamental transfer matrices. These either relate fields across an interface between segment \( i \) and segment \( j = i + 1 \),

\[
T_{i,j} = \frac{1}{t_{i,j}} \begin{pmatrix}
1 & r_{i,j} \\
r_{i,j} & 1
\end{pmatrix},
\]

or propagate the fields along the length \( d \) of segment \( i \),

\[
T_{\text{P}_i} = \begin{pmatrix}
\exp(-j\beta_i d) & 0 \\
0 & \exp(+j\beta_i d)
\end{pmatrix}.
\]
of a single segment $i$ is defined as

$$T_i = T_{i-1,i} T_{P,i}.$$  \hspace{1cm} (5.11)

The segment transfer matrix thus relates the fields immediately to the left of the left and right interfaces of a segment. The transfer matrix of the entire resonator, defined as in Eq. (5.7), is obtained by multiplying the transfer matrices of all segments in the resonator,

$$T = \left( \prod_{i=1}^{N} T_i \right) T_{N,N+1},$$  \hspace{1cm} (5.12)

where $T_{0,1}$ and $T_{N,N+1}$ is the transfer matrix for the left and right facet of the resonator, respectively.

**The lasing condition: calculating the threshold gain spectrum**

When the laser reaches threshold the optical field repeats itself after one roundtrip and the laser produces a steady-state output field without any external input field. Thus, by setting $E_{r,i} = E_{l,i} = 0$ in Eq. (5.7) one finds that the lasing condition is given by the following equation

$$T_{11} = 0.$$  \hspace{1cm} (5.13)

This is a complex-valued equation that determines both the resonance wavelength and the threshold modal gain and must in the general case be solved numerically if all multiple reflections occurring in the resonator are to be considered in the analysis. This implies finding the solutions to the following nonlinear, real-valued, coupled equation system

$$\begin{cases} \text{Re}[T_{11}(n', \lambda)] = 0 \\ \text{Im}[T_{11}(n', \lambda)] = 0. \end{cases}$$  \hspace{1cm} (5.14)

Equation. (5.13) must in the general case be solved numerically. In Paper E it was shown that the numerical solution can be simplified since the resonance wavelengths to a very good approximation are independent on modal gain (through $n'$). In this case they can be determined by the simpler one dimensional equation

$$\text{Im}[T_{11}(n'' = \text{const.}, \lambda)] = 0.$$  \hspace{1cm} (5.15)

### 5.3.2 Longitudinal design

The calculation of the threshold gain spectrum for a given resonator is straightforward and fairly easy by using Eqs. (5.14)-(5.15). However, when designing a SE-FPR the inverse problem needs to be solved, i.e. to find the longitudinal refractive index variation $n(z)$ for a given $\alpha_{\text{SE-FPR}}(\lambda_m)$. In the very first SE-FPRs this problem had not been rigorously solved and they were designed by utilizing that
perturbations inserted at positions \( x = L/2^a, \ a \in \mathbb{N} \) results in a periodic resonator loss (with a period of \( 2^a \) in longitudinal mode number space) \([45–48]\). This approach was used for designing single mode lasers (a periodic resonator loss is also the mechanism used to create single mode lasers using coupled-cavity resonators \([106]\)). In order to design more advanced resonators, for example two-color lasers, a more sophisticated method is needed. A first attempt was reported 1998 which used a transfer matrix based genetic algorithm to design single mode SE-FPRs. However, due to the complexity of the design problem the method was restricted to consider cases with a only a fairly small number of introduced perturbations. Another solution to the inverse problem was subsequently given by O’Brien and O’Reilly in 2005 \([49]\). This is a semianalytical, transfer matrix based approach where the variation of the density of introduced perturbations along the resonator is related to the threshold gain modulation caused by them in mode number space. The approach relies on the assumption that multiple reflections occurring between perturbations can be neglected while reflections between a perturbation and either of the end facets are fully accounted for. As a result the design method is precisely accurate only for weakly perturbed SE-FPRs. The resonator perturbation strength may be quantified by,

\[
S_p = |N_p \Delta n/n|,
\]  

(5.16)

where \( N_p \) denotes the number of introduced perturbations. The design method introduced in \([49]\) can be trusted as long as \( S_p = |N_p \Delta n/n| \ll 1 \), which restricts the number of perturbations that can be introduced for a given \( \Delta n \). This also causes limitations on how large changes in threshold gain that can be achieved in a design. Nevertheless, the method has proven to be very powerful and a large variety of single mode and multiple mode SE-FPLs have been designed and realized \([50–53,254,255]\). These SE-FPRs typically have \( N_p \lesssim 100 \) and \( S_p \lesssim 0.3 \), with the reduction in resonator loss for the selected modes being \( \lesssim 10\% \) of the mirror loss of an unperturbed FP resonator, \( \alpha_{FP} \).

