Integration of Semiconductor Optical Amplifier in Wavelength Division Multiplexing Photonic Integrated Circuits

Application of Selective Area Chemical Beam Etching
Integration of Semiconductor Optical Amplifiers in Wavelength Division Multiplexing Photonic Integrated Circuits

Application of Selective Area Chemical Beam Epitaxy

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR AAN DE TECHNISCHE UNIVERSITEIT DELFT, OP GEZAG VAN DE RECTOR MAGNIFICUS PROF. IR K.F. WAKKER, VOORZITTER VAN HET COLLEGE VOOR PROMOTIES, IN HET OPENBAAR TE VERDEDIGEN OP DINSDAG 19 DECEMBER 2000 OM 13:30 UUR

DOOR

Peter Johan HARMSMA

natuurkundig ingenieur,
geboren te Dokkum.
Dit proefschrift is goedgekeurd door de promotoren:

Prof. dr ir M.K. Smit  
Prof. dr ir H. Blok  

Toegevoegd promotor: Dr Y.S. Oei

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter  
Prof. dr ir M.K. Smit, Technische Universiteit Delft, promotor  
Prof. dr ir H. Blok, Technische Universiteit Delft, promotor  
Dr Y.S. Oei, Technische Universiteit Delft, toegevoegd promotor  
Dr M.R. Leys, Technische Universiteit Eindhoven  
Prof. Dr.-Ing L.M.F. Kaufmann, Technische Universiteit Eindhoven  
Prof. dr ir P. van Daele, Universiteit Gent  
Dr. C.R. Doerr, Bell Labs, Lucent Technologies, USA  
Prof. dr ir J.J.M. Braat, Technische Universiteit Delft, reservelid

This work was supported by the Dutch Ministry of Economic Affairs (IOP Electro-Optics), and by the European Community (ACTS BLISS and APEX).

Harmsma, Peter Johan

Integration of Semiconductor Optical Amplifiers/  
Harmsma, Peter Johan  
Ph.D. Thesis Delft University of Technology. - With ref. - With summary in Dutch.  
ISBN 90-9014315-7  
Keywords: Integrated optics / Optoelectronics.

Cover: photonic integrated circuit containing two 8-channel phased array multi-wavelength lasers  
Photograph by Herman Kempers

Copyright ©2000 Peter Harmsma

Typeset using \LaTeX, Printed in The Netherlands
Contents

1 Introduction .................................................. 1
  1.1 Optical communication .................................. 1
  1.2 Wavelength Division Multiplexing ....................... 2
  1.3 Integrated optics ........................................ 3
      1.3.1 Materials for Photonic Integrated Circuits ........ 4
      1.3.2 Integration of Optical Amplifiers in InP-based PICs 5
      1.3.3 Integration Opportunities ............................ 5
      1.3.4 Conclusions ......................................... 8
  1.4 Scope of this thesis ...................................... 8

2 InP-based materials and devices ............................ 11
  2.1 Introduction ............................................. 11
  2.2 InP-system: material properties ........................ 11
      2.2.1 Crystallographic structure .......................... 12
      2.2.2 Composition-dependent properties ................... 13
  2.3 InP-based passive devices ............................... 14
      2.3.1 Waveguides .......................................... 14
      2.3.2 Phased arrays ....................................... 15
  2.4 Optical amplifiers ...................................... 16
      2.4.1 Device structure .................................... 16
      2.4.2 Characteristic properties ............................ 18
  2.5 Fabry-Perot Lasers ...................................... 23
  2.6 Optical amplification ................................... 27
      2.6.1 Material gain of bulk In_{1-x}Ga_{x}As_{y}P_{1-y} .... 27
      2.6.2 Quantum wells: energy levels ....................... 31
      2.6.3 Quantum wells: material gain ...................... 35
      2.6.4 Quantum wells versus bulk In_{1-x}Ga_{x}As_{y}P_{1-y} 36
      2.6.5 The double heterojunction .......................... 39
  2.7 Conclusions ............................................ 40
3 Technology
3.1 Introduction ........................................ 41
3.2 Epitaxy ............................................. 41
3.2.1 MOVPE .......................................... 42
3.2.2 CBE ............................................ 43
3.2.3 MOVPE versus CBE ............................... 44
3.2.4 Conclusion ...................................... 44
3.3 Integration technologies ............................ 45
3.3.1 Overgrowth ..................................... 45
3.3.2 Butt joint: MOVPE .............................. 47
3.3.3 Butt joint: CBE/MBE ............................ 48
3.3.4 Selective Area MOVPE ......................... 48
3.3.5 Multi Quantum Well Intermixing ............... 49
3.3.6 Evanescent field coupling ....................... 49
3.3.7 Integration technology applied in this work .... 50
3.4 Fabrication of integrated ridge waveguide devices 51
3.4.1 Definition of active and passive regions ....... 51
3.4.2 RIE etched waveguide devices ................ 53
3.4.3 Wet chemically etched waveguide devices .... 55
3.4.4 Dimensions ..................................... 57
3.5 Conclusions ....................................... 58

4 Ridge Lasers and Amplifiers .......................... 59
4.1 Introduction ....................................... 59
4.2 Design ............................................. 60
4.2.1 Device structures ............................ 60
4.2.2 Epitaxial layer stacks ........................ 62
4.2.3 Dimensions ..................................... 64
4.2.4 Mask layout .................................... 65
4.3 Gain-guided devices ................................ 65
4.3.1 Fabrication .................................... 65
4.3.2 Measurement results ............................ 67
4.3.3 Conclusions .................................... 69
4.4 InGaAs/InGaAsP MQW ridge lasers ................. 69
4.4.1 Fabrication .................................... 69
4.4.2 Measurement setup ............................. 70
4.4.3 Measurement results ........................... 72
4.4.4 Conclusions .................................... 80
4.5 InGaAs/InGaAsP MQW ridge amplifiers .......... 80
4.5.1 Experimental setup ............................ 81
4.5.2 Results ........................................ 81
4.5.3 Conclusions .................................... 84
4.6 InGaAs/InP MQW laser structures ................ 84
5 Integrated optical amplifiers

5.1 Introduction ............................................. 93
5.2 Design of integrated optical amplifiers ................. 94
  5.2.1 Device structure and dimensions .................. 94
  5.2.2 Mask layout ....................................... 94
5.3 Integration experiments ................................ 97
  5.3.1 Passive-passive integration ......................... 97
  5.3.2 Integrated optical amplifiers: regrowth at active regions ..... 99
  5.3.3 Integrated optical amplifiers: regrowth at passive regions ... 103
5.4 Extended cavity lasers ................................ 109
  5.4.1 Device layout ...................................... 110
  5.4.2 LI-curves ......................................... 111
  5.4.3 Threshold current density ......................... 111
  5.4.4 Differential efficiency ............................ 115
  5.4.5 Characteristic temperature ......................... 117
  5.4.6 IV-curves ......................................... 118
  5.4.7 Spectra ........................................... 119
  5.4.8 Discussion: residual reflections .................... 121
  5.4.9 Angled facet devices ............................... 123
5.5 Phased array multi-wavelength lasers .................. 124
  5.5.1 Introduction ...................................... 124
  5.5.2 Design ............................................ 126
  5.5.3 4-channel MWLs, active layer on top of the film ........ 131
  5.5.4 4-channel MWLs, active layer in the center of the film .... 140
  5.5.5 8-channel MWLs .................................. 146
5.6 Conclusions ............................................ 151

A MOVPE-grown layer stacks ................................ 153

B CBE-grown layer stacks .................................. 155

References .................................................. 159

Summary .................................................... 171

Samenvatting ................................................ 173
Contents

Dankwoord 175
List of symbols 177
List of Abbreviations 181
Curriculum Vitae 183
List of publications 185
Chapter 1

Introduction

Fiber-optic communication is the key answer to the ever increasing demand for data transmission capacity. Especially optical communication systems that use Wavelength Division Multiplexing (WDM) enable optimal exploitation of the available bandwidth, and potentially offer flexible routing and switching features. In this chapter, a short introduction to optical communication is given, and the basic principle of WDM is explained. In order to fully exploit the possibilities offered by WDM, one should perform routing and switching signal processing in the optical domain, using either hybrid solutions or using Photonic Integrated Circuits (PICs). We discuss the potential role of integrated Semiconductor Optical Amplifiers (SOAs) in such PICs. The realization of integrated Semiconductor Optical Amplifiers for application in WDM Photonic Integrated Circuits is the subject of this thesis.

1.1 Optical communication

In the last few decades the demand for information transmission capacity has rapidly increased. While in the 1950s customers were satisfied with a telephone connection and a few radio stations, nowadays entry to over 20 television channels is considered to be normal, and video-on-demand may soon be available. The main driving force to increase the transmission capacity of communication networks, however, is the rapid growth of telecom applications such as the Internet since the early 1990s.

Fiber-optic communication can meet the ever increasing demand for data transmission capacity. Figure 1.1 shows the basic principle. The information to be transmitted is converted into a serial bit pattern in the electrical domain according to a standardized format. This bit pattern modulates a laser, the output of which is launched into a fiber for transmission. Finally, the optical signal is detected by the detector at the receiver end. For long transmission distances (more that a few tens of kilometers) it is necessary to compensate for the fiber losses (typically 0.2 dB/km) by amplification
of the optical signal using Erbium Doped Fiber Amplifiers (EDFAs). The invention of the EDFA allowed for the realization of long-distance fiber-optic links in which conversion to the electrical domain is not necessary, and triggered the development of optical communication in commercial applications. The EDFA can amplify signals at wavelengths between 1525 and 1560 nm, the so-called ‘EDFA window’, implying an available bandwidth of over 4 THz (!).

### 1.2 Wavelength Division Multiplexing

The transmission capacity of the optical ‘point-to-point’ link in Fig. 1.1 is limited by the speed of the electronics, which is about 40 Gb/s at most. So this strategy does not fully exploit the available bandwidth at all. An adequate way to increase the transmission capacity is Wavelength Division Multiplexing (WDM), i.e. the use of multiple wavelengths in parallel (Fig. 1.2a). The transmission capacity of the WDM link in Fig. 1.2a is simply the capacity of the point-to-point link in Fig. 1.1, multiplied by the number of wavelengths. Optical (de-) multiplexers with 256 channels spaced by 25 GHz have already been demonstrated [1]. One does not need expensive 40 Gb/s electronics\(^1\) in a WDM system that utilizes optical multiplexers with such small channel spacing.

A further advantage of WDM is that it offers routing and switching features. For example, in the small ring-like sub-network in Fig. 1.2b, each user has an Add-Drop Multiplexer (ADM) which enables the user to detect signals at a specific wavelength and to transmit at that same wavelength at the same time. So various users can simultaneously communicate over the ring, using different wavelengths for each connection, without causing any conflicts. The ring itself is connected to a second ring, which represents the rest of the network, by means of an Optical Cross Connect (OXC). Using an OXC, the network operator can decide whether or not a specific wavelength stays in the ring-like sub-network or is shared with the rest of the network.

---

\(^1\) 40 Gb/s electronics is not commercially available yet.
1.3 Integrated optics

Figure 1.2: a) WDM point-to-point link. b) WDM ring-like sub-network. MUX: Optical Multiplexer; DMX: Optical Demultiplexer; ADM: Add-Drop Multiplexer; OXC: Optical Cross Connect.

The components that one needs for the realization of the WDM point-to-point link in Fig. 1.2a are optical (de-) multiplexers, lasers and detectors, and of course the fiber, optional EDFAs and electronics. For the realization of photonic circuits such as ADMs and OXCs, one needs optical switches as well. All these components are commercially available as stand-alone devices which can be connected in such a way that the desired functionality is obtained, the so-called hybrid solution. Alternatively, one can fabricate (a number of) these components on a single chip: a Photonic Integrated Circuit (PIC). This approach has the advantage that one obtains a small and compact unit in which the various components are now connected by means of waveguides instead of by means of fragile fibers. This improves the robustness of the circuit, and reduces its sensitivity to the environment. Even more important, packaging costs are a substantial, if not the main part of the component cost, so it is very cost-effective if one can omit as many intermediate fiber connections as possible. Finally, in Photonic Integrated Circuits one can realize functionalities that are hard, or even impossible to realize with fiber-connected stand-alone components.
1.3.1 Materials for Photonic Integrated Circuits

Several materials in which one can fabricate Photonic Integrated Circuits are available. We briefly discuss the most important ones here.

- Silica-on-silicon: the use of silicon for Photonic Integrated Circuits offers two important advantages. In the first place, the fabrication technology of Si-based PICs partially overlaps with the mature fabrication technology of Si-based electronic devices, and large wafers (standard 8") of good quality are available at low prices. Secondly, the modal field of Si-based PICs matches well with the modal field of monomode fibers, so packaging is relatively easy\(^2\). Phased array (de-) multiplexers with excellent performance have been reported [1] and are commercially available today, as are thermo-optic switches with switching speeds in the order of milliseconds. These components can be integrated on a Si-single wafer for the realization of PICs [2, 3].

- Polymers: the optical properties of polymers are more or less comparable to those of silica-on-silicon, however, the fabrication technology is less mature and long-term stability is still an issue. Also in polymer a number of interesting PICs such as Add-Drop Multiplexers [4] have been reported.

- LiNbO\(_3\): high-speed LiNbO\(_3\) Mach-Zehnder interferometer modulators are widely used in optical communication today. However, crystals that are large enough to fabricate for example OXC's are hardly or not at all available, and are far more expensive than silica-on-silicon wafers of comparable size.

- III-V semiconductors: for WDM applications at wavelengths in the EDFA window, one can fabricate both transparent devices and optical amplifiers using the III-V compound semiconductor material \(\text{In}_{1-x}\text{Ga}_{x}\text{As}_{y}\text{P}_{1-y}\). The fabrication technology for these so-called InP-based devices is still improving, especially in the field of reproducible and uniform epitaxial growth [5, 6]. The high refractive index allows for the fabrication of small devices, and many devices fit on a small area. Therefore, the small diameter of the available substrates (usually 2") and the relatively high waveguide losses (typically 2 dB/cm) are not necessarily a problem. As opposed to the thermo-optic switches in silica-on-silicon and in polymer, the InP-based switches are electro-optic [7–9] and have a negligible power consumption. These electro-optic switches can be integrated with phased array optical (de-) multiplexers [10] to obtain Add-Drop Multiplexers [11] and Optical Cross Connects [12–14]. Furthermore, these switches are potentially very fast, and could in principle be used as high-speed modulators. The main drawback of InP-based PICs is that the optical mode is not fiber matched, resulting in high fiber-chip coupling losses. Research on Spot Size Converters is ongoing in order to tackle this issue [15].

\(^2\)relatively easy does not mean easy; packaging of any photonic device is quite complicated.
1.3 Integrated optics

Considering the four material systems listed above, we see that integration of transparent (passive) devices, amplifying (active) devices and modulators that operate in the GHz-regime is only possible if one uses III-V semiconductor materials. We believe that in the future the integration scale of PICs will increase to allow for the realization of complex functionalities on a single chip. Many of these functionalities require the incorporation of optical amplifiers and/or modulators. While for PICs without amplifiers or modulators silica-on-silicon is probably the most cost-effective solution, III-V semiconductors are the only candidate for the fabrication of more complex PICs in which optical amplification and/or high-speed modulation is required.

1.3.2 Integration of Optical Amplifiers in InP-based PICs

By adjusting the compositional fractions \((x, y)\) of the III-V compound semiconductor material \(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}\), the bandgap energy can be varied from 0.75 eV to 1.35 eV, corresponding to an absorption edge wavelength of 1.65 \(\mu\text{m}\) to 0.92 \(\mu\text{m}\), respectively\(^3\). Therefore, the material is either absorbing or transparent at the signal wavelength around 1.55 \(\mu\text{m}\). \(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}\) is a direct-bandgap semiconductor, so in a properly designed device the optical absorption can be converted into optical gain by stimulated emission when an electrical current is applied. One of the great challenges in the fabrication of InP-based PICs is the definition of regions on a single InP-substrate, in each of which the \(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}\) material has different compositional fractions \((x, y)\). After definition of these regions, one can fabricate transparent devices and optical amplifiers at the appropriate locations on the chip to accomplish the integration of active and passive devices. We will discuss the various ways to achieve the definition of active and passive regions on a single chip in Chapter 3. The benefits of integration will be pointed out in the next paragraph.

1.3.3 Integration Opportunities

At the Delft University of Technology, research on InP-based Photonic Integrated Circuits (Fig. 1.3) has started with the development of Passive Waveguide Devices (PWDs). Excellent performance of PWDs such as phased array optical (de-) multiplexers [10] and Multi-Mode Interference couplers (MMIs) [16] was demonstrated. Incorporation of Phase Modulators (PHMs) enabled the fabrication of Mach-Zehnder interferometer Electro-Optic Switches (EOS) [7–9], which were integrated with a phased array to yield the first InP-based reconfigurable Add-Drop Multiplexer (ADM) [11]. This concept was further explored, resulting in the realization of integrated Optical Cross Connects (OXC)s [12–14]. Maat et al. [17] reported on the fabrication of a tunable phased array which has a phase modulator in each array waveguide. So it has been demonstrated that by integrating passive waveguide devices and phase modulators one can fabricate the PICs that are essential parts of the WDM network in Fig. 1.2b.

\(^3\)Here we assume that the lattice match condition with InP is obeyed.
The integration of Semiconductor Optical Amplifiers (SOAs) makes it possible to improve the performance of these PICs, and to increase their functionality. Consider first the functionalities that can also be offered by non-integrated SOAs, where the use of integrated SOAs has the important advantage that one does not increase the number of fiber-chip couplings.

In the first place, integrated SOAs can provide on-chip gain to compensate for device losses and fiber-chip coupling losses. These losses may be quite substantial; for example in an InP-based OXC, we have an on-chip loss of typically 13 dB [12–14] and a fiber-chip coupling loss of 3 dB when spot-size converters are applied [15], resulting in a fiber-to-fiber loss of around 19 dB. By incorporation of SOAs, the loss can be reduced to zero, or even converted into fiber-to-fiber gain.

Furthermore, non-integrated SOAs are sometimes used for gate switching [18] of optical signals, i.e. the signals are either amplified or absorbed by the SOA. This is also possible using integrated SOAs in a PIC. The crosstalk of such a SOA gate is usually better than the crosstalk of an electro-optic switch. On the other hand, electro-optic switches do not produce spontaneous emission noise and hardly consume any electrical power, and consequently do not cause any thermal problems.
1.3 Integrated optics

Due to its non-linear characteristics, a SOA is can be applied to convert an optical signal to another wavelength by Cross-Gain Modulation (XGM) or by Four-Wave Mixing (FWM) [19, 20], which can be a very attractive function in a WDM network. Finally, the SOA can be used as a detector, or as an optical source by providing optical feedback from (coated) cleaved facets or gratings [21–25].

Integration of SOAs and passive waveguide devices also enables realization of additional useful functionalities that are otherwise hard to obtain. One important example is the Multi-Wavelength Laser (MWL) [26], where optical feedback through a single phased array (de-) multiplexer is applied to a number of integrated SOAs. The lasing wavelengths of the MWL are determined by the characteristics of the phased array, providing a comb of accurately spaced lasing wavelengths. Alternatively, one can combine the outputs of a series of DFB lasers or DBR lasers into a single output waveguide using a phased array [27, 28]. In this way, the phased array provides a low-loss coupling to the common output waveguide for all the different wavelengths, and the PIC only needs to be connected to a single output fiber.

Another useful application of integrated SOAs is the WDM channel selector [29–31]. In this PIC, a multiple wavelength WDM signal is demultiplexed by a phased array. Each wavelength is then individually absorbed or transmitted (amplified) by a SOA gate, after which all channels are multiplexed by a second phased array. One can also use the WDM channel selector to equalize the power levels of all the WDM signals by adjusting the gain of the SOAs. The channel selector/equalizer has only one input fiber and one output fiber, whereas 4N additional fiber-chip couplings would be required if one would use non-integrated SOAs, where N is the number of wavelengths. A PIC with a similar structure is the Multi-Wavelength Receiver (MWR) [32, 33], which detects the WDM channels after demultiplexing. The detector structure in a MWR can be similar to that of a SOA.

Integrated SOAs are also applied as non-linear elements in Cross-Phase Modulation (XPM) wavelength converters [19, 20]. These converters do not only convert a WDM signal to another wavelength, but can also provide 2R regeneration [34, 35], i.e. amplification and pulse reshaping. XPM wavelength converters employ a Mach-Zehnder interferometric structure, and cannot be realized using non-integrated SOAs because the large ends of connecting fiber cause stability problems.

Full advantage of integrated SOAs is taken when all three types of devices, i.e. phase modulators, passive waveguide devices and optical amplifiers, are integrated on a single chip. A key application is compensation for the on-chip losses and for the fiber-chip coupling losses of PICs such as Add-Drop Multiplexers and Optical Cross Connects. In this way, one can realize zero-loss PICs, or even PICs that provide fiber-to-fiber gain.

Furthermore, one can improve the performance of XPM wavelength converters by incorporating phase modulators in series with the amplifiers [36]. Integration of these wavelength converters with OXCs could provide additional routing and switching flexibility.

Wavelength converters require a continuous-wave optical input that provides the
wavelength that the signal is to be converted to. The phased array multi-wavelength laser is well suited for this purpose, and could be integrated with the wavelength converter itself. A PIC consisting of a wavelength converter and a multi-wavelength laser may even be integrated with an OXC on a single chip. As a last example, the output of a MWL can be modulated directly using electro-optic switches, as these devices are potentially very fast. Such a transmitter may itself be integrated with an ADM into a single PIC.

1.3.4 Conclusions

Wavelength Division Multiplexing is an attractive approach to meet the increasing demand for data transmission capacity. Photonic Integrated Circuits are suitable candidates to perform routing and switching operations in future WDM networks.

Silica-on-silicon is the material of choice for PICs in which no optical amplification and/or high-speed modulation is required. For this material, the fiber-matched waveguide mode facilitates packaging of the circuit to a large extent, which is very important to reduce the cost. In addition to this, the performance of Si-based phased arrays is outstanding.

Integration of optical amplifiers is essential for the realization of more advanced PICs, and is only possible in III-V semiconductor materials. Integrated optical amplifiers do not only provide on-chip gain to compensate for device losses and fiber-chip coupling losses, but also offer functionalities that are hard to realize otherwise. Furthermore, semiconductor-based devices are very small, and many of them fit on a single chip. Therefore, the use of III-V semiconductor materials enables fabrication of high-scale integration PICs operating at wavelengths around 1.55 \( \mu m \).

1.4 Scope of this thesis

At the Delft University of Technology, development of Passive Waveguide Devices (PWDs) integrated with Phase Modulators (PHMs) has led to a number of state-of-the-art Photonic Integrated Circuits (PICs), such as Add-Drop Multiplexers and Optical Cross Connects. A logical step to proceed in this development is the integration of Semiconductor Optical Amplifiers (SOAs) to increase the functionality of these circuits, and to reduce the optical loss. These amplifiers must be compatible with all other devices in the PIC in terms of device structure and fabrication technology. The subject of this thesis is the development of integrated Semiconductor Optical Amplifiers in InP-based Photonic Integrated Circuits for Wavelength Division Multiplexing applications. The thesis is organized as follows:

- In Chapter 2, we briefly discuss the relevant properties of InP-based materials, and give a short introduction to the various devices that one can fabricate in this material system. Furthermore, the theory of optical gain by stimulated emission is reviewed.
1.4 Scope of this thesis

- Chapter 3 is all about technology, and starts with a discussion of the various strategies to achieve the definition of active regions and passive regions on a single chip. We motivate the choice for one of these strategies, Selective Area Chemical Beam Epitaxy, and describe the fabrication processes of Photonic Integrated Circuits as carried out at the Delft University of Technology.

- Chapter 4 deals with the fabrication and characterization of non-integrated lasers and SOAs. These experiments allowed us to develop a suitable device structure and fabrication technology for the integrated SOAs without being troubled by integration issues. The integrability of these non-integrated SOAs with passive waveguide devices and phase modulators was kept in mind at all times.

- In Chapter 5, we discuss a number of experiments concerning the integration of the SOAs that were developed in Chapter 4 with passive waveguide devices. We report measurement results on extended cavity lasers and present the successful realization of 4-channel and 8-channel phased array multi-wavelength lasers.
Chapter 2

InP-based materials and devices

In order to understand the operation of InP-based photonic devices, one needs knowledge of the relevant material properties. These properties are addressed in this chapter. Device structures and characteristics of transparent waveguides, optical amplifiers and lasers fabricated in In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material are discussed. Finally, the theoretical background of optical gain in bulk material and quantum wells is reviewed.

2.1 Introduction

The InP-based III-V semiconductor material In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ is suitable for the fabrication of opto-electronic devices which are applied in optical communication systems. The properties of this material can be modified by changing the compositional fractions $x$ and $y$. For example, the bandgap energy of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ lattice matched to InP can be varied from 0.75 eV to 1.35 eV, corresponding to an absorption edge of 1.65 $\mu$m to 0.92 $\mu$m, respectively. Thus, this material is either transparent or absorbing at the wavelengths within the EDFA window around 1.55 $\mu$m. In addition to this, In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ is a direct-bandgap material at the relevant compositions, and the optical absorption can be converted into optical gain by stimulated emission. Therefore, in the InP system, transparent, absorbing and amplifying devices can be fabricated on a single chip, offering great potential for the realization of photonic integrated circuits.

2.2 InP-system: material properties

In this section, we discuss the crystallographic and composition dependent material properties of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$.
2.2.1 Crystallographic structure

The coordinate system of a crystallographic structure is commonly defined in terms of Miller indices. Written as \([pqr]\) or \((pqr)\), these indices denote a vector or a plane perpendicular to this vector, respectively (Fig. 2.1a).

The quaternary \(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}\) material is a III-V compound semiconductor, i.e. it consists of a mixture of group III elements (In, Ga) and group V elements (As, P). These group III and group V elements are each arranged in a face-centered cubic (fcc) sublattice (Fig. 2.1b). Such a lattice has atoms on each cube corner, as well as in the center of each cube plane. The group III and group V sublattices are mutually displaced by 1/4 of the lattice constant \(a\) in the \([111]\) direction, yielding the so-called zinc-blende structure (Fig. 2.1c). P- or n-type doping can be achieved by incorporating group II elements (Zn, Be) at group III lattice sites, or group VI elements (S) at group V lattice sites, respectively. Also the group IV element Si can be used for n-type doping.

All devices presented in this thesis were fabricated on (100) InP substrates, i.e. epitaxial growth is performed on the (100) plane. Such a substrate is schematically shown in Fig. 2.2a. The \([0\overline{1}1]\) and the \([0\overline{1}1]\) direction are marked by the large flat and the small flat, respectively. After device fabrication, the wafer is cleaved parallel to these flats, where the cleaved facets are (ideally) atomically flat \((0\overline{1}1)\) and \((\overline{0}1\overline{1})\) planes. A view on these cleaved planes, and the crystallographic facets that are revealed by wet chemical etching as applied in this work [37], are also shown in Fig. 2.2. The formation of the sloped \((2\overline{1}1)\) and \((\overline{2}1\overline{1})\) facets is applied for the fabrication of ridge lasers in Chapter 4.
2.2 InP-system: material properties

---

![Diagram](image)

Figure 2.2: Substrate orientation (a), view on (0\(\bar{1}1\)) plane (b) and view on (0\(\bar{1}1\)) plane (c) with crystallographic planes revealed by wet chemical etching.

2.2.2 Composition-dependent properties

The quaternary In\(_{1-x}\)Ga\(_x\)As\(_y\)P\(_{1-y}\) material can be considered as an alloy of the four binary constituents InP, InAs, GaAs and GaP. Its material properties can be approximated by linear interpolation (Vegard’s law):

\[
F(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}) = x y F(\text{GaAs}) + x (1 - y) F(\text{GaP}) + (1 - x) (1 - y) F(\text{InP}) + y (1 - x) F(\text{InAs})
\]  

(2.1)

where \(F\) is a material property such as the lattice constant or the bandgap. Interpolation results are in good agreement with the experimental data reported in literature \([38, 39]\), which yield for the lattice-match condition to InP:

\[
x = 0.4526y / (1 - 0.031y)
\]  

(2.2)

and for the lattice-matched bandgap energy:

\[
E_g \text{[eV]} = 1.35 - 0.72y + 0.12y^2
\]  

(2.3)

When the lattice-match condition with InP is satisfied, we omit the compositional fractions \(x\) and \(y\) in this thesis, and abbreviate \(\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}\) as InGaAsP. From Equations 2.2 and 2.3 it follows that it is possible to grow quaternary material lattice-matched to InP, where the bandgap energy can be varied from 0.75 eV (\(x = 0.47, y = 1\), InGaAs) to 1.35 eV (\(x = 0, y = 0\), InP), which corresponds to an absorption edge of 1.65 \(\mu\)m to 0.92 \(\mu\)m, respectively. The lattice-matched quaternary InGaAsP is often denoted by its absorption edge wavelength at room temperature. For example, Q(1.25) has an absorption edge wavelength of 1.25 \(\mu\)m, a bandgap energy of \(E_g = h c / \lambda = h c / 1.25 \, \mu\text{m} = 0.992\,\text{eV}\) and a composition \((x, y) = (0.252, 0.547)\).
2.3 InP-based passive devices

The basic building block of InP-based photonic integrated circuits is the optical waveguide. More sophisticated devices like phased arrays consist of (a large number of) waveguides with properly designed geometries. Hence their name ‘passive waveguide devices’, where ‘passive’ denotes that no amplification takes place. In this section, we discuss the structure and performance of passive waveguide devices.

2.3.1 Waveguides

The function of a waveguide is the same as that of an on-chip optical fiber: transportation of optical signals between the various devices in a photonic integrated circuit, as well as to the optical fibers connected to this circuit. Figure 2.3 shows a typical InP-based ridge waveguide structure as applied in this work.

The layer stack in which the waveguide is fabricated consists of an InP substrate and buffer, an InGaAsP Q(1.25) or Q(1.3) film and an InP cladding. Such a structure, in which a low-bandgap material is sandwiched between high-bandgap materials, is referred to as a double heterostructure. A ridge waveguide is defined using lithography and etching. According to Fiedler and Schlachetzki [40], the refractive indices of Q(1.25), Q(1.30) and InP are 3.36, 3.39 and 3.17, respectively, at a wavelength of 1.55 μm. Since \( n_{\text{InGaAsP}} > n_{\text{InP}} > n_{\text{air}} \), the effective refractive index as experienced by an optical field is highest inside the film underneath the ridge, and the light is confined both in transversal (x) and lateral (y) direction. Only a discrete number of lateral optical modes are supported, similar to the quantized energy levels in a quantum well (Section 2.6.2). All materials have a bandgap energy that is larger than the photon energy, therefore the structure is transparent for the signal wavelengths. Waveguide losses are mainly caused by scattering losses and are typically around 2 dB/cm. For the structure shown in Fig. 2.3, waveguide bends with bending radii down to 500 μm show only a minor increase in loss.
2.3 InP-based passive devices

![Diagram of phased array](image)

**Figure 2.4:** Schematic layout of phased array.

### 2.3.2 Phased arrays

In photonic integrated circuits for WDM applications, a single waveguide may carry a number of optical signals at different wavelengths. In order to process these signals individually, one must be able to (de-) multiplex these optical signals. This operation is performed by the phased array [10], which is schematically shown in Fig. 2.4. Because the phased array is also an essential part of the multi-wavelength lasers presented in Chapter 5, we will explain its operation principle here.

An input waveguide carrying (in this example) four different wavelengths is connected to the first Free Propagation Region (FPR), which is basically a very wide waveguide. In absence of any lateral index contrast, the optical field will diverge, and the equi-phase front is collected by a number of array waveguides. These array waveguides are designed in such a way that for the central wavelength \( \lambda_c \), the phase shift in each array waveguide differs by an integer times \( 2\pi \). Therefore, the phase front at the upper side of the first FPR is reproduced at the upper side of the second FPR, and the optical field is focussed onto a mirror image of the input waveguide. Since the array waveguides have unequal lengths, their phase shift difference depends on the wavelength, and the focal point will sweep along the lower side of the second FPR as a function of wavelength. Thus, by placing output waveguides at the proper positions, we can demultiplex each WDM channel into its individual output waveguide. Similar to a grating, the response of a phased array is periodic: all signals at a wavelength \( \lambda = \lambda_x + m \cdot FSR \) will appear in the output waveguide for \( \lambda_x \), where \( FSR \) is the Free Spectral Range and \( m \) is an integer number. The loss of a phased array is typically around 3 dB, and the crosstalk (power level in the wrong output waveguide) is better than -20 dB.
2.4 Optical amplifiers

Similar to a transparent waveguide, an optical amplifier consists of a double hetero waveguiding structure. For an amplifier, the compositional fractions $x$ and $y$ of the film material are adjusted such that the bandgap energy corresponds to the photon energy. As a result, when the film is pumped (either electrically or optically), spontaneous emission and stimulated emission can take place. The process of stimulated emission inside the film provides the optical gain in semiconductor lasers and optical amplifiers, and the film is therefore referred to as 'active layer'. Device structures and properties of InP-based optical amplifiers are discussed in this section.

2.4.1 Device structure

Cross sections of the most commonly employed amplifier structures are shown in Fig. 2.5. The optical field is transversely confined by the active layer, lateral confinement is achieved either by local removal of the active layer (Fig. 2.5a,b) or by employing a ridge waveguide structure (Fig. 2.5c). In order to achieve optical amplification, a sufficiently high carrier concentration is required in the active layer. Efficient carrier injection is enabled by doping the layers on top and below the active layer such that a p-n junction is formed. When this junction is forward biased by an electrical current, the injected carriers are effectively trapped in the active layer (Section 2.6.5) and can contribute to the process of stimulated emission, resulting in a net optical gain. The thickness of the $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ active layer is typically 200 nm. Optionally, it may be located in the center of a transparent film (Fig. 2.5c), which is common for thin Multi Quantum Well (MQW) active layers (Section 2.6.2). The upper and lower part of the film are then referred to as 'separate confinement layers', as they help to achieve both a high carrier concentration and a high optical intensity at the active layer.
2.4 Optical amplifiers

The current blocking layers in Fig. 2.5a and b make sure that the injected carriers pass through the active layer. Alternatively, a proton implantation can be used for this purpose [24,41,42]. The current blocking layers consist either of semi-insulating Fe-doped InP [23,43–46], resulting in a Semi-Insulating blocked Planar Buried Heterostructure (SIBBH, Fig. 2.5a), or a stack of p-doped and n-doped layers that form a p-n-p-n junction [18,25,30,47] (Fig. 2.5b). In the ridge waveguide optical amplifier (Fig. 2.5c) [48,49], no specific current-confinement measures are taken. However, because the ridge is created by etching almost down to the active layer, or even through it, most injected carriers will contribute to the process of stimulated emission taking place underneath the ridge.

The ridge is effectively shielded from the environment by a dielectric layer (SiO$_2$ or SiN$_x$), which reduces the surface recombination velocity. The polyimide shown in Fig. 2.5c planarizes the structure so that interruptions of the metallization layer at the nearly vertical ridge side walls are avoided.

The electrical series resistance of the amplifier should be as low as possible, as any resistance will result in the generation of heat, thereby reducing the performance of the device. The series resistance decreases for high doping levels of the InP substrate, buffer and cladding layers. However, doping also causes substantial optical loss. Generally, regions close to the active layer are undoped or lightly doped, and higher doping levels are chosen for regions where the optical intensity is low. A highly p-doped contact layer with a low bandgap energy (InGaAs) is applied to minimize the contact resistance. This layer should be located far away from the active layer, as it is an efficient optical absorber. This requirement sets a minimum for the height of the device structure.

For the fabrication of integrated optical amplifiers, the most suitable device structure should be chosen. Lasers employing the structures in Fig. 2.5a and b generally have a better performance than ridge waveguide lasers. If properly designed, the former devices have a small active region which has a high overlap with the optical field, while the structure supports only one single lateral mode. The blocking layers effectively restrict the current to this active region. As a result, threshold currents are lower than those in ridge waveguide lasers [50]. However, fabrication involves at least one epitaxial regrowth step in order to bury the active layer stripe. These devices are therefore referred to as buried heterostructures. For the fabrication of stand-alone optical amplifiers and lasers, thousands of devices can be obtained from a single wafer, and the application of an expensive regrowth step does not significantly increase the fabrication cost per device. On the other hand, only a few photonic integrated circuits fit on a 2" InP substrate, and the number of regrowth steps should be as low as possible. Furthermore, to facilitate the integration of optical amplifiers and passive waveguide devices, one should use devices with a similar structure and which can be fabricated with the same kind of technology [36,48]. Photonic integrated circuits that are relevant in the context of this thesis have a ridge waveguide structure that is very similar to that in Fig. 2.5c [11–14]. Therefore, it is logical to choose the same structure for the optical amplifiers. Although their fabrication process is more complicated, inte-
2. InP-based materials and devices

![Diagram of an optical amplifier](image)

Figure 2.6: Amplification of an optical mode in an unsaturated optical amplifier with length $L$.


2.4.2 Characteristic properties

In this paragraph, we discuss a few important properties of optical amplifiers.

Gain and gain saturation

The unsaturated modal gain of an optical amplifier is given by:

$$G_0 = e^{(g_0 - \alpha)L}$$  \hspace{1cm} (2.4)

where $G_0 = P_{out}/P_{in}$ is the gain as experienced by the optical mode, $\Gamma$ is the confinement factor, $g_0$ is the material gain of the active layer, $\alpha$ represents the internal losses and $L$ is the device length (Fig. 2.6). When expressed in dB, the modal gain is proportional to the material gain:

$$G_0 \text{ [dB]} = 10^{\log \left( e^{(g_0 - \alpha)L} \right)} = 10^{\log (e) (\Gamma g_0 - \alpha) L}, \quad \text{or:}$$

$$G_0 \text{ [dB/cm]} \approx 4.343 \cdot (\Gamma g_0 - \alpha)$$  \hspace{0.5cm} (2.5)

where $\alpha$ and $g_0$ are expressed in units cm$^{-1}$. For a given active material, the material gain $g_0$ depends on the wavelength of the input signal and on the carrier density. The carrier density is a function of the injection current. The material gain is discussed in more detail in Section 2.6. The confinement factor $\Gamma$ is defined as the overlap between the optical mode and the active material:

$$\Gamma = \frac{\int_{\text{active layer}} U(x,y) \, dx \, dy}{\int_{\text{device cross section}} U(x,y) \, dx \, dy}$$  \hspace{1cm} (2.6)
2.4 Optical amplifiers

![Gain saturation in an optical amplifier.](image)

**Figure 2.7:** Gain saturation in an optical amplifier.

where \( U(x, y) \) is the intensity distribution of the optical mode. It should be noted that it is only correct to use Eq. 2.6 in Eq. 2.4 for TE-polarized light [52, 53]. Typically, the device length \( L \) is between 300 \( \mu \)m and 2 mm, and the gain \( G_0 \) can be as high as 30 dB.

For high optical powers \( P \), the carrier density in the active layer is reduced due to the high stimulated recombination rate, and the gain saturates according to [54]:

\[
g = \frac{g_0}{1 + P/P_s}, \quad \text{and} \quad G = e^{(\Gamma g-a)L} \tag{2.7}
\]

where \( g_0 \) and \( g \) are the unsaturated and the saturated material gain, respectively, \( G \) is the saturated modal gain, and \( P_s \) is the saturation power. \( P_s \) is closely related to the saturation output power \( P_{s,\text{out}} \), which is the output power at which the gain \( G = P_{\text{out}}/P_{\text{in}} \) is reduced by 3 dB (Fig. 2.7). In practical situations, \( P_{s,\text{out}} \approx \ln(2) \cdot P_s \), and the amplifier is operated such that the output power does not exceed \( P_{s,\text{out}} \). The saturation output power depends on the injection current, and can be over 12 dBm in commercially available devices.

