Doctoral Thesis

Plasma etched optical mirrors and grating demultiplexers in InGaAsP/InP

Author(s):
Gini, Emilio

Publication Date:
1997

Permanent Link:
https://doi.org/10.3929/ethz-a-001805873

Rights / License:
In Copyright - Non-Commercial Use Permitted

This page was generated automatically upon download from the ETH Zurich Research Collection. For more information please consult the Terms of use.
Plasma Etched
Optical Corner Mirrors and
Grating Demultiplexers
in InGaAsP / InP

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

for the degree of
Doctor of Natural Sciences

presented by

Emilio Gini
dipl. Phys. ETH
born September 20th, 1961
citizen of Davos GR, Switzerland

accepted on the recommendation of
Prof. Dr. H. Melchior, examiner
Prof. Dr. P. Günter, co-examiner

1997
I was often in error,
but never in doubt.

to my family
# Contents

Abstract 1

Zusammenfassung 3

1. Introduction 5
   1.1. Context and motivation of this thesis 6
   1.2. Optical corner mirrors: state of the art in 1996 8
   1.3. Optical wavelength demultiplexers: state of the art in 1996 11
   1.4. Outline of the thesis 14
   1.5. References 15

2. Integrated optical waveguide corner mirrors in InGaAsP/InP 19
   2.1. Introductory overview 20
   2.2. Low loss corner mirrors with 45° deflection angle for integrated optics: Paper A 23
   2.3. Low loss self-aligned optical waveguide corner mirrors in InGaAsP/InP: Paper B 28
   2.4. Measurements of loss and mirror reflectivity in semiconductor optical waveguides: a European interlaboratory comparison experiment: Paper C 33
   2.5. Additional results on corner mirrors 39
   2.6. Applications of corner mirrors 50
   2.7. Conclusions 57
   2.8. References 58

3. Dry etching techniques 61
   3.1. Introductory overview 62
   3.2. Principles of plasma etching 64
   3.3. Available plasma etching equipment 81
3.4. Process development  86
3.5. Results  102
3.6. Conclusions  108
3.7. References  109

4. **InP Grating demultiplexers and their applications**  115
   4.1. Introductory overview  116
   4.2. Polarization independent InP WDM multiplexer/demultiplexer module: Paper D  118
   4.3. Design of demultiplexers  134
   4.4. Packaged 2.5 Gb/s 4-channel WDM receiver module with InP grating demultiplexer and pin-JFET receiver array: Paper E  151
   4.5. Additional results on grating demultiplexers  156
   4.6. The refractive index of InP and its temperature dependence measured with optical demultiplexers  170
   4.7. Conclusions  177
   4.8. References  178

5. **Conclusions and outlook**  185
   5.1. Conclusions  186
   5.2. Outlook  188
   5.3. References  190

List of symbols and constants  191

List of Publications  193

Curriculum vitae  197

Acknowledgments  199
Abstract

This thesis deals with the realization and application of two examples of integrated optical reflectors in InP: corner mirrors and grating wavelength demultiplexers.

Corner mirrors based on the principle of total internal reflection are used as an alternative to waveguide bends for low-loss, compact directional changes of optical beams. The most important parameter is their optical loss. For a reduction of the sensitivity of mirror losses on facet deviations from verticality, we have developed a new design of corner mirrors with 45 degrees deflection angle. Rules for an optimized design are derived from a study of mirrors with variable facet positions, waveguide widths, deflection angles and different geometries in the transition regions in front of the mirrors.

Using a waveguide to mirror self-alignment technique we fabricated such mirrors in InGaAsP/InP with losses as low as 0.3 dB per corner mirror. Facet roughness and non-verticatity are found to be the dominant loss mechanisms. As the fabrication process of the mirrors is compatible with the fabrication of active integrated optic devices, polarization independent optical modulators and low crosstalk waveguide crossings are realized with the help of integrated corner mirrors.