In order to extend the treatment to include SE-FPRs without any limitations on either \( N_p \) or \( \Delta n \) we developed a design approach presented in Paper E. This is based on a numerical optimization algorithm that fully accounts for all multiple reflections events occurring along the resonator and will be shortly described in the following. The design work begins by specifying the wanted threshold gain value for each longitudinal mode in a considered wavelength interval, referred to as the target threshold gain spectrum, \( \gamma_{\text{th,target}}(\lambda_m) \). The modes used in the target threshold gain spectrum are the longitudinal modes of an unperturbed FP resonator according to Eq. (5.1). In practice one should also account for material and waveguide dispersion of the effective index when defining \( \gamma_{\text{th,target}}(\lambda_m) \), although this is only crucial if precise control of the mode separation in the final design is of importance. With a target threshold gain spectrum defined the algorithm proceeds by optimizing the value of the effective index in each segment successively from \( i = 1 \) to \( i = N \). In the optimization one makes a trial change of the current value of the effective index of the segment to its other possible value, i.e. from \( n \) to \( n + \Delta n \) or vice versa. This leads to a change of the threshold gain of each con-
Design examples

Figure 5.3 shows two design examples of strongly perturbed SE-FPRs. In Fig. 5.3(a) an SE-FPR designed to lower the threshold gain for a single mode is illustrated while Fig. 5.3(b) displays an example of an SE-FPR designed to select two modes separated by $\sim 1$ THz. In both designs the resonator length was $L = 300 \ \mu\text{m}$, the effective index of the unperturbed resonator $n = 3.25$ and $\Delta n = -0.01$. The target threshold gain spectra used are also shown in the figures and were specified to provide $\sim 20 \ \text{cm}^{-1}$ lowering of the loss for the selected mode. The new threshold gain spectrum $\gamma_{\text{th}}(\lambda_m)$ obtained after changing the effective index in a single segment is calculated using an efficient algorithm to quickly obtain the new cavity transfer matrix, and a local linear expansion for the solution of Eq. (5.13). This is crucial in the algorithm as the resonator typically is divided into several thousand segments in the design of a strongly perturbed resonator. The optimization is performed by finding the effective index value of each segment that minimizes a quadratic error function, defined as

$$Q = \sum_m \Delta \gamma(\lambda_m)^2,$$

(5.17)

where $\Delta \gamma(\lambda_m) = \gamma_{\text{th, target}}(\lambda_m) - \gamma_{\text{th}}(\lambda_m)$ and the sum is performed over all modes included in the design. The optimization of all segments is iterated until either the error function is sufficiently small or a resonator is obtained in which it is not possible to reduce $Q$ further by changing the effective index in any segment. Since the optimization of a single segment depends on the states of all the other segments, the sequential optimization of all segments must be repeated a few times for the algorithm to converge.
single mode in Fig. 5.3(a), and \( \sim 15 \text{ cm}^{-1} \) lowering of the losses for the two selected modes in Fig. 5.3(b), while all other modes should be unaffected. These are large reductions of the threshold gain, corresponding to \( \sim 47\% \) and \( \sim 37\% \) of the mirror loss for an unperturbed FP resonator, for the single mode and two-color SE-FPR, respectively. Compared to weakly perturbed SE-FPRs, lasers based on these strongly perturbed SE-FPRs may be expected to exhibit a larger SMSR due to a larger loss reduction for the selected mode(s). It should however be noted that SE-FPLs with weakly perturbed SE-FPRs have been demonstrated to still exhibit large SMSR-values (> 30 dB) far above lasing threshold [50, 250, 252].

5.3.3 Transverse design

As mentioned in section 5.2.1 there are two different waveguide perturbation techniques that have been investigated so far for SE-FPLs; ridge waveguides with the perturbation realized as either a top etch [48, 53, 247–252] or a side wall etch [Paper F] of the ridge waveguide. A top etch approach has been successful for cases with a small density of perturbations. However, if one wants to introduce a large number of perturbations, i.e. have a large density of perturbations, a side wall etch is preferred partly due to an associated higher spatial resolution [52]. Etched side wall gratings have, for example, been successfully implemented in the fabrication of DFB lasers using both first and third order gratings with a period of \( \sim 200 \text{ nm} \) and \( \sim 440 \text{ nm} \), respectively [256, 257]. Current injection must also be considered and a large density of a top etch perturbations may e.g. aggravate current injection (which is usually performed through a contact on top of the ridge waveguide), providing incentive for considering a side wall etch for strongly perturbed SE-FPRs with a large number of introduced perturbations.