**Avoiding gain saturation: gain clamping**

In WDM systems, gain saturation causes unwanted crosstalk between the various channels, as a signal at a wavelength \( \lambda_1 \) modulates the carrier density, and hence saturates the gain as experienced by a signal at a wavelength \( \lambda_2 \). This crosstalk contribution can be avoided using gain clamping [55]. In this case, the amplifier is operated at the same time as a laser and as an amplifier. The lasing wavelength is controlled by means of gratings, and is far away from the signal wavelength. Due to the laser operation, the carrier density is clamped and the input signals reduce the laser output power instead of causing crosstalk at other WDM channels.
2. InP-based materials and devices

a: Cross-gain modulation (XGM) coupler amplifier filter

\[
\text{in: signal } \lambda_1 \quad \text{out: signal } \lambda_2
\]

\[
\text{in: } \text{CW } \lambda_2 \quad \text{carrier density, gain} \quad \text{output signal } \lambda_2
\]

b: Cross-phase modulation (XPM)

\[
\text{in: } \text{signal } \lambda_1 \quad \text{out: signal } \lambda_2
\]

\[
\text{in: } \text{CW } \lambda_2 \quad \text{in: signal } \lambda_1
\]

Figure 2.8: Wavelength conversion using SOAs: Cross-Gain modulation, co-propagating scheme with filter to reject \( \lambda_1 \) (a) and Cross-Phase Modulation, counterpropagating scheme.

Application of gain saturation: wavelength conversion

Gain saturation can also be usefully exploited to achieve wavelength conversion, which is likely to be applied in future WDM networks to increase routing and switching flexibility.

Fig. 2.8a illustrates the principle of wavelength conversion by Cross-Gain Modulation (XGM). A signal at \( \lambda_1 \) and a CW signal at \( \lambda_2 \) are combined using a fiber coupler or an on-chip Multi Mode Interference coupler (MMI) \cite{16}. The input signal at \( \lambda_1 \) causes an increase of the stimulated recombination rate, and hence a decrease of the carrier density. As a result, the gain as experienced by the CW signal at \( \lambda_2 \) is modulated by the signal at \( \lambda_1 \), and the signal is converted (and inverted) to \( \lambda_2 \).

Another wavelength conversion technique is Cross-Phase Modulation (XPM, Fig. 2.8b), where two amplifiers are incorporated in an interferometric structure. One can design the interferometer in such a way that the CW signal at \( \lambda_2 \) interferes destructively at the output when no signal at \( \lambda_1 \) is applied. Gain saturation due to an input signal at \( \lambda_1 \) in one of the amplifiers introduces an imbalance in the interferometer, and the CW signal at \( \lambda_2 \) is available at the output as the condition for destructive interference no longer holds. As a result, the signal at \( \lambda_2 \) is modulated (but not inverted) by the signal at \( \lambda_1 \), and wavelength conversion is achieved. A minor part of the imbal-
ance is caused by variation of the gain; its main cause is the associated phase shift, since the effective refractive index of the amplifier is directly related to the gain by the Kramers-Kronig relation. As compared to XGM, XPM requires lower input powers and provides better output extinction ratios, especially for conversion to longer wavelengths. In fact, XPM is capable of improving the extinction ratio, providing 2R regeneration (amplification and pulse reshaping) [34,35]. Realization of stable XPM wavelength converters is an important application of integrated optical amplifiers. For an overview on wavelength conversion techniques, see for example [19].

**Noise**

Just like electrical amplifiers, optical amplifiers produce noise. The noise arises from spontaneous emission, a small portion of which is coupled into the waveguiding structure and is amplified. Hence, it is denoted as Amplified Spontaneous Emission (ASE). The amplifier noise figure $F_n$ is defined as:

$$F_n = \frac{(\text{SNR})_{\text{in}}}{(\text{SNR})_{\text{out}}}, \quad \text{with} \quad \text{SNR} = \frac{(i_{\text{det}})^2}{(i_{\text{noise}})^2} \quad (2.8)$$

The Signal-to-Noise Ratio SNR refers to the electrical power after detection, which is proportional to the square of the current. Obviously, $F_n$ should be as low as possible, and $F_n = 1$ for an amplifier that does not add any noise. It turns out that, upon signal detection using a photodiode, the dominant noise contribution arises from beating of the spontaneous emission noise with the signal itself, similar to heterodyne detection. As a result, $F_n \geq 2$ (3 dB) for amplification by stimulated emission [54]. For commercially available Erbium Doped Fiber Amplifiers (EDFAs), $F_n$ can be as low 3.5 dB; the noise figure of SOAs is typically more than 7 dB.

**Reflections**

After an optical amplifier has been fabricated, the as-cleaved facets have a power reflection coefficient of typically 0.33, whereas no reflections should occur in an ideal amplifier at all. The consequences of residual reflections are understood from Fig. 2.9 [56,57].

An optical signal with power $P_{\text{in}}$ enters an optical amplifier with length $L$, gain $G = \exp [(\Gamma g - \alpha) L]$, and reflection coefficients $R_1$ and $R_2$. The gain $G$ refers to
optical power, consequently the gain for the electric field is $G^{1/2}$. The signal will experience multiple reflections inside the amplifier, resulting in constructive or destructive interference. For the electric field of the output signal, we have in case of constructive interference:

$$E_{out}^{(+)} = E_{in}t_1t_2\sqrt{G} \cdot \sum_{n=0}^{\infty} \left[ \sqrt{G_{rt}} \right]^n = E_{in}t_1t_2\sqrt{G} \frac{1}{1 - \sqrt{G_{rt}}} \quad (2.9)$$

where the round-trip gain (for optical power) $G_{rt} = R_1R_2G^2$. The index $n$ represents the amount of times that the signal has travelled back and forth, and $t_1$ and $t_2$ are the transmission coefficients for the electric field. Similarly, for destructive interference we have:

$$E_{out}^{(-)} = E_{in}t_1t_2\sqrt{G} \cdot \sum_{n=0}^{\infty} \left[ -\sqrt{G_{rt}} \right]^n = E_{in}t_1t_2\sqrt{G} \frac{1}{1 + \sqrt{G_{rt}}} \quad (2.10)$$

We can merge Equations 2.9 and 2.10 into a convenient expression by defining the quantity $Q$, which gives the relation between $P_{out}^{(+)}$, $P_{out}^{(-)}$ and $G_{rt}$:

$$Q = \frac{\sqrt{P_{out}^{(+)} + \sqrt{P_{out}^{(-)}}}}{\sqrt{P_{out}^{(+)}} - \sqrt{P_{out}^{(-)}}} = \frac{E_{out}^{(+)} + E_{out}^{(-)}}{E_{out}^{(+)} - E_{out}^{(-)}} = \frac{1}{\sqrt{G_{rt}}} = \frac{1}{G\sqrt{R_1R_2}} \quad (2.11)$$

The condition of constructive or destructive interference depends on the wavelength of the input signal, and therefore the output power will fluctuate as function of the wavelength in case $R_1 \cdot R_2 \neq 0$. This output power fluctuation is referred to as 'gain ripple'. Consider an amplifier with a gain of 20 dB and a (rather high) gain ripple of 3 dB: $P_{out}^{(+)} = 2P_{out}^{(-)}$. Assuming $R_1=R_2=R$, we find from Eq. 2.11 that this amplifier has a reflection coefficient $R = 1.7 \cdot 10^{-3}$, which is already 200 times smaller than the reflection coefficient of an as-cleaved facet. For a gain ripple of 1 dB at a gain of 30 dB, a reflection coefficient lower than $6 \cdot 10^{-5}$ is required. Such low reflectivities can be achieved if one uses a combination of Anti Reflection (AR) coatings and angled facets, with optional window structures [54, 58, 59]. Amplifiers with a gain ripple of 0.2 dB at a fiber-to-fiber gain of 20 dB are commercially available ($R=1\cdot10^{-4}$).

An important application of Eq. 2.11 is the determination of passive waveguide losses. A probe signal is launched into a waveguide of which the reflection coefficients and length are known, and the wavelength of this probe signal is swept. The power measured at the waveguide output varies between $P_{out}^{(+)}$ and $P_{out}^{(-)}$, and the loss $\alpha$ is obtained from Eq. 2.11 using $G = \exp(-\alpha L)$ for $g = 0$. Furthermore, with Eq. 2.11 we can also find the wavelength-dependent modal gain $G(\lambda)$ of an optical amplifier [56, 57, 60, 61] by measuring the gain ripple in the ASE spectrum over a wide wavelength range using a high-resolution optical spectrum analyzer. The wavelength-dependent gain then follows directly from Eq. 2.11 if the reflection coefficients are accurately known (calculated).
2.5 Fabry-Perot Lasers

An optical amplifier can be considered to be a Fabry-Perot laser without mirrors, or the other way around: a Fabry-Perot laser is an optical amplifier having mirrors on both sides. The as-cleaved facets of an amplifier have a power reflection coefficient of about 0.33, and the device is basically a laser. In order to operate it as an amplifier, one should reduce the reflection coefficient by applying an Anti Reflection coating, angled facets or a window structure (or all three at the same time). Since it is easier to characterize a laser than an amplifier, many devices presented in this work were operated as lasers. A number of important laser properties are discussed in this section.

Threshold current

Consider an amplifier with length $L$, gain $G$ and mirror reflection coefficients $R_1$ and $R_2$. As soon as the gain $G$ exceeds the mirror loss, the round-trip gain $G_{rt} = R_1 R_2 G^2$ becomes larger than 1, and a small amount of noise will be amplified to infinite output power. Of course this is not what happens: the increasing output power saturates the amplifier, thereby decreasing the gain such that $G_{rt}$ is again equal to 1, and the device operates as a laser. Inserting $G = \exp \left[ (\Gamma g - \alpha) L \right]$ in $G_{rt} = R_1 R_2 G^2 = 1$, we obtain the well known laser condition:

$$\Gamma g = \alpha + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right)$$  \hspace{1cm} (2.12)

Note that $g$ is not constant throughout the device. This is easily understood from Fig. 2.10. The total optical intensity is built up from two fields: a field travelling from the left to the right, and a field travelling from the right to the left. The intensity of both fields increases, and as a result, the total optical power is lowest in the longitudinal center of the device. As a result, the gain at both ends of the device is more heavily saturated than in the center, and the material gain $g$ in Eq. 2.12 merely represents the average material gain $g_{avg}$, which satisfies:

$$g_{avg} L = \int_0^L g(x) dx$$  \hspace{1cm} (2.13)

The lowest current at which $G_{rt} = 1$ is the so-called threshold current $I_{th}$. In a graph that shows the output power as a function of the current, the so-called LI-curve, the threshold current is identified as the extrapolation to output power zero (Fig. 2.11a). For currents larger than $I_{th}$, the output power increases linearly with the current. In order to maximize the output power at a given current, a low threshold current is desirable. The threshold current increases with temperature:

$$I_{th}(T) = I_0 \exp \left( \frac{T}{T_0} \right)$$  \hspace{1cm} (2.14)
Figure 2.10: Gain saturation in a laser.

Figure 2.11: Typical LI curve (a) and spectrum (b) of a Fabry-Perot laser.

where $T_0$ is the characteristic temperature. $T_0$ should be as high as possible, because if $T_0$ is higher, the laser performance is affected less by the temperature. For InGaAsP lasers emitting at a wavelength around 1.55 $\mu$m, the value of $T_0$ is typically between 50 and 70 K [38]. When a laser is operated Continuous Wave (CW), the device heats up, mainly due to non-radiative recombination processes such as Auger recombination, and due to dissipation of electrical power in the internal series resistance of the laser. This self-heating affects the performance of the laser in a negative way. In order to reduce self-heating when characterizing a laser, one should operate the device with short pulses ($< 500$ ns) and low duty cycles ($< 1\%$).
Differential efficiency

Another important parameter obtained from the LI-curve is the differential efficiency \( \eta_d \). It represents the number of photons generated per injected carrier:

\[
\eta_d = \frac{e \Delta P}{h \nu \Delta I}
\]  

(2.15)

where \((\Delta P/\Delta I)\) is the slope of the LI-curve above threshold (Fig. 2.11a). Obviously, a high \( \eta_d \) is desired, as this means a larger increase in optical power for an increasing injection current.

For a laser that has zero internal loss \( \alpha \), the differential efficiency \( \eta_d \) (for both facets) is equal to the internal quantum efficiency for the generation of stimulated emission \( \eta_i \). The total optical output power follows directly from Eq. 2.15:

\[
P_{\text{out}} = \eta_d \frac{h \nu}{e} (I - I_{\text{th}}) = \eta_i \frac{h \nu}{e} (I - I_{\text{th}})
\]  

(2.16)

In a realistic device, \( \eta_d \) is reduced by the internal loss \( \alpha \). In order to enable a comparison between the optical output power \( P_{\text{out}} \) and the optical power that is lost due to the internal losses of the device, we account for the emitted light by introducing a mirror loss \( \alpha_m \). This mirror loss is chosen such that \( P_{\text{out}} \) equals the power that would have been absorbed due to the internal loss \( \alpha \) if \( \alpha \) would be increased by \( \alpha_m \). We obtain the mirror losses for both facets by reformulating the laser condition Eq. 2.12 as:

\[
\exp \left[ (\Gamma g - \alpha - \alpha_{m,1} - \alpha_{m,2}) 2L \right] = 1/R_1 R_2
\]  

(2.17)

to arrive at:

\[
\alpha_{m,1} = \frac{1}{2L} \ln \left( \frac{1}{R_1} \right) \quad \text{and} \quad \alpha_{m,2} = \frac{1}{2L} \ln \left( \frac{1}{R_2} \right)
\]  

(2.18)

We can now use Eq. 2.18 to obtain an expression for the differential efficiency. For each facet, \( \eta_{d,i} \) is given by the ratio of the distributed mirror loss of this particular facet and the total losses in the device, multiplied by \( \eta_i \):

\[
\eta_{d,1} = \eta_i \frac{\alpha_{m,1}}{\alpha + \alpha_{m,1} + \alpha_{m,2}} = \frac{\eta_i}{1 + \frac{\ln (R_2)}{\ln (R_1)} - \frac{2\alpha L}{\ln (R_1)}}
\]  

(2.19)

\[
\eta_{d,2} = \eta_i \frac{\alpha_{m,2}}{\alpha + \alpha_{m,1} + \alpha_{m,2}} = \frac{\eta_i}{1 + \frac{\ln (R_1)}{\ln (R_2)} - \frac{2\alpha L}{\ln (R_2)}}
\]  

(2.20)

\[
\eta_{d,\text{tot}} = \frac{\alpha_{m,1} + \alpha_{m,2}}{\alpha + \alpha_{m,1} + \alpha_{m,2}} = \frac{\eta_i}{1 - 2\alpha L / \ln (R_1 R_2)}
\]  

(2.21)

Finally, we also have:

\[
\frac{\eta_{d,1}}{\eta_{d,2}} = \frac{\ln (R_1)}{\ln (R_2)}
\]  

(2.22)
From Eqs. 2.12 and 2.21 it follows that if $R_1 R_2$ is close to unity, both the threshold current and the differential efficiency are low. In order to achieve both a low threshold current and high efficiency, one can apply a High Reflection (HR) coating to one of the cleaved facets to increase $R_1 R_2$, while the other facet forms the laser output with a high differential efficiency given by Eq. 2.19 or Eq. 2.20.

Equation 2.21 is often used to obtain $\eta$ and $\alpha$ from measurements of LI-curves on lasers with various lengths, where it is assumed that $\eta$ and $\alpha$ do not depend on the laser length. This is not necessarily a valid assumption. Especially $\alpha$ may strongly depend on the carrier density, and hence on the laser length [62–64].

**Spectrum**

Substituting of $G_{rt} = 1$ into Eq. 2.11, one finds $P_{out}^{(-)} = 0$. So, the laser output power is available at the wavelengths where the interference is constructive (where Eq. 2.9 holds), whereas in between these wavelengths, the output power is zero. A typical laser spectrum is shown in Fig. 2.11b. It consists of a number of distinct peaks, which each represent a longitudinal mode. The mode spacing follows from the requirement that for constructive interference an integer number of wavelengths must fit in twice the cavity length:

$$2nL = m\lambda$$  \hspace{1cm} (2.23)

where $L$ is the device length, $n$ is the effective refractive index, $\lambda$ is the emission wavelength in vacuum, and $m$ is an integer number. One finds that two adjacent longitudinal modes ($\Delta m=1$) are spaced by a wavelength:

$$\Delta \lambda = \frac{\lambda^2}{2n_g L}, \quad \text{with} \quad n_g = n - \frac{\lambda}{\frac{dn}{d\lambda}}$$  \hspace{1cm} (2.24)

The group index $n_g$ in Eq. 2.24 is associated with the group velocity $v_g = d\omega/dk$ via $n_g = c/v_g$ for plane waves of the form $I(x) = I_0 \exp\left[j(\omega t - kx)\right]$, where $c$ is the speed of light. For two plane waves ($\omega_1, k_1$) and ($\omega_2, k_2$), the group velocity is identified as the propagation speed of the low-frequency envelope ($d\omega = \omega_1 - \omega_2$, $dk = k_1 - k_2$) [65]. The group index of the devices described in this work is typically around 3.7, which is substantially larger than the effective refractive index (typically 3.3) [66].

The lasing wavelength of a Fabry-Perot laser is determined by the wavelength at which the gain $g(\lambda)$ is highest. One can get accurate wavelength control by using gratings instead of reflecting facets. In that case, the lasing wavelength is determined by the grating reflectivity. Examples of grating-based devices are the Distributed Feedback (DFB) laser and the Distributed Bragg Reflector (DBR) laser. In general, the spectrum of these devices shows only a single longitudinal mode with a high (>30 dB) Side Mode Suppression Ratio (SMSR), where the SMSR is defined as the ratio between the power in the laser peak and the highest power at undesired wavelengths.
2.6 Optical amplification

In this section, the physical background of stimulated emission is reviewed. All devices presented in this thesis have a Multi Quantum Well (MQW) active layer. For this reason, we also explain the difference between gain in bulk $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ and gain in MQWs.

2.6.1 Material gain of bulk $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$

Optical gain in semiconductor materials is provided by stimulated emission, where an electron in the conduction band is stimulated by a photon to recombine with a hole in the valence band, thereby emitting a photon. Starting point of the description of this process is the Schrödinger Equation, that governs the behavior of electrons and holes in semiconductor material. For example, the electron wave function $\psi(r)$ is the solution of the Schrödinger Equation:

$$\begin{bmatrix} -\frac{\hbar^2}{2m_0} V^2 + V(r) \end{bmatrix} \psi(r) = E \psi(r)$$

(2.25)

where $m_0$ is the electron mass, $E$ is the electron energy, $\hbar = h/(2\pi)$ where $h$ is Planck's constant, and $V(r)$ is the potential as experienced by the electron. Because of the periodic nature of the semiconductor crystal we have:

$$V(r) = V(r + R)$$

According to Bloch's theorem, the solution of the Schrödinger Equation for such a periodic potential is given by a plane wave $e^{ikr}$ multiplied by a function $u(r)$ that has the same periodicity $R$ as the potential function:

$$\psi(r) = e^{ikr}u(r), \quad \text{with} \quad u(r) = u(r + R)$$

(2.26)

The wave vector $k$ is related to the electron energy by the semiconductor band structure $E = E(k)$. This band structure is quite complicated, but for small $k$, the parabolic band approximation is applicable (Fig. 2.12). The energy of an electron with respect to the bottom of the conduction band $E_c$, and the energy of a hole with respect to the top of the valence band $E_v$ are then approximated by the free-space energy:

$$E_c = \frac{\hbar^2 k_c^2}{2m_e}, \quad E_v = \frac{\hbar^2 k_v^2}{2m_h}$$

(2.27)

where $m_e$ and $m_h$ represent the effective electron mass and the effective hole mass (heavy hole $m_{hh}$ or light hole $m_{lh}$), respectively, and $k_c$ and $k_v$ are the corresponding wave vectors. Equation 2.27 is simply the solution of the Schrödinger Equation 2.25 for $V = 0$. The effective masses are parameters that depend on the material composition (Table 2.1), where it should be noted that values reported in literature show
| electrons:          | $m_e/m_0 = 0.08 - 0.039y$ |
| heavy holes:       | $m_{bh}/m_0 = 0.45 - 0.11y - 0.13y^2$ |
| light holes:       | $m_{lh}/m_0 = 0.12 - 0.10y + 0.017y^2$ |

Table 2.1: Electron, heavy hole and light hole mass dependence on compositional fraction $y$ for $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ lattice matched to InP.

![Conduction and valence bands](image)

Figure 2.12: Semiconductor band structure in the parabolic band approximation.

some discrepancy. Results obtained from various sources are given by [38] and [39]. The values listed in Table 2.1 are the ones that show good agreement between these various sources.

Additional relevant definitions shown in Fig. 2.12 are the bandgap energy $E_g$, which is the separation between the conduction band and valence band at $k = 0$, and the quasi-Fermi levels in these bands, which are $E_{FC}$ and $E_{FV}$, respectively.

Electrons in the conduction band can recombine with holes in the valence band, thereby emitting a photon with energy $E_{ph} = h\nu = E_g + \epsilon_c + \epsilon_v$. If this process is to be efficient, the wave vector $k$ must not change: $k_c = k_v = k$ (k-selection rule). Thus, using Eq. 2.27, we find the photon energy:

$$E_{ph} = E_g + \frac{\hbar^2 k^2}{2m_r}, \quad \text{with} \quad \frac{1}{m_r} = \frac{1}{m_e} + \frac{1}{m_h} \quad (2.28)$$
where \( m_r \) is defined as the reduced mass. Recombination can occur either spontaneously, giving rise to spontaneous emission, or it may be induced by an incoming photon. In the latter case, the emitted and incoming photons have exactly the same phase, i.e. they have the same energy and wave vector. This process is called stimulated emission, and provides the optical gain in lasers and optical amplifiers. Derivation of the expression for the gain due to stimulated emission can be found in literature [38, 67, 68], where the comments in [69] should be taken into account. The material gain is given by:

\[
g(E_{ph}) = \frac{\pi e^2 h}{\varepsilon_0 n c m_0^2} \cdot \frac{1}{E_{ph}} \cdot |M|^2 \cdot \rho_r(E_{ph}) \cdot \left[ f_c(E_{ph}) + f_v(E_{ph}) - 1 \right] \tag{2.29}
\]

The various terms in this expression will be discussed below.

The first term in Eq. 2.29 is a set of constants, where \( e \) is the elementary charge, \( \varepsilon_0 \) is the permittivity in vacuum, \( n \) is the refractive index and \( c \) is the speed of light in vacuum.

The next two terms enter the equation as a result of Fermi’s Golden Rule [70]. The square of the momentum matrix \( M \) gives the probability that an electron actually makes the transition from a state in the conduction band to a state in the valence band. The matrix elements are calculated using perturbation theory, where the perturbation is the magnetic vector potential \( \mathbf{A} \) of the electromagnetic field [38]. From:

\[
\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \quad \text{and} \quad \mathbf{E} = E_0 \cos(\sigma t - \mathbf{k} \cdot \mathbf{r})
\]

it follows that the magnitude of the perturbation \( \mathbf{A} \) is proportional to \( E_0/\sigma \), hence the term \( 1/E_{ph} = 1/h/\sigma \) in Eq. 2.29. The matrix element for bulk material, unpolarized light, with the \( k \)-selection rule obeyed, is given here for the sake of completeness [69]:

\[
|M|^2 = \frac{m_0}{6} \left( \frac{m_0}{m_e} - 1 \right) \frac{E_g (E_g + \Delta)}{E_g + \frac{2}{3} \Delta} \tag{2.30}
\]

where \( \Delta \) is the spin-orbital splitting energy of the valence band.

The reduced density of states \( \rho_r(E_{ph}) \) in Eq. 2.29 gives the number of allowed energy states per unit volume and per unit energy. It enters the equation for the gain in the following way.

In order to calculate the gain at a specific photon energy, the appropriate states in the conduction band and valence band are found by integration over all states:

\[
\int \int \delta(\mathbf{k}_c - \mathbf{k}_v) \delta(E_{ph} - E_g - \varepsilon_c - \varepsilon_v) d^3k_c \, d^3k_v \tag{2.31}
\]

This integral expresses the requirements that the \( k \)-selection rule is obeyed (first \( \delta \)-function) and that the transition energy equals the photon energy (second \( \delta \)-function). After integration over one of the wave vectors, we can change variables to \( E = \varepsilon_c + \varepsilon_v = (h^2 k^2)/2m_r \), and the integral 2.31 can be rewritten as:
\[ \int \delta(E_{ph} - E_g - E) \, d^3k = \left| \frac{d^3k}{dE} \right|_{E=E_{ph}-E_g} \] \hspace{1cm} (2.32)

The last term \(d^3k/dE\) is related to the density of states \(\rho(E)\). Consider a standing wave of the form \(e^{ik \cdot r}\): each component of the wave vector \(k_i = 2\pi n_i/L_i\), where \(i = x, y, z\) and \(n_i\) are integer numbers. Thus the volume taken per \(k\)-vector is given by \((2\pi)^3/(L_x L_y L_z) = (2\pi)^3/V\). When the magnitude of the wave vector increases, the number of allowed states increases according to:

\[ \rho(E) \, dE \, V = 2 \frac{d^3k}{(2\pi)^3/V} \]

where the factor 2 represents the two spin states. Using \(E = (h^2k^2)/2m\) and \(d^3k = 4\pi k^2 dk\), we find the expression for the density of states in a 3-dimensional system:

\[ \rho(E) = 2 \frac{1}{(2\pi)^3} \frac{d^3k}{dE} = \frac{1}{2\pi^2} \left( \frac{2m}{h^2} \right)^{3/2} \sqrt{E} \] \hspace{1cm} (2.33)

Thus, the term \(d^3k/dE\) in Eq. 2.32 can be expressed in terms of the density of states \(\rho(E)\), where it follows from the definition of the integration variable \(E\) that the reduced mass \(m_r\) should be used. For the integral in Eq. 2.31, we arrive at:

\[ \left. \frac{d^3k}{dE} \right|_{E=E_{ph}-E_g} = \frac{(2\pi)^3}{2} \rho_r(E_{ph}), \] \hspace{1cm} (2.34)

with

\[ \rho_r(E_{ph}) = \frac{1}{2\pi^2} \left( \frac{2m_r}{h^2} \right)^{3/2} \sqrt{E_{ph} - E_g} \] \hspace{1cm} (2.35)

where \(\rho_r(E_{ph})\) is the reduced density of states appearing in Eq. 2.29. The densities of states for the valence band and the conduction band are accounted for simultaneously by using the reduced mass \(m_r\) in \(\rho_r(E_{ph})\), where the factor \((2\pi)^3/2\) is placed in the prefactor of Eq. 2.29.

Finally, the Fermi functions \(f_c(E_{ph})\) and \(f_v(E_{ph})\) in Eq. 2.29 give the probability of finding an electron in the conduction band and a hole in the valence band respectively, such that \(E_{ph} = E_g + \epsilon_c + \epsilon_v\):

\[ f_c(E_{ph}) = \frac{1}{1 + \exp \left( \frac{\epsilon_c - E_{FC}}{kT} \right) } = \frac{1}{1 + \exp \left[ \frac{m_r}{m_e} \frac{(E_{ph}-E_g)-E_{FC}}{kT} \right] } \] \hspace{1cm} (2.36)

\[ f_v(E_{ph}) = \frac{1}{1 + \exp \left( \frac{\epsilon_v - E_{FY}}{kT} \right) } = \frac{1}{1 + \exp \left[ \frac{m_e}{m_h} \frac{(E_{ph}-E_g)-E_{FY}}{kT} \right] } \] \hspace{1cm} (2.37)
where $E_{FC}$ and $E_{FV}$ are the Fermi energies of the electrons in the conduction band and of the holes in the valence band, respectively (Fig. 2.12). The probability that a photon with energy $E_{ph}$ is emitted is thus proportional to $f_c(E_{ph})f_v(E_{ph})$, whereas the probability of absorbing one is proportional to $[1 - f_c(E_{ph})][1 - f_v(E_{ph})]$. The net gain is proportional to the difference between these two terms, which is given by:

$$f_c(E_{ph}) + f_v(E_{ph}) - 1$$

This term is directly recognized in Eq. 2.29.

In order to illustrate the discussion above, we calculated the gain spectra of Q(1.55) material for various carrier densities using the commercial software tool PICS3D (Fig. 2.13). For long wavelengths, $E_{ph} < E_g$, and the expression for $\rho_v(E_{ph})$ (Eq. 2.35) no longer holds. The density of states is essentially zero, and therefore $g(E_{ph}) = 0$ cm$^{-1}$. For shorter wavelengths, $\rho_v(E_{ph})$ increases as a square root, whereas $f_c(E_{ph})$ and $f_v(E_{ph})$ decrease exponentially. As a result, there is a wavelength where the gain has a maximum. For shorter wavelengths, the term $[f_c(E_{ph}) + f_v(E_{ph}) - 1]$ becomes negative, and $g(E_{ph}) < 0$ cm$^{-1}$.

### 2.6.2 Quantum wells: energy levels

When the thickness of the active layer is a few tens of nanometers or smaller, quantum-mechanical effects become of importance. Due to these effects, the band structure is
modified, which can be used to improve the performance of lasers and optical amplifiers. The modified band structure can be approximated by the one-dimensional potential well problem, which is well-known from quantum mechanics.

The behavior of a particle in a quantum well with width $w$ (Fig. 2.14a) is again governed by the Schrödinger Equation 2.25, which is in this case given by:

$$\frac{-\hbar^2}{2m_w} \frac{d^2 \psi(x)}{dx^2} = E \psi(x) \quad \text{inside the well} \quad -w/2 < x < w/2$$

$$\frac{-\hbar^2}{2m_b} \frac{d^2 \psi(x)}{dx^2} = (E - V) \psi(x) \quad \text{outside the well} \quad x < -w/2, \quad x > w/2$$

(2.38)

where the effective mass inside the well is $m_w$, and outside the well it is $m_b$. For a bound state, we have $E < V$. The form of Eq. 2.38 suggests a plane wave like solution. Substituting $\psi(x) = e^{ikx}$ in Eq. 2.38, we have:

$$\psi(x) = e^{ikx}, \quad k = \pm \left( \frac{2m_w}{\hbar^2} E \right)^{1/2} \quad \text{inside the well}$$

(2.39)

$$\psi(x) = e^{iqx}, \quad q = \pm \left( \frac{2m_b}{\hbar^2} (V - E) \right)^{1/2} \quad \text{outside the well}$$
The wave function $\psi(x)$ and its derivative $d\psi(x)/dx$ should be continuous at the edges $x = \pm \omega/2$, and $\psi(x) \to 0$ as $|x| \to \infty$. When these conditions are fulfilled, even and odd solutions are found for the wave function $\psi(x)$, where the even solutions are cosine-like: $\psi(x) = e^{ikx}$, and the odd solutions are sine-like: $\psi(x) = e^{ikx} - e^{-ikx}$. The energy $E$ follows from the relation between $q$ and $k$:

$$
even: \quad q = k / \tan \left( \frac{\omega k}{2} \right) \Rightarrow \sqrt{\frac{m_b}{m_w}} \cdot \frac{V - E}{E} = \tan \left( \frac{\omega}{2\hbar} \sqrt{2m_wE} \right)$$

$$
odd: \quad q = -k / \tan \left( \frac{\omega k}{2} \right) \Rightarrow \sqrt{\frac{m_b}{m_w}} \cdot \frac{V - E}{E} = -\tan^{-1} \left( \frac{\omega}{2\hbar} \sqrt{2m_wE} \right)
$$

(2.40)

Eq. 2.40 can only be solved analytically for $V \to \infty$. In this case, we find that the allowed values for the energy $E$ are given by:

$$
even: \quad E = \frac{2}{m_w} \left[ \frac{\pi \hbar}{\omega} \left( n + \frac{1}{2} \right) \right]^2 \quad n = 0, 1, 2, \ldots \Rightarrow E_n = \frac{\pi^2 \hbar^2 n^2}{2m_w \omega^2}
$$

$$
odd: \quad E = \frac{2}{m_w} \left[ \frac{\pi \hbar n}{\omega} \right]^2 \quad n = 1, 2, \ldots
$$

(2.41)

So, solving the Schrödinger Equation 2.38 for a quantum well with infinite $V$ results in an infinite number of discrete states, where the corresponding energies $E_n$ are given by Eq. 2.41.

In practical situations, a quantum well is formed in a double hetero structure: a thin layer (the well) with a low bandgap energy $E_{g,\text{well}}$ is sandwiched between the so-called barriers, which have a high bandgap energy $E_{g,\text{bar}}$. Thus a potential well is created in both the conduction band and the valence band, with potential steps $\Delta E_c$ and $\Delta E_v$, respectively (Fig. 2.14b). Numerically solving Eq. 2.40 again results in a number of discrete states in the conduction band and the valence band, with energy levels $E_{c,n}$ for electrons and $E_{v,n}$ for holes, respectively. The heavy and light holes must be treated separately. The number of states is now limited by the constraints $E_{c,n} < \Delta E_c$ and $E_{v,n} < \Delta E_v$. However, from Eq. 2.40 it follows that there is at least one (even) state.

The devices presented in this thesis employ a Multi Quantum Well (MQW) active region, consisting of a series of InGaAs quantum wells separated by Q(1.25) barriers (Fig. 2.14c). The emission wavelength that corresponds to the lowest energy transition ($E_{ph} = E_{g,\text{well}} + E_{c,1} + E_{v,1}$, where $E_{v,1}$ corresponds to heavy holes) is shown as a function of the well width $\omega$ in Figure 2.15a. The results for InP barriers and barriers of a hypothetical material with infinite bandgap energy are also shown. In the calculation, the material parameters listed in Table 2.1 were used, and we assumed that $\Delta E_c/\Delta E_v = 0.39/0.61$ [38]. From Figure 2.15a we can conclude that the quantum well width can be used as a design parameter to cover a wide wavelength range for stimulated emission. On the other hand, this also implies that we should be able to
Figure 2.15: a) Emission wavelength of an InGaAs quantum well as a function of well width for barrier materials Q(1.25), InP and infinite bandgap. b) Emission wavelength of an infinite row of InGaAs/Q(1.25) quantum wells as a function of barrier width.

accurately control the well width during epitaxial growth. For example, according to Fig. 2.15a, $d\lambda/dw = 8\text{ nm/nm}$ at $\lambda = 1550\text{ nm}$. The lattice constant of InP is 0.587 nm, so each monolayer (0.294 nm) shifts the emission wavelength by 2.3 nm.

If the barriers are very narrow, the wave functions of adjacent quantum wells have a non-zero overlap. The overlap affects the energies of the allowed states. For an infinite number of quantum wells and barriers, the wave function $\psi(x)$ is periodic, and the energy is obtained from:

$$4qk = \sin (kw) \left( e^{qB} - e^{-qB} \right) \left( q^2 - k^2 \right) + 2qk \cos (kw) \left( e^{qB} + e^{-qB} \right)$$ (2.42)

where $b$ is the barrier width, and $q$ and $k$ are as defined in Eq. 2.39. The emission wavelength for an infinite InGaAs/Q(1.25) MQW as calculated from Eq. 2.42 is shown in Figure 2.15b as a function of the barrier width for well widths 4.5 nm and 8 nm. If the barriers are narrower than 10 nm, the coupling between the wells becomes significant. As $b \to \infty$, Eq. 2.42 is equal to the even (lowest energy) expression in Eq. 2.40: $q = k \tan (wk/2)$, and the emission wavelengths asymptotically approach the values in the graph in Fig. 2.15a. For $b \to 0$, there is only one solution $k = 0$: the energy shift is zero, and the MQW behaves as bulk material with bandgap energy $E_{g,\text{well}}$.

Note that the wave function described in Eq. 2.42 is constructed from the wave functions in the separate quantum wells that have the lowest energy for infinitely thick barriers. As the wave functions become coupled, the discrete energy levels merge into an energy band, and Eq. 2.42 no longer corresponds to the superstate that has the lowest energy. However, Fig. 2.15b does correctly indicate the barrier width at which
2.6 Optical amplification

coupling becomes significant. Devices employing MQW structures with very narrow barriers are discussed in Chapters 4 and 5.

2.6.3 Quantum wells: material gain

The material gain of a quantum well is again given by Eq. 2.29, but we must reconsider the expressions for the various terms in this equation.

The Fermi functions expressing the occupation probabilities are now given by:

\[ f_{c,n}(E_{ph}) = \frac{1}{1 + \exp \left[ \frac{E_{c,n} + \frac{m_e}{m_e} (E_{ph} - E_{g} - E_{c,n} - E_{v,n}) - E_{FC}}{kT} \right]} \]  \hspace{1cm} (2.43)

\[ f_{v,n}(E_{ph}) = \frac{1}{1 + \exp \left[ \frac{E_{v,n} + \frac{m_h}{m_h} (E_{ph} - E_{g} - E_{c,n} - E_{v,n}) - E_{FW}}{kT} \right]} \]  \hspace{1cm} (2.44)

where \( n \) is the index of the energy level (Eq. 2.41). Similar to the definition for bulk material in Section 2.6, we measure the energy of electrons \( E_{c,n} \) from the bottom of the well-material conduction band, and the energy of holes \( E_{v,n} \) from the top of the well-material valence band. \( E_{v,n} \) refers to either heavy or light holes; the type of hole also affects \( m_r \).

The square of the momentum matrix is now given by:

\[ |M_{hh}(E_{ph})|^2 = \frac{3}{4} |M_{bulk}|^2 \left[ 1 + \frac{E_{c,n}}{E_{c,n} + \frac{m_e}{m_e} (E_{ph} - E_{g,well} - E_{c,n} - E_{v,n})} \right] \]  \hspace{1cm} (2.45)

for heavy hole transitions, and for light holes we have [71]:

\[ |M_{lh}(E)|^2 = 2 |M_{bulk}|^2 - |M_{hh}(E)|^2 \]  \hspace{1cm} (2.46)

where \( |M_{bulk}|^2 \) refers to Eq. 2.30. Thus, the matrix is now energy dependent. However, for example for an 8 nm InGaAs/Q(1.25) quantum well, \( |M_{hh}(E)|^2 \) varies only 5% over a wavelength range of 20 nm, and the momentum matrix can be considered to be constant in a first approximation.