The main problem in corner mirror fabrication is to achieve smooth vertical facets at precisely defined positions. The fabrication of masks is optimized for the realization of self-aligned features. The principles of plasma etching are considered with particular emphasis on process parameters at the disposal of operators. The influence of RF power, pressure and gas composition on the etching results is theoretically modeled and experimentally determined. Based on this knowledge, plasma etching processes with hydrogen/methane gas mixtures are developed that push the limits of dry etching. We achieved smooth mirror facets whose deviation from verticality is less than 1 degree, with etching rates up to 250 nm/min.

A grating demultiplexer is a more advanced application of a reflector. Instead of one mirror facet that reflects light from one waveguide into another, a grating is built from several hundreds of small mirrors that not only reflect light, but due to the correlated positions of the individual mirrors also work as dispersive elements. Based on this concept, we designed and fabricated InP grating
demultiplexers for fiber optical links using wavelength division multiplexing (WDM).

Problems encountered were the polarization sensitivity, the absolute wavelength allocation of the demultiplexer passbands and the optical losses. We developed a grating multiplexer/demultiplexer (MUX/DEMUX) with a large-core n/n⁺-InP waveguide structure with the advantages of easy and homogeneous layer growth, very low birefringence, high coupling efficiency to optical single mode fibers and accurate control of the refractive index. The design of the demultiplexer is optimized in terms of resolution, aberrations and efficiency.

A fully packaged wavelength demultiplexer in InP was developed and realized that separates four channels with 4 nm wavelength spacing in the 1.55 μm window. The TE/TM shift of the filter passbands is less than 0.1 nm. Optical crosstalk is less than -17 dB and fiber to fiber losses of 15 dB are achieved. The demultiplexer is designed for self-aligned flip-chip mounting on a silicon motherboard in order to optically couple light from the waveguides to an array of lensed single mode fibers with measured coupling efficiencies higher than 80%. The package includes temperature control that allows for fine-tuning of the channel passbands over a range of more than 5 nm. The fabrication of the demultiplexers relies on the further improved plasma etching technique for the definition of the deeply etched diffractive grating.

The grating demultiplexer has been tested in a WDM transmission experiment. Hybridized with a 4-channel receiver array we demonstrated the error-free detection of a 4 × 2.5 Gbit/s WDM transmission. The sensitivity of the WDM receiver is improved by 30 dB with the insertion of erbium doped optical fiber pre-amplifiers, without the need of additional narrow-band filtering.

Besides the application in WDM transmission systems, the grating demultiplexer allows measurements of the effective refractive index of planar waveguide structures. With our modules we measured the refractive index of InP in the wavelength range from 1.2 μm to 1.6 μm with a relative accuracy of 2×10⁻⁴ and its temperature dependence. The refractive index varies linearly with temperature with a coefficient between 2.3 and 1.9×10⁻⁴/K. This method has also been applied to the measurement of the effective index of planar InP/InGaAsP/InP doublehetero waveguide structures with an absolute accuracy of better than 0.001.
Zusammenfassung


Ein Gitterspektrograph ist eine komplexere Anwendung von Reflektoren. Anstelle eines Spiegels, der Licht von einem Wellenleiter in den andern reflektiert, ist ein Gitter aus hunderten von kleinen Fazetten aufgebaut, die das Licht

Hauptschwierigkeiten für Wellenlängenfilter sind die Polarisationsabhängigkeit, die Kontrolle der absoluten Werte der Durchlaß-Wellenlängen und die optischen Verluste. Wir entwickelten eine einfache n+/n-InP Wellenleiterstruktur, die homogen hergestellt werden kann, mit kleiner Doppelbrechung und genau definiertem effektiven Brechungsindex. Mit einem theoretischen Modell wird der Gitterspektrograph optimiert in bezug auf Auflösung, Bildfehler und Effizienz.