In our design with a side wall etch the width of the waveguide is varied between two values such that \( w = w_{\text{wide}} \) and \( w = w_{\text{narrow}} \) for segments where the effective index is equal to \( n_{\text{wide}} \) and \( n_{\text{narrow}} \), respectively. A simple estimation of the effective index perturbation is given as \( \Delta n = n_{\text{narrow}} - n_{\text{wide}} \). The effective index of the narrow and wide segments are found by solving the 2D scalar wave equation

\[
\nabla^2 E(x, y) + (k^2 n_r(x, y)^2 - k^2 n^2) E(x, y) = 0,
\]

(5.18)

following the treatment in [100]. Here \( E(x, y) \), \( n_r(x, y) \) and \( k = 2\pi/\lambda \) denote the transverse field profile of the guided optical mode, refractive index distribution in the waveguide layers and wavevector, respectively, and \( n = n_{\text{narrow}} \) or \( n_{\text{wide}} \) depending on the geometry of the waveguide. Calculated dispersion curves of the effective index for waveguide widths of 3 \( \mu \text{m} \) and 6 \( \mu \text{m} \) are shown in Fig. 5.4, together with an example of an obtained transverse mode profile (given in the inset at the bottom left corner). The material dispersion of the refractive index in the AlGaAs waveguide layers used in the calculations was taken from [258]. As can be seen in Fig. 5.4, \( \Delta n \) is to a very good approximation constant throughout the considered wavelength region, suggesting that it is sufficient to account for dispersion for the unperturbed effective index \( n \) only.
The transverse dimensions of the waveguide should be chosen such that the magnitude of the index difference $|\Delta n|$ is as large as possible, since this enhances the effect of the introduced perturbations. In order to maximize $|\Delta n|$ the difference between the narrow and wide ridge widths, as well as the ridge height, should be as large as possible. In addition, for a given width difference between the wide and narrow waveguide segments, $w_{\text{narrow}}$ should be taken as small as possible. The smallest width of $w_{\text{narrow}}$ that can be used is in practice limited by the lithographical process steps used during the waveguide fabrication. For the upper limitations of $w_{\text{wide}}$ and the ridge height the situation is less clear but related to a requirement of the entire perturbed waveguide to support only a single transverse spatial mode. For example, even though the wider waveguide supports higher order lateral modes it is not certain that the perturbed waveguide with its modulated width will also be multimode.

Another important characteristic that must be considered when choosing a transverse design is how much additional propagation loss an introduced index perturbation may cause. At each interface between perturbed and unperturbed waveguide segments the optical mode will not only be partially reflected but may also be scattered to some extent, causing additional scattering losses that add to the overall propagation loss (internal optical loss). In Paper F it was demonstrated that the additional propagation loss increases for a waveguide with a low density of perturbations (few perturbations), if a side wall etch geometry is employed. This may be explained by a large mode mismatch in the transverse direction in such
Figure 5.5: The rms deviation of the threshold gain spectrum from the desired as a function of the longitudinal error in position of the facet mirrors relative to the ridge waveguide. The insets show the calculated threshold gain spectra for the longitudinal modes for three different values of positioning error ΔL. (Paper F)

waveguides, since the mode may expand laterally when propagating in fairly long unperturbed (wide) waveguide segments. This causes a larger scattering and/or absorption losses of the mode at each perturbation. If the perturbation density is high on the other hand, the mode likely adjusts to an average profile which reduces the mode mismatch.

5.3.4 Fabrication tolerances and design robustness

The performance of an SE-FPR relies highly on the position of the index perturbations relative to the end facets. Although this has been pointed out previously (e.g. in [50]), an analysis of the sensitivity has not been reported. In Paper F we investigated the sensitivity to misalignment of the end facets for our SE-FPRs. The result is illustrated in Fig. 5.5 which shows a plot of rms deviation of the threshold gain spectrum from the desired as a function of a rigid misalignment ΔL of the perturbations relative the end facets. The rms deviation is periodic such that the spectral properties of the original design (ΔL = 0) are retrieved for misalignments close to a multiple of a half wavelength, which reflects the FP half wavelength resonance condition of the resonator. Any misalignment other than a multiple of a half wavelength results in a significant increase of the rms deviation with an associated change in threshold spectrum, as seen in the insets. Due to the very stringent requirement in precise positioning of the perturbations with respect to
Figure 5.6: (a) Effect of dispersion on threshold gain spectrum for a SE-FPR designed for two-color emission with dispersion neglected during the design. (b) Longitudinal mode separation (free spectral range) for the resonators in (a).