Finally, the expression for the density of states \( \rho(E) \) in quantum wells differs significantly from the expression that was derived for bulk material in Section 2.6.1. For a quantum well with the barrier-well interfaces in the \((x, y)\)-plane, the carrier motion in the \( z \)-direction is quantized into discrete energy levels. Therefore, the density of states should be calculated for a two-dimensional system, where the volume taken per \( k \)-vector is given by \((2\pi)^2 / (L_x L_y) = (2\pi)^2 / A\). Thus we have:

\[ \rho(E) dE V = 2 \frac{d^2 k}{(2\pi)^2 / A} \quad \text{or} \quad \rho(E) = \frac{k}{2\pi} \frac{dk}{dE} = \frac{m}{2\pi h^2} \]  \hspace{1cm} (2.47)
where we have used the fact that \( d^2k = 2\pi k dk \) and \( V = A \cdot w \). The factor 2 again accounts for the two spin states. Eq. 2.47 shows that for each quantized energy level \( E_n \) that corresponds to carrier motion in the \( z \)-direction, the density of states does not depend on the energy of carrier motion in the \((x,y)\)-plane. Each level increases \( \rho(E) \) by \( m / w \pi h^2 \), resulting in a step-like function. This is illustrated in Fig. 2.16, where \( \rho(E) \) of a quantum well with barriers of infinite bandgap energy is compared to \( \rho(E) \) of bulk material. Comparing Equations 2.33, 2.41 and 2.47, we observe that \( \rho_{\text{bulk}}(E_n) = n \cdot \rho_{\text{MQW}} \). For a photon with energy \( E_{\text{ph}} \) to be emitted, the \( k \)-selection rule must be obeyed, and the density of states in the conduction band and the valence band are again simultaneously accounted for by using the reduced mass \( m_r \) in Eq. 2.47:

\[
\rho_r(E) = \frac{m_r}{w \pi h^2}
\]  

(2.48)

2.6.4 Quantum wells versus bulk \( \text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y} \)

The obvious difference between quantum wells and bulk active material is that the energy levels of the quantum well depend on the well and barrier width. Thus, the properties of the MQW material are highly dependent on the layer thicknesses. So using an MQW active layer instead of a wide \( \text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y} \) bulk active layer provides an additional degree of freedom in the design of active devices. However, the gain characteristics of quantum wells and bulk \( \text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y} \) material are also quite different. In order to clarify this, we discuss the densities of states.

The quantum well situation is illustrated in Fig. 2.17a,b,c, where the reduced density of states and the Fermi functions of a quantum well are schematically shown as a function of energy. In this figure, \( E_{\text{abs}} \) is the lowest possible photon energy, which is equal to \( E_{\text{g,well}} + E_{c,1} + E_{v,1} \), where \( E_{v,1} \) refers to heavy holes. The gain \( g(E) \) is
Figure 2.17: Normalized quantum well Fermi function, reduced density of states and gain spectrum for increasing carrier densities (a,b,c). Normalized bulk Fermi function, reduced density of states and gain spectrum (d). For the Fermi function: \[ F(E) = \left[ f_c(E_{ph}) + f_v(E_{ph}) - 1 \right]. \]

proportional to \( F(E) \cdot \rho_r(E) \), with \( F(E) = \left[ f_c(E_{ph}) + f_v(E_{ph}) - 1 \right] \) (Eq. 2.29). The gain spectra are represented by the dark areas. As more and more carriers are injected, the Fermi energies increase, and consequently \( F(E) \) shifts to higher energies. Due to the step-like density of states, the maximum gain increases rapidly (Fig. 2.17a,b). However, as the Fermi energies increase further, the gain approaches its maximum value and saturates (Fig. 2.17c). For bulk material with the same absorption edge \( E_{g,bulk} = E_{abs} \), the reduced density of states at \( E_{abs} \) is zero, and increases only slowly with energy. As a result, the gain does not increase and saturate as fast as in a quantum well (Fig. 2.17d). The quantum well saturation is further enhanced by the fact that the quantum well material gain may be well in the saturation regime in many practical situations. This is because a high material gain is required to compensate for the low confinement factor \( \Gamma \) (Eq. 2.6). In quantum well active layers, \( \Gamma \approx 1 - 2\% \) per quantum well, as opposed to 20 - 40\% for bulk active layers. As a result of the saturation behavior, one finds experimentally that in bulk material the material gain depends linearly on the current: \( g_{bulk} = \beta_{bulk} (I - I_0) \), whereas for quantum wells this dependence is logarithmic: \( g_{MQW} = \beta_{MQW} I_0 \ln (I/I_0) \) [71–74]. In these expressions, the parameter \( I_0 \) is the transparency current at which \( g = 0 \) cm\(^{-1}\), and \( dg/dI = \beta \) at \( I = I_0 \). Normally, \( \beta_{MQW} > \beta_{bulk} \). The same current dependence is observed for the modal gain \( G \) expressed in dB (Eq. 2.5). In spite of the low confinement factor of quantum wells, also for the modal gain one generally finds that \( \beta_{MQW} \approx \beta_{bulk} \).

Fig. 2.18 schematically shows the current dependence of the modal gain for bulk and MQW materials, where the curves refer to optical amplifiers that have equal gain \( G_x \) at a current \( I_x \). At low injection currents, the gain of the MQW amplifier is only
weakly saturated, and the differential gain (expressed in terms of current) \(dg/dI\) is higher than for the bulk amplifier. At high injection currents, the reverse is true, and a substantial increase in current only results in a minor increase in MQW gain. As a result, the MQW amplifier has a high saturation output power when operated at high currents, since a reduction of the carrier density due to a high stimulated emission rate will only have a small effect on the gain. If the MQW amplifier must provide a much higher gain than \(G_x\), one can increase the confinement factor by increasing the number of quantum wells, or one can use a longer device. From Fig. 2.17, it also follows that the gain spectrum broadens at high injection currents, which is a desired feature of optical amplifiers in WDM applications.

On the other hand, a MQW-based device can also be designed in such a way that it operates in a region where the gain is only weakly saturated. In this case, the gain spectrum is narrow, and the differential gain is higher than achievable with bulk materials. When such a device is applied as a laser, it generally has a low linewidth enhancement factor \(\alpha_{\text{enh}} = (dn/dN)/(dg/dN)\), where \(n\) is the refractive index, \(g\) is the material gain and \(N\) is the carrier density. A low linewidth enhancement factor results in a small laser linewidth, a high direct modulation speed [75] and a low chirp [38, 67].

From Fig. 2.18 we see that the use of MQW active layers offers the opportunity to adjust the degree of gain saturation at the operating point of the device in order to optimize the performance for a specific application. The degree of gain saturation can be tailored by modification of the device structure, in particular the confinement factor (the number of quantum wells), the (grating) reflection coefficients and the device length.

Many more design parameters are involved in the optimization of MQW-based devices. For example, materials which are not lattice matched to InP (strained materials)
may be applied for the wells and/or the barriers. The number of quantum wells does not only affect the confinement factor, but also the uniformity of the carrier distribution throughout the MQW stack. A non-uniform carrier distribution results in a high gain at the p-side and a low gain at the n-side [76, 77]. Thus, the use of MQW active layers offers many ‘knobs to adjust’ in order to optimize the device. Adjusting all these knobs to the right position requires a thorough knowledge of MQW physics and sophisticated design tools.

The last issue that we address in this section is the polarization dependence of optical amplifiers. For the realization of polarization independent photonic integrated circuits, the modal gain of integrated optical amplifiers should itself be polarization independent. Even in bulk material, the TE and TM material gains are not entirely equal. Furthermore, the modal gain may be polarization dependent even if the material gain would be polarization independent, because the TE and TM modes satisfy different wave equations [52, 53]. In quantum wells, on the other hand, the situation is quite different. The heavy holes only interact with TE polarized light (with the electric field parallel to the barrier-well interfaces), whereas the light holes mainly interact with TM polarized light. The quantum well energy levels are different for light holes and heavy holes because of their different effective masses, and hence the corresponding gain spectra (wavelength dependence i.e. energy dependence of the gain) are quite different. Furthermore, the heavy hole and light hole matrix elements are also different (Eqs. 2.45 and 2.46). Consequently, the quantum well material gain is polarization dependent. Generally, the TE gain is higher than the TM gain. Polarization independent material gain in quantum wells can be achieved by adjustment of the In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material composition in such a way that the (composition dependent) heavy and light hole masses are equal [78, 79]. This requires the use of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material which is not lattice matched to InP. Successful realization of a polarization independent integrated MQW optical amplifier operating at 1.5 μm was demonstrated by Newkirk et al. [80].

2.6.5 The double heterojunction

One of the key issues in the design of lasers and optical amplifiers is the creation of a region where there are many electrons in the conduction band and many holes in the valence band. In this way, the term \( f_c(E_{ph}) + f_v(E_{ph}) - 1 \) in the expression for the gain is maximized (Eq. 2.29). Furthermore, this region should have a large overlap with the optical field. The best way to achieve this is to make use of a p-i-n junction in a double heterostructure, which is depicted in Fig. 2.19.

The undoped active In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material where recombination takes place (optionally containing a number of quantum wells) is sandwiched between p- and n-doped transparent In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ layers that have a larger bandgap energy than the active layer. In the p-doped material, the Fermi energy is close to the valence band, whereas in the n-doped material, it is close to the conduction band. Due to the applied bias voltage \( V_{bias} \), the Fermi energy is not constant throughout the structure;
it is split into two quasi Fermi energies, $E_{QF,p}$ and $E_{QF,n}$, for the p- and n-regions respectively, where $E_{QF,n} - E_{QF,p} = e \cdot V_{bias}$. Note that in this case the Fermi energies relate to electrons. Under forward bias, electrons and holes can easily move to the active layer. However, they are restricted to cross over to the other side because there is a potential barrier which originates from the bandgap difference. As a result, a high concentration of electrons and holes builds up in the active region, where they can recombine to provide the optical gain.

Fortunately, the refractive index of the small-bandgap active material is higher than the index of the ‘sandwich’ layers, which is the reason why passive waveguide devices are based on undoped double heterostructures. This makes it relatively easy to achieve a high overlap between the optical field and the recombination region.

### 2.7 Conclusions

In this chapter, the properties of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ were briefly reviewed, as well as the main characteristics of devices fabricated in this material. By using a number of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ layers with different compositional fractions $x$ and $y$, one can fabricate both passive waveguide devices and active devices such as optical amplifiers and lasers. The double heterostructure provides optical confinement, and enables an efficient carrier injection into the active layer, where the carriers can participate in the process of stimulated emission to provide optical gain. The active layer can either be a bulk In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ layer, or a Multi Quantum Well (MQW) stack. The use of MQW active layers offers many design parameters which one can adjust to arrive at an optimized design. However, if a specific application requires polarization independent gain at wavelengths around 1.55 $\mu$m, the use of bulk active layers is more favorable.
Chapter 3

Technology

This chapter is dedicated to fabrication technologies for InP-based photonic integrated circuits, starting with epitaxial growth. Integration of optical amplifiers and passive waveguide devices requires the definition of (at least) two different epitaxial layer stacks on a single substrate. The various strategies to this end are compared, and one of them is selected for the work carried out in this thesis. Device fabrication is described in detail.

3.1 Introduction

The first fabrication step of a photonic integrated circuit is the growth of the epitaxial layer stack. The first paragraph of this chapter discusses the epitaxial growth techniques that are applied for the realization of the devices presented in this work. For the passive waveguide devices and the phase modulators, the bandgap energy of all materials should be larger than the photon energy, otherwise the optical signals would experience high absorption losses. For the optical amplifiers, on the other hand, the bandgap energy must correspond to the photon energy in order to have optical gain. A number of strategies to overcome this contradiction are described, and the selection of one of these for the experiments carried out in Chapter 5 is motivated. Finally, we describe the fabrication steps of the devices themselves, for which the facilities available at the Delft University of Technology were used.

3.2 Epitaxy

In the next two sections, we shortly introduce the epitaxial growth technologies that are relevant for this work: Metal Organic Vapor Phase Epitaxy (MOVPE) and Chemical Beam Epitaxy (CBE). MOVPE-grown wafers are purchased from a commercial supplier, while CBE growth is carried out at the Eindhoven University of Technology.
3.2.1 MOVPE

Metal Organic Vapor Phase Epitaxy (MOVPE) has become the most popular epitaxial growth technology for industrial production of III-V semiconductor devices. The configuration of an MOVPE system is schematically shown in Fig. 3.1. The group III elements are introduced in the reactor chamber using metal organic precursors such as trimethylindium (TMIn) and trimethylgallium (TMGa), which are transported using \( \text{H}_2 \) as a carrier gas. Precursors for the group V elements are the hydrides phosphine (\( \text{PH}_3 \)) and arsine (\( \text{AsH}_3 \)). The metal organic precursor diethylzinc (DEZn) is commonly used for the introduction of p-type doping, for n-type doping one generally uses the hydrides hydrogen sulphide (\( \text{H}_2\text{S} \)) or silane (\( \text{SiH}_4 \)) (not shown in Fig. 3.1). The precursor flow is controlled using mass-flow controllers (MFCs). The precursors can be sent to the reactor chamber (run mode) or vented to an exhaust line (vent mode). Such a run/vent configuration allows for fast changes in gas composition inside the reactor chamber, which is essential for the growth of thin layers as applied in Multi Quantum Well structures.

The substrate is positioned on a graphite susceptor, which is heated to the desired growth temperature using RF-heating or lamps. Normally, the growth temperature is between 600 and 800 °C, the pressure ranges from 10 to 760 torr (13 to 1000 mbar). Under these conditions, the precursors decompose, and the group III and group V elements are epitaxially grown on the substrate. For a good growth uniformity, the precursors must be mixed sufficiently, and the flow pattern must be uniform. Therefore, one should pay special attention to the design of the reactor geometry. Growth uniformity is further enhanced by rotation of the substrate. In actual state-of-the-art MOVPE mass production tools, epitaxial growth is performed simultaneously on 35 2” wafers, using a planetary configuration [5].
3.2 Epitaxy

3.2.2 CBE

Chemical Beam Epitaxy (CBE) is a relatively young epitaxial growth technology, in which growth pressures and temperatures are much lower than in MOVPE. A schematic configuration of the CBE system applied for this work (Riber CBE 32P) is shown in Fig. 3.2.

The substrate is mounted on a rotating molybdenum holder inside the high-vacuum reactor chamber, which is evacuated to a growth pressure in the order of \(10^{-4}\) to \(10^{-5}\) torr. Similar to the situation in MOVPE, metal organic precursors are used for the group III elements, in this case trimethylindium (TMI and triethylgallium (TEGa). These metal organics are introduced into the reactor chamber by a common low-temperature injector (50 °C). Their flux is regulated using pressure control, since this is more accurate than the use of mass flow controllers at the low precursor consumption in CBE. Due to the low operating pressure, the precursors travel to the substrate in a ballistic way, and no complex gas flow patterns across the substrate are involved.

The group V precursors \(\text{PH}_3\) and \(\text{AsH}_3\) are premixed in a high temperature cracker (900 °C), and are fully decomposed before they head for the substrate. Thus, the substrate temperature is not set by the cracking temperature of these hydrides, and can be kept low (≈ 500 °C).

In short, CBE combines the vapour group V precursors of gas-source MBE (Molecular Beam Epitaxy) and the vapour metal organic group III precursors of metal organic MBE. The use of vapour sources allows for accurate flow control, and the precursors can be rapidly changed without opening the reactor chamber. The CBE dopants that are applied for this work are Si and Be; these dopants are introduced by thermal evaporation from solid elemental sources as applied in ‘normal’ MBE.
3.2.3 MOVPE versus CBE

The low-pressure and low-temperature growth conditions in CBE offer a number of important advantages. Due to the beam-like nature of material transport from injector to substrate, fast switching between precursors is enabled. This allows for the epitaxial growth of very thin layers with atomically sharp interfaces. Furthermore, CBE-grown layers are in general highly uniform, since growth uniformity is not affected by complex gas flow patterns across the substrate. In principle, the thickness of CBE grown layers is controlled with monolayer accuracy over practically the entire wafer. Uniformities of MOVPE grown wafers (thickness, composition, dopant concentration) are typically between 2 and 5 % over the inner 40 mm of a 2” wafer, depending on the particular system. The low growth pressure in CBE also enables in-situ growth monitoring, using for example Reflective High Energy Electron Diffraction (RHEED). Pre-cracking of the group V precursors is highly efficient, and as a result, the CBE consumption of (toxic) hydrides is about ten times smaller than in MOVPE.

An important issue in CBE is accurate control of the substrate temperature. For example, for the epitaxial growth of InGaAs lattice matched to InP, the temperature window is only 30 °C, as compared to 150 °C for an MOVPE system. Thus, the substrate temperature must be controlled accurately, within a few °C.

Selective Area Epitaxy (SAE), e.g. epitaxy on substrates that are partially masked by a dielectric layer, is an important technology for integrating passive waveguide devices and optical amplifiers. In case of perfect selectivity, no material is deposited on the mask. As the growth rate is mainly determined by the group III species, growth conditions should be such that these species do not adsorb and/or decompose on the mask material. Excellent growth selectivity can be achieved both in MOVPE and in CBE.

For MOVPE-grown InGaAs, typical growth conditions involve pressures in the order of 15 torr and temperatures around 650 °C. For selective area epitaxy at such high temperatures, deterioration of the previously grown material cannot be ruled out. This problem does not arise at the low growth temperatures common in CBE (≈ 500 °C).

In SAE using MOVPE, the growth rate at the edges of the masked regions is enhanced up to a factor 3. Due to the complex gas flow pattern across the substrate and the non-uniform gas depletion, local growth rate and material composition depend to a large extent on the mask geometry, and are hard to predict accurately. In CBE, on the other hand, the growth rate does not depend on the masked area, and the SAE-grown material is uniform in thickness and composition over the whole substrate. This is a strong advantage of CBE over MOVPE for application in selective area epitaxy.

3.2.4 Conclusion

MOVPE is a well-established technology, and is widely used in industrial mass production systems. CBE, on the other hand, is much younger, and has not yet been
developed as far as MOVPE. However, CBE offers a number of important advantages, not only regarding uniformity of layer thickness and composition, but especially in the field of Selective Area Epitaxy. Considering the benefits of CBE in SAE, and the availability of reliable MOVPE-grown active layer stacks, a combination of CBE and MOVPE is likely to be advantageous for the fabrication of integrated optical amplifiers. We discuss this in more detail in the following section.

3.3 Integration technologies

A number of strategies to achieve the integration of optical amplifiers and passive waveguide devices have been reported in literature. These strategies are shown in Fig. 3.3, and will be discussed in the following sections. Subsequently, one of these is selected for the work carried out in this thesis.

3.3.1 Overgrowth

From an epitaxial point of view, overgrowth is the simplest of the integration technologies that involve a regrowth step (Fig. 3.3a). First, an n-InP buffer, the lower part of an undoped quaternary film, and an undoped active layer are grown on an n-InP substrate. The active layer is then locally removed using lithography and etching, after which the etching mask is removed. The upper part of the film, a p-InP cladding and a highly p-doped InGaAs contact layer are subsequently grown, and active and passive devices are fabricated in their appropriate regions. Alternatively, the active layer may be on top or below the film. Öberg et al. [81] applied overgrowth for the fabrication of integrated extended cavity lasers, i.e. lasers with a passive waveguide section on at least one end. These devices operated at a wavelength of 1.3 μm, the active-passive transition loss was satisfactory low: 0.9 dB per interface. Fish et al. [49] reported on the realization of a 4x4 switch matrix (λ = 1.55 μm) using overgrowth.

The main disadvantage of overgrowth is that the InP cladding is grown over the entire wafer. For proper operation of the amplifiers, the cladding must be p-doped, however, p-doping also causes substantial waveguide losses at the passive regions. This problem may be solved by introducing the p-doping only at the active regions, using Zn-diffusion after the regrowth step. However, this fairly complicates the integration process. Alternatively, an additional regrowth step can be introduced to obtain active devices of the SIPBH-type (Semi-Insulating blocked Planar Buried Heterostructure, Section 2.4.1) integrated with buried rib passive waveguides (Fig. 3.4). In this case, the waveguides are defined directly after the local removal of the active layer. The waveguides in the passive sections are shallowly etched, i.e. partly into the film, whereas the waveguides for the active devices are deeply etched, i.e. completely through the film. Subsequently, semi-insulating current blocking layers are selectively grown (see next section) adjacent to the active layer stripes using low-pressure MOVPE. These semi-insulating layers are also grown on the film in the passive re-
Figure 3.3: Strategies to achieve the definition of active and passive regions on a single chip. For each strategy, three processing steps are schematically shown (from left to right), except for evanescent field coupling, where the decomposition of the ‘supermodes’ is shown.
3.3 Integration technologies

![Diagram of optical amplifier and passive waveguide](image)

**Figure 3.4:** Cross section of optical amplifier and passive waveguide fabricated using the PPro-2 process.

regions. As a result, the film is optically shielded from the p-doped layers that are subsequently grown on the entire wafer. Incorporation of etch stop layers enables planarization and removal of p-doped material in order to obtain a high mutual electrical isolation. This approach was used for the first phased array multi-wavelength laser [43], and has evolved to the PPro-2 [21, 23, 45, 46, 82–84] and to the PPro-3 process [25, 47] in which pnpn current blocking layers are used.

Another drawback of overgrowth is that the active and passive layer stacks share the same film, which limits the design flexibility. Furthermore, the thicknesses of the layer stacks are not equal. As a result, they have slightly different effective refractive indices and modal fields, with associated reflections and coupling losses. An elegant alternative is to create a butt joint using selective area epitaxy, where the regrowth step(s) is (are) performed using either MOVPE or CBE. Both cases are discussed in the next section.

### 3.3.2 Butt joint: MOVPE

One can create a butt joint between the active and passive layer stacks by growing these stacks in separate epitaxial steps. In this case, each layer stack can be optimized individually (Fig. 3.3b). In the first growth step, the active layer stack with optional separate confinement layers is grown, and is then removed at the passive regions using a SiN$_x$ or SiO$_2$ etching mask. This mask remains on the wafer in the first regrowth step, and a film layer is grown, the modal field of which matches the modal field of the active layer well. In case of perfect growth selectivity, no material is deposited on the mask, and a butt joint is created. The etching mask is subsequently removed, and the remaining p-doped cladding and contact layers are grown on the entire wafer during a second regrowth step.

Because of non-uniform gas depletion in selective area MOVPE, the material composition and layer thickness of the epitaxially grown material are not uniform at the mask edges. This non-uniformity is minimized when butt joints between thin layers (typically below 500 nm) are created; coupling losses below 0.4 dB/interface have been demonstrated [85, 86]. Successful realization of low-loss butt joints between
thicker layer stacks (2.8 μm) was reported by Brenner et. al. [87]. However, in general such large height steps result in a worse interface morphology and increased coupling losses [85]. The problem of waveguide losses due to p-doping in the passive regions can be reduced to a large extent by incorporation of a thin undoped InP-layer on top of the passive film layer in the first regrowth [30]. MOVPE is a well-established epitaxial technology, and high-quality MOVPE-grown butt joints are widely used for the realization of WDM photonic integrated circuits [24, 30, 36, 48].

3.3.3 Butt joint: CBE/MBE

In Chemical Beam Epitaxy (CBE) and Molecular Beam Epitaxy (MBE), the presence of a dielectric mask does not affect the epitaxial growth rate at the unmasked regions, apart from shadowing effects at the very mask edges due to the beam-like material transport in these technologies. Therefore, CBE and MBE can provide excellent accuracy, uniformity and reproducibility of the regrown layers stacks. Consequently, high-quality butt joints between layer stacks with thicknesses up to 3 μm can be fabricated, and entire active and passive layers stacks including the p-doped cladlings and contact layers are butt-joined using a single regrowth step (Fig. 3.3c). The SiN₄ mask or SiO₂ mask that is used for the local removal of the entire active layer stack provides perfect selectivity for the regrowth. Active and passive layer stacks can be optimized individually, and no p-doping is introduced in the passive regions.

Gas-source MBE-grown butt joints have been applied for the realization of WDM channel selectors [31, 88] and multi-wavelength sources [27, 28]. Coupling losses of CBE-grown butt joints are typically between 0.7 and 1.4 dB/interface [89–92]. A value of only 0.12 dB/interface was reported by Wachtet et al. [93], who used a prototype multi-wafer metal-organic MBE system, which is modified such that it is actually a CBE. In these reports, a perpendicular group III injector was used, and shadowing effects were effectively eliminated. Shadowing effects, i.e. a decrease of the growth rate at the regions that are not directly covered by the ballistic beam [94], become of importance in more common CBE systems with a tilted geometry. We have demonstrated that butt joints with coupling losses as low as 0.1 dB/interface can be fabricated using a CBE system with a tilted geometry [95, 96]. Integration of DFB-lasers, optical amplifiers, modulators and passive waveguides with coupling losses in the order of 1 dB/interface [91] has been demonstrated using SA-CBE [90, 97, 98].

3.3.4 Selective Area MOVPE

In selective area MOVPE, the non-uniform growth at the mask edges can also be used as an advantage in the following way (Fig. 3.3d). The absorption edge of a Multi Quantum Well (MQW) layer stack is (among other things) dependent on the well thickness and the barrier thickness. For a fixed growth time, the thickness depends on the growth rate, which in turn depends on the mask geometry. In selective area MOVPE, using a carefully designed mask that has narrow openings where the growth
rate is high and wide openings where the growth rate is low, one can respectively define regions with thick quantum wells (active regions) and regions with thin quantum wells (passive regions) in the same epitaxial step. After removal of the mask, cladding and contact layers are grown in an additional regrowth step. Bandgap energy shifts around 140 meV have been demonstrated [99], and were applied to fabricate phased array multi-wavelength lasers, either with [44] or without [100] an integrated electroabsorption modulator. Another interesting application is the fabrication of vertically tapered film layers for the realization of spot-size converters [18].

The main drawback of selective area MOVPE for integration purposes is that the active and passive layer stacks must consist of MQW layers, which makes the fabrication of polarization-independent photonic integrated circuits very difficult. Furthermore, these MQW layers cannot be optimized individually as they are grown in a single epitaxial step. Finally, design of the mask geometry requires special attention and extensive growth calibration.

3.3.5 Multi Quantum Well Intermixing

An integration technology that does not necessarily require a regrowth step is MQW intermixing (Fig. 3.3e). A MQW structure is modified by interdiffusion of the group III elements and the group V elements across the barrier-well interfaces. In the In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material system, the group V interdiffusion is dominant [101,102], resulting in a blueshift of the MQW absorption edge. So by MQW intermixing, an active MQW structure can be modified such that it becomes transparent. Interdiffusion can be locally induced by laser irradiation [103] or by an annealing step in a Rapid Thermal Processor (RTP) at a temperature higher than 800 °C. In the latter case, the interdiffusion process can be greatly enhanced by local application of a dielectric capping layer [101,104,105] or a preceding ion implantation [102,106]. It is hard to predict the optical properties of the intermixed regions and of the non- (or partially) intermixed regions. This is a serious problem for the reproducible fabrication of passive waveguide devices like phased arrays. Intermixing is only applicable to MQW structures, and the design flexibility is low. Furthermore, devices are inherently polarization dependent, and waveguide losses are high (> 9 dB/cm).

3.3.6 Evanscent field coupling

Integration of active and passive devices by evanescent field coupling also does not require a regrowth step. In this integration strategy, the active layer and the film are grown on top of each other, separated by an InP buffer (Fig. 3.3f). The optical modes in such a layer structure can be considered to be composed of even and odd ‘supermodes’, which each travel at a different speed. As a result, the optical field will continuously travel from the film to the active layer and vice versa. The length that it takes for the field to travel from the film to the active layer and back is the so-called ‘beat length’. By locally removing the active layer, leaving blocks with a length that is
equal to the beat length, integration is accomplished. This concept is rather fabrication
intolerant, since the beat length depends critically on layer thicknesses and material
composition. Improvements using a mode selection layer [107] or an asymmetric twin
guide structure [108], optionally with a taper [109], have resulted in the realization of
extended cavity lasers with a reasonable performance ($J_{th} = 0.72$ kA/cm$^2$, efficiency
25% per facet).

3.3.7 Integration technology applied in this work

Key issues in the realization of photonic integrated circuits are a good performance
of all the active and passive devices, and a high fabrication tolerance to increase the
yield and the reproducibility. Furthermore, one should be able to optimize the active
and passive layer stacks individually, and the coupling losses and residual reflections
between these layer stacks should be low.

Considering all the options described in the previous sections, butt joint coupling
is the most attractive integration technology. If desired, multiple regrowth steps can be
performed to optimize the layer stack for each type of device. However, in general the
number of regrowth steps should be minimized in order to reduce the fabrication com-
plexity and processing costs, and to achieve a high yield. Comparing MOVPE-grown
butt joints with CBE or MBE regrowth, we see that the latter technologies enable
fabrication of high quality butt joints between entire layer stacks using only a single
regrowth step. Furthermore, growth temperatures of CBE and MBE are relatively low,
and thermal degradation of the primary layer stack is avoided [91, 92].

Of course, for the selection of an integration technology the availability of (re-
growth) facilities is of crucial importance. The integration experiments described in
this thesis are based on butt-joining active and passive regions using a Selective Area
Chemical Beam Epitaxy (SA-CBE) regrowth step. Regrowth is performed by our co-
workers at the Department of Physics of the Eindhoven University of Technology. We
have performed the following integration experiments:

- Passive-passive integration (Section 5.3.1): as a first step towards the integration
  of optical amplifiers and passive waveguide devices, we have applied SA-CBE
  for the fabrication of butt joints between two similar transparent ($\lambda = 1.55$
  $\mu$m) epitaxial layer stacks. In this way, we were able to investigate the butt joint
coupling efficiency using standard Fabry-Perot measurement techniques.

- Active-passive integration, regrowth at the active regions (Section 5.3.2): in
  these experiments, we fabricated the layer stack of the optical amplifiers during
  the SA-CBE regrowth step, while the passive waveguide devices were fabric-
  ated in the primary layer stack. The quality of the resulting butt joints was
  very good, however, the gain of the amplifiers was not satisfactory due to the
  non-optimal design of the active layer stack. Nevertheless, these experiments
demonstrated the design flexibility offered by SA-CBE, as one could in prin-
ciple repeat the regrowth procedure to achieve the integration of other types of devices such as electro-absorption modulators.

- Active-passive integration, regrowth at the passive regions (Section 5.3.3): in this case we performed the regrowth at the passive regions, and we fabricated the amplifiers in the primary MOVPE-grown InGaAs/InGaAsP MQW active layer stack. In this way, we exploited the advantages of both MOVPE (well-established, reliable growth of active layer stacks) and CBE (selective area growth characteristics). Two experiments were carried out: one in which the active layer was on top of the waveguiding film layer, and one in which it was in the center. These two experiments have resulted in the successful fabrication of integrated optical amplifiers, which were applied in extended cavity lasers (Section 5.4) and in phased array multi-wavelength lasers (Section 5.5).

The photonic integrated circuits that have been fabricated using SA-CBE [90, 97, 98] were all reported by France Telecom/CNET, and were designed for high-speed applications. Regrowth was performed using a perpendicular group III injector in these cases, and the coupling losses were in the order of 1 dB/interface. At the Eindhoven University of Technology, the CBE reactor employs a more common tilted geometry, and growth conditions should be optimized such that shadowing effects are reduced [95, 96]. Low butt joint coupling losses are desired, and residual reflections should be minimized. Applications of SA-CBE in WDM photonic integrated circuits have not yet been reported to our knowledge. It is a challenge to use this technology for integrating optical amplifiers, advanced passive waveguide devices such as phased arrays, and phase modulators.

3.4 Fabrication of integrated ridge waveguide devices

The photonic integrated circuits fabricated at the Delft University of Technology are based on ridge waveguide structures in InP-based materials. The various processing steps for the fabrication of integrated active and passive ridge waveguide devices are discussed in this section.

3.4.1 Definition of active and passive regions

Fig. 3.5 shows the processing steps for the fabrication of integrated dry-etched waveguide devices. Processing starts with the definition of active and passive regions using Selective Area Chemical Beam Epitaxy. Active and passive devices are subsequently fabricated in their appropriate regions.

Starting point of the processing as described here is the layer stack of the active devices (Fig. 3.5a). This layer stack consists of an n-InP substrate and buffer, a non-intentionally doped Q(1.25) or Q(1.3) film, a p-doped InP cladding and a p'-InGaAs contact layer. In Fig. 3.5, the non-intentionally doped MQW active layer is in the
Figure 3.5: Processing of integrated RIE etched optical amplifiers (left sides) and passive waveguides devices (right sides).
3.4 Fabrication of integrated ridge waveguide devices

center of the film; alternatively, it may be on top of the film. The InGaAs contact layer, which has a thickness of only 25 nm, is not shown in the figure for clarity.

First fabrication step is the deposition of a 100 nm SiN_x layer using Plasma Enhanced Chemical Vapor Deposition (PE-CVD) (Fig. 3.5a). The regions where the active devices will be fabricated are then covered with photoresist by means of contact lithography (Fig. 3.5b). This photoresist serves as an etching mask for the local removal of the SiN_x using CHF_3 Reactive Ion Etching (RIE). After removal of the resist using acetone and O_2-plasma (Fig. 3.5c), we remove the active layer stack at the regions where the passive waveguides will be fabricated using the SiN_x layer as an etching mask (Fig. 3.5d). For the removal of the active layer stack, we use the selective wet-chemical etchants H_2O:H_2O_2:H_2SO_4 = 10:1:1 and H_3PO_4:H_2O = 1:10 for the InGaAs contact layer and for the InP cladding, respectively. The film and the active layer are removed using an optimized CH_4/H_2-RIE process [110]. Further details are separately given for each integration experiment in Chapter 5.

Alternatively, we could etch the active layer stack using the photoresist as an etching mask, without the intermediate SiN_x layer. However, we found that in that case polymers are deposited on the wafer during CH_4/H_2-RIE. The process described above was developed for the fabrication of low-loss waveguides, and the use of the intermediate SiN_x layer has become the standard in our laboratory.

After local removal of the active layer, we thoroughly clean the wafer using three sequences of O_2-stripping and subsequent oxide removal in H_3PO_4:H_2O = 1:10 phosphoric acid, followed by a clean-up etch in 98% H_2SO_4 in H_2O for 150 seconds. The wafer is then ready for the SA-CBE regrowth of a suitable passive waveguide layer stack at the unmasked regions (Fig. 3.5e). Preferably, we perform the last cleaning step shortly before the regrowth, i.e. just before transportation of the wafer to the Eindhoven University; upon arrival, it is immediately loaded into the CBE load lock. After regrowth and subsequent removal of the SiN_x layer using diluted HF, we deposit a new 100 nm PE-CVD SiN_x layer (Fig. 3.5f) to arrive at a similar point as in Fig. 3.5a, except for the fact that now we have accomplished the definition of active and passive regions.

3.4.2 RIE etched waveguide devices

For the fabrication of the waveguide devices, we proceed by defining the waveguide geometry in the SiN_x by means of contact lithography and CHF_3-RIE (Fig. 3.5g). The waveguide structure is etched in the InGaAsP material using the optimized CH_4/H_2-RIE process [110] (Fig. 3.5h), after which we thoroughly clean the wafer in the same way as mentioned in the previous section to remove the damaged InP surface [110]. The H_2SO_4 etch slightly reduces the waveguide width (typically by 100 nm). We subsequently remove the SiN_x using HF, and deposit a new 200 nm PE-CVD SiN_x passivation/protection layer (Fig. 3.5i). Contact openings are defined in this new SiN_x layer (Fig. 3.5j) by means of contact lithography and wet chemical etching using buffered HF (NH_4F (40%):HF (49%) = 6:1) for 3 minutes.
The use of buffered HF (BHF) instead of CHF₃-RIE reduces possible damage due to RIE, and prevents additional exposure to a hydrogen plasma, which may degrade the device performance (Section 4.3). However, RIE is essential for the definition of the waveguide geometry into the SiNx in order to obtain low-loss waveguides. Wet etching of SiNx using diluted HF results in a severe undercut, and the contact openings are not sharply defined in that case. We found that the undercut is greatly reduced by using BHF instead of HF.

After definition of the contact openings, the structure in Fig. 3.5j must be planarized in order to avoid interruption of the metallization layer at the vertical side walls, as the metal is deposited only on horizontal planes. A photosensitive polyimide film is applied for this purpose (Fig. 3.5k), where the same contact lithography mask is used as for the opening in the SiNx passivation layer. The incorporation of the SiNx may appear to be redundant since the polyimide also effectively protects the device from the environment. However, the polyimide shrinks by ≈ 50% during its postbake step, and may be torn off the ridge sidewalls. The SiNx is included to increase the process yield, even though this requires an additional (critical) lithography step. Using the polyimide as an etching mask for the contact opening in the SiNx layer would avoid this lithography, but this would result in a severe undercut.

For the metallization lithography, an image-reversal or negative photoresist is used in order to obtain a typical lift-off profile (Fig. 3.5l). A metallization layer stack is then evaporated on top (Ti/Pt/Au = 25/75/250 nm, Fig. 3.5m) and on the back (Ti/Pt/Au = 25/75/100 nm) of the wafer. The metallization stack on the back is slightly thinner than on the top, since thicker metallization on the back remains intact upon cleaving the wafer, and has to be torn apart in order to separate the cleaved parts. After lift-off in acetone (Fig. 3.5n), the wafers are annealed in a Rapid Thermal Processor (RTP) in an Ar/H₂-ambient for 30 seconds at a temperature of 325°C to reduce the contact resistance. Finally, the wafer is cleaved, and the devices are soldered with Indium on a temperature-controlled copper holder for characterization.

A SEM photograph of a RIE-etched ridge laser is shown in Fig. 3.6, where the
structure on the left side of Fig. 3.5n can be recognized. In order to illustrate possible problems that may arise during processing, we have depicted a device with a few imperfections (alternatively, see Fig. 5.8a). Note that, in contrast to Fig. 3.5n, RIE-etching in Fig. 3.6 has intentionally been performed almost through the film. As a result of the slightly sloped ridge sidewalls (10°), the ridge width at the position of the active layer is 0.4 \( \mu m \) wider than the design width of 3.5 \( \mu m \) for this particular device. The polyimide opening is 1.5 \( \mu m \), as designed. The alignment error of the polyimide with respect to the ridge is 0.6 \( \mu m \), indicating the required alignment tolerance for this fabrication process. The polyimide is torn off the left side of the ridge during the polyimide postbake step, resulting in a small gap. It is likely that without the SiNx layer this device would not work properly. Also visible in Fig. 3.6 is a flaw in the cleaved facet, which is generally observed when samples shorter than 1 mm are cleaved. From the reproducible performance of ridge lasers, we believe that these flaws have only a marginal effect on the device performance.

### 3.4.3 Wet chemically etched waveguide devices

There are two aspects of the processing of RIE etched active waveguide devices that are not optimal:

- The exposure to a hydrogen plasma during CH\(_4\)/H\(_2\)-RIE etching causes passivation of acceptors. This causes an increase in the electrical series resistance, as will be discussed in Section 4.3.

- The use of polyimide implies that the most critical lithography step in terms of alignment tolerance (opening on top of a ridge) has to be performed twice. Furthermore, the lithographic properties of polyimide are poorer than those of photoresist.

For the realization of discrete lasers and optical amplifiers, i.e. non-integrated devices, we have developed an alternative fabrication process. In this process, the waveguide structure is etched using selective wet chemical etchants instead of CH\(_4\)/H\(_2\)-RIE. By comparing the performance of wet chemically etched devices with the performance of RIE etched devices fabricated from the same wafer, we can investigate the influence of CH\(_4\)/H\(_2\)-RIE. The fabrication of wet chemically etched devices does not require any polyimide planarization, and is therefore relatively simple. These devices are therefore suitable to quickly establish the performance of an active epitaxial layer stack. An additional advantage of wet chemical etching is that the selectivity of the etchants makes it possible to accurately determine the thickness of the epitaxial layers using a surface profiler.