Der Gitterspektrograph erlaubt Messungen des effektiven Brechungsindexes von planaren Wellenleiterstrukturen mit hoher Genauigkeit. Mit unseren Modulen haben wir den Brechungsindex von InP im Wellenlängenbereich von 1.2 μm bis 1.6 μm mit einer relativen Genauigkeit von 2×10⁻⁴ bestimmt, sowie dessen Temperaturabhängigkeit. Wir finden eine lineare Abhängigkeit des Brechungsindexes von InP von der Temperatur mit wellenlängenabhängigen Koeffizienten zwischen 2.3 und 1.9×10⁻⁴/Kelvin. Mit dieser Methode wurden auch effektive Brechungsindices von InP/InGaAsP/InP Doppelhetero-Wellenleiterstrukturen mit einer absoluten Genauigkeit von 0.001 gemessen.
1. Introduction
1.1. Context and motivation of this thesis

Communication and telecommunication have been important to mankind for a long time. Since the discovery of electro-magnetic waves and the invention of the telephone, an increasing part of data has been processed as electronic signals. From 1960 onwards, there started an immense effort to fabricate electronic integrated circuits. Integration of electronic components on one chip resulted in increased performance, reliability, reduced size and power consumption. The possibility of mass production resulted in a reduced price per chip.

Towards 1970, the revolution in optical telecommunications has been initiated by the development of the low-loss glass fiber and the realization of room temperature continuous wave semiconductor lasers. Data started to be transmitted as optical signals. The wavelengths of interest are in the 1.3 \mu m and 1.55 \mu m windows, in which the optical fibers exhibit zero dispersion and lowest loss, respectively. Optical data transmission initiated not only the need for optical sources and detectors, but also the demand for additional optical data processing.

In 1969, S. E. Miller created the expression “Integrated Optics” [1.1]. Integrated optics is based on the guiding of electro-magnetic energy at optical frequencies by thin films. It aims at the realization of several optical components on a single substrate. Vigorous efforts to investigate and develop a sound and reliable thin film technology for optical communication purposes have been undertaken.

Opto-electronics deals with the integration of optical and electronic functions on a single chip. A special role has been played by semiconductors, which now appear to be most promising in promoting the goal of opto-electronic integrated circuits (OEIC’s). The semiconductor laser, a combination of laser and integrated electronics may be considered as the first product of opto-electronics.

InP and lattice matched In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ is the material of choice for opto-electronics because its bandgap can be adjusted to energies corresponding to wavelengths of interest for fiber optical communication between 0.92 \mu m and 1.65 \mu m. Epitaxial layers for optical sources, detectors, waveguides and switches operating at wavelengths of 1.3 \mu m and 1.55 \mu m, as well as for electronic circuits can be grown on the same substrate.

New functionalities, increase of reliability and the reduction of cost are driving forces for integration not only in electronics but also in integrated optics. The components studied in this thesis, integrated optical corner mirrors and
1.1. Context and motivation of this thesis

Wavelength demultiplexers based on reflective gratings, contribute and demonstrate the potential of opto-electronic devices towards high performance and high packaging density.

This thesis reports developments and results obtained in the frame of European projects on optical communication that aimed to develop and demonstrate key technologies and components required for the evolution towards integrated optical networks. Especially mentioned are the RACE (Research and Development in Advanced Communications-Technologies in Europe) project OSCAR (1988-1992, Optical Switching Systems, Components and Applications Research), in which the integrated optical corner mirrors were developed and the ESPRIT (European Strategic Programme for Research and Development in Information Technology) project MOSAIC (1992-1995, Monolithic and hybrid Optoelectronic Smart Assembled Integrated Circuits), for which we realized the grating demultiplexers.

The opportunity of collaboration in these two projects, as well as in other RACE II, ACTS and COST projects, with many personal contacts to other research groups throughout Europe was a valuable experience in my research activity.