Apart from requiring a highly precise relative positioning of the end facets and the index perturbations the performance is also sensitive to deviations in $\Delta n$ as well as $n$. A deviation in mirror reflectivity does, however, not have a significant influence on the performance as long it is identical for both facets. The sensitivity to deviations in parameter values is similar for most SE-FPRs that have been investigated in this thesis; no significant difference between weakly and strongly perturbed designs has e.g. been observed. However, the details of the change in threshold gain spectrum depend on the specific resonator design.

The effect of neglecting effective index dispersion during the design is illustrated in Fig. 5.6(a). The figure shows the obtained threshold gain spectrum from the design of a two-color SE-FPR where effective index dispersion was neglected during the design. The figure also shows the result of a calculation of the threshold gain spectrum for the resonator when dispersion is included. As seen, the only effect is a narrowing of the spectrum due to a smaller mode spacing according to Eq. (5.2). This is also clearly seen in Fig. 5.6(b) which shows the mode spacing (free spectral range) for the two cases as a function of wavelength. An additional interesting feature is also seen in this figure: there is a modulation of the mode spacing in the vicinity of the selected lasing modes. This effect is enhanced in strongly perturbed resonators and provides a way to estimate the obtained $\Delta n$ if only the FSR can be measured accurately.
Experimental results

In Paper F results from measurements on fabricated lasers with SE-FPRs are reported. The fabrication process is described in section 6.3.4. Several lasers with SE-FPRs designed for either single mode emission (at $\lambda = 1774.6$ nm) or two-color emission (at $\lambda = 1174.6$ nm and $\lambda = 1169.9$ nm) were fabricated. A strongly mode selective mechanism was evident in both single mode and two-color SE-FPLs, with SMSR-values ($\geq 30$ dB), as shown in Fig. 5.7. Due to uncertainties in material parameters the emission spectra differed somewhat from the designs (the selected modes differed within a few longitudinal modes from the target modes).
6 Laser fabrication and characterization

This chapter describes the procedure of fabricating an edge emitting laser, starting from the design of the laser structure and the epitaxial growth of the laser material. The fabrication processes that have been used to fabricate the various lasers presented in the thesis are described, with an emphasis on the spectrally engineered FP lasers.

6.1 From idea to laser

Since there are several parameters that will have an influence on the final device performance the process of fabricating a semiconductor laser tends to be of iterative nature. In the fabrication process all parameters should be optimized in order to meet the requirements put on the final device. The first thing that needs to be optimized is the quality of the material the components will be fabricated from. A typical material optimization procedure is displayed in Fig. 6.1. One always begins by designing the epitaxial laser material structure and proceeds by growing the material, using either MBE or MOCVD. When the material has been grown its quality must be assessed, usually through photoluminescence measurements. If the material quality is poor one changes the growth conditions and grows new material, and this step is iterated until one believes that the material quality is good enough for making lasers from it. The material is then taken to a cleanroom where it is processed into broad area lasers. Optical and electrical characterization techniques are then used to assess the performance of these lasers. If the result from the BA laser characterization is not satisfying the whole process is repeated again, from either the design or the growth step. About 90% of the time is spent in the growth-photoluminescence-growth loop, indicated by “A” in Fig. 6.1. When the material quality is good enough one may proceed with fabrication of more advanced lasers. This laser fabrication also needs to be optimized and is an iterative process mainly governed by Murphy’s law: what can go wrong does go wrong.
Material design - Material growth - Material quality?

Fabricate BA lasers - Laser quality?

Figure 6.1: Procedure for assessing material quality. The material quality is first controlled using photoluminescence measurements. A final evaluation is performed by BA laser fabrication and characterization.

6.2 Epitaxial growth and characterization

The first step in designing a semiconductor laser is to design the epitaxial SCH structure. This includes both choosing an active region material and design that will provide optical gain at the desired wavelength as well as suitable waveguiding layers. The various design parameters one can change include the thickness of the QWs and intermediate barriers, the material in intermediate barriers and the material composition and the doping levels of the confinement and cladding regions. In order to improve the carrier injection efficiency graded index layers are commonly used [259, 260].