The fabrication process is depicted in Fig. 3.7. The waveguide geometry is again transferred to a 100 nm SiNx layer using contact lithography and CHF\(_3\)-RIE, after

---

1The 1 \( \mu m \) reference bar in Fig. 3.6 actually represents 1.12 \( \mu m \), as was confirmed by analysis of structures with accurately known dimensions.
Figure 3.7: Processing of wet chemically etched active devices (a ... d) and SEM photograph of wet chemically etched ridge laser (e).

which the resist is removed (Fig. 3.7a). Etching of the epitaxial layers is performed using $\text{H}_2\text{O}:\text{H}_2\text{O}_2:\text{H}_2\text{SO}_4 = 10:1:1$ and $\text{HCl}:\text{H}_3\text{PO}_4 = 1:4$ for the InGaAs contact layer and the InP cladding, respectively (Fig. 3.7b). By orienting the waveguides in the $[0\bar{1}1]$ direction, we obtain tilted $[211]$ sidewalls with an angle of $35.26^\circ$ with respect to the (100)-plane. A ridge laser with such sidewalls does not require any polyimide planarization, and after deposition and patterning of the 200 nm SiNx layer (Fig. 3.7c), the metallization layer stack can be applied directly onto the wafer (Fig. 3.7d). Note that this metallization stack, which has a high optical absorption, is rather close to the film. Nevertheless, the metallization stack has a marginal confinement because it is only close to the film in the very lower corners of the waveguide, where the optical intensity is low. Furthermore, the 200 nm SiNx layer has a significantly lower refractive index ($n \approx 2$) than the III-V semiconductor materials, and effectively shields
3.4 Fabrication of integrated ridge waveguide devices

the optical field from the metallization stack. Therefore, the optical absorption in the metallization stack of a wet chemically etched device is comparable to that of a RIE etched device.

A SEM photograph of a wet chemically etched laser is shown in Fig. 3.7e. This particular device was designed to have a top ridge width of 3 \( \mu m \) and a contact opening width of 1.5 \( \mu m \). We measured values of 2.9 \( \mu m \) and 1.5 \( \mu m \), respectively, so the undercut for the wet chemical etching steps is acceptable. Due to the sloped \([211]\) sidewalls, the bottom of the ridge is 3.7 \( \mu m \) wider than the top.

Wet chemical etching is not applicable to curved waveguide structures such as phased arrays. The etching is not completely determined by the waveguide geometry, but will reveal crystallographic planes, and high waveguide losses will be the result. Consequently, one must etch passive waveguide devices using RIE, and their integration with wet chemically etched optical amplifiers requires a separate etching step for each type of device. The wet chemically etched devices presented in this work are fabricated as references, the performance of which can be compared to the performance of RIE etched devices, and which provide insight in the quality of the epitaxial layer stacks.

3.4.4 Dimensions

For ridge lasers and optical amplifiers, the ridge width \( w_{\text{ridge}} \) should be as small as possible for two reasons. In the first place, the gain is determined by the carrier and current \textit{density}. The current density \( J \) is given by \( J = I / (L \cdot w_{\text{ridge}}) \), where \( I \) is the current and \( L \) is the device length. Thus, the injection current that is required to achieve a specified gain, i.e. a specified current density, is reduced by reducing the ridge width \( w_{\text{ridge}} \). In addition to this, a ridge laser with a large \( w_{\text{ridge}} \) will support a large number of lateral modes, which may result in so-called ‘kinks’ in the LI-curves [38,50,67].

On the other hand, the ridge width cannot be chosen arbitrarily small. First of all, the loss of passive waveguides that are fabricated using the technology described in Section 3.4.2 rapidly increases when \( w_{\text{ridge}} \) is reduced below 2 \( \mu m \) [111]. Thus, also for lasers and amplifiers, \( w_{\text{ridge}} \) should be larger than 2 \( \mu m \). For a laser, high waveguide losses will result in a high threshold current (Eq. 2.12) and a low differential efficiency (Eq. 2.19).

More important, an additional requirement for the ridge width is set by the width of the contact opening \( w_{\text{open}} \). As the opening is located on top of the ridge, \( w_{\text{ridge}} \) must be larger than \( w_{\text{open}} \). The opening itself must be sufficiently wide to make sure that it will really be opened during the processing. Reasonable safe dimensions for \( w_{\text{open}} \) are 1 \( \mu m \) in photoresist and 2 \( \mu m \) in polyimide.

The difference between \( w_{\text{ridge}} \) and \( w_{\text{open}} \) provides the alignment tolerance for positioning the opening on top of the ridge during fabrication. A margin of 0.5 \( \mu m \) on both sides of the opening provides the minimum alignment tolerance required for the contact lithography equipment available. Thus, \( w_{\text{ridge}} \) must be larger than \( w_{\text{open}} + 1 \mu m \).
Figure 3.8: a) Mask layout of alignment mark b) Mask layout of nonius. (c) Optical microscope photograph of a complete set of these marks and nonii on a processed wafer.

The alignment tolerances mentioned above are achievable using the alignment marker shown in Fig. 3.8a. During alignment, the wafer is positioned such that the crosses on the wafer and on the mask are on top of each other; the arms of complementary crosses have widths of 5 μm and 10 μm (coarse alignment), and widths of 7 μm and 8 μm (fine alignment), respectively. The so-called nonius (Fig. 3.8b) gives a good indication of the resist pattern quality immediately after lithography. A photograph of a processed set of markers and nonii is also shown (Fig. 3.8c).

In conclusion, the smallest ridge width for a RIE etched ridge laser or amplifier is 3 μm (2 μm for the polyimide and 1 μm alignment tolerance). The top ridge width of a wet chemically etched device must be larger than 2 μm (1 μm for the opening and 1 μm alignment tolerance). The bottom ridge width of the latter device is increased due to the sloped sidewalls by $2h / \tan(35.26°) = 2.8h$, where the factor 2 accounts for both sides of the ridge and $h$ is the device height (etch depth). In general, $h > 1$ μm to avoid absorption losses due to the InGaAs contact layer. As a result, the bottom ridge width of a wet chemically etched device is typically larger than 5 μm, which is quite wide. RIE etched devices are more promising for the realization of amplifiers and lasers that operate at low injection currents, while the wet chemically etched devices are suitable as test structures.

3.5 Conclusions

We have chosen Selective Area Chemical Beam Epitaxy (SA-CBE) as the integration technology for the fabrication of integrated optical amplifiers. SA-CBE enables the definition of active and passive regions using a single regrowth step, where the optical coupling loss between these regions is low. It is however advantageous to use MOVPE for the epitaxial growth of the active layer stack, and in this way to combine the reliability of this well-established epitaxial technology with the excellent selective area growth characteristics of CBE. The processing steps for ridge waveguide devices have been discussed in detail, and will be applied in the next two chapters.
Chapter 4

Ridge Lasers and Amplifiers

Two important issues can be distinguished in the fabrication of integrated semiconductor optical amplifiers: the fabrication of the amplifiers themselves, and their integration with passive waveguide devices. This chapter focuses on the first of these two issues, and deals with the fabrication and characterization of non-integrated ridge lasers and amplifiers.

4.1 Introduction

As a first step towards the realization of integrated optical amplifiers, we fabricated a number of non-integrated active devices, i.e. devices that are not integrated with passive waveguide devices. In this way, we were able to develop a suitable device structure and fabrication technology for the integrated amplifiers, without being troubled by integration issues. However, we always kept in mind the compatibility with the passive ridge waveguide devices as fabricated at the Delft University of Technology. The non-integrated devices were also very suitable for the development of the proper characterization tools.

As a first experiment, we fabricated a number of gain-guided devices, which employ the simplest active device structure conceivable. In the succeeding experiments, we increased the fabrication complexity to subsequently fabricate wet chemically etched and Reactive Ion Etched (RIE etched) ridge lasers and amplifiers. In this way, we arrived at a device structure that is suitable for integration with passive waveguide devices, as described in Chapter 5. We applied a number of different epitaxial layer stacks in order to optimize the device performance and to investigate the suitability of the available Chemical Beam Epitaxy (CBE) system for the regrowth of active material.

As was already pointed out in Section 2.5, the facets of an as-cleaved optical amplifier have a power reflection coefficient of about 0.33. Thus, in case no anti-
reflection measures are taken, the device is basically a laser. Since it is easier to characterize a laser than an amplifier, most devices presented in this chapter were operated as lasers. Measurements on anti-reflection coated devices will be presented in Section 4.5.

### 4.2 Design

In this section, we discuss the design of the three types of non-integrated active devices. These types are, in order of increasing fabrication complexity: gain-guided, wet chemically etched ridge and RIE etched ridge. All devices were fabricated using the same set of four contact lithography masks. Device structures, epitaxial layer stacks and mask layout are discussed.

#### 4.2.1 Device structures

The non-integrated active devices are shown in Fig. 4.1, where it assumed that they all employ a similar epitaxial layer stack.

The gain-guided device (Fig. 4.1a) is the simplest from a fabrication point of view. It is a planar structure, except for the trenches, which provide mutual electrical isola-
4.2 Design

tion. Fabrication does not involve any ridge etching or critical mask alignment, which is the reason why this structure was selected for the first preliminary experiments. The active layer that provides the optical gain is electrically pumped through a contact opening in a SiNx dielectric layer. There is no waveguiding structure that provides any lateral index contrast. In fact, the refractive index underneath the contact opening is reduced due to carrier injection, and the structure is anti-guiding. This implies that a high material gain is required to achieve laser operation. Furthermore, injected carriers are not confined in any way, and can easily move away from the contact opening. As a result, current injection is quite inefficient to achieve a high carrier concentration, and the threshold current of a gain-guided laser is high.

When a ridge waveguide structure is used, both the lateral optical confinement and the current injection efficiency are much better. The ridge can be etched by means of wet chemical etching (Fig. 4.1b) or by means of Reactive Ion Etching (RIE, Fig. 4.1c).

Comparing the suitability of wet chemically etched and RIE etched ridge amplifiers for integration with passive waveguide devices, we observe that the latter are advantageous as RIE is applied for the fabrication of the passive waveguide devices as well. So we can define the ridges of the amplifiers and the ridges of the passive waveguide devices in the same RIE step. On the other hand, RIE etched active devices are more difficult to fabricate than wet chemically etched devices (Section 3.4), and additional hydrogen passivation or damage due to CH4/H2-RIE etching may be introduced.

Fabrication of wet chemically etched devices, on the other hand, is relatively easy and ‘gentle’. However, integration with RIE etched passive waveguide devices requires a two-step etching process. Furthermore, the sidewalls of wet chemically etched devices are sloped, and therefore the bottom ridge width as experienced by the optical field is wider than the top ridge width as defined by lithography. Due to this large bottom ridge width, the threshold current of a wet chemically etched ridge laser is expected to be higher than that of a RIE etched device which has nearly vertical sidewalls, assuming that the threshold current densities are comparable. The large bottom ridge width may also cause kinks in the LI-curve due to multimode behavior. Alternatively, we can orient the wet chemically etched devices along the [011] direction instead of the [011] direction in order to obtain nearly vertical sidewalls. However, these vertical sidewalls require a (polyimide) planarization to avoid interruption of the metallization pattern, and the fabrication of such devices is not easier than the fabrication of RIE etched devices.

In this chapter, we present the fabrication and characterization of both wet chemically etched and RIE etched lasers and amplifiers. The wet chemically etched devices are oriented in the [011] direction to obtain sloped sidewalls for ease of fabrication. We compare the performance of both types of devices, and establish possible degradation of performance due to RIE.
4. Ridge Lasers and Amplifiers

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>CBE-grown</th>
<th>MOVPE-grown</th>
</tr>
</thead>
<tbody>
<tr>
<td>contact layer</td>
<td>InGaAs</td>
<td>InGaAs</td>
</tr>
<tr>
<td>cladding</td>
<td>InP</td>
<td>InP</td>
</tr>
<tr>
<td>film/SC</td>
<td>MQW: InGaAs/InP</td>
<td>Q(1.25)</td>
</tr>
<tr>
<td>active layer</td>
<td>MQW: InGaAs/InP</td>
<td>MQW: InGaAs/Q(1.25)</td>
</tr>
<tr>
<td>film/SC</td>
<td>MQW: InGaAs/InP</td>
<td>Q(1.25)</td>
</tr>
<tr>
<td>substrate/buffer</td>
<td>InP</td>
<td>InP</td>
</tr>
</tbody>
</table>

Figure 4.2: Layer stacks for non-integrated lasers and optical amplifiers, grown by CBE or by MOVPE. SC stands for separate-confinement.

4.2.2 Epitaxial layer stacks

We will apply a Selective Area Chemical Beam Epitaxy (SA-CBE) regrowth step for the integration of optical amplifiers and passive waveguide devices (Chapter 3). If the flexibility of this technology is to be exploited fully, SA-CBE regrowth of the active layer should be possible. At the time of the first experiments, CBE growth of the complete quaternary In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ material, in particular Q(1.25), was still under development at the Eindhoven University of Technology, and the only materials available for regrowth were InP and lattice-matched InGaAs. Therefore, we decided to fabricate devices with CBE-grown InGaAs/InP Multi Quantum Well (MQW) active layers and separate confinement layers. The bandgap energy of these layers is controlled by varying the well width and the barrier width.

It would also be useful to compare the performance of a fabricated device to results reported in literature. In this way, processing quality and device structure are judged, instead of the performance of the active layer. Therefore, we also fabricated a number of devices with more commonly used MOVPE-grown InGaAs/Q(1.25) MQW active layers, which were purchased from a commercial supplier. Using MQW active layers in this case as well makes it possible to compare the performance of these devices to the performance of the InGaAs/InP MQW devices. The main drawback of MQW active layers is the polarization dependent gain. The design of polarization-independent optical amplifiers for routing and switching applications in WDM-systems requires further investigation.

For details on the epitaxial layer stacks applied in this work, see Appendices A and B. The layer stacks were chosen according to the following considerations:

Active layer

The thickness of the quantum wells in the active layer determines the wavelength dependence of the gain, i.e. the gain spectrum\(^1\). The wavelength where the gain is high-

\(^1\)The gain spectrum also depends on other parameters such as the current density and the temperature.
est, i.e. the peak of the gain spectrum, should be around 1.55 \mu m. From literature, we find that the quantum well thickness in the MOVPE-grown InGaAs/Q(1.25) MQW active layer should be between 4 nm [112] and 8 nm [71]. In a first experiment, we chose a well width of 8 nm for the InGaAs/Q(1.25) active MQW. The emission wavelength of ridge lasers with this active layer stack was quite long (1580 nm), therefore we reduced the well thickness to 4.5 nm in the succeeding experiments. We found that the emission wavelength of extended cavity lasers\(^2\) with 4.5 nm quantum wells was satisfactory close to 1.55 \mu m. The barriers are 10 nm thick in all cases, the number of quantum wells is five. The well thickness of the CBE-grown InGaAs/InP MQW active layers is 8 nm.

From calculations (Section 2.6.2) it follows that the lowest energy transition of an 8 nm InGaAs well with 10 nm Q(1.25) barriers should correspond to a wavelength of 1530 nm, whereas for a 4.5 nm well this wavelength should be 1450 nm (Fig 2.15b). The discrepancy between the calculations and the experimental results is caused by the limited validity of the ‘particle in the box’ model (parabolic bands on top of discrete energy levels is a crude approximation, especially at high carrier concentrations), by the inaccuracy of the material parameters that are used in the calculations (effective masses, band offsets), and by the limited accuracy of the epitaxial growth (thickness, composition, strain, interface layers).

**Film/separate confinement layers**

In a photonic integrated circuit, the mode profiles of the passive waveguide devices and the optical amplifiers should match well to ensure minimal butt joint coupling losses and minimal residual reflections. Therefore, we chose the composition and the total thickness of the amplifier separate-confinement layers similar to what we use for the film of the passive waveguide devices (composition Q(1.25) or Q(1.30), thickness 500 nm < \(d_{\text{film}}\) < 600 nm).

The well width and barrier width of the CBE-grown InGaAs/InP MQW separate-confinement layers were chosen such that these layers satisfy two conditions: in the first place, these layers should be transparent at the operating wavelength of the device (around 1.55 \mu m). Hence, the quantum wells should be much thinner than the quantum wells of the active layer. Secondly, we designed the MQW such that the refractive index for TE-polarized light corresponds to the refractive index of the same Q(1.25) separate-confinement layers that were applied in the MOVPE-grown layer stacks. The refractive index of a MQW is approximated by [113]:

\[
\eta_{\text{MQW, TE}}^2 = \frac{d_{\text{well}}\eta_{\text{well}}^2 + d_{\text{bar}}\eta_{\text{bar}}^2}{d_{\text{well}} + d_{\text{bar}}} \tag{4.1}
\]

where \(d\) and \(n\) are the thickness and the refractive index, referring to the wells and the barriers, respectively. Assuming \(n_{\text{InP}} = 3.17\) and estimating \(n_{\text{InGaAs}} = 3.6\) by

\(^2\)Extended cavity lasers have a passive waveguide section on at least one end.
<table>
<thead>
<tr>
<th>device number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{\text{ridge}} (\mu m)$</td>
<td>2</td>
<td>2.5</td>
<td>2.5</td>
<td>10</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3.5</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>$w_{\text{open}} (\mu m)$</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>7</td>
<td>1.5</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>device number</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{\text{ridge}} (\mu m)$</td>
<td>3.5</td>
<td>3.5</td>
<td>10</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$w_{\text{open}} (\mu m)$</td>
<td>2</td>
<td>2.5</td>
<td>7</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>5</td>
<td>2.5</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>device number</th>
<th>21</th>
<th>22</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{\text{ridge}} (\mu m)$</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>$w_{\text{open}} (\mu m)$</td>
<td>3.5</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 4.1:** Lateral dimensions of non-integrated devices.

The extrapolation of data presented in [54], we have taken $d_{\text{well}} = 1.85 \text{ nm}$ and $d_{\text{bar}} = 2.55 \text{ nm}$ to obtain $n_{\text{MQW, TE}} = n_{\text{Q(1.25)}} = 3.36$. An InGaAs/InP MQW with such thin quantum wells is transparent at a wavelength of $1.55 \mu m$.

**Cladding**

The thickness of the cladding should be sufficient to avoid optical absorption in the highly p-doped contact layer and in the metallization stack. On the other hand, a thick cladding will increase the electrical series resistance, so the design of the cladding involves a trade-off between optical and electrical properties. The cladding typically consists of a 200 nm lightly doped ($5 \cdot 10^{17} \text{ cm}^{-3}$) InP layer to avoid high absorption losses due to p-doping, and a thicker (600 nm $< d_{\text{cladding}} < 1000 \text{ nm}$) more heavily doped ($1 \cdot 10^{18} \text{ cm}^{-3}$) InP layer on top.

**Contact layer**

The contact resistance of the devices is reduced by incorporating a highly p-doped ($1 \cdot 10^{19} \text{ cm}^{-3}$) low-bandgap material as a contact layer. A 25 nm InGaAs contact layer is used for this purpose.

**4.2.3 Dimensions**

As was discussed in Section 3.4.4, it is advantageous to keep the lateral device dimensions small, however, lower limits are set by the fabrication technology. It was concluded that for wet chemically etched devices, the ridge width $w_{\text{ridge}}$ and the contact opening width $w_{\text{open}}$ (Fig. 4.1) should be larger than 2 \mu m and 1 \mu m, respectively. For RIE etched devices, these numbers are 3 \mu m and 2 \mu m, respectively. The ridge width and the contact opening width of the fabricated devices are varied as shown in Table 4.1. From a fabrication point of view, these dimensions range from 'easy'
to ‘almost impossible’. In this way, the optimal lateral device dimensions that are achievable with the available fabrication technology can be established.

The device length is determined by cleaving, and is typically larger than 1 mm. For shorter lengths, the device length comes too close to the substrate thickness (350 μm), and the cleaved edges show a lot of flaws, especially for wet chemically etched devices in the [011] direction. Cleaving of shorter devices requires thinning of the substrate. However, we observed a lot of damage in a preliminary thinning experiment, and decided to keep the substrate thickness as it is.

4.2.4 Mask layout

A set of four contact lithography masks (Fig. 4.3) was designed for the realization of the non-integrated active devices. Three masks define the ridges, the contact openings and the metallization pattern, respectively. The fourth mask is used to define the isolation trenches for the gain-guided devices. Lithography of the contact openings in SiNₓ and polyimide is performed using the same mask.

The mask set defines two identical blocks of 23 ridge structures of various lateral dimensions, and nine groups of alignment marks. A photograph of these alignment marks is shown in Fig. 3.8. The metallization stripes are 20 μm wide, and completely cover the ridge in order to facilitate mask alignment. Each metallization stripe is provided with contact pads of 80 x 100 μm², spaced with a period of 600 μm. The separation between the ridges is 250 μm.

4.3 Gain-guided devices

As a preliminary step towards the fabrication of ridge lasers and amplifiers, we fabricated two samples with gain-guided devices (Fig. 4.1a). These are the simplest active devices from a fabrication point of view, as their fabrication does not involve any ridge etching or critical mask alignment. Still, fabrication and characterization of gain-guided devices can provide useful information and experience.

4.3.1 Fabrication

The devices were fabricated in the [011] direction from a commercially purchased MOVPE-grown wafer (Fig. 4.2). The layer stack is given in detail in Appendix A, Table A.1, and consists of a (100) n-InP substrate, a 200 nm n-InP buffer, a 2 x 250 nm non-intentionally doped (n.i.d.) Q(1.25) film/separate-confinement layer with an n.i.d.-MQW active layer in the center (5 x 8 nm InGaAs well, separated by 10 nm Q(1.25) barriers), an 800 nm p-InP cladding and finally a 25 nm p⁹⁺-InGaAs contact layer. The two samples used for this experiment were both located adjacent to the large flat. For one sample, we etched the opening in the SiNₓ using Reactive Ion Etching (RIE), while for the other we applied the wet chemical etchant HF. By comparing
Figure 4.3: Layout of mask set for non-integrated devices, the structures of which are shown in Fig. 4.1. A quarter of a 2" wafer is drawn on the same scale. The figure on the bottom shows a schematical enlargement.

the performance of the devices from these two samples, we can investigate possible damage due to RIE. Application of HF results in a large undercut of the SiN_x etching; we solved this problem later on by using buffered HF. Still, also the HF-etched contact openings were sharply defined in the SiN_x as was verified using a Nomarski microscope. For details on processing the reader is referred to Section 3.4. The isolation trenches were defined by selective wet chemical removal of the InGaAs contact layer and the of InP cladding layer, resulting in an etch depth of 900 nm. This is approximately 8 % thicker than the specified total thickness of these layers.
4.3 Gain-guided devices

![Figure 4.4: ASE spectra of HF etched device for currents of 10, 20, 30, 40 and 50 mA, TE (solid) and TM (dashed). Device length is 624 μm, opening is 5 μm.](image)

### 4.3.2 Measurement results

A rather short sample (624 μm) was Indium-soldered on a copper heat sink without temperature control. As a first check, one of the cleaved facets was monitored using a microscope objective (numerical aperture 0.65), an infra-red camera and a TV monitor. Upon injection of a DC current, a bright horizontal stripe with a width of typically 200 μm appeared on the monitor. So the area that is electrically pumped, i.e. the area where the carrier density is sufficient to generate spontaneous emission (or at least where the absorption of spontaneous emission is low), is much larger than the contact opening width of 7 μm or less. The performance of devices with different contact opening widths was essentially the same. This indicates that the current can easily flow in the lateral direction.

The output spectrum was measured for TE and TM polarization (Fig. 4.4) using the same microscope objective, a polarizer and an optical spectrum analyzer. The spectra clearly demonstrate the polarization dependence of the MQW active layer. The TE-polarized emission wavelength (heavy holes) of the 8 nm quantum wells is rather long (1570 nm), whereas the TM-polarized emission wavelength (light holes) is approximately 50 nm shorter. Also, the TM intensity is less than for TE. The ASE spectra did not show the slightest Fabry-Perot ripple up to the maximum available current of 500 mA. This excludes the possibility of laser operation at a low injection current for these devices. This is not surprising, since for a device width of 200 μm, a current of 500 mA corresponds to a current density of only 0.16 kA/cm². This is much lower than the threshold current densities of the ridge lasers that were fabricated from the same wafer. These lasers will be described in the next section.
In order to compare the performance of the two different types of devices, i.e. the devices that have HF etched or RIE etched contact openings, we characterized samples of similar length (1.04 mm and 1.17 mm respectively) and with an equal contact opening width (5 μm). As compared to the HF etched device, the RIE etched device has a higher reverse bias saturation current (Fig. 4.5a), a higher series resistance (Fig. 4.5b), and its ASE intensity 30 % lower. From the slopes in Fig. 4.5b we find that the series resistances are lower than 10 Ω and 3 Ω for the RIE etched device and for the HF etched device, respectively.

The worse performance of the RIE etched device is most likely caused by hydrogen passivation of the Zn-acceptors in the p-type material during the RIE etching step [114]. Passivation does not only occur for CH$_4$/H$_2$-RIE etching of InP/InGaAsP [115–117], but also for CHF$_3$-RIE etching of dielectric layers [118] as was used for this particular device. Hydrogen passivation effectively decreases the p-type carrier concentration $p_p$ in the p-side of the pn-junction down to depths of typically 1 μm, which explains the increased series resistance. Furthermore, the decrease in $p_p$ causes the observed increase in the reverse bias saturation current: effectively, the p-n junction becomes more similar to a ‘junction’ between non-intentionally doped regions, and the rectifying behavior of the junction is reduced.

The effect of acceptor passivation can be reduced by applying an annealing step at a temperature $T > 300$ °C. This causes a redistribution of the hydrogen atoms to larger depths, typically a few microns. In our experiment, the effect of hydrogen passivation of Zn-acceptors in the CHF$_3$-RIE etched device is probably not sufficiently reduced because of the short annealing time ($t = 30$ s) and the low annealing temperature ($T = 325$ °C) as compared to refs. [115, 116, 118] ($t > 60$ s, $T > 350$ °C).
The thermal stability of the Zn-H complex in the InGaAs contact layer is lower than in the InP cladding [114], so even after an annealing step at moderate time and temperature the passivation in the contact layer will not be very pronounced. As a consequence, carriers can easily move away from the contact opening through the highly doped contact layer, so the region where the carrier concentration is high is much wider than the contact opening width. As a result, we see a broad stripe of ASE emission for both the RIE-etched devices and the HF etched devices.

4.3.3 Conclusions

We have fabricated and characterized two types of gain-guided devices. The contact opening was etched either by wet chemical etching or by Reactive Ion Etching (RIE). ASE emission stripes of 200 \(\mu\)m wide indicate that the current can easily flow in the lateral direction for both types of devices. As a result, the current density is low, even at high injection currents, and no laser operation is observed. The use CHF\(_3\)-RIE slightly degrades the device performance due to hydrogen passivation, however, RIE is essential for the fabrication of low-loss active and passive ridge waveguide devices. The effect of hydrogen passivation can be reduced by applying an optimized annealing step.

4.4 InGaAs/InGaAsP MQW ridge lasers

A logical sequel to the experiments of the gain-guided devices is to increase both the lateral optical confinement and the current injection efficiency by etching a ridge waveguide. In this section, we discuss the fabrication and characterization of wet chemically etched and RIE etched ridge waveguide lasers. An Anti-Reflection (AR) coating was applied to a number of these devices in order to enable characterization as optical amplifiers. Amplifier characterization is presented in Section 4.5.

4.4.1 Fabrication

The ridge lasers were fabricated from two commercially purchased MOVPE-grown wafers that both have an InGaAs/Q(1.25) MQW active layer in the center of a 500 nm Q(1.25) film/separate-confinement layer (Fig. 4.2). The first wafer, which was also used for the fabrication of the gain-guided devices, has a quantum well thickness of 8 nm and an InP cladding thickness of 800 nm. We decreased the quantum well thickness of the second wafer to 4.5 nm in order to have the emission wavelength closer to 1550 nm, and we increased the cladding thickness to 1200 nm to minimize absorption losses in the InGaAs contact layer. Details on the layer stacks are given in Appendix A, Tables A.1 and A.3, respectively.

Wet chemically etched ridge lasers were fabricated from both wafers. From the 8 nm quantum well wafer we fabricated RIE etched ridge lasers as well. In order
to investigate possible damage due to CH$_4$/H$_2$-RIE, etching of the latter devices was performed *through* the active layer. In this way, we have created a ‘worst case scenario’ in which any negative effect of CH$_4$/H$_2$-RIE on the device performance should be revealed. For details on processing, see Section 3.4. SEM photographs of RIE etched devices and wet chemically etched devices are shown in Figs. 3.6 and 3.7c, respectively.

### 4.4.2 Measurement setup

Fig. 4.6a shows the setup that is used for measurement of the LI-curves (output power vs. current characteristics). The devices are indium-soldered on a copper mount, which is temperature controlled using a peltier element, a thermistor and a Thermo Electric Controller (TEC). All measurements are performed at a mount temperature of 20 °C unless stated otherwise. A current source provides a DC current that can be applied directly to the device using probe needles. The needle for the n-contact is positioned on the Cu-mount.

For characterization purposes, lasers are often characterized using short electrical pulses instead of a DC current. In this way, the effect of current-dependent heating of the active layer on the laser performance is minimized. The pulses should be shorter than the time that it takes the active layer to warm up substantially (t$_{pulse} < 500$ ns) and the duty cycle should be low (<1%) to ensure a low average power.

Pulsed measurements are also presented in this section. A pulsed voltage source (0V < V$_{source}$ < 50V) is available instead of a current source. In order to convert the voltage to a current, we connect the laser in series with a 50 Ω load, which is actually a digital oscilloscope with a 20 dB attenuator (Fig. 4.6b). In this way, the current can be obtained by dividing the pulse voltage as measured on the scope by 50 Ω, taking into account the attenuator which is required to reduce the pulse voltage to a value below the maximum input voltage of the oscilloscope (670 mV). Fig. 4.8 shows a typical
200 ns pulse. The oscillations and the non-zero rise and fall times are mainly caused by the non-optimized electrical circuitry. The laser current is obtained by averaging the pulse amplitude over the last 50 ns, where the pulse is reasonably flat. In order to ensure that the voltage source operates in a suitable range, we insert a 10 dB attenuator between the source and the laser. This also reduces electrical reflections due to slight impedance mismatching, which can seriously degrade the pulse quality. The pulsed output power is obtained by multiplying the measured output power by the duty cycle.

The measurement setup is computer controlled via a GPIB bus. For all instruments in the setup, and for all measurement procedures presented in this thesis, we have written LabVIEW-based routines. Modification of these modular routines is relatively simple, so any user can create his or her personal library with dedicated software.

Photographs of the measurement setup are shown in Fig. 4.7. The optics (fiber tip, microscope objective) are mounted on \((xyz)\) translation stages with piezo control, allowing for accurate in- and outcoupling of light. The position of the chip itself can be adjusted in the vertical \((x)\) and lateral \((y)\) direction. Rotation in the \((x, z)\)-plane \((\phi)\) is possible as well, enabling characterization of amplifiers that have angled facets to reduce the facet reflectivity (Chapter 5).
4. Ridge Lasers and Amplifiers

![Graph showing current vs time with peak and threshold currents marked, and a 200 ns pulse duration indicated.](image)

**Figure 4.8:** 200 ns pulse as obtained using the oscilloscope. The threshold current corresponds to the RIE etched laser with the smallest ridge width (2.5 \( \mu \text{m} \)).

### 4.4.3 Measurement results

In this section, we discuss the most important characteristics of the three types of ridge lasers that we have fabricated: devices with 8 nm quantum wells (RIE etched and wet chemically etched lasers) and devices with 4.5 nm quantum wells (wet chemically etched lasers).

**LI-curves**

Fig. 4.9 shows a number of typical LI-curves, both pulsed (200 ns, 10 kHz) and CW (Continuous Wave, i.e. operated with a DC current). For clarity, LI-curves of devices with 8 nm quantum wells are only shown for a ridge width of 2.5 \( \mu \text{m} \). Device lengths are between 1.23 and 1.30 mm.

It follows from Fig. 4.9 that the CW threshold currents are higher than the pulsed threshold currents. This is because for CW operation the temperature of the active layer increases, whereas for pulsed operation the temperature of the active layer is approximately equal to the temperature of the copper mount. The temperature dependence of the threshold current is described by the characteristic temperature \( T_0 \) (Eq. 2.14). \( T_0 \) is obtained by measuring the pulsed LI-curves for various mount temperatures (Fig. 4.10a) and fitting the extracted threshold currents to the temperature according to Eq. 2.14 (Fig. 4.10b). For example, for the wet chemically etched laser with 8 nm quantum wells and a ridge width of 4 \( \mu \text{m} \), we find that the characteristic temperature \( T_0 = 52 \text{ K} \). This value is quite low, but realistic [38]. Using Eq. 2.14, we can express the difference between pulsed threshold currents and CW threshold cur-
4.4 InGaAs/InGaAsP MQW ridge lasers

Figure 4.9: Pulsed (top) and CW (bottom) LI-curves of all three types of lasers: devices with 8 nm quantum wells (RIE etched and wet chemically etched) and devices with 4.5 nm quantum wells (wet chemically etched). The ridge widths $w_{\text{ridge}}$ are indicated in $\mu$m. For clarity, LI-curves of lasers with 8 nm quantum wells are only shown for devices with $w_{\text{ridge}} = 2.5$ $\mu$m.

The currents for this particular device (59 and 65 mA, respectively) in terms of temperature: for CW operation around 65 mA and a mount temperature of 20 $^\circ$C, the temperature increase of the active layer is approximately 5 $^\circ$C.

Fig. 4.10a reveals that kinks appear in the LI-curves at output powers around 2 mW. We believe that these kinks are caused by a change in the lateral mode distribution [38, 50, 67], because the ridge waveguides are highly multimode and the kinks are accompanied by a modification of the far-field pattern. The gain characteristics and refractive indices are temperature dependent; therefore, also the appearance of the kinks depends on the temperature.
Threshold current and current densities

In order to properly compare the three different types of lasers of which the LI-curves are shown in Fig. 4.9, we should consider devices of equal lengths and ridge widths. The lateral index contrast of the RIE etched lasers, which are etched deeply, is much higher than the lateral index contrast of the wet chemically etched lasers; these have been etched shallowly. As a result, the lateral width of the optical mode is larger for the latter devices, even after correction for the increase in ridge width due to the sloped sidewalls. A proper comparison is possible by introducing an effective device width.

We define the effective width of a ridge waveguide which is etched to an arbitrary depth (Fig. 4.11a) as the width of the deeply etched ridge waveguide fabricated in the same layer stack (Fig. 4.11b), the modal field of which has the highest overlap with the modal field of the original, arbitrarily deeply etched ridge waveguide.

The RIE etched ridge lasers are etched almost through the film, and their modal field will resemble the modal field of a deeply etched structure. So we take their effective width to be the width of the active layer, which is equal to the design ridge width increased with 0.44 μm as was observed from the SEM photographs (Section 3.4.2). For the wet chemically etched lasers, we obtained the effective width from photonic CAD simulations [119] on a junction between a deeply etched waveguide and a shallowly etched waveguide (Fig. 4.12). The waveguide layer stack is identical to the stack that was used for the lasers, except for the contact layer and the active layer, which have been omitted. For a specific value of \( w_{\text{shallow}} \), the value of \( w_{\text{deep}} \) that gives the lowest coupling loss was obtained from the simulations. This was then taken to be the effective width of a wet chemically etched laser that has a ridge width \( w_{\text{shallow}} \) at the bottom of the ridge. We found that for the concerned ridge widths, \( w_{\text{deep}} = w_{\text{shallow}} + 1.25 \mu\text{m} \).
4.4 InGaAs/InGaAsP MQW ridge lasers

**Figure 4.11:** Concept of effective width.

Fig. 4.13 shows the pulsed threshold current $I_{th}$ and the pulsed threshold current density $J_{th}$ as a function of the effective device width. The threshold current density $J_{th}$ is given by $J_{th} = I_{th} / (w_{eff} L)$, where $w_{eff}$ is the effective width and $L$ is the device length. Results for CW operation are similar. All data points fall on a single curve, so we observe that the concept of effective width is valid, and that the three different types of lasers have a comparable performance. The threshold current decreases with the ridge width (Fig. 4.13a), so it would be advantageous to make the ridge width as small as possible. However, in that case the device also becomes less efficient, as is observed from the increasing threshold current density (Fig. 4.13b).

**Figure 4.12:** The effective width of a RIE etched laser is equal to the width of the active layer; the effective width of a wet chemically etched laser is obtained from photonic CAD simulations on a junction between a deeply etched waveguide and a shallowly etched waveguide.

In Fig. 4.13a we see that the threshold current of the wet chemically etched lasers depends linearly on the effective width. Extrapolating to an effective width of zero microns, we find that $I_{th}$ ($w_{eff} = 0 \mu m$) = 12.4 mA. This current is identified as the lateral leakage current $I_{lat}$, which is the current that can escape from the region underneath the ridge due to the lack of current confinement below the InP cladding.
The lateral leakage current does not contribute to laser operation, and is essentially lost. It does, however, contribute to the threshold current, and causes a minor increase in $J_{th}$ as $w_{eff}$ decreases. We expect that the contribution of the lateral leakage current to the threshold current density becomes more pronounced for smaller ridge widths ($J_{th} \to \infty$ as $w_{eff} \to 0$), however, no data is available for wet chemically etched lasers with $w_{eff} < 6 \ \mu m$. From the linear relation between $w_{eff}$ and $I_{th}$ we observe that $I_{lat}$ depends only weakly on the ridge width for the ridge widths of concern. This is in agreement with Letal et al. [120], who also reported a similar value for $I_{lat}$ for devices with a length of 250 $\mu m$. We expect the lateral leakage current to be linearly dependent on the device length, hence the value in [120] seems rather high. This is probably caused by the smaller etch depth in that case, resulting in a worse current confinement and consequently in a higher $I_{lat}$.

For the RIE etched lasers, the threshold current density increases as the ridge width decreases, but this is not caused by lateral leakage currents. The etching has been performed through the active layer, and therefore the carriers cannot escape laterally from the ridge: $I_{lat} = 0$ mA. It is most likely that the increase in $J_{th}$ for decreasing $w_{eff}$ is caused by surface recombination at the ridge sidewalls. The sidewalls are a strong perturbation of the semiconductor lattice, with many dangling bonds that can act as non-radiative recombination centers. The surface recombination rate may be further increased due to possible RIE damage, in spite of the wet chemical cleaning steps.

In Fig. 4.13a, the data points of the RIE etched lasers deviate from the linear fit for ridge widths below 5 $\mu m$, so the surface recombination cannot be accounted for by a width-independent current. This is explained as follows. The surface recombination
reduces the carrier density at the ridge sidewalls, and creates regions of low gain (or even loss) on both sides of the ridge [121]. The confinement of these low-gain regions becomes higher as the ridge width decreases, and a higher material gain, i.e. a higher carrier density is required in the center of the ridge to achieve threshold. The increased carrier density is accompanied by increased Auger and surface recombination rates, and by a higher device temperature. As a consequence, the threshold current density increases rapidly with decreasing ridge width. It is very well possible that the threshold current increases if one reduces the ridge width below 3 μm.

In Fig. 4.13, comparison of laser threshold currents is only possible for effective ridge widths larger than 6 μm, since wet chemically etched devices with smaller ridge widths are not available. When the ridge widths are large, the effect of the fabrication technology on the device performance is small, and the performance of RIE etched lasers and wet chemically etched lasers approaches the performance of a broad-area laser. Such a device, with a similar epitaxial layer stack as applied for the devices presented here, also has a similar threshold current density (0.5 kA/cm² [71], compare Fig. 4.13b). For a comparable 2 μm wide RIE etched ridge laser with a length of 1 mm, \( J_{\text{th}} \approx 1.25 \text{ kA/cm}^2 \) [112], which is somewhat better than what can be expected from Fig. 4.13b. However, in that case, RIE etching was not performed through the active layer. This indicates that the rapid increase in \( J_{\text{th}} \) for decreasing \( w_{\text{eff}} \) for the RIE etched lasers is indeed caused by surface recombination, and may be reduced by stopping the RIE etch above the active layer [121]. Note that in this case the lateral leakage current may result in a slight increase in \( J_{\text{th}} \) after all, especially for small ridge widths. From the comparison of experimental results with results reported in literature we conclude that the quality of the epitaxial layer stacks and the quality of the device structures are satisfactory.