7
1.2. Optical corner mirrors: state of the art in 1996

Waveguides with large angle directional changes are an important part of high-packing density integrated optical circuits. They are necessary in order to reduce the large length to width ratios of waveguide chips consisting of several coupled devices. They are also essential in the input and output ports of electro-optical switches and modulators for the separation of parallel waveguides to a distance suitable for fiber coupling. The large radii required for bends of semiconductor waveguides without strong lateral guiding renders them very space consuming. Abrupt directional changes (corner bends) allow only for small displacement angles. Corner mirrors based on total internal reflection are well suited because of their compactness. Fig. 1.1 shows applications that take advantage of integrated corner mirrors.

![Diagram of corner mirrors](image)

Device connection  Waveguide separation  Waveguide crossing

Fig. 1.1 Applications that take advantage of integrated waveguide corner mirrors.

To be practically useful, such corner mirrors must have low optical losses and be compatible in their fabrication with other waveguide structures. Fig. 1.2 illustrates the fabrication of corner mirrors. The waveguides and the mirror facet are defined by two different masks and etched into the material. For low loss, precise lateral position and angular orientation of the mirror relative to the waveguides are mandatory. Corner mirrors based on this masking technique were first demonstrated 1984 on photoelastic GaAs waveguides [1.2] with wet chemically etched mirror facets. The first dry etched corner mirrors in GaAs were reported in 1985 [1.3]. The advantages of dry etching are almost vertical etch profiles that are independent of the orientation of the mirror facet and with no mask undercut.
1.2. Optical corner mirrors: state of the art in 1996

Fig. 1.2 Fabrication of corner mirrors. The waveguides are structured by a first mask and the mirror facet is defined by a second mask that is aligned with respect of the position of the waveguides to be connected.

With a self-aligned technique corner mirrors with perfect alignment of the mirror facet in terms of horizontal angle and lateral shift have been obtained [1.4]. The fabrication process of these corner mirrors is illustrated in Fig. 1.3.

Fig. 1.3 Fabrication of self-aligned corner mirrors. The mirror facet and the waveguides are defined by the same mask level. The purpose of the second mask is to limit the area that is deeply etched.
1. Introduction

With the self-alignment technique the impact of misalignment of the second mask on mirror misorientation and hence increased loss was eliminated. Surface roughness and deviations from facet verticality are the remaining major contributors to the mirror losses and strongly related to the quality of the etching of the mirror facet. Corner mirrors were realized by a number of research groups in GaAs based as well as in InP based III-V semiconductor compounds. Reported results are listed in Tab. 1.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Material</th>
<th>Typical loss/mirror</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>GaAs</td>
<td>2.6 dB</td>
<td>[1.2]</td>
</tr>
<tr>
<td>1985</td>
<td>GaAs</td>
<td>1.6 dB</td>
<td>[1.3]</td>
</tr>
<tr>
<td>1987</td>
<td>InGaAsP/InP</td>
<td>1.5 dB</td>
<td>[1.4]</td>
</tr>
<tr>
<td>1989</td>
<td>AlGaAs/GaAs</td>
<td>2 dB</td>
<td>[1.5]</td>
</tr>
<tr>
<td>1990</td>
<td>AlGaAs/GaAs</td>
<td>5 dB</td>
<td>[1.6]</td>
</tr>
<tr>
<td>1992</td>
<td>AlGaAs/GaAs</td>
<td>0.5 dB</td>
<td>[1.7]</td>
</tr>
<tr>
<td>1993</td>
<td>InGaAsP/InP</td>
<td>1 dB</td>
<td>[1.8]</td>
</tr>
<tr>
<td>1993</td>
<td>InGaAsP/InP</td>
<td>0.6 dB</td>
<td>[1.9]</td>
</tr>
<tr>
<td>1994</td>
<td>InGaAs/GaAs</td>
<td>2.7 dB</td>
<td>[1.10]</td>
</tr>
<tr>
<td>1995</td>
<td>InGaAs/GaAs/AlGaAs</td>
<td>0.5 dB</td>
<td>[1.11]</td>
</tr>
<tr>
<td>1992</td>
<td>InGaAsP/InP</td>
<td>0.3 dB</td>
<td>Section 2.2</td>
</tr>
<tr>
<td>1992</td>
<td>InGaAsP/InP</td>
<td>0.5 dB</td>
<td>Section 2.3</td>
</tr>
</tbody>
</table>