6.2.1 Molecular beam epitaxy

The epitaxial material used in this work for fabrication of SE-FPLs was grown with MOCVD\(^1\) and consisted of an InGaAs SQW embedded between AlGaAs cladding layers. All InGa(N)As materials in this work have however been grown \textit{in-situ} on \textit{n}-doped \(2^\circ\) off (001) GaAs-substrates in an EPI 930 solid-source MBE system. For the growth of InGaNAs a load-lock RF nitrogen plasma source has been used. The nitrogen source was not equipped with deflection plates. In MBE, epitaxial growth is obtained through nucleation of molecular beams of different elements on a heated substrate. The molecular beams are created through thermal evaporation of the constituent (highly pure) materials in effusion cells. The evaporation takes place in an ultra-high vacuum chamber with the chamber background pressure typically being in the low \(10^{-11}\) torr range. The fluxes of the molecular beams are controlled by the temperature of the effusion cells. Shutters are used in front of the cells in order to rapidly alter between the different material sources. The rapid shutter control enables the thickness of a grown film to be controlled as precisely as fractions of a monolayer, which makes MBE an excellent method for growth of low-dimensional structures such as QWs and QDs. The substrate is heated and rotated in order to obtain a uniform composition of the deposited material. The quality of the grown film is heavily dependent on growth conditions such as the molecular beam flux, the chamber pressure and the growth temperature, all of which need to

\(^1\)Supplied by \texttt{http://www.iqep.com/}
be precisely controlled. A more detailed description of MBE systems is found in reference [261].

6.2.2 Photoluminescence

When the material has been grown one needs to characterize its optical quality and investigate if the material provides efficient radiative recombination. The most widely used method for this is photoluminescence. The principle of PL is to measure the spectrum of the light emitted from the sample, its luminescence, by creating electron-hole pairs through optical excitation with a laser of appropriate wavelength. The photon energy of the exciting laser should be larger than the bandgap of the cladding layers, so that electron-hole pairs can be generated and subsequently captured in the active region, where they can recombine through spontaneous recombination. In our setup we use an Argon laser emitting at 514.5 nm. The spontaneously emitted photons are then collected by a large lens and the intensity is recorded as a function of wavelength by focusing the light into a monochromator, with gratings for wavelength selection, and detecting the monochromator output with a liquid nitrogen cooled Ge-detector. The parameters of importance in a PL spectrum are the peak wavelength and intensity, as well as the full-width-at-half-maximum (FWHM) of the spectrum. Materials of good optical quality have strong intensity at the peak wavelength (which should match the design wavelength) together with a narrow FWHM. Although strong intensities imply low laser threshold current densities I have noticed that a narrow FWHM sometimes is an even more important characteristic.

6.3 Laser fabrication

The following sections describe the process used to fabricate conventional FP lasers with broad and narrow resonator widths, as well as the spectrally engineered FP lasers based on the resonator design described in chapter 5.

6.3.1 Processing techniques

The fabrication of a laser includes a range of different processing techniques to e.g. pattern, remove and deposit materials, such as dielectrics and metals. For deposition of materials, resistive and electron beam evaporation, sputtering, plasma enhanced chemical vapor deposition and spin coating have been used in the work presented in this thesis. Inductively coupled plasma (ICP) dry etching has been the main method used for removing materials. Wet etching has been used in cases where an anisotropic etch has not been necessary. Patterning has been performed using both standard photolithography as well as electron beam lithography (EBL). Inspection of the fabrication process is crucial and has been performed with optical microscopes and scanning electron microscopy (SEM) for visual inspections, while surface profilers have been used to measure surface topography. The reader
is referred to [262] for a detailed description of commonly used GaAs processing techniques.