Differential efficiency

For a further comparison of the three types of lasers, i.e. wet chemically etched and RIE etched lasers with 8 nm quantum wells and wet chemically etched lasers with 4.5 nm quantum wells, we consider the differential efficiency \( \eta_d \) which is obtained from the slope of the LI-curve above threshold.

Theoretically, the differential efficiency as measured under CW operation (\( \eta_{d, \text{CW}} \)) is lower than as measured under pulsed operation (\( \eta_{d, \text{pulsed}} \)). This is because heating of the active layer does not only increase the threshold current, but it also reduces the slope of the LI-curves (Fig. 4.10a), resulting in a decrease of \( \eta_{d, \text{CW}} \). However, from the measurements we observe the opposite: \( \eta_{d, \text{pulsed}} < \eta_{d, \text{CW}} \). For example for the wet chemically etched device with 8 nm quantum wells and a top ridge width of 2.5 μm, \( \eta_{d, \text{pulsed}} \) and \( \eta_{d, \text{CW}} \) are 9.2 % and 10.6 % per facet, respectively. The loss of the optics is not accounted for in these numbers. The fact that \( \eta_{d, \text{pulsed}} \) is smaller than \( \eta_{d, \text{CW}} \) must be an erroneous observation, and is explained by examination of the shape of the electrical pulse. As was already observed in Section 4.4.2, the pulse has non-zero rise and fall times, and shows some oscillations. We can estimate the average
measured laser power as:

\[ P_{\text{out}} = \frac{1}{t_{\text{pulse}}} \frac{hc}{\lambda} \int_{t_{\text{pulse}}} \eta_{\text{d, pulsed}} \cdot (I_{\text{pulse}} - I_{\text{th}}) \cdot H(I_{\text{pulse}} - I_{\text{th}}) \, dt \quad (4.2) \]

where \( H \) is the Heaviside step function: \( H(x) = 0 \) for \( x < 0 \), \( H(x) = 1 \) for \( x \geq 0 \), and \( t_{\text{pulse}} \) is the pulse time as set by the operator. In this equation, \( \eta_{\text{d, pulsed}} \) is the real efficiency of the device, not the erroneous measured efficiency. Using Eq. 4.2, we find that for the pulse shape and threshold current depicted in Fig. 4.8, the laser output power is reduced by 87\% as compared to the case of a perfectly rectangular pulse. As a consequence, the measured differential efficiency is reduced by the same amount. For reliable measurement of \( \eta_{\text{d, pulsed}} \) a rather thorough modification of the measurement setup is required. Nevertheless, since the same systematic error is made for all pulsed measurements (equal pulse width, comparable pulse quality), comparison of \( \eta_{\text{d, pulsed}} \) of the different types of lasers is allowed.

The difference between \( \eta_{\text{d, pulsed}} \) and \( \eta_{\text{d, CW}} \) depends on the type of device. We find from Fig. 4.9 that \( \eta_{\text{d, CW}} \) of the wet chemically etched lasers with 8 nm quantum wells is 15 \% higher than \( \eta_{\text{d, pulsed}} \) (10.6 \% and 9.2 \% per facet, respectively). For the RIE etched lasers, the difference is only 4 \% (9.8 \% and 9.4 \%, respectively). In order to explain this, we consider the CW IV-curves (Fig. 4.14). The IV-curves of the wet chemically etched lasers with 4.5 nm and 8 nm quantum wells are similar, however, the IV-curve of the RIE etched laser has a lower slope \( dI/dV \). This lower slope represents a higher series resistance of the RIE etched laser, which is most likely caused by hydrogen passivation during CH₃/H₂-RIE. The values that we find from the slopes in Fig. 4.14 as an upper limit for the series resistances are 3.5 \( \Omega \) for the wet chemically etched laser and 6 \( \Omega \) for the RIE etched laser.

We also observe that the IV-curve of this device has its ‘knee’ at a higher voltage than that of the wet chemically etched lasers. So it appears that the contact resistance of the RIE etched laser is not ohmic; the reason for this is not clear. At an injection current of 100 mA, the voltage drop over the RIE etched laser is 0.86 V higher than the voltage drop over the wet chemically etched lasers, corresponding to 86 mW of extra dissipated power. Therefore, heating of the active layer is most pronounced in the RIE etched lasers, and consequently the CW differential efficiency of these devices is relatively low. The active layer heating in these devices may also play a role in the non-linearly increasing threshold current density for small ridge widths.

The differential efficiencies of lasers with 4.5 nm quantum wells are almost 30 \% higher than those of lasers with 8 nm quantum wells. The reason for this is two-fold. In the first place, the lasers with the 8 nm quantum wells have a thinner InP cladding. The tail of the optical mode still ‘feels’ the highly absorbing contact layer and metallization stack, resulting in a higher loss, and consequently in a lower efficiency \( \eta_{\text{d}} \) (Eq. 2.21). Secondly, the active layer loss is higher for the devices with 8 nm quantum wells because of their higher confinement factor (\( \Gamma = 0.068 \), as opposed to \( \Gamma = 0.039 \)). Note that also the value of \( \eta_{\text{i}} \) may depend on the quantum well width.
4.4 InGaAs/InGaAsP MQW ridge lasers

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{fig4_14.png}
\caption{CW IV-curves of lasers with an effective width of 10 \textmu m.}
\end{figure}

Spectra

Fig. 4.15 shows some typical output spectra of all three types of lasers. The emission wavelengths of the wet chemically etched lasers and the RIE etched lasers with 8 nm quantum wells are slightly different, even though these were fabricated from the same wafer. This is caused by a variation of the quantum well thickness due to the non-uniformity of the wafer. Devices were fabricated from samples opposite to the large flat and the small flat, respectively.

The target emission wavelength of all devices is 1550 nm. As the emission wavelength of the lasers fabricated in the first wafer with 8 nm quantum wells was too long, we reduced the quantum well thickness to 4.5 nm for the second wafer, in consultation with the wafer supplier. The emission wavelength of extended cavity lasers fabricated from this second wafer is around 1555 nm (Chapter 5), practically at the target wavelength. Thus, the identical MQW active layer stack was also chosen for a third wafer, in which the lasers with 4.5 nm quantum wells in Fig. 4.15 were fabricated. These devices emit around 1535 nm. This clearly indicates that the emission wavelength of lasers which are fabricated from MOVPE-grown wafers is currently not reproducible. It should be emphasized that this is not an issue of growth technology, but merely of growth calibration. We order only one wafer at a time, and extensive calibration is omitted to reduce the cost.

Due to the long cavities (> 1 mm), the longitudinal mode spacing $\Delta \lambda$ is quite small (< 0.3 nm), and a large number of modes are lasing simultaneously. From Eq. 2.24, a group index $n_g = 3.7$ is found, which is in good agreement with values reported in literature [66].
4.4.4 Conclusions

We have fabricated and characterized wet chemically etched ridge lasers and RIE etched ridge lasers. Comparing devices with equal effective widths, we see that both types of devices perform equally well, and that their performance is comparable to results reported in literature. Therefore, we conclude that our fabrication technology is good, and that this also holds for the quality of both the device structures and the epitaxial layer stacks.

We observed that the threshold current density increases for small ridge widths, either due to the lateral leakage currents (wet chemically etched lasers) or due to surface recombination (RIE etched lasers). In our experiments, we performed the RIE-etching through the active layer in order to investigate a ‘worst case scenario’ regarding surface recombination, and still obtained a good laser performance.

If RIE etched optical amplifiers and passive waveguide devices are integrated, all devices can be etched in the same RIE step. This facilitates the fabrication of photonic integrated circuits to a large extent, while no concessions are being made with respect to device performance. Therefore, we conclude that RIE etched optical amplifiers are the most suitable ones for integration with passive waveguide devices.

4.5 InGaAs/InGaAsP MQW ridge amplifiers

All devices that we have discussed so far were characterized as lasers instead of amplifiers. Characterization as a laser is relatively easy, as one does not need to apply an Anti-Reflection (AR) coating, and incoupling of an optical probe source is avoided.
However, for flexible application in WDM photonic integrated circuits, we need to integrate optical amplifiers instead of lasers. We want to explore possible difficulties that may arise during amplifier characterization, and we want to gain further insight in the performance of the devices presented in the previous section. Therefore, we applied an AR-coating to a number of wet chemically etched lasers, and characterized these devices as optical amplifiers. Results are presented in this section.

### 4.5.1 Experimental setup

Wet chemically etched lasers with a quantum well thickness of 8 nm and a length of 1.13 mm were AR-coated by the Optics Research Group, Department of Applied Physics, Delft University of Technology. A device with a top ridge width of 3 μm \( (w_{\text{eff}} = 6.6 \, \mu \text{m}) \) was characterized as an optical amplifier using the measurement setup shown in Fig. 4.16. A modulated (≈ 1 kHz) probe signal from a Tunable Laser Source (TLS) was launched into the amplifier using microscope objectives, a polarization controller (PC) and a polarizer. The polarization state was set to TE. We measured the signal power which has passed through the amplifier using a photodiode, a current amplifier and a lock-in amplifier. In this way, the spontaneous emission of the amplifier was rejected. The wavelength of maximum gain corresponds to the emission wavelength of lasers fabricated from this wafer (1580 nm). Unfortunately, the longest wavelength available from the TLS is only 1565 nm. At this wavelength, the signal is rather noisy, therefore, we performed the measurements at 1560 nm.

### 4.5.2 Results

At various amplifier currents, we measured the detector current while sweeping the output power of the TLS from 10 to 400 μW. We obtain the total gain including the coupling losses of the measurement setup by comparing the results to measurements that we had performed without the chip. Figure 4.17 shows the obtained value as a function of the natural logarithm of the current density. The data points are well fitted by a straight line:

\[
G \, [\text{dB}] = -2.6 + 27.9 \cdot \ln(J \, [\text{kA/cm}^2]) \tag{4.3}
\]
Figure 4.17: Gain of a wet chemically etched optical amplifier, length 1.13 mm, top ridge width 3 \( \mu \)m, 8 nm quantum wells. Data is with respect to measurements that were performed with the amplifier removed from the setup in Fig. 4.16, where the microscope objectives are realigned to maximize the measured power.

which is in agreement with the fact that the material gain \( g \) depends logarithmically on the current density \( J \) [71–74]:

\[
g_{\text{mat}} = \beta_{\text{mat}} J_0,\text{mat} \ln \left( \frac{J}{J_0,\text{mat}} \right)
\]  

(4.4)

It follows from straightforward mathematics that this logarithmic dependence also holds for the modal gain \( G_{\text{mode}} \), which is expressed in \( \text{cm}^{-1} \), and consequently also for the amplifier gain \( G \) in Eq. 4.3, which is expressed in dB (see also Eq. 2.5):

\[
G_{\text{mode}} \left[ \text{cm}^{-1} \right] = \Gamma g - \alpha_{\text{act}} = \beta J_0 \ln \left( \frac{J}{J_0} \right)
\]  

(4.5)

\[
G \left[ \text{dB} \right] = 10 \cdot \log (e) \cdot G_{\text{mode}} \cdot L
\]  

(4.6)

In these equations, \( G_{\text{mode}} \) is the modal gain, \( \Gamma \) is the confinement factor, \( \alpha \) represents the losses of the active layer and \( L \) is the amplifier length. Eq. 4.5 satisfies:

\[
G_{\text{mode}} \big|_{J=J_0} = 0,
\]  

and:

\[
\left. \frac{d (G_{\text{mode}})}{dJ} \right|_{J=J_0} = \beta
\]  

(4.7)

so we identify \( J_0 \) as the transparency current density, and \( \beta \) as the differential gain at \( J = J_0 \).

In order to estimate the values of \( \beta \) and \( J_0 \) from the measurements, we should subtract the coupling losses from the data in Fig. 4.17 to obtain the on-chip gain at the signal wavelength of 1560 nm. These coupling losses cannot be measured separately,
however, we can estimate the on-chip gain at the wavelength of maximum gain in the following way.

From the measurements on the ridge lasers, we know that the CW threshold current density $J_{th}$ of a similar device without coating is 0.715 kA/cm$^2$ ($I_{th}$=59 mA). The emission wavelength of such a device is 1580 nm. At this current density, the on-chip gain at $\lambda = 1580$ nm is equal to the mirror loss of 4.7 dB. Inserting $J = 0.715$ kA/cm$^2$ into Eq. 4.3, we find that the on-chip gain at $\lambda = 1580$ nm is 16.67 dB higher than as described by the fit Eq. 4.3. The difference is explained by the coupling losses and by the fact that the gain at $\lambda = 1560$ nm is a few dB lower than the gain at $\lambda = 1580$ nm. So we have at the wavelength of maximum gain:

$$ G \ [\text{dB}] \ = \ 14.06 + 27.9 \cdot \ln(J \ [\text{kA/cm}^2]), \quad \text{or} \quad (4.8) $$

$$ G_{mode}\ [\text{cm}^{-1}] \ = \ 28.65 + 56.9 \ln(J[kA/cm^2]) = 56.9 \ln(J/0.604) \quad (4.9) $$

Comparing Eqs. 4.5 and 4.9, we find that $J_0 = 0.60$ kA/cm$^2$, $\beta = 94$ cm/kA and $\beta J_0 = 57$ cm$^{-1}$. We will compare these numbers with results on extended cavity lasers in Section 5.4.

From Eq. 4.9 we can calculate the laser length that results in the lowest threshold current. At threshold, we have:

$$ e^{G_{mode}L} = 1/R \quad (4.10) $$

Inserting Eq. 4.5 into Eq. 4.10 and using $I = w_{eff}LJ$, we find that we can optimize the device length such that the threshold current is minimized:

$$ L_{opt} = \frac{\ln(1/R)}{\beta J_0}, \quad I_{th} (L) = I_0 e^{L_{opt}/L} \quad (4.11) $$

with $I_0 = w_{eff}LJ_0$. Inserting the values for $\beta$ and $J_0$, we find that we can reduce the threshold current to 20.6 mA at a device length $L_{opt} = 190 \mu m$. This length is even shorter than the substrate thickness of 350 $\mu m$. We cannot cleave such short devices in our laboratory, however, these results clearly indicate that it would be advantageous to thin the substrate in order to reduce the minimum cleavable device length. Furthermore, short devices have a higher distributed mirror loss, and consequently a higher differential efficiency (Eq. 2.21). An additional advantage of thinned substrates is an improved heat transfer to the heat sink.

Note that at a wavelength of 1580 nm and a current of 100 mA ($J = 1.34$ kA/cm$^2$), the gain is around 22 dB. We estimate that the coupling loss is 6.5 dB/facet, and that consequently the gain at $\lambda = 1560$ nm is 3.67 dB lower than the gain at $\lambda = 1580$ nm to account for the 16.67 dB difference between Eq. 4.3 and Eq. 4.8. So a probe power of 400 $\mu W$ (-4 dBm) at $\lambda = 1560$ nm implies an output power of $-4 - 6.5 + (22 - 3.67) \approx 8$ dBm. The measured gain did not depend on the input power, so this amplifier has a high saturation output power of over 8 dBm.

In spite of the AR-coating, this particular amplifier started lasing at a current of 167 mA, or $J = 2.24$ kA/cm$^2$. Assuming that the curve fit in Fig. 4.17 still holds
for such high current densities, we find that the residual reflection coefficient is 0.015, which is rather high.

4.5.3 Conclusions

We applied an AR-coating to a wet chemically etched ridge waveguide laser, and characterized this device as an optical amplifier. The residual reflections of the AR-coated facets are quite large (1.5%) and the device operates as a laser at high injection currents. The mismatch between the available probe signal wavelength and the amplifier gain spectrum complicates the characterization.

As expected, we obtained a logarithmic dependence of the on-chip gain on the current density. At an injection current of 100 mA, the on-chip gain is approximately 22 dB, and the corresponding saturation output power is larger than 8 dBm.

We found that the performance of the ridge lasers discussed in the previous section can be greatly improved by using shorter devices. Substrate thinning is required in order to reduce the minimum device length that can be cleaved from a substrate. An additional advantage of substrate thinning is the improved heat transfer from the laser to the heatsink.

4.6 InGaAs/InP MQW laser structures

The ridge lasers and amplifiers described in the previous sections were fabricated from commercially purchased MOVPE-grown wafers. As was already pointed out in Chapter 3, the technology of choice for the integration of active and passive devices in this thesis is Selective Area Chemical Beam Epitaxy (SA-CBE). Full integration flexibility requires that SA-CBE regrowth of the active layer is possible. In this section, we present the fabrication and characterization of CBE-grown laser structures.

4.6.1 Fabrication

At the time of the experiments described in this section, CBE-growth of InP and InGaAs was available, however, CBE-growth of the complete quaternary InGaAsP-material was still under development. Thus, it was not possible to use Q(1.25) material for the film/separate-confinement layers and for the Multi Quantum Well (MQW) barriers, and the use of a Q(1.55) bulk active layer was ruled out as well. Alternatively, we used InGaAs/InP MQWs for both the film (well/barrier width = 1.85/2.55 nm, 120 periods in total) and the active layer (well/barrier width = 9.15/9.5 nm, 5 periods). Due to the different well and barrier widths, the film is transparent at the absorption edge of the active layer (λ ≈ 1.55 μm). Fig. 4.18a shows the resulting layer stack; details are given in Appendix B, Table B.1. Device fabrication was as reported for the wet chemically etched ridge lasers.
4.6 InGaAs/InP MQW laser structures

Figure 4.18: InGaAs/InP MQW layer stacks with active layer in the center (a) or on top (b) of the film.

Figure 4.19: ASE spectra of laser structures with an InGaAs/InP MQW active layer in the center or on top of an InGaAs/InP MQW film layer. Current density $J = 0.7 \text{ kA/cm}^2$.

At this point, it is convenient to discuss one of the SA-CBE experiments that will be presented in Chapter 5. In this particular experiment, we applied the identical InGaAs/InP MQWs as mentioned above to fabricate integrated optical amplifiers. The active layer was epitaxially grown in an SA-CBE regrowth step on top of the film (Fig. 4.18b). For details, see Chapter 5 and Appendix B, Tables B.2 through B.5 and Appendix A, Table A.4. After fabrication, a number of RIE etched integrated optical amplifiers were cleaved off the chip in such a way that they did not have any passive sections. These devices were characterized as stand-alone SA-CBE-grown lasers.
4.6.2 Measurement results

The InGaAs/InP MQW devices did not operate as lasers. Typical spontaneous emission spectra for both types of devices are shown in Fig. 4.19 at a current density of 0.7 kA/cm². We did not observe any gain ripple.

The performance of these devices is explained by the large bandgap difference between the InGaAs wells and the InP barriers. This is illustrated in Fig. 4.20, which shows the energy levels in the quantum wells of the film/separate-confinement layer, i.e. the energy levels in the 1.85 nm InGaAs quantum wells with 2.55 nm InP barriers. The energy levels were estimated using Eq. 2.42 and are shown as a function of the barrier width, so we can establish the amount of coupling between the wells at a barrier width of 2.55 nm, which is the barrier width in the actual devices.

In Fig. 4.20a we see that, at a barrier width of 2.55 nm, the ground state energy level of an electron in the conduction band of the film/separate-confinement MQW is significantly reduced with respect to the conduction band energy level of an identical quantum well with infinitely thick InP barriers. So the electron wave functions of two neighboring quantum wells are coupled. As a result, the escape energy of an electron, i.e. the energy that an electron requires to escape from the quantum well, is increased to approximately $3kT$ as opposed to $kT$ for an uncoupled well. This would imply that, due to the coupling, it is more difficult for an electron to travel through the MQW. On the other hand, electron transport is facilitated by the fact that electrons can
tunnel through the barriers. We believe that electron transport is this MQW structure is satisfactory, and does not seriously affect the performance of the InGaAs/InP devices in a negative way.

For the light holes in the valence band, the situation is similar (Fig. 4.20b); the light hole escape energy is approximately $3kT$ and tunneling of light holes through the barriers is possible. So transport of light holes is comparable to transport of electrons.

The escape energy of the heavy holes, on the other hand, is approximately $7kT$ (Fig. 4.20b), and the coupling of the heavy-hole wave functions of neighboring quantum wells is negligible. As a result, the heavy holes are effectively trapped in the film quantum wells, and hardly contribute to charge transportation. So transport of holes should be mainly by means of light holes. However, if the light hole states are occupied, the heavy hole states must be occupied as well, and therefore the carrier density must be high. Consequently, charge transportation by light holes is accompanied by a high non-radiative recombination rate. Carrier transport through the active layer is even more difficult; for electrons, heavy holes and light holes, the quantum well wave functions in the active layer are uncoupled, and the escape energies are as high as $7kT$, $13kT$ and $11kT$, respectively.

The consequences of these observations on the device performance are rather severe. For the devices with the active layer on top, the holes are effectively captured in the first quantum well that they encounter, i.e. the quantum well of the active layer that is on top (on the p-side) of the device. The holes are practically unable to cross the 9.5 nm InP barriers in the active layer, and the hole concentration in the other four (n-side) active-layer quantum wells is low. The electrons injected from the n-side are able to travel through the film and reach the upper active layer quantum well, attracted by the positively charged holes. Thus, recombination mainly takes place in this upper active-layer quantum well, where both the hole concentration and the electron concentration are high, and we observe a spontaneous emission peak at 1590 nm (Fig. 4.19). The hole concentration in the four n-side active layer quantum wells is low, and consequently these quantum wells are highly absorbing. The net gain of the active layer stack is therefore low\(^3\), and the device will never work as a laser.

The situation for the devices with the active layer in the center is even worse. Also in this case we may have gain in the upper active layer quantum well, whereas the other four quantum wells are absorbing. In addition to this, the holes that recombine in the active layer have travelled through the upper part of the film, and therefore these holes are mainly light holes. This means that the heavy-hole states in the film quantum wells must be occupied, and that the hole density in the upper part of the film is high. A substantial fraction of the holes already recombines in the upper part of the film with electrons that have crossed the active layer, attracted by the high density of positively charged holes. Radiative recombination in the film causes the peak around 1390 nm (Fig. 4.19). We believe that, because of the high hole concentration, the non-radiative recombination rate in the upper part of the film is substantial. The carriers

---

\(^3\)The net gain is probably even be lower than zero, and we have loss instead of gain.
that recombine in the film do not contribute to gain of the active layer, and are lost.

4.6.3 Discussion

From the results obtained in the previous paragraph, it appears that the realization of lasers emitting around 1.55 \( \mu \text{m} \) using only InGaAs/InP MQWs is impossible. However, such a laser has been demonstrated by Tsang [122]. He fabricated CBE-grown lasers consisting of 4 to 8 InGaAs wells with a thickness between 7 and 15 nm. The InP barriers were 15 nm thick. He reported threshold current densities of broad area lasers down to 1 kA/cm\(^2\) for pulsed operation at a heat sink temperature around 20 °C. So these threshold current densities are two times higher than the ones of our InGaAs/Q(1.25) MQW lasers from Section 4.4 which have a non-optimized length. So considering the threshold current densities, the performance of these InGaAs/InP MQW lasers is much worse than the performance of our InGaAs/Q(1.25) MQW lasers.

Another InGaAs/InP MQW laser was reported by Ginty et al. [123]. In this device, not only the film/separate-confinement layers, but also the barriers that separate the 10 nm active InGaAs wells consist of 1.5 nm/1.5 nm InGaAs/InP MQWs. For such small well widths and barrier widths, coupling between the quantum wells facilitates carrier transport, and laser operation is enabled. In fact, the coupling becomes so strong that the emission wavelength of this particular device is 1.64 \( \mu \text{m} \) (threshold current density 1.9 kA/cm\(^2\)), close to the emission wavelength of bulk InGaAs. In other words, the InGaAs/InP MQW barriers between the 10 nm active InGaAs wells are virtually not there, and this is not a true MQW laser.

It should be noted that when a coupled InGaAs/InP quantum well stack is used as a barrier, the effective bandgap of such a barrier critically depends on the well width and barrier width of this coupled quantum well stack (Fig. 2.15). So the latter two parameters will also strongly affect the emission wavelength of the laser. Considering the fact that a 1.5 nm quantum well is only 5 monolayers thick (neglecting any interface layers), design and fabrication of MQW active layers with MQW barriers is quite difficult if the emission wavelength of the laser is specified in advance.

4.6.4 Conclusion

We have fabricated and characterized CBE-grown InGaAs/InP MQW structures that were intended for application as lasers. However, laser operation was not observed, and the gain of the MQW active layers is insufficient. We deduced that this is caused by insufficient carrier transport due to the large bandgap difference between the quantum wells and the barriers. This holds especially for the holes, in agreement with [76, 77]. Therefore, either an InGaAs/InGaAsP MQW or a bulk InGaAsP active layer should be used for the successful realization of lasers and optical amplifiers operating at a wavelength of 1.55 \( \mu \text{m} \). Alternatively, very thin wells and barriers enable proper carrier transport, however, design and fabrication of such layer stacks is quite difficult.
4.7 Pics3D simulations

In the previous section, we posited that hole transportation in an InGaAs/InP MQW is difficult because of the large bandgap difference between the quantum wells and the barriers. In order to verify this, we performed a number of simulations using the commercial laser simulator Pics3D (Photonic Integrated Circuit Simulator in 3D). Simulation tools for lasers and optical amplifiers can provide important information, as the simulations are able to provide data that is hard, or even impossible to obtain experimentally. Pics3D is based on physical models, and self-consistently combines a two-dimensional device simulator and a longitudinal mode solver. The user has to provide the proper device structure, as well as material parameters in case these are believed to deviate from the default settings. Excellent agreement of Pics3D simulation results with experimental data has been reported for broad-area lasers [124].

We performed simulations on ridge laser structures that are similar to the 8 nm quantum well devices presented in Section 4.4. Fig. 4.21a shows the band diagram of these structures. The MQW active layer consists of five 8 nm InGaAs quantum wells separated by 10 nm Q(x) barriers, where x is the absorption edge wavelength of 1.30, 1.25 or 1.15 μm. The MQW is sandwiched between two 250 nm film/separate-confinement layers that have the same material composition as the barriers. In the limiting case where x → 0.92 μm, the barriers and the film/separate-confinement layers consist of InP. This situation is depicted in Fig. 4.21b, and was also simulated. Finally, we simulated this InGaAs/InP MQW with a Q(1.30) film (Fig. 4.21c). In this case, we chose Q(1.30) for the low-bandgap film as a trade-off between the wavelength of the film recombination peaks in Fig. 4.19 on the one hand, and the material compositions applied in the other simulations and in the fabricated devices on the other hand. Simulation of an InGaAs/InP MQW film as applied in Section 4.6 would require impractically long calculation times, because in this case the number of grid points should be increased by a factor of 20. Apart from the replacement of the InGaAs/InP MQW film by a Q(1.30) film, the structure in Fig. 4.21c corresponds to the device with the active layer in the center which is described in the previous section (see also Appendix B, Table B.1). Length and width of the simulated structures are 400 μm and 4 μm, respectively.

For each simulated structure, Fig. 4.22 shows the material gain in each quantum well at the longitudinal edge and the lateral center of the device at a current density of 3 kA/cm^2. For the simulations with Q(x) film and barriers, this is well above threshold (∼ 0.4 kA/cm^2 for all three cases). The simulations with InP barriers did not show laser operation.

It is clear from Fig. 4.22 that the material gain is non-uniform throughout the quantum well stack; the p-side quantum wells have the highest gain. This non-uniformity becomes stronger as the barrier bandgap increases. This is consistent with the assumption in Section 4.6 that if the bandgap energy of the barrier material is high, it is difficult for the holes to travel from one quantum well to the other. The hole concentration in the n-side quantum wells decreases for increasing barrier bandgap energy,
4. Ridge Lasers and Amplifiers

Figure 4.21: Band diagrams of quantum well structures as simulated using Pico3D: a) InGaAs/Q(x) MQW in the center of a Q(x) film/separate confinement layer, where $x = 1.30$, $1.25$ or $1.15$. b) InGaAs/InP MQW, no film. c) InGaAs/InP MQW in the center of a Q(1.30) film.

Figure 4.22: Local gain in the quantum well structures of Fig. ???. All graphs correspond to a current density $J = 3 \text{kA/cm}^2$, the p-side is on the right.
4.8 Conclusions

and the gain decreases as well. For the InGaAs/InP MQWs, only the p-side quantum well has a (low) positive material gain. In the simulation with the InGaAs/InP MQW in the center of the Q(1.30) film layer, the holes have to overcome an InP barrier before they reach the first quantum well on the p-side. As a result, even this quantum well has an extremely low gain. Note that for the device with Q(1.15) barriers, it is advantageous to omit the three quantum wells on the n-side. Indeed, simulation of this layer stack with only two quantum wells showed a decrease of the threshold current and an increase of the differential efficiency, both by approximately 7%. Thus, the number of quantum wells that provides the lowest threshold current depends on the material composition of the barriers and wells.

4.8 Conclusions

In this chapter, we presented the fabrication and characterization of non-integrated active devices. From measurements of gain-guided devices we conclude that CHF₃ Reactive Ion Etching (RIE) of SiNx slightly degrades the device performance due to hydrogen passivation of Zn-acceptors. This is even more pronounced in CH₄/H₂-RIE etched ridge lasers, which have a higher series resistance than wet chemically etched ridge lasers. The performance of both wet chemically etched ridge lasers and RIE etched ridge lasers is good, and comparable to results reported in literature. We should be able to improve their performance by cleaving shorter samples. However, this requires thinning of the substrate, which is currently not a reliable process in our laboratory. We observe that the threshold current density increases for small ridge widths, either due to lateral leakage currents (wet chemically etched lasers) or due to surface recombination (RIE etched lasers).

By integrating RIE etched optical amplifiers and RIE etched passive waveguide devices, all devices can be etched in the same RIE step. This facilitates the fabrication of photonic integrated circuits to a large extent. This in contrast to integration of wet chemically etched amplifiers, which requires a two-step etching process. Furthermore, RIE etched amplifiers provide a higher design flexibility, since smaller lateral dimensions are achievable, and the etch depth can easily be adjusted. Therefore, we select RIE etched optical amplifiers as the most suitable devices for integration with passive waveguide devices. The performance of these amplifiers can be improved by reducing the etch depth such that the active layer itself is not etched. In this way, the surface recombination rate is reduced. Optimization of the annealing process may result in a reduction of the effect of hydrogen passivation.

From measurements and simulations, we found that using InGaAs/InP Multi Quantum Well active layers for the realization of CBE-grown integrated optical amplifiers is not possible. Carrier transport is severely hampered by the high bandgap energy of the barrier material in this case. Therefore, we will perform the integration experiments using MOVPE-grown InGaAs/InGaAsP Multi Quantum Well active layers.
Chapter 5

Integrated optical amplifiers

In this chapter, we present experiments on the integration of optical amplifiers and passive waveguide devices using a Selective Area Chemical Beam Epitaxy regrowth step. As an important application, we report on the fabrication and characterization of several phased array multi-wavelength lasers.

5.1 Introduction

The RIE etched ridge optical amplifier presented in the previous chapter is suitable for integration with passive waveguide devices. The integration is carried out by defining active and passive regions on a single chip using a Selective Area Chemical Beam Epitaxy (SA-CBE) regrowth step. Active and passive devices are subsequently fabricated in their appropriate regions.

The simplest device that consists of active and passive sections is an optical amplifier that has a passive waveguide on (at least) one end. If one does not take any anti-reflection measures, such a device will operate as an extended cavity laser (ECL) if the amplifier gain is sufficient to overcome all the losses, i.e. the mirror losses, the butt joint coupling losses and the passive waveguide losses. Characterization of a number of ECLs with various active section lengths will be presented. These devices have passive waveguides on both ends.

Using the same fabrication technology, one can integrate a phased array optical (de-) multiplexer as well. Incorporation of a phased array allows for, amongst other things, the realization of multi-wavelength lasers. A phased array multi-wavelength laser can simultaneously generate a number of accurately spaced wavelengths, and is a very attractive source for WDM applications. We briefly discuss the operation principle of a phased array multi-wavelength laser, and present a number of 4-channel devices and 8-channel devices.
5.2 Design of integrated optical amplifiers

In this section we address a few design issues of integrated optical amplifiers, and we present the layout of the contact lithography mask set.

5.2.1 Device structure and dimensions

The device structure of the integrated optical amplifier is similar to that of the RIE etched ridge laser that was presented in Chapter 4 (Fig. 4.1c). It is fabricated on a wafer in which active and passive regions have been defined by Selective Area Chemical Beam Epitaxy. A cross section and a top view of an integrated optical amplifier are shown in Figs. 5.1a and 5.1b, respectively.

As pointed out in Section 3.4.4, the ridge width and the contact opening width of the RIE etched ridge laser/amplifier should be larger than 3 $\mu$m and 2 $\mu$m, respectively. Using these values, the alignment tolerance is only 1 $\mu$m. To be on the safe side, we increased the alignment tolerance to 2 $\mu$m or more by using a ridge width of 4, 6 or 8 $\mu$m with a contact opening width of 2, 3 or 4 $\mu$m, respectively.

The width of the passive waveguides must be larger than 2 $\mu$m to allow for the reproducible fabrication of low-loss waveguides. On the other hand, the waveguide width should not be too large, as a wide waveguide supports many lateral modes. We used a waveguide width of 3 $\mu$m to anticipate a possible width reduction due to wet chemical cleaning steps.

The ridges of the amplifier and the ridges of the access waveguides are connected by means of linear tapers which have a length of 100 $\mu$m. After definition of the ridges, the active region is completely covered by a SiNx passivation layer and by a polyimide planarization layer, which both extend 50 $\mu$m into the passive region\(^1\). The contact openings in these layers are located on top of the amplifier ridge, and are 2x2.5 $\mu$m shorter than the amplifier length. In this way, current injection is restricted to the active region, while the amplifier will be electrically pumped over its entire length due to the highly conducting p$^+$-InGaAs contact layer. The metallization pattern is 20 $\mu$m wide, and extends 20 $\mu$m into the passive regions. Thus, the amplifier is completely covered by the metallization for ease of mask alignment, while the metallization pattern can never be short-circuited to the substrate, as it is always on top of the passivation and planarization layers.

5.2.2 Mask layout

The mask set that is used for the fabrication of the integrated optical amplifiers consists of four contact lithography masks, which define the regrowth areas, the ridge waveguides, the contact openings and the metallization pattern, respectively. The ridges for the passive waveguide devices and the ridges for the optical amplifiers are defined

\(^1\)The SiNx passivation layer and the polyimide planarization layer are defined using the same lithography mask, and have identical geometries.
in a single lithography step. The mask layout (all four masks on top of each other) is shown in Fig. 5.2, where the grey triangular and rectangular areas represent the active regions, and the tiny white squares represent the amplifier metal probe pads.

Directly after the SA-CBE regrowth step, we can examine the butt joint morphology, i.e. the quality of the connection between the active and passive regions, using a Scanning Electron Microscope (SEM). For this purpose, the rectangles in the regrowth mask that surround the device area are interrupted several times. By cleaving the chip through these interruptions after regrowth and characterizing the cleaved-off samples, we can investigate the morphology of the butt joints that are parallel to the waveguides (cleaved at ‘top’ or ‘bottom’ in Fig. 5.2) or in the perpendicular orientation (cleaved at ‘left’ or ‘right’).

When all the processing steps are completed, the chip is cleaved as indicated by the arrows in Fig. 5.2, so that eight smaller sections are obtained which are individually characterized. The first cleave is made at the position ‘center’ in order to avoid damage to the reference waveguides upon further cleaving. One should not cleave through the cleave marks which are defined in the metallization pattern, since in that case a
number of devices is destroyed. Four of the eight sections (left side of Fig. 5.2) contain integrated optical amplifiers of various lengths which can be characterized as extended cavity lasers. Similar devices with angled facets are available in two other sections (right side of Fig. 5.2). The purpose of the angled facets is to reduce the facet reflection coefficient, so that these devices can be characterized as amplifiers. The two remaining sections contain 4-channel and 8-channel phased array multi-wavelength lasers. Further details on the design of extended cavity lasers and multi-wavelength lasers are discussed in Section 5.4 and Section 5.5, respectively.
5.3 Integration experiments

In this section we discuss four Selective Area Chemical Beam Epitaxy (SA-CBE) regrowth experiments. We present SEM photographs of the butt joints, as well as measurement results on the butt joint coupling losses. The SA-CBE regrowth steps were performed by our co-workers at the Department of Physics of the Eindhoven University of Technology [94]. All other processing steps, including the lithography and etching of the regrowth areas, were performed at the Delft University of Technology.

5.3.1 Passive-passive integration

For the integration of passive waveguide devices and optical amplifiers, a butt joint between two different epitaxial layer stacks is created using SA-CBE. In order to investigate the butt joint quality, we created butt joints between two transparent layer stacks, and subsequently fabricated and characterized ridge waveguides that pass through both the primary and the regrown regions. In this way, standard measurement techniques can be applied, and butt joint characterization does not involve fabrication of rather complex devices such as RIE etched optical amplifiers. These experiments were published previously [95, 96], and will be summarized below.

Fabrication

The primary epitaxial layer stack for these regrowth experiments consists of a 60-period InGaAs/InP Multi Quantum Well (MQW) film with an InP cladding on top (thickness either 300 nm or 600 nm). The thickness of the quantum wells is between 2 and 3 nm, resulting in a room temperature Photo-Luminescence (PL) peak between 1350 and 1400 nm, i.e. the MQW is transparent at the characterization wavelength of 1535 nm (TE-polarization). The thickness of the barriers is 6 nm.

A 100 nm SiN$_x$ layer was deposited using PE-CVD, and was removed at the regrowth regions using CHF$_3$-RIE (Fig. 5.3a). Using this SiN$_x$ layer as a mask, we etched trenches using an optimized CH$_4$/H$_2$-RIE process [110] (Fig. 5.3b) to a depth of approximately 200 nm below the MQW film. We thoroughly cleaned the samples using three sequences of O$_2$-stripping and subsequent oxide removal in phosphoric acid H$_3$PO$_4$:H$_2$O = 1:10 for 2 minutes, followed by a clean-up etch in 98% H$_2$SO$_4$ in H$_2$O for 150 seconds. Finally, we briefly etched the samples in diluted Br$_2$/CH$_3$OH to create a slight undercut below the SiN$_x$ (Fig. 5.3c). This prevents the formation of 'regrowth ears'.

The samples were then mounted on a molybdenum holder, and we performed the Selective Area Chemical Beam Epitaxy regrowth step. Perfect growth selectivity was provided by the SiN$_x$ layer (Fig. 5.3d). The regrown layer stack was identical to the primary layer stack, except for the thickness of the InP buffer layer. After removal of the SiN$_x$, we obtained a planar wafer in which we fabricated ridge waveguides that pass through both the primary layer stack and the regrown layer stack. Processing
steps for waveguide fabrication were discussed in Section 3.4; the waveguides were oriented either in the [011] or in the [011] direction.

**Results**

The Photo-Luminescence wavelengths and FWHM widths of the primary material before and after regrowth are identical within the measurement accuracy. Therefore, we conclude that no material degradation occurs at low regrowth temperatures (515 °C), as expected [91,92].

Fig. 5.3e shows a SEM photograph of a typical butt joint of the sample with a 300 nm InP cladding. The SiNₓ layer is still present in this picture. The morphology of
the interface is quite good; there are no regrowth ears, and we see only a tiny air gap in the cladding. Furthermore, we observed that there are only a few defects over the entire regrown area, and that the regrowth selectivity is nearly perfect. Unfortunately, the Br₂/CH₃OH etch was too short to prevent the formation of regrowth ears on the wafers with an 800 nm InP cladding. Apart from the ears, also for those samples the interface morphology was good.