*Tab. 1.1 Reported mirror losses for integrated optical corner mirrors.*

In this context we give the 1989 goal of the OSCAR project: to establish the fabrication of InP based integrated optical corner mirrors with losses below 0.8 dB per mirror.
1.3. Optical wavelength demultiplexers: state of the art in 1996

A basic property of single mode optical fiber is its enormous low-loss bandwidth of many terahertz (THz). Unfortunately, single channel transmission is limited in speed to much less than the fiber capacity due to limitations in opto-electronic component speed and dispersive effects in the fibers. However, a method of more fully utilizing the fiber bandwidth is to transmit several channels simultaneously on a single fiber, with each channel located on a different wavelength. Such wavelength division multiplexing (WDM) or multiwavelength networks not only enable significant capacity enhancements, but will also enable new networks in which the routing path is wavelength dependent. These networks offers enormous aggregate capacity and greater flexibility. The research challenges in WDM networks involve also novel device approaches. The interested reader finds a review on the status of multiwavelength optical technology and networks in a special issue of the IEEE Journal of Lightwave Technology [1.12].

Important devices for cost effective implementation of WDM are integrated wavelength multiplexers and demultiplexers. They couple sources emitting at different wavelengths into a single optical fibre and separate the signals after transmission towards different receivers (Fig. 1.4).

![Schematic view of the functionality of optical wavelength multiplexers/demultiplexers in WDM transmission networks.](image)

Depending on the dispersive element employed, two main types of monolithic wavelength demultiplexers are distinguished: reflection grating devices and devices using a phased array of curved waveguides (phasars) [1.13]. The reflection grating type devices are usually operated at low order, offering
typically more than 50 nm free spectral range for the demultiplexing of a high
number of wavelength channels [1.14], [1.15]. However, the losses of these
devices depend critically on the quality of the vertically etched grating mirror.
Phasars have become increasingly popular due to their more simple and tolerant
technology [1.16]. They are usually operated at orders higher than 100th with
reduced free spectral ranges of less than 15 nm. Taking into account their specific
advantages, both types of devices are being pursued in InP as well as in SiO₂/Si.
The choice of the material is dependent on the desired functionality and
performance of the multiplexers and demultiplexers. Silica based devices usually
offer lower losses [1.17] and higher coupling efficiencies to single mode fibers,
while InP based materials are chosen in regard of the integration with amplifying
[1.18] and detecting features. More and more complex devices with high
functionality have been fabricated: a monolithically integrated semiconductor
optical amplifier followed by a WDM grating filter and pin photodetectors [1.19],
as well as a single chip incorporating an eight channel waveguide grating router
and eight pin photodetectors followed by eight preamplifiers constructed from
heterojunction bipolar transistors [1.20] have been reported.

Due to the birefringence of conventional InGaAsP/InP waveguides, these
demultiplexers may exhibit a significant TE/TM shift. Different approaches have
been used to eliminate this shift: layer structures with large core and low contrast
[1.21], square cross-section waveguides [1.22], special design of grating order
[1.23], and birefringence compensation [1.24].

Because a high accuracy for the refractive index of the demultiplexer material is
needed for the control of the channel wavelength allocations, tunability is
advantageous. InP offers a high temperature coefficient of the refractive index
[1.25], [1.26] and in addition, the passband center wavelengths can be tuned by
carrier injection [1.27].