### 6.3.2 Broad area lasers

The fabrication of BA lasers is rather simple and involves only a few processing steps. One starts by cleaving out a small $8 \times 10$ mm$^2$ sized chip from the wafer. After this the chip is cleaned with a standard acetone cleaning procedure in order to remove any dirt on the surface that may deteriorate the subsequent processing steps. A stripe pattern that will define the top $p$-contact is then transferred to the chip using photolithography. The stripe width used in this work is 100 $\mu$m and the stripes are separated by 50 $\mu$m. Having defined a stripe pattern the processing continues by depositing the $p$-contact metal using sputtering. Ti/Au metal films with approximate thicknesses of 15/250 nm have been used. The thin Ti layer merely acts as a glue to increase the adhesion of the metals to the semiconductor. A standard lift-off process is used to remove the excess metal. The lateral waveguide is next defined by etching away the upper cladding layers at the sides of the ridge with wet etching. This also reduces the amount of current spreading above the active region. The etch depth is controlled with a surface profiler in order to make sure that one does not etch through the active region, which would introduce a large density of surface defects and deteriorate radiative recombination efficiency. The chip is next thinned down to roughly 150 $\mu$m by lapping, in order to facilitate cleaving for the formation of mirrors, and a Ni/Ge/Au $n$-contact is evaporated on the backside of the chip. The $n$-contact is subjected to rapid thermal annealing in order to make the contact ohmic$^2$. The annealing temperature and time have been optimized in order to reduce contact resistance, with the optimum conditions being 440 °C during 30 s. The final processing step is to cleave the lasers into bars of different cavity lengths using a diamond scriber.

### 6.3.3 Ridge waveguide lasers

The fabrication of RWG lasers is similar to the fabrication of BA lasers, but involves a few more processing steps. A Ti/Au/Ni $p$-contact is first deposited using thermal evaporation and lift-off. ICP dry etching is then used to etch away the materials on the sides of the ridge. The $p$-contact acts as an etch mask and the high etching selectivity between Ni and GaAs results in sharp vertical sidewalls and smooth etching interfaces (for BA lasers a Ni layer is not needed since the Au:AlGaAs selectivity is sufficient for the wet etch process used to define the waveguide). Since the ridge is much more narrow ($\sim 4$ $\mu$m) compared to a BA laser, large ($\sim 100$ $\mu$m wide) bond pads are positioned on top of the ridge $p$-contact in order to avoid physical pressure on the ridge from the current injection probes used for laser characterization. Before depositing the bond pads the ridge is isolated by covering

$^2$The annealing drives the Ge into the the semiconductor and dopes the GaAs. Annealing is not necessary for the $p$-contact since the top GaAs is highly doped.
the chip with an insulating layer of SiNx. Photolithography and dry etching is used to open a window in the SiNx on top of the narrow ridge for current injection. Finally, the sample is thinned to \( \sim 150 \) \( \mu \)m and an \( n \)-contact is deposited on the backside of the chip before laser bars of different lengths are cleaved.

### 6.3.4 Spectrally engineered Fabry-Perot lasers

For the fabrication of an SE-FPL it is necessary to dry etch the facets and the perturbed (width modulated) waveguide. In order to ensure that the etched side walls are both vertical and smooth care must be taken when choosing the etch mask. Any roughness of the mask edges would be transferred to the etched structure during the etching process which may result in both surface roughness and non-verticality of the etched side walls. In this work Ni has exclusively been used as an etch mask in all dry etching steps since Ni is a hard material and therefore very resistant to mask erosions. ICP dry etching with a SiCl\(_4\)-Ar chemistry has been used to etch AlGaAs layers. The etch selectivity of Ni to AlGaAs in the used etch process is very high, with a typical value of \( \sim 80 \). As a comparison the selectivity of Au:AlGaAs and Cr:AlGaAs are \( \sim 5 \) – 10 and \( \sim 50 \), respectively. An additional advantage with Ni is that it does not easily oxidize. It is therefore possible to include the Ni layer in a \( p \)-contact without increasing the contact resistance too much. Thus, by defining the ridge waveguide with a Ni-mask it is possible to obtain self-alignment of the \( p \)-contact to the top of the ridge. However, when Ni is used as an etch mask in a chlorine-based etch chemistry it is very important that the sample is rinsed in de-ionized water immediately after etching in order to prevent corrosion of any remaining Ni. Since a metallic etch mask usually is defined by a standard lift-off process it is beneficial to define the mask on a surface that does not have
a pronounced topography. This is because it can be difficult to obtain a uniform resist thickness when spinning resist on a non-flat surface, which may result in a poor resolution in the lithography process. For this reason the very first processing step in the fabrication of an SE-FPL was to define the p-contact. Examples of some dry etched structures are shown in Figs. 6.2(a)-6.2(b). Figure 6.2(a) shows an SE-FPR realized as a laterally corrugated ridge waveguide with a smallest feature size (length of a perturbed waveguide segment) of 270 nm. The etch depth was 1.4 µm which translates into an aspect ratio of ~ 5.