From Fabry-Perot measurements on the waveguides that pass through both the primary and the regrown material, we deduced that the butt joint coupling loss is typically between 0.2 and 0.3 dB/interface. For the waveguides in the [011] direction on the sample with the 300 nm cladding, the losses were as low as 0.1 ± 0.04 dB/interface. The effect of regrowth ears on the coupling loss is only marginal, and reproducibility is excellent as was observed from the small scatter in the data.

Conclusions

We have fabricated and characterized SA-CBE-grown butt joints between two similar transparent MQW layer stacks. The coupling losses are typically between 0.2 and 0.3 dB/interface, the best values are below 0.1 dB/interface. The interface morphology is good, and the area selectivity of the regrowth is excellent. So SA-CBE is a promising technology for the integration of passive waveguide devices and optical amplifiers.

5.3.2 Integrated optical amplifiers: regrowth at active regions

In our first experiments on the fabrication of integrated optical amplifiers, the primary layer stack was the layer stack for the passive waveguide devices; the optical amplifier layer stack was grown in a Selective Area Chemical Beam Epitaxy (SA-CBE) regrowth step. In this way, we fully exploited the design flexibility offered by SA-CBE, as we could, in principle, repeat the regrowth procedure to integrate other devices such as electro-absorption modulators. In these first experiments, the active layer consisted of an InGaAs/InP Multi Quantum Well (MQW). As demonstrated in Section 4.6, such an active layer hardly provides any gain, or no gain at all. Nevertheless, these experiments provided useful experience in the fabrication of integrated optical amplifiers, and will be briefly discussed here.

Fabrication

The fabrication steps for the integration of CBE-grown optical amplifiers are depicted in Fig. 5.4. We start with the epitaxial layer stack for the passive waveguide devices. In one of the experiments we used an MOVPE-grown wafer consisting of an n-InP substrate and buffer, a 600 nm Q(1.30) film and a 1000 nm InP cladding (Appendix A, Table A.4). We also performed experiments on CBE-grown wafers with an InGaAs/InP MQW film. The thickness of the quantum wells and barriers is such that this MQW film is transparent at the intended signal wavelength of 1.55 μm. For details on these layer stacks, see Appendix B, Tables B.4 and B.5.
5. Integrated optical amplifiers

- **a:** layer stack for passive waveguide devices with patterned \( \text{SiN}_x \) layer

- **b:** wet chemical removal of InP cladding

- **c1:** regrowth of active MQW layer

- **c2:** regrowth of InP cladding and InGaAs contact layer

- **d:** removal of \( \text{SiN}_x \)

**Figure 5.4:** Fabrication of SA-CBE grown butt joints between a transparent layer stack and an amplifier layer stack (a ... d). The active layer is an InGaAs/InP MQW, in these photographs the film material is O(1.30). SEM photographs of the butt joints are shown for two crystallographic orientations (e, f).
The first fabrication step is the deposition of a 100 nm PE-CVD SiN$_x$ layer, which is subsequently removed from the regrowth regions using contact lithography and CHF$_3$ Reactive Ion Etching (RIE) (Fig. 5.4a). We use this SiN$_x$ layer as a mask for the wet chemical selective etching of the InP cladding using HCl:H$_3$PO$_4$ = 1:4 (Fig. 5.4b). The resulting trenches have nearly vertical sidewalls when viewed on the (011) plane, and tilted [211] sidewalls when viewed on the (0T1) plane. Then we perform the SA-CBE growth of the InGaAs/InP MQW active layer (Fig. 5.4c1), and of the p-InP cladding and the p$^+$-InGaAs contact layer (Fig. 5.4c2). Details on the active layer stack are given in Appendix B, Tables B.2 and B.3. During SA-CBE, there is no material deposition on the SiN$_x$ layer, which is finally removed (Fig. 5.4d).

**Butt joint morphology**

As a first characterization, we examined the butt joints using a Scanning Electron Microscope (SEM). The samples were stain etched using K$_3$Fe(CN)$_6$ in concentrated KOH in order to increase the contrast between InP and InGaAs(P). Figures 5.4e and 5.4f show two typical SEM photographs, where one can clearly recognize the geometries depicted in Fig. 5.4d. Especially the morphology of the butt joint in Figure 5.4e is excellent: the wafer is planar and there is no air gap at all. In Fig. 5.4f we see that material has grown on the tilted [211] sidewalls, resulting in a regrowth ‘ear’. Fortunately, also in this case, the butt joint morphology is good, and we do not expect that the ear will drastically increase the coupling loss since the optical field is well confined in the film. We did not experience any contact lithography problems due to the ear during further processing.

**Coupling loss**

We continued this integration experiment by fabricating passive waveguide devices and optical amplifiers in their appropriate regions using the mask set that was described in Section 5.2.2 and using the fabrication technology that was discussed in Section 3.4.2. The butt joint coupling loss was then obtained from Fabry-Perot measurements on the shortest ($L \leq 100$ $\mu$m) integrated optical amplifiers; these were characterized as if they were passive waveguides, without applying any bias current. Consider an optical amplifier with passive waveguides on both ends (Fig. 5.5). We have:

\[
\text{loss [dB]} = \alpha_{\text{act}} \cdot L_{\text{act}} + \alpha_{\text{pass}} (L_{\text{chip}} - L_{\text{act}}) + 2\alpha_{\text{joint}}
\]  

where $\alpha_{\text{act}}$ and $\alpha_{\text{pass}}$ are the losses in the active and passive regions, respectively (in dB/cm), $L_{\text{act}}$ and $L_{\text{chip}}$ are the amplifier length and the chip length, respectively, (in cm) and $\alpha_{\text{joint}}$ is the butt joint coupling loss (in dB). The effect of the tapers on the loss is negligible, as was deduced from Fabry-Perot measurements on reference waveguides without tapers and on reference waveguides with three tapers. From these measurements we found that $\alpha_{\text{pass}} = 3.5$ dB/cm. Fig. 5.6 shows the loss of amplifiers.
Figure 5.5: Optical amplifier with passive waveguides on both ends, as used for obtaining the butt joint coupling loss.

with ridge widths of 6 μm and 8 μm as a function of the amplifier length. Inserting $L_{\text{chip}} = 0.33$ cm and $\alpha_{\text{pass}} = 3.5$ dB/cm in Eq. 5.1 and extrapolating to $L_{\text{act}} = 0$ cm, we find that the coupling loss $\alpha_{\text{joint}}$ is lower than 0.2 dB/-interface, which is very low.

Figure 5.6: Determining the butt joint coupling loss for amplifiers with ridge widths of 6 μm and 8 μm.

Further measurements

Measurements on devices with InGaAs/InP MQW active layers were already presented in Section 4.6. In summary, we found that the bandgap energy of the InP barriers is too high to allow for efficient carrier transport through the InGaAs/InP MQW structure. As a result, the amplifier gain is low, and the extended cavity lasers do not
work. We did not find any significant difference in the ASE spectra and ASE output power between devices with an InGaAs/InP MQW film and devices with a Q(1.30) film. The film is on the n-side of the device with respect to the active layer, so this observation confirms our proposition that electron transportation through the MQW film is not more difficult than through a Q(1.30) film, and that the low gain of these devices is caused by the fact that the holes are effectively trapped by the upper (p-side) active layer quantum well.

Conclusions

We have applied a Selective Area Chemical Beam Epitaxy regrowth step for the definition of active and passive regions on a single chip. Regrowth was performed at the active regions in this case. We obtained an excellent butt joint morphology and a low coupling loss of less than 0.2 dB/interf ace. The active layer consisted of an InGaAs/InP MQW, and as a consequence the gain of the integrated optical amplifiers was low. Nevertheless, we have demonstrated that we can fabricate high-quality butt joints using SA-CBE.

5.3.3 Integrated optical amplifiers: regrowth at passive regions

From the results that were presented in Section 5.3.2 and in Section 4.6, we observe that it is not very sensible to carry on with the integration of InGaAs/InP MQW optical amplifiers. In order to achieve substantial optical gain, we should decrease the bandgap energy of the MQW barriers or use a bulk active layer. We have already fabricated a number of InGaAs/InGaAsP MQW ridge lasers and amplifiers that performed quite well (Chapter 4), and we would like to use the performance of these devices as a benchmark for our integrated optical amplifiers. Therefore, we continued by integrating optical amplifiers that have a similar InGaAs/InGaAsP MQW active layer as the devices presented in Chapter 4.

At the time of the first experiment on the integration of InGaAs/InGaAsP MQW optical amplifiers, CBE growth of the complete quaternary InGaAsP material was not yet available. So regrowth of the active layer in the SA-CBE regrowth step was impossible. Therefore, we used an MOVPE-grown amplifier layer stack as the primary layer stack, and performed the regrowth at the passive regions. In this primary layer stack, the active layer was on top of the film, and we were able to perform the integration by carrying out a regrowth of only InP. Later on, CBE of Q(1.25) became available, and we carried out a second experiment in which the active layer was in the center of the film in order to increase the confinement factor. These two experiments have resulted in the successful fabrication of integrated optical amplifiers. The integration technology and butt joint characterization are presented in this section.
Figure 5.7: Fabrication of SA-CBE grown butt joints between a transparent layer stack and an amplifier layer stack (a ... e). The active layer is on top of the film in this case. SEM photographs of the butt joints are shown for two crystallographic orientations (f, g).
Active layer on top of the film

Figs. 5.7a through 5.7e show the fabrication steps for the integration of optical amplifiers with the active layer on top of the film. The primary layer stack consists of an n-InP substrate and buffer, a 550 nm Q(1.25) film, an InGaAs/Q(1.25) MQW active layer, a thin (30 nm) Q(1.25) separate confinement layer, a 1200 nm p-InP cladding and a 25 nm p+ InGaAs contact layer. The thicknesses of the quantum wells and barriers are 4.5 nm and 10 nm, respectively. The number of quantum wells is five. For details see Appendix A, Table A.2.

Similar to the processing steps for the fabrication of the InGaAs/InP MQW integrated optical amplifiers, we start with the deposition of a 100 nm PE-CVD SiNx layer, which is subsequently removed at the regrowth regions using CHF3-RIE (Fig. 5.7a). The SiNx layer is then used as a mask for the wet chemical selective etching of the InGaAs contact layer and the InP cladding. The etchants are H2O:H2O2:H2SO4 = 10:1:1 for the InGaAs contact layer and HCl:H3PO4 = 1:4 for the InP cladding, respectively. When viewed on the (011) plane, the sidewalls are nearly vertical, while we see tilted [211] sidewalls in the perpendicular direction (Fig. 5.7b). The active layer is subsequently removed using an optimized CH4/H2-RIE process [110] (Fig. 5.7c).

Because we first selectively remove the InGaAs contact layer and the InP cladding, the required RIE etch depth is only about 120 nm. Alternatively, we could perform all the etching using RIE, and conclude with a brief etch in diluted Br2/CH3OH in order to create a slight undercut below the SiNx as in Section 5.3.1. However, because of the non-uniformities in the cladding thickness (> 50 nm over the area covered by the mask in Fig. 5.2) and the non-uniformities in the large RIE etch depth that would be required in this case (1200 nm, giving a non-uniformity of typically 30 nm), we would have to include an impractically large safety margin in the etch depth in order to make sure that the active layer is removed over the entire passive region. On the other hand, the wet chemical etch rates of InGaAs and Q(1.25) are similar, so we cannot make use of any etchant selectivity to perform an accurately controlled wet chemical etch that stops just below the active layer. So we have to control the etch depth by means of the etching time, which is more accurate if we use RIE instead of wet chemical etchants. Therefore, we selected RIE for the removal of the active layer, and first performed a wet chemical etch in order to minimize the required RIE etch depth.

After RIE, the wafer is thoroughly cleaned using three sequences of O2-stripping and subsequent oxide removal in phosphoric acid H3PO4:H2O = 1:10 for 2 minutes, followed by a clean-up etch in 98% H2SO4 in H2O for 150 seconds. Then we perform the SA-CBE growth of an undoped InP cladding at the passive regions (Fig. 5.7d), and we remove the SiNx layer wet chemically using HF (Fig. 5.7e).

SEM photographs of the resulting butt joints are shown in Figs. 5.7f and 5.7g. Clearly, we have an excellent butt joint morphology; only a tiny air gap is visible in Fig. 5.7f, and no regrowth ears are present. In Fig. 5.7g, we see that material has grown on the tilted [211] sidewall, resulting in a 'planarized ear'. Nevertheless, also
Figure 5.8: Cross section of an integrated optical amplifier (a) and cross section of a passive waveguide (b); see also Fig. 5.1a. The active layer of the amplifier is on top of the film. These photographs were taken from the same sample.

in this case the connection is good. The flaws in the cleaved facets arise from the fact that the samples were cleaved with the SiN$_x$ layer still in place. We found that this layer introduced a severe stress after SA-CBE in this particular experiment; the cleaved edge is angled by approximately 5° with respect to the (011) direction or the (0\overline{1}1) direction. When we cleave a sample after removal of the SiN$_x$ layer, the cleaved edge is of good quality.

Finally, passive waveguide devices and optical amplifiers were fabricated in the regrown passive regions and in the primary active regions, respectively, using the fabrication steps that were discussed in Section 3.4.2. Typical cross sections of an amplifier and of a waveguide are shown in Figs. 5.8a and 5.8b, respectively.

Active layer in the center of the film

In the course of this work, CBE growth of Q(1.25) became available. This offered us the opportunity to carry out a similar integration experiment where the active layer is in the center of the film instead of on top. This has the advantage that the confinement factor of the active layer is increased, and consequently that a lower material gain is required to achieve a specified modal gain. So we expect that the devices fabricated in this experiment will operate at lower currents as compared to the devices fabricated in the previous experiment. Details on the primary MOVPE-grown active layer stack are given in Appendix A, Table A.3.

Figs. 5.9a through 5.9e show the processing steps for this integration experiment. These steps are practically identical to the processing steps for the devices with the active layer on top of the film. The main difference is that, in order to be able to remove the active layer, we have to remove the upper part of the film as well, using the same CH$_4$/H$_2$-RIE step as for the removal of the active layer (Fig. 5.9c). The etch depth of this RIE step is typically between 350 nm and 400 nm, equal to the thickness of the active layer increased by the thickness of the upper part of the film,
5.3 Integration experiments

a: layer stack for optical amplifiers with patterned SiN$_x$ layer

b: wet chemical removal of InGaAs contact layer and InP cladding

c: RIE removal of upper part of film and of active MQW layer

d: regrowth of upper part of film and of InP cladding

e: removal of SiN$_x$

Figure 5.9: Fabrication of SA-CBE grown butt joints between a transparent layer stack and an amplifier layer stack (a ... e). The active layer is in the center of the film in this case. SEM photographs of the butt joints are shown for two crystallographic orientations (f, g).
Figure 5.10: ‘Birds-eye’ view of regrowth ears.

and increased by a safety margin of a few tens of nanometers. During the SA-CBE regrowth step (Fig. 5.9d), we regrow the upper part of the film at the passive regions, in such a way that the modal field of the resulting passive layer stack matches well with the modal field of the active layer stack. After removal of the SiN$_x$ layer, we fabricate passive waveguide devices and optical amplifiers in their appropriate regions.

Unfortunately, in this case the butt joint morphology is characterized by air gaps (Fig. 5.9f) and regrowth ears (Figs. 5.9f and 5.9g). In Fig. 5.9f we see that the upper part of the film has not grown at the very edge of the butt joint due to shadowing effects. The regrowth ears are probably caused by the large RIE etch depth, which gives slightly sloped sidewalls (see also Fig. 3.6) with rough surfaces. On these surfaces, the quaternary Q(1.25) material grows in the [01T] and the [01T] direction, thereby providing a base from which InP can rapidly grow in the [100] direction, causing an ear. Fig. 5.10 shows a ‘birds-eye’ view of the regrowth ears. We remark here that the optical field has only a small overlap with the regrowth ears. Therefore, we believe that the butt joints in Fig. 5.9g have a reasonable low coupling loss and reflection coefficient. For the butt joints in Fig. 5.9f, on the other hand, the air gap and the interrupted film may degrade the butt joint quality.

**Butt joint coupling loss**

The butt joint coupling losses were again obtained from Fabry-Perot measurements on integrated optical amplifiers which have a length of 100 $\mu$m or less, and using Equation 5.1; values are listed in Table 5.1. We see that the coupling losses of the devices with the active layer on top of the film are below 0.5 dB/interface in all cases, which is satisfactory low. Considering the excellent butt joint morphology, the butt
Table 5.1: Butt joint coupling losses as obtained from Fabry-Perot measurements on short integrated optical amplifiers.

<table>
<thead>
<tr>
<th>quantum wells</th>
<th>orientation</th>
<th>Figure</th>
<th>loss [dB/interface]</th>
</tr>
</thead>
<tbody>
<tr>
<td>top</td>
<td>(011)</td>
<td>5.7f</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>top</td>
<td>(011)</td>
<td>5.7g</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>center</td>
<td>(011)</td>
<td>5.9f</td>
<td>−</td>
</tr>
<tr>
<td>center</td>
<td>(011)</td>
<td>5.9g</td>
<td>0.25 ± 0.25</td>
</tr>
</tbody>
</table>

Joint loss is mainly caused by the fact that the waveguiding layer stack is slightly thicker in the active regions than in the passive regions in this case, causing a small mode mismatch. Using photonic CAD simulations [119], we estimated that the mode mismatch causes a coupling loss of 0.2 dB. A better mode match is achieved for the butt joints where the active layer is in the center of the film. In spite of the regrowth ears, we see a reduction of the coupling loss, which is in agreement with the 0.2 dB mentioned above. For the butt joint in Fig. 5.9f we were not able to obtain reliable Fabry-Perot measurement results because of reflections at the butt joint interface.

Conclusions

We have performed two SA-CBE experiments where the regrowth was carried out at the passive regions. In the first experiment, the InGaAs/InGaAsP MQW active layer was on top of the film layer, and a regrowth of only InP was required. In this way, the integration technology is facilitated as much as possible. However, the confinement factor of the active layer is relatively low, and the mode mismatch between the active and passive regions causes a small increase in the butt joint coupling loss. We achieved an excellent butt joint morphology and a low coupling loss of 0.4 dB/interface.

In the second experiment in which the active layer was in the center of the film, Q(1.25) material was regrown as well. The optical modes in the active and passive regions are better matched in this case, and we obtained an improved butt joint coupling loss in the (011) orientation (0.25 dB/interface) in spite of the regrowth ears that were observed. However, the butt joint morphology in the perpendicular direction is rather poor, and no reliable measurement results could be obtained. The formation of regrowth ears can be avoided by proper tailoring of the side wall profile using a wet chemical etch, as was demonstrated for a butt joint between two passive regions.

5.4 Extended cavity lasers

In the previous Section 5.3.3 we presented two SA-CBE experiments concerning the definition of active and passive regions on a single chip. We have applied the resulting active-passive wafers for the fabrication of integrated optical amplifiers and phased array multi-wavelength lasers. The amplifiers were characterized as extended
cavity lasers (ECLs), i.e. as lasers which have passive waveguides on both ends\textsuperscript{2}. In this way, application of anti-reflection coatings is avoided, and characterization is relatively easy. The results on the ECLs are presented in this section, the multi-wavelength lasers are discussed in Section 5.5.

### 5.4.1 Device layout

In Section 5.2.2 we presented the layout of the mask set that is used for the fabrication of the integrated optical amplifiers (Fig. 5.2). The eight triangular regions on the left side of Fig. 5.2 define active regions in which integrated optical amplifiers of various lengths are defined. Such a region is shown on a more convenient scale in Fig. 5.11a.

In this figure, the light-grey area indicates the active region. The SiN\textsubscript{x} passivation layer and the polyimide planarization layer completely cover the active region, and extend 50 \( \mu \text{m} \) into the passive region. This 50 \( \mu \text{m} \) is shown as a dark-grey edge around the light-grey active region, similar to Fig. 5.1b. All amplifiers in a triangular region have equal ridge widths (4, 6 or 8 \( \mu \text{m} \)) and equal contact opening widths (2, 3 or 4 \( \mu \text{m} \), respectively). The amplifier length is varied from 10 \( \mu \text{m} \) to 1500 \( \mu \text{m} \). The longer devices are operated as extended cavity lasers, while the short devices are suitable to obtain the butt joint coupling loss. The laser cavity is determined by the as-cleaved facets of the chip, so for each amplifier ridge width we have a set of ECLs with various amplifier lengths, while the total device length is constant.

\textsuperscript{2}Extended cavity lasers with a passive waveguide on one end were not considered.
5.4 Extended cavity lasers

On the right side of the mask set (Fig. 5.2) we have included similar devices, however, in this case the access waveguides are angled to reduce the facet reflectivity (Fig. 5.11b). These devices are meant to be operated as amplifiers instead of as extended cavity lasers. For measurement purposes, an alignment aid is included, consisting of a dummy ridge waveguide which should be perpendicular to the optical axis of the measurement setup. The angular adjustment is easily made by means of the rotation stage, which is included in the device mount. The angle of the alignment aid is approximated using Snellius’ Law, assuming a transition from $n = 3.3$ to $n = 1$, where the angle in the $n = 3.3$ region is 5, 7, 10, 12.5 or 15 degrees. In practice, this approximation is satisfactory, and the alignment aid is indispensable.

5.4.2 LI-curves

Fig. 5.12 shows some representative extended cavity laser LI-curves, both for devices with the active layer on top of the film (a, b) and for devices with the active layer in the center of the film (c, d). We see that the LI-curves of the devices with the active layer on top show a few kinks when operated Continuous Wave (CW), whereas the other LI-curves are smooth. These kinks have quite a different appearance than the kinks of the non-integrated lasers in Fig. 4.10a. We discuss the nature of the kinks later on in this section, when we present the CW output spectra of the various ECLs. The two important parameters that can be extracted from the LI-curves are the threshold current (density) and the differential efficiency; these parameters are discussed below.

5.4.3 Threshold current density

The lengths and widths of the integrated optical amplifiers which provide the gain in the extended cavity lasers are quite different. So it is more suitable to compare the devices by means of their threshold current densities than by means of their threshold currents. In order to calculate the current density, we have to consider what the appropriate device width is in this case. In Section 4.4.3 we introduced the concept of the effective device width $w_{\text{eff}}$. The effective width of a ridge waveguide which is etched to an arbitrary depth is defined as the width of the deeply etched ridge waveguide fabricated in the same layer stack, the modal field of which has the highest overlap with the modal field of the original, arbitrarily deeply etched ridge waveguide. Using the effective device width, we were able to compare the performance of RIE etched ridge lasers and wet chemically etched ridge lasers, even though the lateral index contrasts of these two types of devices are quite different.

The concept of effective width is not directly applicable in the case of the integrated optical amplifiers. In the devices with the active layer on top of the film, all the current goes through the active layer\(^3\), so from an electrical point of view the width of the active layer should be the appropriate effective device width $w_{\text{eff}}$ for calculating the current density $J$ from $J = I/(w_{\text{eff}}L_{\text{act}})$, where $I$ is the current and $L_{\text{act}}$ is

\(^3\)Apart from surface recombination currents.
Figure 5.12: LI-curves of extended cavity lasers. For each curve, the amplifier length is indicated in \( \mu \text{m} \). The device length is typically 3 mm, the amplifier ridge width is 8 \( \mu \text{m} \) in all cases.
Figure 5.13: Threshold current densities of extended cavity lasers.

the amplifier length. On the other hand, the effective width should correspond to the width of the optical mode, which is wider than the width of the active layer for these devices. As a compromise, we have used the ridge width at the position of the active layer for the calculation of the current density. This width was obtained from SEM photographs. From an electrical point of view, this is the best approach for the devices with the active layer on top of the film. For the devices with the active layer in the center, we may slightly underestimate the effective device width, and thus overestimate the current density, as compared to the approach that we applied in Section 4.4.3.

First we will theoretically show that the natural logarithm of the ECL threshold
current density depends linearly on the inverse amplifier length. Consider an extended cavity laser which has equal facet reflection coefficients \( R \) on both sides of the device. At threshold, we have:

\[
e^{(\Gamma g - \alpha_{\text{act}})2L_{\text{act}}} \cdot e^{-\alpha_{\text{pass}}2(L_{\text{chip}} - L_{\text{act}})} \cdot T_{\text{joint}}^4 \cdot R^2 = 1
\]

(5.2)

where \( \Gamma \) is the confinement factor of the active layer, \( g \) is the material gain, \( \alpha_{\text{act}} \) and \( \alpha_{\text{pass}} \) are the optical losses in the active and passive sections of the ECL (expressed in cm\(^{-1}\)), respectively, \( L_{\text{act}} \) and \( L_{\text{chip}} \) are the active section (amplifier) length and the chip length, respectively, and \( T_{\text{joint}} \) is the power transmission coefficient of the butt joint. Note that \( T_{\text{joint}} \) is expressed as a dimensionless fraction: \( 0 < T_{\text{joint}} < 1. \) The term on the left of Eq. (5.2) gives the round trip gain of the ECL, where the first exponent is the amplifier modal gain and the second exponent represents the losses in the passive sections. We have two butt joints which are each passed two times during a round trip, where each passage introduces a term \( T_{\text{joint}}. \)

From Eq. (5.3), we have:

\[
\Gamma g - \alpha_{\text{act}} = \beta J_0 \ln (J/J_0)
\]

(5.3)

where \( J_0 \) is identified as the transparency current density, and \( \beta \) as the differential gain at \( J = J_0. \) Using Equations 5.2 and 5.3, we arrive at:

\[
\ln (J_{\text{th}}) = \frac{1}{L_{\text{act}}} \left[ \frac{\alpha_{\text{pass}}L_{\text{chip}} - \ln \left( R T_{\text{joint}}^2 \right)}{\beta J_0} \right] = \frac{\alpha_{\text{pass}}}{\beta J_0} + \ln (J_0)
\]

(5.4)

So according to Eq. 5.4, the logarithm of the threshold current density \( J_{\text{th}} \) depends linearly on the inverse amplifier length \( 1/L_{\text{act}}. \) This relation is confirmed by the linear fits in Fig. 5.13.

From this figure, it follows that \( J_{\text{th}} \) increases more rapidly with decreasing amplifier length for the devices with the active layer on top than for the devices with the active layer in the center. This rapid increase in \( J_{\text{th}} \) is mainly caused by the low value of the product \( \beta J_0 \) for the former devices. We can estimate \( \beta J_0 \) from the slope of the fits: for the devices with the active layer on top of the film we have \( \beta J_0 \approx 21 \) cm\(^{-1}\) (pulsed) and \( \beta J_0 \approx 18 \) cm\(^{-1}\) (CW); for the devices with the active layer in the center we find \( \beta J_0 \approx 35 \) cm\(^{-1}\) (pulsed) and \( \beta J_0 \approx 30 \) cm\(^{-1}\) (CW). The accuracy of these numbers is limited by the uncertainty in \( \alpha_{\text{pass}}, R, \) and \( T_{\text{joint}}, \) and is estimated to be around 10%. It is clear that \( \beta J_0 \) is almost a factor two higher for the devices with the active layer in the center. This is because these devices have a higher confinement factor \( \Gamma \) (0.039 as compared to 0.023), and hence a higher differential gain \( \beta. \) When the ECL is operated CW, the temperature increase of the active layer decreases the product \( \beta J_0. \)

The obtained values for \( \beta J_0 \) are somewhat lower than the value we found for the non-integrated amplifier that was discussed in Section 4.5: \( \beta J_0 \approx 57 \) cm\(^{-1}\) (CW). The
high value of $\beta J_0$ for this amplifier is again explained by the even higher confinement factor ($\Gamma = 0.068$) due to the thicker quantum wells (8 nm as opposed to 4.5 nm).

Extrapolating to $1/L_{\text{act}} = 0$ cm$^{-1}$ we can obtain values for $J_0$ and for $\beta$. However, for each graph a, b, c, d in Fig. 5.13, we find a different extrapolation to $1/L_{\text{act}} = 0$ cm$^{-1}$ for each device width. This is because the effective device width is not accurately known, and because the contributions of surface recombination currents and lateral leakage currents to the measured current density depend on the ridge width, which causes additional uncertainty concerning the active layer current density. So we do not perform any further parameter extraction here, and we only establish that $J_0$ of the ECLs is comparable to, or even lower than $J_0$ of the non-integrated optical amplifier in Section 4.5, which has a transparency current density of 0.60 kA/cm$^2$.

So the difference in device performance between the integrated amplifiers and the non-integrated amplifiers is fully explained by the different layer stacks, i.e. by the confinement factor of the active layer, and we believe that the processing quality and the material quality of both types of devices are good. Therefore, no significant degradation of the primary active layer stack occurs during the SA-CBE regrowth step.

For a non-integrated Fabry-Perot laser, we found in Section 4.5 that the device length at which the threshold current is minimized, is given by:

$$L_{\text{opt,FP}} = \frac{\ln (1/R)}{\beta J_0} \quad (5.5)$$

which is around 190 $\mu$m for a device with $\beta J_0 \approx 57$ cm$^{-1}$. Using Eq. 5.4, we can do the same for an extended cavity laser. This equation has the form: $\ln (J_{\text{th}}) = a/L_{\text{act}} + b$, and using $l_{\text{th}} = n_{\text{eff}} L_{\text{act}} J_{\text{th}}$ we easily find that the lowest threshold current is obtained if $L_{\text{act}} = a$, and we obtain for the optimum amplifier length $L_{\text{opt,ECL}}$:

$$L_{\text{opt,ECL}} = \frac{\ln (1/R)}{\beta J_0} + \frac{\alpha_{\text{pass}} L_{\text{chip}} + 2 \ln (1/T_{\text{joint}})}{\beta J_0} \quad (5.6)$$

The optimum length is directly given by the slope of the linear fits in Fig. 5.13, so its value is easily obtained. We find for the devices with the active layer on top of the film that $L_{\text{opt,ECL}} = 680 \mu$m (pulsed) and 790 $\mu$m (CW), and for the ECLs with the active layer in the center of the film we obtain $L_{\text{opt,ECL}} = 390 \mu$m (pulsed) and 460 $\mu$m (CW), respectively. These values are in agreement with the measured LI-curves.

### 5.4.4 Differential efficiency

The second parameter that one can obtain from the LI-curves is the differential efficiency $\eta_d$. For an extended cavity laser, the inverse differential efficiency $1/\eta_d$ is proportional to the length of the active section. We can easily show this by rewriting
Figure 5.14: Differential efficiencies of extended cavity lasers.
the laser condition of an extended cavity laser Eq. 5.2 in terms of distributed losses:

\[ \Gamma_g = a_{\text{act}} - a_{\text{pass}} + 2a_m + 4a_{bj} + \frac{L_{\text{chip}}}{L_{\text{act}}} a_{\text{pass}}, \text{ with:} \]

\[ a_m = \frac{1}{2L_{\text{act}}} \ln \left( \frac{1}{R} \right) \]

\[ a_{bj} = \frac{1}{2L_{\text{act}}} \ln \left( \frac{1}{T_{\text{joint}}} \right) \]  

where \( a_m \) is the distributed mirror loss and \( a_{bj} \) is the distributed butt joint coupling loss. Similar to the case of a Fabry-Perot laser, the differential efficiency (per facet) is given by the quotient of the mirror loss and the total loss:

\[ \eta_d = \eta_i \frac{a_{m,1}}{a_{\text{act}} - a_{\text{pass}} + 2a_m + 4a_{bj} + \frac{L_{\text{chip}}}{L_{\text{act}}} a_{\text{pass}}} \quad \text{or:} \]

\[ \frac{1}{\eta_d} = \frac{2}{\eta_i \ln (1/R)} \left( a_{\text{act}} - a_{\text{pass}} \right) L_{\text{act}} \]

\[ + \frac{2}{\eta_i \ln (1/R)} \left[ L_{\text{chip}} a_{\text{pass}} - \ln \left( R T_{\text{joint}}^2 \right) \right] \]  

So from Eq. 5.11 we see that \( 1/\eta_d \) depends linearly on \( L_{\text{act}} \).

However, Fig. 5.14 shows that the linear relation described above is not at all satisfied by the measurement data. So any parameter extraction that uses Eq. 5.11 and Fig. 5.14 does not really make sense. Especially in the data of the devices with the active layer on top of the film we observe a lot of scatter, indicating that the accuracy of the measurements is rather poor.

It should be mentioned that parameter extraction using Eq. 5.11 and Fig. 5.14 may result in unreliable results, even if the data is well fitted by a straight line. This is because for ECLs with short amplifiers the gain per unit length at threshold is very high. As a consequence, the amplifier carrier density that is required to achieve laser operation increases with decreasing amplifier length, especially at amplifier lengths where the gain at threshold is heavily saturated. The increasing carrier density in turn increases \( a_{\text{act}} \) [63,64]. So the loss in the active section \( a_{\text{act}} \) depends on the amplifier length \( L_{\text{act}} \), and Eq. 5.11 is not really a linear relation. In Figs. 5.14a and 5.14b the differential efficiency tends to decrease for shorter \( L_{\text{act}} \), in agreement with the argumentation above.

### 5.4.5 Characteristic temperature

One can obtain the characteristic temperature \( T_0 \) from a set of pulsed LI-curves that are measured at different device temperatures. Fig. 5.15a shows such a set of LI-curves that were measured on an extended cavity laser that has the active layer on top of the
Figure 5.15: Pulsed I-I-curves (500 ns, 10 kHz) at temperatures as indicated in °C (a), and fit to obtain $T_0$ (b).

film. The amplifier is 1000 $\mu$m long, and has a ridge width of 6 $\mu$m. The measurement temperatures are indicated in °C. By plotting the logarithm of the threshold current as a function of the temperature (Fig. 5.15b) we can obtain the characteristic temperature $T_0$, using:

$$I_{th}(T) = I_0 \exp \left( \frac{T}{T_0} \right)$$

(5.12)

For this device, we find that $T_0 = 56$ K, which is similar to the value we found for the non-integrated ridge lasers in Chapter 4: $T_0 = 52$ K.

5.4.6 IV-curves

Fig. 5.16 shows a typical IV-curve of an extended cavity laser. The IV-curves of a wet chemically etched ridge laser and of a RIE etched ridge laser are shown as a reference; these devices were discussed in Chapter 4.

The IV-curve of the wet chemically etched laser is much steeper than the IV-curves of the ECL and of the RIE etched device. The slopes of the IV-curves of the latter devices are similar. This is a further indication that hydrogen passivation during CH$_4$/H$_2$-RIE causes an increase in the series resistance. The IV-curve of the wet chemically etched ridge laser and the IV-curve of the ECL have their 'knee' at a similar low voltage, however the high-voltage knee of the IV-curve of the RIE etched ridge laser is rather strange, and its cause is unclear.
5.4 Extended cavity lasers

![Graph showing IV-curves for extended cavity lasers](image)

**Figure 5.16:** Typical IV-curve of an extended cavity laser that has the active layer in the center of the film. The amplifier ridge width is 6 μm, the amplifier length is 1500 μm. IV-curves of non-integrated devices are shown for comparison.

5.4.7 Spectra

We further characterized the extended cavity lasers by measuring the output spectra. Fig. 5.17 shows some typical CW spectra of ECLs that have the active layer on top (a) or in the center (b) of the film. Before discussing the different appearance of these spectra, we first note that the emission wavelengths differ by 30 nm, even though the active layers should be identical. So the reproducibility of the MOVPE-grown active layer stacks that are available to us is currently not satisfactory.

The laser spectra of the devices with the active layer on top are generally quite narrow. Only a few (typically 3 to 5) longitudinal modes are present. This is rather surprising, considering the small longitudinal mode spacing $\Delta \lambda$ (0.10 nm $< \Delta \lambda < 0.15$ nm)$^4$. A mode hop may occur upon increasing the current. In this case, the set of longitudinal modes suddenly hops to a longer wavelength by typically 1 nm or more; lasing at the intermediate wavelengths does not occur.

The spectra of the ECLs that have the active layer in the center, on the other hand, are quite broad, and lasing simultaneously occurs at many longitudinal modes. Upon increasing the current, we do not observe a sudden mode hop, but the longitudinal modes at longer wavelengths gradually increase in power, whereas the shorter wavelength modes disappear. So the whole broad spectrum gradually moves to longer wavelengths.

This behavior is in agreement with the LI-curves in Fig. 5.12. As a first approx-

---

$^4$The resolution of the spectrum analyzer is 0.10 nm, so we cannot accurately observe these modes separately.
Figure 5.17: CW spectra of extended cavity lasers that have the active layer on top (a) or in the center (b) of the film (primary y-axis). Both devices have an active section length of 1 mm, the ridge width of the amplifier is 8 μm. Also the CW output spectra at currents just below the threshold current are shown (secondary y-axis).
imation, the carrier density is fixed above threshold. For pulsed operation, the active layer temperature is in principle independent of the current. So the gain spectrum hardly changes if one increases the current above threshold, and no mode hops are observed. Consequently, the LI-curves are smooth. For CW operation, on the other hand, the active layer temperature increases for increasing current. As a result, the wavelength of maximum gain shifts to longer wavelengths, and so does the emission wavelength. The kinks in the CW LI-curves of the ECLs that have the active layer on top of the film (Fig. 5.12b) are associated with the sudden spectral mode hops, where the emission wavelength hops by 1 nm or more. The CW LI-curves of the ECLs with the active layer in the center of the film are smooth; also in this case longitudinal modes appear and disappear, however, the associated output power fluctuations are averaged over many longitudinal modes and are not visible in the LI-curves.

5.4.8 Discussion: residual reflections

The difference between the spectra of the two types of extended cavity lasers is caused by residual reflections at the butt joints. For the fabrication of ECLs which have the active layer on top of the film, we completely removed the active layer at the passive regions. Subsequently, a regrowth of only InP was performed, so the removed material was not replaced by a material that has a similar refractive index as the active layer. Therefore, the thickness of the waveguiding layers in the active and in the passive regions are quite different, which is also clearly visible in the SEM photographs of the butt joints (Fig. 5.7f, g). Consequently, the butt joint has a non-zero reflection coefficient, and the extended cavity lasers do not consist of a single cavity, but of three cavities in series (passive-active-passive). Laser operation is favored if there is constructive interference in all (combinations of) these three cavities. So the butt joint reflections provide the additional wavelength filtering, which explains the narrow spectrum of these devices. The mode hops and the associated kinks in the LI-curves are caused by the fact that the DC injection current causes a temperature increase of the device, which in turn affects the wavelength of maximum gain. Furthermore, the wavelengths that are filtered due to the butt joint reflections depend on the temperature as well.

For the fabrication of the ECLs that have the active layer in the center of the film, we performed a regrowth of Q(1.25) material to obtain similar effective refractive indices in the active and passive regions. So for these devices the butt joint reflection coefficient is much lower, and these ECLs operate as single-cavity Fabry-Perot lasers. This single cavity is quite long (up to 3 mm), so the longitudinal mode spacing is very small. As a result, these devices operate at many longitudinal modes simultaneously, so the laser spectra are broad and the LI-curves are smooth.

In Fig. 5.17b, we see that the sub-threshold CW spectrum of the ECL with the active layer in the center is regular, whereas the spectrum of the ECL with the active layer on top (Fig. 5.17a) is distorted. The distortion is a further indication that the butt joint reflections of the ECLs with the active layer on top are indeed the highest.
Figure 5.18: Fourier transform of ECL spectrum just below threshold (a). The active layer \( L_{\text{act}} = 1 \) mm is on top of the film in this case. In (b), the position of the peaks in (a) is plotted for devices with different amplifier lengths.