The fabrication of an SE-FPL is similar to the fabrication of a conventional RWG laser, although more processing steps are necessary, which makes fabrication a little more complicated. The main difference is the required precise positioning of the perturbations along the ridge waveguide with respect to the end facets, which translates into a few more lithography steps. A detailed description of the fabrication process is given in Paper F and will therefore only be briefly summarized here. The most important processing steps are indicated in Fig. 6.3.

(1) A Ti/Au/Ni p-contact that defines the SE-FPR is fabricated in a lift-off process (using direct-write EBL for the pattern definition). The mask layout is depicted in the left part of Fig. 6.3 and consists of a perturbed ridge waveguide with an extended waveguide width near the end facets, forming a T-bar at each end. This is useful in order to obtain good quality etched facets. Some examples of a few SE-FPRs after lift-off are shown in Fig. 6.4(a).

(2) Dry etching of the perturbed ridge waveguide with the area where the facets will be etched protected with photoresist.

(3) Deposition of SiNx for electrical insulation of the ridge waveguide.

(4) Deposition of large area bondpads.

(5) Dry etching of the end facets with the perturbed waveguides protected with photoresist. The resist mask is aligned along the symmetry line of the T-bar, as indicated in the left part of Fig. 6.3.

(6) Lapping of the sample and n-contact deposition on the backside of the chip. An example of a fabricated SE-FPL is shown in Fig. 6.4(b).
6.4 Laser characterization

The lasers in this thesis have mainly been characterized by their static electrical and optical properties. Most of them are obtained by measuring the LI-characteristics. The threshold current is obtained by extending a straight line from the lasing portion of the LI-curve until it intersects with the horizontal axis. Only the lower part of the LI-curve above threshold should be used in order to avoid influence from non-linearities that may occur at higher power levels. The laser under investigation is typically placed on a copper heatsink connected to a Peltier element for temperature dependent measurements. The characteristic temperature is obtained by measuring the threshold current at different heat sink temperatures. By plotting the logarithm of $I_{th}$ versus temperature $T_0$ is calculated as the slope of the curve. The efficiency of a laser is quantified by the external differential efficiency, defined as

$$\eta_d = \frac{q\lambda}{hc} \left. \frac{\Delta P}{\Delta I} \right|_{I> I_{th}},$$

where $\Delta P/\Delta I$ denotes the slope efficiency. By measuring $\eta_d$ for lasers of different lengths it is possible to deduce the internal optical loss and the internal quantum efficiency since they are related by [264]

$$\frac{1}{\eta_d} = \frac{\alpha_i}{\eta_i \ln \frac{R}{R_i}} L + \frac{1}{\eta_i}.$$  

3Other definitions of $I_{th}$ also exist where it is calculated by plotting the first or second derivative of the LI-curve [263].
It is also possible to deduce the transparency current density $J_{tr}$ and material gain coefficient $g_0$ by measuring $J_{th}$ for different resonator lengths, using the relation [264]

$$\ln(\eta J_{th}) = \frac{(\ln 1/R)}{\Gamma g_0} \frac{1}{L} + \frac{\alpha_i}{\Gamma g_0} - J_{tr}. \quad \text{(6.3)}$$

Equation (6.3) assumes a logarithmic dependence of material gain on current density which is roughly valid for QW active regions. To avoid lateral diffusion effects these measurements are typically performed on broad area lasers.

**Optical gain measurements**

By measuring the amplified spontaneous emission spectra it is possible to calculate the net modal gain as a function of wavelength. There are several methods that can be used and one of the most common and straightforward methods is the Hakki-Paoli (HP) method [265]. In the HP method the net modal gain is given by

$$\Gamma g - \alpha_i = \frac{1}{L} \ln \frac{\sqrt{\rho} - 1}{\sqrt{\rho} + 1} + \alpha_m, \quad \text{(6.4)}$$

where $\rho$ is the modulation depth (the ratio of the power in a peak and in an adjacent minimum at some wavelength in the spectrum) of the FP resonances.
7 Summary of appended papers

This thesis consists of six appended papers. The first four papers cover the work performed on dilute nitride lasers while the final two papers concern spectrally engineered Fabry-Perot laser resonators. Papers A-B deal with the development of low threshold current density 1.29 µm GaInNAs TQW lasers. The stability of the threshold current against temperature variations in 1.28 µm GaInNAs DQW lasers is the subject of Papers C-D. Paper E presents a numerical method for the design of weakly and strongly perturbed spectrally engineered FP resonators. The fabrication of lasers with SE-FPRs is the topic of Paper F which presents fabrication procedures and an analysis of the sensitivity of SE-FPR performance to fabrication tolerances. All papers are summarized below together with my contributions to each paper.