The butt joint reflections become more clear when we apply a Fourier transform to the sub-threshold spectra and express the ‘frequency’ axis of the transformed data in terms of the cavity length. Fig. 5.18a shows an example of such a Fourier transform. Each peak corresponds to a resonance in the 3-cavity laser. We observe a clear peak at the cavity length that is equal to the chip length of this particular device (2.29 mm). We can proceed by applying a Fourier transform to a set of ECLs which are located on the same sample and thus only differ by their amplifier length; typical results are shown in Fig. 5.18b. In this figure, each black dot indicates a cavity length that is identified with a resonance peak in the Fourier transform. From the position of these dots as a function of the amplifier length, we identify some of these dots as resonances that include the passive regions of the ECLs (solid lines ABCD), or as resonances between the cleaved facets (solid vertical line E, and second harmonic solid line F). So all those resonances involve at least one reflection at the cleaved facet. The resonance between the two butt joints is not visible because \( R_{\text{joint}}^2 \ll R_{\text{joint}} R_{\text{facet}} \), where \( R_{\text{joint}} \) and \( R_{\text{facet}} \) are the reflection coefficients of the butt joint and of the cleaved facet, respectively.

The positions of the other resonances in Fig. 5.18b (dashed lines) do not depend on the amplifier length. These resonances are all harmonics of a reflection that involves a cavity that has a length of 0.3 mm (in InP) or 1 mm (in air). The origin of this reflection is not clear.

For the ECLs with the active layer in the center we can make a similar graph, however in this case we mainly see the peaks which are identified with cavity lengths that do not depend on the amplifier length. This further confirms that the butt joint reflections in these devices are small.
5.4 Extended cavity lasers

Figure 5.19: Spectra of 1000 μm long integrated optical amplifiers with access waveguides angled by 7° (a) or 10° (b). The active layer is on top of the film; the amplifier ridge width is 6 μm. DC current is 200 mA.

5.4.9 Angled facet devices

The last devices that we discuss in this section are integrated optical amplifiers, the access waveguides of which are angled with respect to the cleaved facets (Fig. 5.11b). As a result, the facet reflection coefficient is reduced, and we can operate these devices as amplifiers instead of extended cavity lasers.

Surprisingly, some of these angled-facet devices operate as lasers after all. Fig. 5.19a shows a typical CW laser spectrum for a device, the access waveguides of which have an angle of 7° with respect to the cleaved facets; the active layer is on top of the film. The threshold currents of this particular device are 114 mA and 165 mA for pulsed and CW operation, respectively. From these threshold currents, using the results on the extended cavity lasers, we obtain the residual facet reflectivity \( R = 0.14 \).

The high reflectivity of the angled waveguides is explained by means of Fig. 5.20. The access waveguides support at least 3 modes, and even though the reflection coefficient from the zero-order mode to the zero-order mode (0-0 in Fig. 5.20) rapidly decreases for increasing angle, the higher-order mode reflection coefficients are considerable for any angle. At an angle of 7°, the highest reflection coefficients are from the zero-order mode to the second-order mode, and from the first-order mode to the first-order mode. If the second-order mode would be involved in the laser operation, a similar device with its waveguides at an angle of 10° would also operate as a laser (Fig. 5.20), however, it does not. This is clear from Fig. 5.19b, which shows that the Fabry-Perot modulation depth is very low for this 10° device. Therefore, the second-order mode does not play a role in the device performance, and the 7° device operates at the first-order mode. So it is useless to apply angled facets to an optical amplifier if the access waveguides are not monomode.
In Fig. 5.19b, one can clearly distinguish two different frequency contributions. Using Eq. 2.11 and the results on the extended cavity lasers, we find from the low-frequency modulation depth in Fig. 5.19b that the butt joint reflection coefficient of the amplifiers with the active layer on top is below 0.1%.

5.5 Phased array multi-wavelength lasers

In this section we present the experimental results on phased array multi-wavelength lasers. These devices employ integrated optical amplifiers which are similar to those described in the previous section. First, a short introduction on multi-wavelength lasers is given, and a few design issues are addressed.

5.5.1 Introduction

Two strategies for the realization of Multi-Wavelength Lasers (MWLs) have been reported in literature.

In the first approach (Fig. 5.21a), all the wavelengths are generated by an array of integrated DFB lasers or DBR lasers, and are combined into a single output waveguide using a combiner or a multiplexer [21–24]. Combining $N$ wavelengths, a combiner reduces the optical power in each wavelength by a factor $1/N$, therefore this approach is unfavorable for large $N$. This problem does not occur when an optical multiplexer
is used instead of a combiner, but in this case the laser emission wavelengths and the multiplexer response must be matched accurately. Multiplexing of 10 DBR laser outputs into a single output waveguide using a phased array was demonstrated by Ménézo et al. [27, 28], who achieved the wavelength matching by adjusting the currents through the DBR Bragg tuning sections, and by providing the phased array with additional output waveguides.

Alternatively, the optical multiplexer can be incorporated inside the laser cavity (Fig. 5.21b). In this case, the multiplexer is used as an inter-cavity wavelength filter that sets the operating wavelengths of a Fabry-Perot laser. The multiplexer spatially separates the different wavelengths such that they can be individually controlled by current injection in the appropriate optical amplifier, while at the same time all the wavelengths are available in a single output waveguide.

The first device that was based on this approach is the MAGIC laser [125–127], which uses an etched grating as the inter-cavity multiplexer. It operates only under pulsed conditions. CW operation and wavelength conversion at 2.5 Gb/s were demonstrated in an improved device with parabolic mirrors [128, 129]. Fabrication of gratings and mirrors requires extremely smooth and vertical etching, therefore, the use of a phased array instead of a grating is more favorable for ease of fabrication. A phased array multi-wavelength laser was demonstrated for the first time by Zirngibl et al. [26], and many devices have been reported since then [44, 48, 51, 100, 130–137]. Fig. 5.22 shows the layout of such a (4-channel) device.

Comparing these two approaches for the realization of Multi-Wavelength Lasers (MWLs), we see that multiplexing of integrated DFB lasers or DBR lasers has the disadvantage that the fabrication of gratings is required. This generally involves an
additional regrowth step and holographic or e-beam lithography. Furthermore, matching of the DFB/DBR lasing wavelengths and a phased array response is fabrication intolerant, or requires additional current sources for each Bragg tuning section. On the other hand, DFB lasers and DBR lasers are highly stable, and can directly be modulated at high speeds. Stability of phased array MWLs is a matter of concern, and their modulation speed is limited by the cavity length. For example, in a typical device with cavity length $L = 8 \text{ mm}$, the round trip time $t_{RT} = (2nL)/c = 18 \text{ ns}$, where $n$ is the effective refractive index and $c$ is the speed of light. Thus, the upper limit on the modulation speed is given by $f_{RT} = 1/t_{RT} = 5.7 \text{ GHz}$. An important advantage of phased array MWLs is that, even if the central wavelength of the phased array is not at the design wavelength due to fabrication errors or wafer inhomogeneities, the mutual wavelength spacing of the channels is still accurate. The whole comb of wavelengths can then be shifted to the desired emission wavelengths by temperature tuning.

In this section, we present the realization and characterization of a number of phased array multi-wavelength lasers. The phased arrays that were applied in these MWLs are similar to those in monolithically integrated optical cross connects on InP [14]. Therefore, the successful realization of phased array MWLs is a demonstration of the suitability of Selective Area Chemical Beam Epitaxy as the technology of choice for the integration of optical amplifiers and passive waveguide devices for WDM applications.

### 5.5.2 Design

Two sections on the mask set that is used for the fabrication of integrated optical amplifiers (Section 5.2.2, Fig. 5.2) define a number of 4-channel and 8-channel MWLs. These sections are shown on a more convenient scale in Fig. 5.23, where we clearly recognize the schematic representation of Fig. 5.22. A MWL consists of two different devices: a phased array and (a number of) amplifiers. We discuss a few issues in the design of these two devices in the next two paragraphs.
5.5 Phased array multi-wavelength lasers

Figure 5.23: Enlargements of the multi-wavelength laser sections on the mask in Fig. 5.2: 4-channel devices (a) and 8-channel devices (b). The lengths of the amplifier sections are indicated.

Design of multi-wavelength laser amplifiers

The length $L$ of a multi-wavelength laser amplifier can be optimized in a similar way as described in Section 4.5, where we calculated the laser length $L_{\text{opt}}$ that results in the lowest threshold current:

$$ L_{\text{opt}} = \frac{\ln \left( 1/R \right)}{\beta J_0} \quad (5.13) $$

where $R$ is the reflection coefficient, which is assumed to be equal for both facets, $J_0$ is the transparency current density and $\beta$ is the differential gain at $J = J_0$. In order to calculate $L_{\text{opt}}$ for a multi-wavelength laser, we have to account for the phased array transmission $T_{\text{PH}}$ and for the butt joint transmission $T_{\text{joint}}$. We express these as dimensionless fractions: $0 < T_{\text{PH}} < 1$, and $0 < T_{\text{joint}} < 1$. In each laser round trip, the light is reflected two times, passes the phased array twice and encounters both butt joints two times. So the laser condition Eq. 4.10 now becomes\(^5\):

$$ e^{2G_{\text{mode}}L} \cdot R^2 T_{\text{PH}}^2 T_{\text{joint}}^4 = 1 \quad (5.14) $$

\(^5\)In this equation, all the passive waveguide losses are included in the phased array loss.
and we find for the optimized MWL amplifier length $L_{\text{opt,MWL}}$ and for the corresponding threshold current:

$$L_{\text{opt,MWL}} = \frac{\ln \left(1/RT_{\text{PH}} T_{\text{joint}}^2\right)}{\beta J_0}, \quad I_{\text{th}}(L) = L w_{\text{eff}} J_0 \exp \left[\frac{L_{\text{opt,MWL}}}{L}\right]$$  (5.15)

where $w_{\text{eff}}$ is the effective device width. Typical parameter values are estimated to be $T_{\text{PH}} = 0.5$ (phased array loss 3 dB), $T_{\text{joint}} = 0.9$ (butt joint coupling loss 0.45 dB/interface), $w_{\text{eff}} = 6 \mu$m and $R = 0.34$. In Section 4.5, we found that $J_0 = 0.60$ kA/cm$^2$ and that $\beta J_0 = 57$ cm$^{-1}$, so we can calculate the threshold current of a Fabry-Perot laser (curve ‘FP’ in Fig. 5.24) and the threshold current of a multi-wavelength laser (curve ‘MWL1’ in Fig. 5.24) as a function of the device length, i.e. the amplifier length. We see that the threshold current of a MWL is higher than that of a Fabry-Perot laser, and that we need a longer amplifier ($L_{\text{opt}} = 350 \mu$m).

In the integration experiments, the quantum well thickness is decreased from 8 nm to 4.5 nm. As a result, the confinement factor has decreased by almost a factor 2, and consequently the differential gain is also reduced. So we also calculated $I_{\text{th}}(L)$ assuming that $\beta J_0 = 30$ cm$^{-1}$ (curve ‘MWL2’ in Fig. 5.24); the optimum amplifier length is now 660 $\mu$m. Furthermore, in two of the integration experiments, the active layer is not in the center of the film, but on top. In this case, the confinement factor is further reduced, approximately by a factor 2, and we also calculated $I_{\text{th}}(L)$ assuming

---

**Figure 5.24:** Calculated threshold currents of a Fabry-Perot laser and of three multi-wavelength lasers as a function of the amplifier length. FP: Fabry-Perot laser; MWL1: $\beta J_0 = 57$ cm$^{-1}$; MWL2: $\beta J_0 = 30$ cm$^{-1}$; MWL3: $\beta J_0 = 15$ cm$^{-1}$. Other parameters see text. The dashed line gives the threshold current at $L = L_{\text{opt,MWL}}$. 

---
that $\beta J_0 = 15 \text{ cm}^{-1}$ (curve ‘MWL3’ in Fig. 5.24); $L_{\text{opt}} = 1321 \ \mu\text{m}$ in this case. Obviously, in order to achieve moderate threshold currents, we need a high differential gain to compensate for the phased array losses and for the butt joint coupling losses.

In the mask design, the amplifier lengths are 1000 $\mu\text{m}$ and 1500 $\mu\text{m}$ for the 4-channel MWLs, and 750 $\mu\text{m}$ and 1000 $\mu\text{m}$ for the 8-channel devices. The amplifiers all have a ridge width of 6 $\mu\text{m}$ and a contact opening width of 3 $\mu\text{m}$. Each wafer that contains MWLs also provides us with a number of extended cavity lasers. From the characterization of these ECLs, we may find that the amplifiers have a high differential gain after all, and that the MWL amplifiers should be much shorter in order to minimize the threshold current. Optionally, we can shorten the amplifiers in an additional cleave\(^6\).

**Design of multi-wavelength laser phased arrays**

In a phased array multi-wavelength laser, the phased array is applied as an inter-cavity wavelength filter. Similar to a grating, a phased array can operate in different orders. As a result, the filter characteristic from an input waveguide to the output waveguide is periodic, and for channel $x$ we find transmission peaks at the wavelengths $\lambda = \lambda_x + m \cdot FSR$, where $FSR$ is the so-called Free Spectral Range and $m$ is an integer number.

When designing a MWL, one must make sure that all the channels will operate in a single phased array transmission order. This is illustrated in Fig. 5.25. For a 4-channel phased array, we have a set of four transmission peaks for each order $m$. If one of these sets coincides with the peak of the gain spectrum, the MWL will operate at adjacent wavelengths as it should (Fig. 5.25a). However, if the gain peak is in between two of these sets, the device will operate at wavelengths of different orders (Fig. 5.25b), and these wavelengths are not adjacent. Occasionally, for a specific channel, the amplifier gain may be approximately equal at $\lambda = \lambda_x$ and at $\lambda = \lambda_x + FSR$. In this case, the MWL will emit both wavelengths simultaneously, while only one amplifier is switched on. This is an undesired way of multi-wavelength lasing called ‘multi-passband lasing’.

We can achieve an accuracy of a few nanometers in the wavelength response of a phased array. The gain spectrum of the amplifiers, however, may be shifted in wavelength by 30 nm (Fig 5.17), and the situation in Fig. 5.25b can easily occur. Basically, there are two strategies to avoid this situation. In the first place, one can make the $FSR$ very large, such that the wavelengths of the next-order phased array transmission peaks are far off the wavelength of maximum gain. The main drawback of this approach is that the size of a phased array increases with the $FSR$. Alternatively, one can apply a so-called ‘chirped’ phased array [131], which does not have a periodic response; it has a set of low-loss transmission peaks at only one order, while the transmission at other orders is suppressed. In both strategies, the MWL will operate in a single phased array transmission order. Note that the further the emission wavelengths

\(^6\)If one shortens the amplifiers of an MWL by cleaving, another MWL may be sacrificed.
Figure 5.25: Matching (a) and mismatching (b) of the gain spectrum and the phased array response. Laser operation will occur at the channels in the shaded area.

Figure 5.26: By matching the phased array response of two multi-wavelength lasers A and B as shown here, at least one of these devices will operate in one order.

are away from the wavelength of maximum gain, the higher the threshold currents of the channels will be.

In order to avoid the use of rather sophisticated chirped gratings in these first experiments and still making sure that we obtain a device that operates in a single phased array transmission order, we have applied a different strategy for the 4-channel MWLs (Fig. 5.26). The channel spacing of these devices is 3.2 nm (400 GHz), the FSR is 8 times the channel spacing: \( FSR = 25.6 \text{ nm} \). For each amplifier length (1000 \( \mu \text{m} \) and 1500 \( \mu \text{m} \), Fig. 5.23a), we have fabricated two devices (A and B) that are identical except for the central wavelengths of the phased arrays. These are mutually shifted by half the FSR (12.8 nm): \( \lambda_{c,A} = 1550 \text{ nm}, \lambda_{c,B} = 1562.8 \text{ nm} \). So
the joint wavelength response of the two devices is a continuous series of transmission peaks, mutually spaced by 3.2 nm. As a result, no matter where the wavelength of maximum gain is, at least one of the two devices will operate in a single order as it should, while the other probably will not. The emission wavelengths are always close to the wavelength of maximum gain, so the threshold current is not increased due to a mismatch between the phased array response and the gain spectrum. Of course, the yield in this strategy is limited to 50%.

For the 8-channel devices, we have taken the $FSR$ as large as possible, since there is no space to fabricate two 8-channel MWLs with identical amplifier lengths. The channel spacing, $FSR$ and central wavelength are 3.2 nm, 45 nm and 1550 nm, respectively.

### 5.5.3 4-channel MWLs, active layer on top of the film

In this paragraph, we present the measurements on the 4-channel MWLs that have amplifiers with the active layer on top of the film. Fig. 5.27 shows a photograph of a processed chip, and defines the labeling of the various devices. We have two sets of two MWLs, which have amplifiers with a length of either 1500 $\mu$m (MWLs A and B) or 1000 $\mu$m (MWLs C and D). For each set (AB, CD) the joint wavelength response of the phased arrays of both MWLs is a continuous series of transmission peaks, mutually spaced by 3.2 nm, as explained in the previous section. The devices with 1000 $\mu$m long amplifiers were damaged, so we discuss mainly MWLs A and B. All measurements were performed at a mount temperature of 20 °C.

#### Spectra

In order to characterize the phased arrays, we operated the amplifiers at a DC current of 50 mA, which is well below the CW threshold current. The phased array response is obtained by measuring the amplifier spontaneous emission spectrum at the amplifier side, and by subtracting it from the spontaneous emission spectrum measured at the common MWL output waveguide. Fig. 5.28a shows that the joint wavelength response of the phased arrays of MWLs A and B consists of a continuous series of transmission peaks, as intended. The phased array loss and crosstalk are better than 4 dB and 20 dB, respectively, so the phased array performance is satisfactory.

The next characterization step is the pulsed operation of the MWLs at a current above threshold. Fig. 5.28b shows the pulsed laser spectra of each channel at a pulsed (250 ns, 10 kHz) current of 150 mA. Coincidentally, the wavelength of maximum gain is around 1557 nm, so both devices operate at adjacent wavelengths, i.e. in a single phased array transmission order.

When we apply a DC current of 150 mA to these MWLs (Fig. 5.28c), we see that the two shortest-wavelength channels of MWL A now operate in a longer-wavelength

---

7 Occasionally, both MWLs operate in a single order, as will be demonstrated.

8 These spectra were measured in units dBm/nm.
phased array transmission order, and that only MWL B provides four adjacent wavelengths. The hop of the two channels of MWL A from one transmission order to the other is caused by the redshift of the gain spectrum due to heating of the active layer. Depending on how close MWL A is to hopping, the gain spectrum redshift must be between 3.2 nm and 9.6 nm. We can estimate the temperature dependence of the gain spectrum by observing the pulsed emission wavelength of an extended cavity laser that is located on the same chip as these MWLs. From an ECL with an amplifier length of 1000 μm, we find that the gain spectrum redshift $d\lambda/dT$ is around 0.37 nm/°C. This is a rather rough estimation, as the ECL emission wavelength is also affected by the wavelength filtering due to the butt joint reflections. From the characteristic temperature and from the difference between the pulsed and CW threshold currents we find that the temperature increase of the MWL active layer is around 9 °C, causing a gain spectrum redshift of 3.3 nm. This is a bit low, but in the correct order of magnitude.

We discuss a few features of the spectra in Fig. 5.28c in more detail. In the first place, we see that each laser peak is standing on a 'pedestal', which is visible at power levels below -65 dBm/0.1 nm. Note that the power level in the laser peak is more than 35 dB higher, so we have a good side mode suppression ratio. The pedestals arise from TE spontaneous emission which is filtered by the phased array. The TM spontaneous emission causes a small 'bump' on the short-wavelength side of each pedestal. This is shown in more detail in Fig. 5.29a, where we see the polarization-
Figure 5.28: Phased array transmission (a), pulsed laser spectrum (b) and CW laser spectrum (c) of MWL A (solid) and MWL B (dashed).
Figure 5.29: CW laser spectrum at a current of 150 mA (a) and phased array transmission (b) of MWL B, channel 1 for TE polarization (solid) and TM polarization (dashed). Operating temperature is 20 °C.

resolved laser spectrum of MWL B, channel 1. In the TE-polarized laser spectrum, only the pedestal is visible, whereas in the TM-polarized spectrum the pedestal has disappeared and we see a TM-polarized peak which is the ‘bump’ of this particular channel in Fig. 5.28c. The laser peak suppression in the TM-polarized spectrum is 20 dB, which corresponds to the extinction ratio of the polarizer. The difference in wavelength between the TM-polarized peak and the TE-polarized laser emission is caused by the polarization dependence of the phased array ⁹ (Fig. 5.29b).

Some channels in Fig. 5.28b and Fig 5.28c emit multiple longitudinal modes simultaneously. This is more clear in Fig. 5.30, which shows detailed spectra of two adjacent channels of MWL A. Each laser peak consists of a number of longitudinal modes which cannot be investigated individually because the spectrum analyzer resolution (0.1 nm) is larger than the longitudinal mode spacing of 0.046 nm. The mode spacing follows from Eq. 2.24, where we use a cavity length \( L = 7.14 \) mm and assume that the group index is equal to the value that we obtained in Section 4.4.3: \( n_g = 3.7 \). Note that it appears as if the longitudinal modes are individually visible in Fig. 5.30 after all, however, the modes in this figure are spaced by two or three times the calculated longitudinal mode spacing.

Experimentally, one may find that a phased array multi-wavelength laser operates on a single longitudinal mode. The reason for this is that beating between neighboring modes causes a spatial modulation in the amplifier carrier density, and hence in the (complex) refractive index; in other words, the beating induces a grating. Due to this grating, the longer-wavelength longitudinal modes experience a higher gain, and the

⁹The phased array was not designed to be polarization independent.
shorter wavelength modes are suppressed [130, 138]. This can lead to single-mode stability. The lasers, the spectra of which are shown in Fig. 5.30, obviously do not take advantage of this effect. The reason for this is that the current density at threshold is quite high (1.7 kA/cm²). At such a high current density, the amplifier gain is already in the saturation regime (Fig. 2.18), so a substantial increase in current density causes only a minor increase in gain. As a result, the carrier density modulation from the beating of the longitudinal modes also has only a minor effect on the complex refractive index, and the grating ‘depth’ is not sufficient to achieve single mode stability.

Apart from the multiple longitudinal modes, we even observe an inter-passband mode hop in channel 1; such a hop was observed only in this particular channel. Lasing starts at the wavelength where the phased array transmission is highest (150 mA). When the current is increased, the spectrum splits into two distinct sets of longitudinal modes (180 mA). At a current of 200 mA, only one of these sets remains. This inter-passband mode hop is similar to the mode hops that occurred in the extended cavity lasers with the active layer on top of the film. The amplifiers of these ECLs are identical to the amplifiers of the MWL, and we believe that also in the MWL the inter-passband mode hop is caused by residual reflections at the butt joint interfaces. For example, the mode spacing of the cavity that is formed by the waveguide cavity and the amplifier cavity in series (Fig. 5.31) is 0.13 nm, where we assume a group index \( n_g = 3.7 \). So laser operation of the MWL is favored at wavelengths that are spaced by 0.13 nm. This mode spacing equals three times the wavelength interval of the inter-
passband mode hop: $\Delta \lambda_{\text{hop}} = 0.4 \text{ nm}$, and therefore it is likely that this particular cavity plays an important role in the appearance of the hop. It is not straightforward to clarify the role of the other cavities in the laser, especially because the cavity lengths are long and involve a phased array, and because of the fact that the group index is not accurately known.

**LI-curves: threshold currents**

Fig. 5.32 shows the pulsed (250 ns, 10 kHz) and the CW LI-curves of each MWL channel. The most striking feature is that the pulsed LI-curves are quite smooth, whereas the CW LI-curves show a lot of kinks. The difference between these curves can only be explained by thermal effects, and we believe that the kinks are caused by a temperature increase of the active layer, which induces changes in the amplifier refractive index. As a result of these index changes, the wavelengths that experience constructive or destructive interference in the cavity (or set of cavities) shift with increasing temperature, i.e. with increasing DC current, and longitudinal modes appear and disappear at various wavelengths in the spectrum. As only a few modes are lasing simultaneously, this translates into power changes in the CW LI-curves. For pulsed operation, the active layer temperature increase is negligible, and the LI-curves are smooth.

We can compare the MWL threshold currents with the threshold currents of the extended cavity lasers (ECLs) that were discussed in the previous section. In the laser condition for a MWL, we have to take the loss of the phased array into account. Defining $T_{\text{PH}}$ as the fraction of light that is transmitted by the phased array ($0 <$
\( T_{\text{PH}} < 1 \), we find from Eq. 5.4 that the MWL threshold current density is given by:

\[
\ln\left( J_{\text{th, MWL}} \right) = \frac{1}{L_{\text{act}}} \left[ \frac{\alpha_{\text{pass}} L_{\text{chip}} - \ln \left( \frac{RT_{\text{PH}} T_{\text{joint}}^2}{\beta J_0} \right)}{\beta J_0} \right] - \frac{\alpha_{\text{pass}}}{\beta J_0} + \ln(J_0)
\]

\[
= \ln\left( J_{\text{th, ECL}} \right) - \frac{\ln(T_{\text{PH}})}{\beta J_0 L_{\text{act}}}, \quad \text{or:} \quad (5.16)
\]

\[
J_{\text{th, MWL}} = J_{\text{th, ECL}} \cdot \exp\left[ -\frac{\ln(T_{\text{PH}})}{\beta J_0 L_{\text{act}}} \right] \quad (5.17)
\]

Inserting \( T_{\text{PH}} = 0.4 \) (phased array loss 4 dB), \( L_{\text{act}} = 1500 \mu m \) and \( \beta J_0 = 21 \text{ cm}^{-1} \) (pulsed) or 18 cm\(^{-1}\) (CW) into Eq. 5.17, we find that the threshold current (density) of MWLs A and B should be increased by a factor 1.34 (pulsed) or by a factor 1.40 (CW) with respect to an ECL that has identical 1500 \( \mu m \) long amplifiers. From the ECL threshold current data of the previous section, we can expect MWL threshold currents of 111 mA and 130.9 mA for pulsed operation and CW operation, respectively. These numbers are in excellent agreement with the LI-curves of MWL B in Fig. 5.32, so the amplifiers of this MWL and the amplifiers of the extended cavity lasers perform equally well. The performance of MWL A is slightly worse, probably due to small fabrication errors.

The amplifier length that results in the lowest MWL threshold current can be calculated in a similar way as in Section 5.4, and is equal to the term between brackets in Eq. 5.16:

\[
L_{\text{opt, MWL}} = \frac{\alpha_{\text{pass}} L_{\text{chip}} - \ln \left( \frac{RT_{\text{PH}} T_{\text{joint}}^2}{\beta J_0} \right)}{\beta J_0} = L_{\text{opt, ECL}} + \frac{\ln(1/T_{\text{PH}})}{\beta J_0} \quad (5.18)
\]

We find that \( L_{\text{opt, MWL}} = 1120 \mu m \) (pulsed) and 1300 \( \mu m \) (CW). For pulsed operation, we find from Eqs. 5.16 and 5.18 that the pulsed threshold currents of MWLs with 1000 \( \mu m \) and 1500 \( \mu m \) long amplifiers are only 0.6% and 4% higher than those that we can expect for MWLs with amplifiers which have the optimal length. So there is no need to shorten the amplifiers by cleaving in order to reduce the pulsed threshold current. For three channels of MWL C, which has amplifiers of 1000 \( \mu m \), we were able to obtain pulsed threshold currents of around 100 mA\(^10\) (Fig. 5.33). This is even better than expected; probably the phased array loss of MWL C is lower than the assumed 4 dB. The weak dependence of the threshold current on the amplifier length is due to the low differential gain, compare also with the calculated line 'MWL3' in Fig. 5.24.

Concerning the CW threshold currents, reducing the amplifier length to the optimal CW length of 1300 \( \mu m \) would result only in a minor decrease in CW threshold current by 1%, so we left the MWLs as they were. Note that if the amplifier length is reduced, also a butt joint is cleaved off, resulting in a slightly further reduction of the threshold current.

\(^{10}\)These LI-curves are the only reliable measurements on MWLs C and D.
5. Integrated optical amplifiers

Figure 5.32: LI-curves of the four channels of MWL A and MWL B.

Assuming that the phased array loss is equal for all channels, the channels that are at the wavelength of maximum gain should have the lowest threshold currents. Fig. 5.34 shows the threshold currents of all channels as a function of the emission wavelength. We observe that, probably due to processing non-uniformities, the threshold currents of MWL A are slightly higher than those of MWL B. This fact makes it hard to observe any reduction in threshold current for the channels at the wavelength of maximum gain; also for the differential efficiency we do not observe a clear wavelength dependence. It appears that the gain spectrum is quite flat around the emission wavelengths.
Figure 5.33: Pulsed (250 ns, 10 kHz) LI-curves of three channels of MWL C; the amplifier length is 1000 μm.

Figure 5.34: Threshold currents of all channels of MWL A and MWL B as a function of wavelength.
Differential efficiency

By introducing the phased array transmission $T_{PH}$ into Equation 5.11 for the differential efficiency of an extended cavity laser, we obtain for a multi-wavelength laser:

$$\frac{1}{\eta_{d,MWL}} = \frac{2}{\eta_i \ln (1/R)} (\alpha_{act} - \alpha_{pass}) L_{act}$$

$$+ \frac{2}{\eta_i \ln (1/R)} \left[ L_{chip} \alpha_{pass} - \ln \left( R T_{PH} T_{joint}^2 \right) \right]$$

$$= \frac{1}{\eta_{d,ECL}} + \frac{2 \ln (T_{PH})}{\eta_i \ln (R)}$$

Equation 5.20 offers a nice opportunity to obtain a value for $\eta_i$ from the comparison of $\eta_{d,MWL}$ and $\eta_{d,ECL}$, as $T_{PH}$ and $R$ are known. However, the pulsed differential efficiency of MWL C ($\eta_d = 0.066$) is slightly lower than that of MWLs A and B (best channels: $\eta_d = 0.070$), while we would expect from Eq. 5.20 that the device with the longest amplifiers has the lowest efficiency. The situation is similar to what we found for the extended cavity lasers in the previous section: the accuracy of the values that we obtain for the differential efficiency is rather poor, and the high carrier density in the short amplifier increases the loss, and hence reduces the efficiency. So in order to properly compare the efficiencies of MWLs and ECLs, one should compare devices, the amplifiers of which have the same lengths and operate at similar carrier densities. These two conditions can never be fulfilled at the same time, so a proper comparison is not possible.

We close the discussion on efficiencies by remarking that the MWL efficiency is lower than the ECL efficiency by typically a factor 2.5 due to the loss of the phased array and due to the loss that is caused by the high carrier density in the amplifiers.

### 5.5.4 4-channel MWLs, active layer in the center of the film

The next multi-wavelength lasers that we discuss are also 4-channel devices, and are identical to the MWLs discussed in the previous section apart from the fact that now the active layer is in the center of the film. In this case, all MWLs A, B, C and D worked properly, although one channel of MWL B has a rather high threshold current.

**Spectra**

First of all, we examine the pulsed laser spectra (Fig. 5.35). For each peak in Fig. 5.35a, the corresponding peak in Fig. 5.35b is shifted to a shorter wavelength by approximately 0.5 nm. This shift is attributed to slightly different phased array responses due to wafer non-uniformities.

All channels of MWLs A and B operate at adjacent wavelengths, whereas one channel of MWL D operates in a shorter-wavelength phased array transmission order. We can give two possible reasons for this. In the first place, the amplifiers of MWLs C
Figure 5.35: Pulsed laser spectra just above threshold (200 ns, 10 kHz) for MWLs AB (a) and MWLs CD (b). Devices A and C: solid lines; devices B and D: dashed lines.
Figure 5.36: CW spectra of MWL A (solid) and MWL B (dashed) just above threshold (a), at 115 mA (b) and at 125 mA (c).
5.5 Phased array multi-wavelength lasers

Figure 5.37: CW spectra of MWL C (solid) and MWL D (dashed) at 80 mA (a) and at 100 mA (b).
and D have to provide the same amount of gain in a shorter length ($L_{\text{act}} = 1000 \ \mu\text{m}$) than the amplifiers of MWLs A and B ($L_{\text{act}} = 1500 \ \mu\text{m}$). Therefore, the carrier density in the former amplifiers is higher, and consequently the gain spectrum is shifted towards shorter wavelengths. Secondly, the long amplifiers are located opposite the small flat of the 2" wafer, where the epitaxial layers are slightly thicker than at the position of the short amplifiers. This results in a further redshift of the long-amplifier gain spectra.

As a next step, we applied a DC current to the MWL amplifiers, and recorded the CW laser spectra. Fig. 5.36a shows that CW lasing of all channels of MWLs A and B starts at the same wavelengths as for pulsed operation. However, as the current increases, the amplifier temperature increases, and the gain spectrum shifts to longer wavelengths. This is clear from Fig. 5.36b, where the shortest-wavelength channel of MWL A is on its way to hop to the longer-wavelength phased array transmission order. In fact, this channel is lasing in two orders simultaneously, and we observe a clear example of Multi-PassBand lasing (MPB). At a current of 125 mA, the hop is completed (Fig. 5.36c). The CW spectra were recorded over a long wavelength span, and spontaneous emission which is filtered by the phased arrays is visible at multiple transmission orders for each channel.

The behavior of MWLs C and D is similar (Fig. 5.37): the short-wavelength channel of MWL D hops to a longer-wavelength phased array transmission order, such that at a CW current of 100 mA both MWL C and MWL D operate at adjacent wavelengths.

**LI-curves**

Fig. 5.38 shows the pulsed LI-curves (a) and the CW LI-curves (b) of all the 4-channel MWLs that have the active layer in the center of the film. All channels have a comparable performance, except for one channel of MWL B. The pulsed LI-curves are smooth: no kinks are visible. Also the CW LI-curves look quite good for powers up to 1 mW. At higher powers, thermal effects become of importance. Heating of the active layer causes a change in the amplifier refractive index, and as a result the wavelengths that ‘fit’ in the cavity are shifted. Each refractive index change that causes a wavelength shift comparable to the longitudinal mode spacing forces the device to operate at the next longitudinal mode, resulting in a kink in the CW LI-curve.

As compared to the devices with the active layer on top of the film, the threshold currents are significantly reduced due to the higher confinement factor; the differential efficiencies are comparable (pulsed) or slightly better (CW). We observe that the efficiencies of the MWLs with the short amplifiers is better than those of the MWLs with the long amplifiers, so the increasing absorption due to the higher carrier density in the former devices is not as severe as in the devices with the active layer on top.

Assuming a phased array loss of 3 dB, the optimal amplifier lengths are 590 \ mu\text{m} and 650 \ mu\text{m} for pulsed and CW operation, respectively. By cleaving the chip in such a way that the amplifier lengths becomes optimal, we should be able to reduce the
pulsed and CW threshold currents by approximately 10% with respect to the threshold currents that we obtain with 1000 μm long amplifiers. We did not reduce the amplifier length in an attempt to do so, as this is a rather dangerous operation.

Finally, Fig. 5.39 shows the threshold currents as a function of the emission wavelength. The threshold currents of the outer channels are typically more than 5 mA higher than those of the channels that emit at the wavelength of maximum gain, which is comparable to the situation for the MWLs that have the active layer on top of the film.
In conclusion, the performance of the 4-channel MWLs that have the active layer in the center of the film is improved with respect to the devices with the active layer on top of the film. The former devices have lower threshold currents, smoother L-I-curves, and no inter-passband mode-hops were observed in the CW spectra. Both types of MWLs were fabricated using the same set of contact lithography masks. This indicates that further improvement of the device performance is possible, since the amplifier differential gain, and consequently the optimal amplifier lengths of both types of MWLs are quite different.

### 5.5.5 8-channel MWLs

The last devices that we discuss are two 8-channel multi-wavelength lasers, the amplifiers of which have the active layer in the center of the film. The amplifiers have a length of 750 μm or 1000 μm.

The pulsed (500 ns, 10 kHz) spectra are shown in Fig. 5.40. The wavelength of maximum gain is around 1520 nm, and both MWLs operate in two different phased array transmission orders. Again we observe that the gain spectrum of the device with the 750 μm long amplifiers is blueshifted with respect to the other device, mainly because of the higher carrier density that is required in these short amplifiers to achieve threshold.

When we apply a DC current to the MWL amplifiers, we observe that the CW emission wavelengths of all channels of the device with the 1000 μm long amplifiers are in a single phased array transmission order (Figs. 5.41 and 5.42). The spontaneous
5.5 Phased array multi-wavelength lasers

Figure 5.40: Pulsed laser spectra just above threshold of 8-channel MWLs with 750 \( \mu \)m long amplifiers (a) and with 1000 \( \mu \)m long amplifiers (b).
emission power in the shorter-wavelength transmission order is much higher than in the longer-wavelength order, so the central wavelength of the phased array does not coincide with the peak of the gain spectrum; the MWL channel that operates at the longest wavelength could easily have operated in the shorter-wavelength phased array transmission order. Fortunately it does not, and we have eight channels operating at adjacent wavelengths as intended, which is shown in more detail in Fig. 5.42. This figure also shows the phased array response, which is at slightly shorter wavelengths than the laser emission. This observation indicates that for this device, interference of the longitudinal modes induces a spatial modulation in the amplifier carrier density, which in turn favors lasing at the longer-wavelength longitudinal modes and increases the single mode stability [130, 138]. Indeed, we were not able to distinguish multiple longitudinal modes in the spectra, however, because of the limited resolution of the spectrum analyzer, multiple longitudinal modes may be present after all. Note that the loss and the crosstalk of the phased array are better than 3 dB and 25 dB, respectively, so the performance of this device, which is fabricated in the regrown region of the chip, is more than satisfactory. This indicates that the quality of the regrown material is excellent.

We do not discuss results on the CW operation (i.e. spectra and LI-curves) of the 8-channel MWL with the 750 μm long amplifiers, because a number of channels of this device broke down during the measurements.

LI-curves of all channels of the MWL with 1000 μm long amplifiers are shown in Fig. 5.43. Similar to the 4-channel devices with the active layer in the center, the LI curves of which were shown in Fig. 5.38, we observe that the pulsed LI-curves are
5.5 Phased array multi-wavelength lasers

Figure 5.42: CW spectra (solid) and TE phased array transmission peaks (dashed) of 8-channel MWL with 1000 µm long amplifiers. Currents were adjusted to obtain equal output laser power levels for each channel.

rather smooth, while the CW L1-curves show a number of small kinks.

The threshold currents and differential efficiencies of the MWLs with the 1000 µm amplifiers are comparable to those of the 4-channel MWLs with identical amplifiers. The threshold currents of the few channels with 750 µm amplifiers are even lower, indicating that the estimation of the optimum amplifier lengths (590 µm and 650 µm for pulsed and CW operation, respectively) is reasonable.

Finally, Fig. 5.44 shows the threshold currents of the 8-channel MWL as a function of the emission wavelengths. Obviously, there is a wavelength where the threshold current is minimum. The reason that this is so much clearer than in the results for the 4-channel MWLs, even though two 4-channel devices cover the same wavelength span as a single 8-channel device, is that the 8-channel MWL does not automatically operate at the wavelength of maximum gain; its emission wavelength is set by the phased array response, while for the two complementary 4-channel devices the eight emission wavelengths are automatically at the peak of the gain spectrum. We see in Fig. 5.44 that some of the eight channels operate at the ‘red’ side of the gain peak, where the gain rapidly decreases with wavelength. As a consequence, these channels have relatively high threshold currents. The increase in threshold current is further enhanced by the saturation of the gain, i.e. by the fact that at high currents a substantial increase in current is required to achieve a relatively small increase in gain. So if there is a small mismatch of the lasing wavelength and the wavelength of maximum gain, the small amount of required ‘extra’ gain causes a rapid increase of the threshold current.
5. Integrated optical amplifiers

Figure 5.43: LI curves of 8-channel MWL with 1000 μm long amplifiers.