Paper A
In this paper MBE growth of highly strained InGaAs/GaAs QWs is optimized as a first step towards growth of GaInNAs/GaAs QWs. High-quality 1.2 µm InGaAs/GaAs single and triple quantum well lasers are demonstrated. For the triple quantum well, a record low threshold current density of 107 A/cm²/well is achieved for a 100 x 1000 µm² laser.

My contribution
I performed all photoluminescence measurements, laser fabrication, measurements and data analysis and wrote the paper.

Paper B
In this paper we demonstrate a record low threshold current density for a GaInNAs/GaNAs/GaAs TQW laser emitting at 1.29 µm. The laser structure was grown by MBE after extensive optimizations of growth and in situ annealing conditions.
Broad area lasers with a cavity length of 1 mm showed a record low threshold current density of 400 A/cm$^2$ (133 A/cm$^2$/QW), a high differential efficiency of 0.32 W/A/facet and a characteristic temperature of 94 K in the temperature range 10 to 110 °C.

**My contribution**
I performed photoluminescence measurements, measured the temperature dependence of the threshold current and co-authored the paper.

**Paper C**
In this paper we present an experimental and theoretical investigation of the temperature dependence of the threshold current for double quantum well GaInNAs/GaAs lasers in the temperature range 10 - 110 °C. Pulsed measurements of the threshold current are performed on BA and RWG lasers. The RWG lasers exhibit high characteristic temperatures ($T_0$) of 200 K up to a critical temperature ($T_c$), above which $T_0$ is reduced by approximately a factor of 2. The $T_0$-values for BA lasers are significantly lower than those for the RWG lasers, with characteristic temperatures on the order of 100 (60) K below (above) $T_c$. Numerical simulations, using a model that accounts for lateral diffusion effects, show good agreement with experimental data and reveal that a weakly temperature dependent lateral diffusion current dominates the threshold current for RWG lasers. This explains the observed high $T_0$-values for RWG GaInNAs lasers as an effect not intrinsic to GaInNAs but rather related to the geometry of the laser resonator.

**My contribution**
I made the literature study of published $T_0$-values, performed all measurements and data analysis, numerical simulations and wrote the paper.

**Paper D**
This experimental paper presents results from scanning near-field optical microscopy measurements of the lateral spontaneous emission profile for ridge waveguide 1.3 μm GaInNAs/GaAs DQW lasers. The measurements reveal significant lateral carrier diffusion, in agreement with the results obtained in Paper C.

**My contribution**
I implemented the measurement setup and performed all measurements, numerical simulations and wrote the paper.
**Paper E**

In this paper a numerical design algorithm is developed for the design of spectrally engineered FP resonators where refractive index perturbations are introduced along the waveguide in order to tailor the spectral properties of the resonator. Unlike previous designs, the approach fully accounts for all multiple-reflection events and uses a search space that permits any distribution of the locations and lengths of the perturbations. It is therefore possible to design resonators with almost arbitrary spectral properties with very low threshold gain values for, e.g., the lasing modes of a two-color resonator.

**My contribution**

I co-developed the design algorithm and implemented it in MATLAB, performed all design simulations and wrote a major part of the paper.

**Paper F**

In this paper a method for fabrication of lasers based on spectrally engineered FP resonators is proposed. The SE-FPR is realized as a ridge waveguide with a varying width that introduces a perturbation of the effective index. The end facets are etched which enables a precise positioning of the perturbations relative the end facets. It is shown that this is required in order to ensure that an SE-FPR performs according to its design. A range of lasers with SE-FPRs designed for single mode and two-color emission are fabricated and evaluated through measurements of spectra and light-current characteristics. For example, it is found that SE-FPRs with a large number of index perturbations exhibit lower additional loss than devices with a small of number of perturbations.

**My contribution**

I designed the photolithography masks used in the fabrication and developed most fabrication procedures. Further, I performed all laser fabrication except the e-beam lithography, measurements and data analysis, numerical simulations and wrote a major part of the paper.
References


First semiconductor laser demonstration.


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[66] The scientists that perhaps have contributed most to our understanding of light are Isaac Newton, Christian Huygens (wave theory) and Albert Einstein (quantum theory).


First introduction of light quanta.


Theory of spontaneous and stimulated emission of radiation.


First MASER demonstration.


Theory for the extension of the maser to optical frequencies.


First LASER demonstration.


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