Figure 5.44: Threshold currents of 8-channel MWL with 1000 μm long amplifiers as a function of wavelength. Open markers: pulsed; closed markers: CW.

In conclusion, we have fabricated an 8-channel phased array multi-wavelength laser which operates CW at eight adjacent wavelengths. The lowest threshold currents are around 80 mA, the device was characterized for output powers up to 1 mW. The performance of the phased array is very good, and this MWL demonstrates the feasibility of SA-CBE for the realization of complex photonic integrated circuits for WDM applications.
5.6 Conclusions

We presented a number of experiments on the fabrication of integrated optical amplifiers. The integration is based on the definition of active and passive regions on a single chip using a Selective Area Chemical Beam Epitaxy (SA-CBE) regrowth step. We obtained butt joint coupling losses of typically less than 0.5 dB/interface, even down to 0.1 dB/interface. In most cases, the butt joint morphology is excellent. In one of the experiments, regrowth ‘ears’ were formed, however, we found that such ears do not heavily affect the butt joint coupling efficiency, and do not cause any problems for subsequent contact lithography steps. The formation of ears can be avoided by proper tailoring of the side wall profile using wet chemical etchants.

The performance of phased arrays which were fabricated in the passive regrown regions was more than satisfactory, so we conclude that the quality of the regrown material is excellent. Furthermore, the quality of the primary active layer stack is not degraded after regrowth, as was confirmed by the good performance of extended cavity lasers as compared to the non-integrated devices that were discussed in Chapter 4. So SA-CBE enables the fabrication of efficient butt joints between different high-quality epitaxial layer stacks, and is therefore a powerful technology for the realization of photonic integrated circuits.

We have fabricated two types of integrated optical amplifiers: low-confinement devices ($\Gamma = 0.023$) that have the active layer on top of a waveguiding film, and high-confinement devices ($\Gamma = 0.039$) in which the active layer is in the center of this film. We found that the performance of these two types of devices shows a few interesting differences.

In the low-confinement devices, the match between the waveguiding structures in the active and passive regions is not ideal. As a result, the butt joint coupling loss and the butt joint reflection coefficient of these devices are higher than those of the high-confinement devices. The low-confinement residual butt joint reflectivity is in the order of 0.001, which turns out to be sufficient to provide wavelength filtering inside a laser cavity. This filtering narrows the laser spectrum of extended cavity lasers, and causes kinks in the LI-curves. These kinks are associated with spectral hops over wavelengths of typically 1 nm. One can visualize residual butt joint reflections by performing a Fourier transform of a sub-threshold laser spectrum. The residual butt joint reflections also provide wavelength filtering in phased array multi-wavelength lasers; we observed that even within a single phased array passband, a mode hop over 1 nm can occur.

The low-confainment devices operate at rather high currents, as a high material gain is required to achieve threshold. As a consequence, these devices operate in a regime where the quantum well gain is saturating, i.e. where an increase in current density results only in a relatively small increase in gain. As a result, the threshold current density rapidly increases with decreasing amplifier length. Furthermore, at high optical power levels, the decrease in carrier density due to a high stimulated recombination rate also results only in a minor decrease in gain. So in phased array
multi-wavelength lasers, the spatial modulation in the complex refractive index which is caused by beating of longitudinal modes is insufficient to achieve a good single longitudinal mode stability.

In the high-confinement devices, we were able to greatly reduce the residual butt joint reflections by performing a regrowth of InGaAsP material at the passive regions, such that the match between the waveguiding structures in the active and passive regions is improved. So the inter-cavity wavelength filtering is suppressed. As a result, the LI-curves of the extended cavity lasers are smooth, and their emission spectra are broad. The increased confinement factor results in a decrease of the operating currents, and, as compared to similar low-confinement devices, the high-confinement devices operate in a regime where the gain is not yet heavily saturated. Therefore, in multi-wavelength lasers, beating of longitudinal modes can create a spatial modulation in the complex refractive index, which increases the stability of these devices.

It is well known from literature that one can greatly reduce reflections at the cleaved facets of the chip by application of access waveguides which are angled with respect to the crystallographic directions. We demonstrated that in this case it is essential to make sure that the access waveguides support only a single lateral mode.

We applied SA-CBE for the fabrication of an 8-channel phased array multi-wavelength laser which operates CW in a single phased array transmission order, i.e. at eight adjacent wavelengths. The CW threshold currents are as low as 80 mA, the ASE power levels in the next phased array transmission orders are 40 dB below the laser emission power level. The performance of the phased array of this device is comparable to what is common in InP-based Optical Cross Connects. So the successful realization of this device is a clear demonstration of the suitability of SA-CBE for the fabrication of photonic integrated circuits for WDM applications.
Appendix A

MOVPE-grown layer stacks

This appendix gives the epitaxial layer stacks of the commercially purchased MOVPE-grown wafers. Substrate orientation is (100) ± 0.5°, all layers are lattice matched to InP with |Δa/a| < 0.075%. In some cases, etch stop layers were included for integration flexibility, however, these were never used. All values mentioned in the tables are target values. From measurements on test wafers performed by the manufacturer, it follows that doping levels have an accuracy of about ±30 %, layers are usually 5 % too thick, wafer non-uniformity not included.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>25</td>
<td>Zn, &gt;1E+19</td>
</tr>
<tr>
<td>6</td>
<td>InP</td>
<td>cladding</td>
<td>600</td>
<td>Zn, 1E+18</td>
</tr>
<tr>
<td>5</td>
<td>InP</td>
<td>cladding</td>
<td>200</td>
<td>Zn, 5E+17</td>
</tr>
<tr>
<td>4</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>MQW</td>
<td>active layer</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>200</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>S, 3 . . . 8E+18</td>
</tr>
</tbody>
</table>

Table A.1: Layer stack of wafer with 8 nm quantum wells, active layer in center of film layer: fabrication of gain guided devices, wet and dry etched ridge lasers. MQW: 5 x InGaAs well (8 nm) separated by Q(1.25) barriers (10 nm). Serial number EPIQ9601240.
A. MOVPE-grown layer stacks

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>25</td>
<td>Zn, &gt;1E+19</td>
</tr>
<tr>
<td>8</td>
<td>InP</td>
<td>cladding</td>
<td>1000</td>
<td>Zn, 1E+18</td>
</tr>
<tr>
<td>7</td>
<td>InP</td>
<td>cladding</td>
<td>200</td>
<td>Zn, 5E+17</td>
</tr>
<tr>
<td>6</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>MQW</td>
<td>active layer</td>
<td>62.5</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>550</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>buffer</td>
<td>200</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>2</td>
<td>Q(1.25)</td>
<td>etch stop</td>
<td>20</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>200</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>S, 3...8E+18</td>
</tr>
</tbody>
</table>

Table A.2: Layer stack of wafer with 4.5 nm quantum wells, active layer on top of film layer: fabrication of integrated optical amplifiers. MQW: 5 x InGaAs well (4.5 nm) separated by Q(1.25) barriers (10 nm). Serial number EPIQ9604240.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>25</td>
<td>Zn, &gt;1E+19</td>
</tr>
<tr>
<td>8</td>
<td>InP</td>
<td>cladding</td>
<td>1000</td>
<td>Zn, 1E+18</td>
</tr>
<tr>
<td>7</td>
<td>InP</td>
<td>cladding</td>
<td>200</td>
<td>Zn, 5E+17</td>
</tr>
<tr>
<td>6</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>MQW</td>
<td>active layer</td>
<td>62.5</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Q(1.25)</td>
<td>confinement</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>buffer</td>
<td>200</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>2</td>
<td>Q(1.25)</td>
<td>etch stop</td>
<td>20</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>200</td>
<td>S, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>S, 3...8E+18</td>
</tr>
</tbody>
</table>

Table A.3: Layer stack of wafer with 4.5 nm quantum wells, active layer in center of film layer: fabrication of wet etched ridge lasers and integrated optical amplifiers. MQW: 5 x InGaAs wells (4.5 nm) separated by Q(1.25) barriers (10 nm). Serial number EPIQ9605240.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>InP</td>
<td>cladding</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Q(1.30)</td>
<td>film</td>
<td>600</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>1000</td>
<td>S, 2...4E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>S, 3...8E+18</td>
</tr>
</tbody>
</table>

Table A.4: Layer stack of MOVPE-grown DH-wafer used for SA-CBE regrowth of active material. Serial number EPIQ9500487.
## Appendix B

### CBE-grown layer stacks

<table>
<thead>
<tr>
<th>layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>50</td>
<td>Be, 4E+19</td>
</tr>
<tr>
<td>11</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>10</td>
<td>Be, 1E+19</td>
</tr>
<tr>
<td>10</td>
<td>InP</td>
<td>cladding</td>
<td>800</td>
<td>Be, 4E+17</td>
</tr>
<tr>
<td>9</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>Be, 1E+18</td>
</tr>
<tr>
<td>(19 x)</td>
<td>InP</td>
<td>passive MQW barrier</td>
<td>2.55</td>
<td>Be, 1E+16</td>
</tr>
<tr>
<td>8</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>InP</td>
<td>passive MQW barrier</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>(40 x)</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>InGaAs</td>
<td>active MQW well</td>
<td>9.15</td>
<td>-</td>
</tr>
<tr>
<td>(4 x)</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>passive MQW barrier</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>(59 x)</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>InP</td>
<td>buffer</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>497</td>
<td>Si, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>Sn, 1.2E+18</td>
</tr>
</tbody>
</table>

**Table B.1:** Layer stack of CBE-grown InGaAs/InP laser structure. The Ga-fraction in InGaAs is 0.47, except for the passive MQW wells where it is 0.525. Serial number C5146.
### B. CBE-grown layer stacks

<table>
<thead>
<tr>
<th>layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>50</td>
<td>Be, 4E+19</td>
</tr>
<tr>
<td>6</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>10</td>
<td>Be, 1E+19</td>
</tr>
<tr>
<td>5</td>
<td>InP</td>
<td>cladding</td>
<td>890</td>
<td>Be, 4E+17</td>
</tr>
<tr>
<td>4</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs</td>
<td>active MQW well</td>
<td>9.15</td>
<td>-</td>
</tr>
<tr>
<td>(3 x)</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>InGaAs</td>
<td>active MQW well</td>
<td>9.15</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>50</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table B.2:** Layer stack of SA-CBE-regrowth on MOVPE-grown wafers. The Ga-fraction in InGaAs is 0.47. Serial number C518.

<table>
<thead>
<tr>
<th>layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>50</td>
<td>Be, 4E+19</td>
</tr>
<tr>
<td>6</td>
<td>InGaAs</td>
<td>contact layer</td>
<td>10</td>
<td>Be, 1E+19</td>
</tr>
<tr>
<td>5</td>
<td>InP</td>
<td>cladding</td>
<td>615</td>
<td>Be, 4E+17</td>
</tr>
<tr>
<td>4</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs</td>
<td>active MQW well</td>
<td>9.15</td>
<td>-</td>
</tr>
<tr>
<td>(3 x)</td>
<td>InP</td>
<td>active MQW barrier</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>InGaAs</td>
<td>active MQW well</td>
<td>9.15</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>50</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table B.3:** Layer stack of SA-CBE-regrowth on CBE-grown wafers. The Ga-fraction in InGaAs is 0.47. Serial number C519.

<table>
<thead>
<tr>
<th>layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>InP</td>
<td>cladding</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>(63 x)</td>
<td>InP</td>
<td>passive MQW barrier</td>
<td>6.45</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>InP</td>
<td>buffer</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>497</td>
<td>Si, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 $\mu$m</td>
<td>Sn, 2.7E+18</td>
</tr>
</tbody>
</table>

**Table B.4:** Layer stack of CBE-grown DH-wafer used for SA-CBE-regrowth. The Ga-fraction in InGaAs is 0.52. Serial number C510.
<table>
<thead>
<tr>
<th>layer</th>
<th>Material</th>
<th>Description</th>
<th>Thickness (nm)</th>
<th>Dopant (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>InP</td>
<td>cladding</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>InP</td>
<td>passive MQW barrier</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs</td>
<td>passive MQW well</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>InP</td>
<td>buffer</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>InP</td>
<td>buffer</td>
<td>497</td>
<td>Si, 5E+17</td>
</tr>
<tr>
<td>0</td>
<td>InP</td>
<td>substrate</td>
<td>350 μm</td>
<td>Sn, 1.2E+18</td>
</tr>
</tbody>
</table>

**Table B.5:** Layer stack of CBE-grown DH-wafer used for SA-CBE-regrowth. The Ga-fraction in InGaAs is 0.525. Serial number C512.
References


159


Summary

Fiber-optic communication systems can provide the data transmission capacity, the demand for which is ever increasing due to the rapid development of telecom applications such as internet. Especially Wavelength Division Multiplexing (WDM) fiber-optic systems, i.e. systems in which multiple wavelengths are used in parallel, enable optimal exploitation of the available bandwidth. For the implementation of the nodes in a WDM system, one can either use stand-alone components which are connected by means of optical fiber, or one can integrate (a number of) components on a single chip: a Photonic Integrated Circuit (PIC). The use of PICs can be advantageous, as the number of fragile and expensive fiber-chip connections is significantly reduced. The benefits of PICs become most pronounced, however, when one is able to achieve the integration of optical amplifiers. Integrated optical amplifiers do not only enable amplification of WDM signals, but also allow for the realization of functionalities which are hard, or even impossible to achieve by means of stand-alone components. The subject of this thesis is the integration of optical amplifiers in InP-based photonic integrated circuits for WDM applications.

Epitaxial layer stacks which are suitable for the fabrication of optical amplifiers are substantially different from epitaxial layer stacks in which one can fabricate passive waveguide devices. Therefore, a key issue in the fabrication of integrated optical amplifiers is the selection of a suitable integration technology to achieve the definition of (at least) two different epitaxial layer stacks on a single chip. We have carried out the integration using Selective Area Chemical Beam Epitaxy (SA-CBE). This technology enables the fabrication of low-loss butt joints between (in principle) arbitrary layer stacks using only a single regrowth step. The regrowth was performed by our co-workers at the Department of Physics of the Eindhoven University of Technology.

As a first step towards the integration of optical amplifiers, we have fabricated and characterized a number of stand-alone devices, while maintaining compatibility with the passive ridge waveguide devices as fabricated at the Delft University of Technology. In this way, we were able to develop the amplifier device structure and fabrication technology, without yet being troubled by integration issues. These experiments have led to an optical amplifier structure which is based on the Reactive Ion Etched ridge waveguide.

We subsequently carried out a number of integration experiments, and character-
ized the integrated optical amplifiers as extended cavity lasers. The performance of these devices was comparable to that of the non-integrated devices, so SA-CBE does not deteriorate the active (amplifying) material. The butt joint coupling losses were below 0.5 dB/interface in all cases, and even values as low as 0.1 dB/interface were obtained. In one of the integration experiments, we obtained a relatively high butt joint reflection coefficient in the order of 0.001; even though this value may seem quite low, we found that such small residual reflections strongly affect the device performance.

As an important application of integrated optical amplifiers, we fabricated a number of 4-channel and 8-channel phased array Multi Wavelength Lasers (MWLs). CW operation of eight channels in one phased array transmission order was demonstrated. The phased arrays that we used in these devices performed very well, and were similar to the ones that are applied in InP-based Add-Drop Multiplexers and Optical Cross Connects. Therefore, the successful realization of phased array MWLs is a clear demonstration that SA-CBE is suitable for the realization of InP-based PICs for WDM applications.

Peter Harmsma, October 2000
Samenvatting

De snelle groei van telecom diensten, met name op het gebied van internet, veroorzaakt een toenemende vraag naar data transmissie capaciteit. Optische communicatie via glasvezel netwerken kan aan deze vraag voldoen. Optische communicatie houdt in dat informatie via een glasvezel wordt verstuurd in de vorm van lichtpulsen die afkomstig zijn van een gemoduleerde lichtbron, meestal een laser. Door meerdere lasers tegelijkertijd te gebruiken die op verschillende golflengten (kleuren) werken, kan men meerdere signalen ook simultaan door een enkele glasvezel sturen. Op die manier wordt de beschikbare bandbreedte optimaal benut, en is een bestaand netwerk uit te breiden zonder dat de straat moet worden opengebroken. Het simultaan gebruik van meerdere golflengten wordt aangeduid met golflengte multiplexing, ofwel Wavelength Division Multiplexing (WDM).

Voor de implementatie van de knooppunten in een WDM netwerk kan men losse optische componenten gebruiken die onderling zijn verbonden met eindjes glasvezel, of men kan meerdere componenten op een enkele chip fabriceren. Een dergelijke chip noemt met een geïntegreerd optisch circuit, of een Photonic Integrated Circuit (PIC). Een groot voordeel van PICs is dat het aantal chip-glasvezel verbindingen sterk wordt gereduceerd. Dergelijke verbindingen zijn duur en kwetsbaar. De toepassing van geïntegreerde optische circuits wordt bijzonder aantrekkelijk als deze circuits ook optische versterkers bevatten. Optische versterkers zijn niet alleen in staat om de WDM signalen te versterken, maar kunnen ook gebruikt worden voor de realisatie van optische circuits die met losse componenten praktisch niet te maken zijn. Het onderwerp van dit proefschrift is de integratie van optische versterkers in geïntegreerde optische circuits voor WDM toepassingen.

De optische circuits die in dit proefschrift worden beschreven zijn opgebouwd uit een aantal laagjes van het halfgeleider materiaal InGaAsP (Indium Gallium Arseen Phosphor) op InP-substraten. De fracties van de vier genoemde elementen worden zodanig gekozen dat in dit materiaal een transparante optische component (passief materiaal), of juist een versterker kan worden gemaakt (aktief materiaal). De grote uitdaging in de realisatie van geïntegreerde optische versterkers is het definiëren van aktieve en passive gebieden op een enkele chip.

In de aanpak die wij hiertoe hebben gevolgd gaan we uit van een chip die alleen uit aktief materiaal bestaat. We etsen lokaal het aktieve materiaal weg, om de ontstane
laagliggende delen vervolgens weer ‘op te vullen’ met passief materiaal. Dit ‘opvullen’ moet bijzonder netjes gebeuren, het eindresultaat is in principe een enkel kristal; ‘opvullen’ is dan ook een tamelijk oneerbiedige naam voor ‘groeien’, oftewel epitaxie. De in dit proefschrift toegepaste epitaxiale technologie is Chemische Bundel Epitaxie (CBE), waarbij de groei alleen lokaal plaatsvindt: Selective Area Chemical Beam Epitaxy (SA-CBE). Deze technologie maakt het mogelijk om actieve en passieve gebieden op een chip te definiëren in een enkele selectieve groeistap, waarbij de aansluiting tussen deze gebieden van hoge kwaliteit is. Alle lokale groeistappen zijn uitgevoerd door onze collega’s van de faculteit Natuurkunde aan de Universiteit Eindhoven.

Als eerste stap naar de realisatie van geïntegreerde optische versterkers hebben we een aantal losse versterkers en lasers gemaakt, waarbij de compatibiliteit met de transparante componenten niet uit het oog werd verloren. Op die manier konden we een optische versterker ontwikkelen zonder dat groei-technische aspecten de zaak nodeloos ingewikkeld maakten. Het eindresultaat was een optische versterker die is gebaseerd op de droog-geëetste ridge-golfgeleider structuur.

Vervolgens hebben we een aantal integratie experimenten uitgevoerd, en de geïntegreerde optische versterkers gekarakteriseerd als lasers met een passief stuk golfgeleider: een z.g. Extended Cavity Laser. Deze lasers werken praktisch net zo goed als de losse lasers, dus onze integratie technologie heeft geen nadelig effect op de kwaliteit van de actieve materialen. De koppelverliezen tussen de aktieve en passieve gebieden waren kleiner dan 0.5 dB, soms zelfs 0.1 dB. Reflecties aan de overgangen waren in een enkel experiment relatief hoog: ongeveer 0.001. Dat lijkt weinig, maar deze reflecties hebben een grote invloed op de werking van een component of circuit.

Als demonstratie van een belangrijke toepassing van geïntegreerde optische versterkers hebben we een aantal meer-kleuren-lasers gemaakt, zowel 4-kanaals als 8-kanaals exemplaren. Onder andere demonstreerden wij laser werking in acht aansluitende golflengtes. Het golflengte filter in deze lasers, de z.g. phased array, is een essentieel onderdeel in optische circuits die nodig zijn in de eerder genoemde WDM netwerken. Dit filter, dat gefabriceerd was in gehergroeid materiaal, werkte in alle gevallen uitstekend. Hieruit concluderen wij dat onze integratie technologie SA-CBE uitstekend geschikt is voor de fabricage van geïntegreerde optische circuits voor toepassing in WDM netwerken.

Peter Harmsma, Oktober 2000
Dankwoord

In films en boeken worden wetenschappers nogal eens neergezet als wereldvreemde figuren die contact met andere mensen zoveel mogelijk uit de weg gaan. Ze sluiten zich bij voorkeur op in een laboratorium, om daar in volstrekte eenzaamheid onbegrijpelijke dingen te doen. Als in een film weer eens zo'n 'wetenschapper' wordt geïntroduceerd moet ik altijd een beetje glimlachen, want in werkelijkheid gaat het allemaal heel anders. Het werk dat ik in dit proefschrift heb beschreven had ik nooit helemaal in m'n eentje kunnen doen, en ik wil graag iedereen die een steentje heeft bijgedragen van harte bedanken.

Hierbij denk ik in de eerste plaats natuurlijk aan Meint Smit en Siang Oei. Verhalen over onbereikbare promotoren zijn mij vreemd; de dagelijkse begeleiding was uitstekend, en ik vond altijd een luisterend oor, niet alleen voor vragen maar ook voor ideeën. Er was een grote vrijheid, en voor de aanschaf van (prijzige) apparatuur waren altijd wel mogelijkheden. Ook wil ik Hans Blok bedanken voor zijn rol als promotor, en voor zijn waardevolle input bij het schrijven van dit proefschrift. Verder wil ik graag Maarten Leys, Chris Doerr, Prof. Kaufmann, Prof. van Daele en Prof. Braat van harte bedanken voor hun bereidheid zitting te nemen in mijn commissie.

In de afgelopen vijf jaar heb ik met heel wat collega's samengewerkt. Mijn eerste kamergenoot Kees Vreeburg bracht mij de fijne kneepjes van het processen bij. Ik weet ook nog dat ik verbaasd stond te kijken hoe Kees een meetopstelling in drie minuten uitlijnde, terwijl ik daar zelf al de hele middag tevergeefs mee bezig was geweest. Die handigheid heb ik gelukkig zelf ook snel verworven. Verder gaat mijn dank uit naar Cor van Dam, met name vanwege die thermoskan koffie in de auto naar Eindhoven, en voor zijn hulp met MDS. Het gebruik van computers in het algemeen was hoe dan ook onmogelijk geweest zonder de support van Xaveer Leijtens.

Hoewel ze al bijna vertrokken waren toen ik begon, heb ik met Kees Steenbergen, Leo Spiekman en Tammo Uitterdijk heel wat nuttige discussies gevoerd. En Leo, bedankt voor het AR-coaten van mijn samletjes! Ook aan de AR-coatings van Adri Looyen heb ik veel gehad, en zonder zijn vele nanometers titaan, platina en goud hadden mijn versterkertjes het nooit gedaan.

Onmisbare inbreng was er met name van Koos van Uffelen, die ervoor zorgde dat het paviljoen operationeel bleef. Bovendien was hij er altijd als je zijn hulp nodig had, en heeft hij bijna altijd een goed humeur! Ook de technische ondersteuning
van Aad de Vreede, Frans van Ham, Tom Scholtes en Tjibbe de Vries was van groot belang. In de beginperiode zorgden Ed Metaal en Jørgen Pedersen voor de nodige process faciliteiten bij KPN Research. Anja Suurling, bedankt voor de maskers met de bananen!

Essentiële inbreng was er natuurlijk vanuit de Universiteit Eindhoven. Maarten Leys, Coen Verschuren en Bert Vonk: zonder jullie was er helemaal niks gebeurd, dit proefschrift weerspiegelt het belang van inter-universitaire samenwerking. Ik wens ook Jos Haverkort, Bas Dorren en Jos van der Tol veel succes in de toekomst. Martin Hill, bedankt voor de hoge-resolutie metingen aan mijn multi-wavelength lasertjes. Fouad Karouta bood de mogelijkheid om in Eindhoven mijn eerste gepulste metingen te doen, en Eduard Tangdiongga en Johan van Zantvoort, dat was te gek met die skibox in Madrid! De conferenties waren hoe dan ook erg gezellig, niet in de laatste plaats dankzij de pijnprokende Huig de Waardt.


Ook wil ik iedereen van de vakgroep optica bedanken voor de prettige jaren. Fokke Groen die overal wel iets zinnigs over kan zeggen, en Youchai Zhu de technoloog: het was me een waar genoegen. Peter Maat, ik hoop dat je geen blijvend letsel oploopt van al die mensa maaltijden!

Men zegt wel eens dat studenten meer tijd kosten dan ze opleveren, maar de resultaten van Annemarie Bloot, Mats Fillerup en Peter Tettelaar waren uiterst nuttig. Alle studenten die onze groep hebben bezocht wil ik graag bedanken voor de gezelligheid en (on) zinnige gesprekstof. Mia van der Voort, Wendy Murtinu-Schagen en Henriette Alemgeest, bedankt voor de secretariële ondersteuning, zonder jullie had ik nog geen schrijfblokje gehad! Verder wens ik Heino Bukkems en mijn voormalige kamergenote Annet Siefke veel succes toe.

Dit proefschrift was een stuk minder leesbaar geweest zonder het correctiewerk van Mirjam Nieman. Niet alleen ik ben haar uiterst dankbaar, ook U, lezer, bent haar grote dank verschuldigd! Herman Kempers en Arjan van der Raadt, bedankt voor alle grafische ondersteuning!

Tot slot wil ik mijn familie bedanken voor alle steun, niet alleen gedurende de laatste vijf jaar, maar ook tijdens mijn studie in Twente. Zonder de steun van thuis in Dokkum had ik de stap om te gaan promoveren nooit kunnen zetten.

Peter Harmsma, Oktober 2000
# List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>speed of light</td>
<td>$2.99792 \cdot 10^8$</td>
<td>m/s</td>
</tr>
<tr>
<td>$e$</td>
<td>elementary charge</td>
<td>$1.60219 \cdot 10^{-19}$</td>
<td>C</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>permittivity in vacuum</td>
<td>$8.85419 \cdot 10^{-12}$</td>
<td>F m$^{-1}$</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
<td>$6.62618 \cdot 10^{-34}$</td>
<td>Js</td>
</tr>
<tr>
<td>$\hbar$</td>
<td>$h/2\pi$</td>
<td>$1.05459 \cdot 10^{-34}$</td>
<td>Js</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann’s constant</td>
<td>$1.38066 \cdot 10^{-23}$</td>
<td>JK$^{-1}$</td>
</tr>
<tr>
<td>$m_0$</td>
<td>atomic mass unit</td>
<td>$1.66054 \cdot 10^{-27}$</td>
<td>kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>magnetic vector potential</td>
<td></td>
<td>V sm$^{-1}$</td>
</tr>
<tr>
<td>$A$</td>
<td>area</td>
<td></td>
<td>m$^2$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>loss</td>
<td></td>
<td>cm$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_{act}$</td>
<td>loss in active section</td>
<td></td>
<td>cm$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_{enh}$</td>
<td>linewidth enhancement factor</td>
<td></td>
<td>cm</td>
</tr>
<tr>
<td>$\alpha_{joint}$</td>
<td>butt joint coupling loss</td>
<td></td>
<td>cm$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>distributed mirror loss</td>
<td></td>
<td>cm$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_{pass}$</td>
<td>loss in passive section</td>
<td></td>
<td>cm$^{-1}$</td>
</tr>
<tr>
<td>$b$</td>
<td>barrier width</td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>$\beta$</td>
<td>differential gain</td>
<td></td>
<td>cm k A$^{-1}$</td>
</tr>
<tr>
<td>$D$</td>
<td>diffusion coefficient</td>
<td></td>
<td>m$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>spin-orbital splitting energy</td>
<td></td>
<td>eV</td>
</tr>
<tr>
<td>$\Delta E_c$</td>
<td>conduction band offset</td>
<td></td>
<td>eV</td>
</tr>
<tr>
<td>$\Delta E_v$</td>
<td>valence band offset</td>
<td></td>
<td>eV</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field</td>
<td></td>
<td>V m$^{-1}$</td>
</tr>
<tr>
<td>$E$</td>
<td>energy</td>
<td></td>
<td>eV</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit 1</td>
<td>Unit 2</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>$E_g$</td>
<td>bandgap energy</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{g, \text{bar}}$</td>
<td>bandgap energy barrier</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{g, \text{well}}$</td>
<td>bandgap energy well</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_n$</td>
<td>numbered energy level</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{c,n}$</td>
<td>numbered energy level conduction band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{v,n}$</td>
<td>numbered energy level valence band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{FC}$</td>
<td>Fermi energy conduction band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{FV}$</td>
<td>Fermi energy valence band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$E_{ph}$</td>
<td>photon energy</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$\varepsilon_c$</td>
<td>energy with respect to bottom of conduction band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$\varepsilon_v$</td>
<td>energy with respect to top of valence band</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>$f_c$</td>
<td>conduction band fermi function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{c,n}$</td>
<td>conduction band fermi function in quantum well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_v$</td>
<td>valence band fermi function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{v,n}$</td>
<td>valence band fermi function in quantum well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_n$</td>
<td>noise figure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g$, $g_0$</td>
<td>material gain</td>
<td>cm$^{-1}$</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$G$, $G_0$</td>
<td>modal gain</td>
<td>cm$^{-1}$</td>
<td>m$^{-1}$</td>
</tr>
<tr>
<td>$G_{rt}$</td>
<td>round-trip gain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_d$</td>
<td>differential efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_i$</td>
<td>injection efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>height</td>
<td>nm</td>
<td>m</td>
</tr>
<tr>
<td>$I$</td>
<td>current</td>
<td>mA</td>
<td>A</td>
</tr>
<tr>
<td>$I_{lat}$</td>
<td>lateral leakage current</td>
<td>mA</td>
<td>A</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>threshold current</td>
<td>mA</td>
<td>A</td>
</tr>
<tr>
<td>$I_o$</td>
<td>reverse bias saturation current, transparency current</td>
<td>mA</td>
<td>A</td>
</tr>
<tr>
<td>$J$</td>
<td>current density</td>
<td>kAcm$^{-2}$</td>
<td>Am$^{-2}$</td>
</tr>
<tr>
<td>$J_{th}$</td>
<td>threshold current density</td>
<td>kAcm$^{-2}$</td>
<td>Am$^{-2}$</td>
</tr>
<tr>
<td>$J_0$</td>
<td>transparency current density</td>
<td>kAcm$^{-2}$</td>
<td>Am$^{-2}$</td>
</tr>
<tr>
<td>$k$, $K$</td>
<td>wave vector</td>
<td>m$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$k_c$</td>
<td>conduction band wave vector</td>
<td>m$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$k_v$</td>
<td>valence band wave vector</td>
<td>m$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>confinement factor</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>$L$</td>
<td>length (device, diffusion)</td>
<td>$\mu$m</td>
<td>m</td>
</tr>
<tr>
<td>$L_{\text{act}}$</td>
<td>active section length</td>
<td>$\mu$m</td>
<td>m</td>
</tr>
<tr>
<td>$L_{\text{chip}}$</td>
<td>chip length</td>
<td>$\mu$m</td>
<td>m</td>
</tr>
<tr>
<td>$L_{\text{opt}}$</td>
<td>optimal active section length to minimize $I_{th}$</td>
<td>$\mu$m</td>
<td>m</td>
</tr>
<tr>
<td>$L_{\text{pass}}$</td>
<td>passive section length</td>
<td>$\mu$m</td>
<td>m</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
<td>nm</td>
<td>m</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
<td>$m_0$</td>
<td>kg</td>
</tr>
<tr>
<td>$m_b$</td>
<td>mass in MQW barrier</td>
<td>$m_0$</td>
<td>kg</td>
</tr>
<tr>
<td>$m_e$</td>
<td>electron mass</td>
<td>$m_0$</td>
<td>kg</td>
</tr>
<tr>
<td>$m_h$</td>
<td>hole mass (light or heavy)</td>
<td>$m_0$</td>
<td>kg</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit 1</td>
<td>Unit 2</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>( m_{hh} )</td>
<td>heavy hole mass</td>
<td>( m_0 )</td>
<td>kg</td>
</tr>
<tr>
<td>( m_{lh} )</td>
<td>light hole mass</td>
<td>( m_0 )</td>
<td>kg</td>
</tr>
<tr>
<td>( m_r )</td>
<td>reduced mass</td>
<td>( m_0 )</td>
<td>kg</td>
</tr>
<tr>
<td>( m_w )</td>
<td>mass in MQW well</td>
<td>( m_0 )</td>
<td>kg</td>
</tr>
<tr>
<td>( M )</td>
<td>matrix transition element</td>
<td>kg J</td>
<td></td>
</tr>
<tr>
<td>( M_{bulk} )</td>
<td>bulk matrix transition element</td>
<td>kg J</td>
<td></td>
</tr>
<tr>
<td>( M_{hh} )</td>
<td>heavy hole matrix transition element</td>
<td>kg J</td>
<td></td>
</tr>
<tr>
<td>( M_{lh} )</td>
<td>light hole matrix transition element</td>
<td>kg J</td>
<td></td>
</tr>
<tr>
<td>( n )</td>
<td>refractive index</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( n_g )</td>
<td>group refractive index</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( n_i )</td>
<td>intrinsic carrier density</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( n_n )</td>
<td>n-type carrier density in n-region</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( n_p )</td>
<td>n-type carrier density in p-region</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( N )</td>
<td>carrier density</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( v )</td>
<td>frequency</td>
<td>s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>( p_n )</td>
<td>p-type carrier density in n-region</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( p_p )</td>
<td>p-type carrier density in p-region</td>
<td>cm(^{-3})</td>
<td>m(^{-3})</td>
</tr>
<tr>
<td>( P )</td>
<td>power</td>
<td>W</td>
<td>Js(^{-1})</td>
</tr>
<tr>
<td>( P_s )</td>
<td>saturation power</td>
<td>W</td>
<td>Js(^{-1})</td>
</tr>
<tr>
<td>( P_{s,\text{out}} )</td>
<td>saturation output power</td>
<td>W</td>
<td>Js(^{-1})</td>
</tr>
<tr>
<td>( q )</td>
<td>wave vector</td>
<td>m(^{-1})</td>
<td></td>
</tr>
<tr>
<td>( Q )</td>
<td>modulation depth</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( r )</td>
<td>electric field reflection coefficient</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( R )</td>
<td>power reflection coefficient</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( r, R )</td>
<td>vector</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>( \rho )</td>
<td>density of states</td>
<td>J(^{-1}) m(^{-3})</td>
<td></td>
</tr>
<tr>
<td>( \rho_r )</td>
<td>reduced density of states</td>
<td>J(^{-1}) m(^{-3})</td>
<td></td>
</tr>
<tr>
<td>( t )</td>
<td>time</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>( t )</td>
<td>electric field transmission coefficient</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( T )</td>
<td>temperature</td>
<td>°C</td>
<td>K</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>characteristic temperature</td>
<td>°C</td>
<td>K</td>
</tr>
<tr>
<td>( T_{\text{joint}} )</td>
<td>butt joint transmission coefficient</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( T_{\text{PH}} )</td>
<td>phased array transmission coefficient</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( U(x, y) )</td>
<td>intensity distribution</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( V )</td>
<td>potential</td>
<td>eV</td>
<td>J</td>
</tr>
<tr>
<td>( V )</td>
<td>volume</td>
<td>cm(^3)</td>
<td>m(^3)</td>
</tr>
<tr>
<td>( V )</td>
<td>voltage</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>( v_g )</td>
<td>group velocity</td>
<td>ms(^{-1})</td>
<td></td>
</tr>
<tr>
<td>( w )</td>
<td>(quantum well) width</td>
<td>nm</td>
<td>m</td>
</tr>
<tr>
<td>( w_{\text{eff}} )</td>
<td>effective ridge width</td>
<td>( \mu ) m</td>
<td>m</td>
</tr>
<tr>
<td>( w_{\text{open}} )</td>
<td>contact opening width</td>
<td>( \mu ) m</td>
<td>m</td>
</tr>
<tr>
<td>( w_{\text{ridge}} )</td>
<td>ridge width</td>
<td>( \mu ) m</td>
<td>m</td>
</tr>
<tr>
<td>( \psi )</td>
<td>wavefunction</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>( \omega )</td>
<td>angular frequency</td>
<td>rad s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADM</td>
<td>Add-Drop Multiplexer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>Anti Reflection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBE</td>
<td>Chemical Beam Epitaxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBR</td>
<td>Distributed Bragg Reflector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DFB</td>
<td>Distributed FeedBack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMX</td>
<td>DeMultipleXer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECL</td>
<td>Extended Cavity Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOS</td>
<td>Electro-Optical Switch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPR</td>
<td>Free-Propagation Region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPIB</td>
<td>General Purpose Interface Bus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR</td>
<td>High Reflection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular Beam Epitaxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MFC</td>
<td>Mass Flow Controller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMI</td>
<td>Multi-Mode Interference (coupler)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOVPE</td>
<td>Metal-Organic Vapor Phase Epitaxy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MQW</td>
<td>Multi Quantum Well</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX</td>
<td>MUltipleXer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLW</td>
<td>Multi-Wavelength Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MWR</td>
<td>Multi-Wavelength Receiver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OXC</td>
<td>Opticalal Cross Connect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>Polarization Controller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PE-CVD</td>
<td>Plasma-Enhanced Chemical Vapor Depostion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHM</td>
<td>Phase Modulator</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

181
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIC</td>
<td>Photonic Integrated Circuit</td>
</tr>
<tr>
<td>PL</td>
<td>Photo-Luminescence</td>
</tr>
<tr>
<td>PWD</td>
<td>Passive Waveguide Device</td>
</tr>
<tr>
<td>RHEED</td>
<td>Reflective High Energy Electron Diffraction</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>RTP</td>
<td>Rapid Thermal Processor</td>
</tr>
<tr>
<td>SA-CBE</td>
<td>Selective Area Chemical Beam Epitaxy</td>
</tr>
<tr>
<td>SAE</td>
<td>Selective Area Epitaxy</td>
</tr>
<tr>
<td>SC</td>
<td>Separate Confinement</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SIPBH</td>
<td>Semi-Insulating blocked Planar Buried Heterostructure</td>
</tr>
<tr>
<td>SMSR</td>
<td>Side Mode Supression Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SSC</td>
<td>SpotSize Converter</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermo-Electric Cooler</td>
</tr>
<tr>
<td>TLS</td>
<td>Tunable Laser Source</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross-Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
</tr>
</tbody>
</table>
Curriculum Vitæ

Peter Harmsma was born in Dokkum, The Netherlands, on January 23rd 1969. After receiving his VWO diploma from the ‘Christelijke Scholengemeenschap Oostergo’ in Dokkum in 1987, he studied Applied Physics at the University of Twente. The subject of his graduation work was experimental and theoretical aspects of Laser Doppler measurements on turbid media as applied in skin blood flow velocity measurements. After his graduation in 1993, he fulfilled his military service as a platoon commander in the rank of 2nd lieutenant, infantry, at the Johannes Post Kazerne in Havelte. In 1995 he started his PhD research at the Photonic Integrated Circuits Group, Delft University, on the integration of optical amplifiers in InP-based Photonic Integrated Circuits.
List of publications