Tab. 1.2 gives a list of realized optical wavelength demultiplexers with some key
parameters. For the evaluation of optical demultiplexers one must not only
consider these numbers but also the specific application for which it is designed.
Beside high performance, features like package, control, stability, flexibility and
last but not least the costs are important for a successful device.
1.3. Optical wavelength demultiplexers: state of the art in 1996

<table>
<thead>
<tr>
<th>Year</th>
<th>Material</th>
<th>Type</th>
<th>Ports</th>
<th>Loss</th>
<th>$\Delta\lambda_{\text{Pol}}$</th>
<th>FSR</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>InGaAsP</td>
<td>Grating</td>
<td>78</td>
<td>16 dB</td>
<td>0.2 nm</td>
<td>80 nm</td>
<td>[1.14]</td>
</tr>
<tr>
<td>1991</td>
<td>InGaAsP</td>
<td>Grating</td>
<td>31</td>
<td>14-17 dB</td>
<td>0.5 nm</td>
<td>300 nm</td>
<td>[1.15]</td>
</tr>
<tr>
<td>1992</td>
<td>InGaAsP</td>
<td>Phasar</td>
<td>15</td>
<td>2-7 dB</td>
<td>4.7 nm</td>
<td>10.5 nm</td>
<td>[1.16]</td>
</tr>
<tr>
<td>1993</td>
<td>InGaAsP</td>
<td>Grating</td>
<td>65</td>
<td>13 dB</td>
<td>1.9 nm</td>
<td>92 nm</td>
<td>[1.28]</td>
</tr>
<tr>
<td>1994</td>
<td>InGaAsP</td>
<td>Grating</td>
<td>8</td>
<td>10 dB</td>
<td>4.8 nm</td>
<td>90 nm</td>
<td>[1.29]</td>
</tr>
<tr>
<td>1994</td>
<td>InGaAsP</td>
<td>Phasar</td>
<td>16</td>
<td>11 dB</td>
<td>0.5 nm</td>
<td>40 nm</td>
<td>[1.21]</td>
</tr>
<tr>
<td>1994</td>
<td>Polymer</td>
<td>Phasar</td>
<td>14</td>
<td>11 dB</td>
<td>0.03 nm</td>
<td>9.1 nm</td>
<td>[1.30]</td>
</tr>
<tr>
<td>1995</td>
<td>InGaAsP</td>
<td>Grating</td>
<td>8</td>
<td>16 dB</td>
<td>4.8 nm</td>
<td>90 nm</td>
<td>[1.31]</td>
</tr>
<tr>
<td>1995</td>
<td>InGaAsP</td>
<td>Phasar</td>
<td>16</td>
<td>8 dB</td>
<td>0 nm</td>
<td>32 nm</td>
<td>[1.32]</td>
</tr>
<tr>
<td>1995</td>
<td>air</td>
<td>Grating</td>
<td>40</td>
<td>6-9 dB</td>
<td>0 nm</td>
<td>800 nm</td>
<td>[1.33]</td>
</tr>
<tr>
<td>1996</td>
<td>SiO$_2$</td>
<td>Phasar</td>
<td>128</td>
<td>3.5-6 dB</td>
<td>?</td>
<td>25.6 nm</td>
<td>[1.17]</td>
</tr>
<tr>
<td>1995</td>
<td>InP</td>
<td>Grating</td>
<td>4</td>
<td>11 dB</td>
<td>0.1 nm</td>
<td>47 nm</td>
<td>Section 4.2</td>
</tr>
</tbody>
</table>

*Tab. 1.2 Reported results on WDM demultiplexers with some key parameters. Loss: on chip, $\Delta\lambda_{\text{Pol}}$: TE/TM shift, FSR: free spectral range.*
1. Introduction

1.4. Outline of the thesis

The body of this thesis is divided into three main chapters. Chapter 2 describes the work on optical corner mirrors. We start with the illustration of the self-alignment technique used for the proper alignment of the mirror facet in respect to the waveguides. Based on this technique we develop rules for an optimized design of corner mirrors taking into account both theoretical considerations as well as experimental results. Techniques are studied for the fabrication of low-loss corner mirrors and their characterization. The results achieved prove the validity of the concepts developed. The chapter ends with the description of realized devices that take advantage of the successful integration with corner mirrors.

Chapter 3 starts with an introduction to plasma etching. A physical view on key plasma parameters like power and frequency of plasma excitation, pressure, temperature and gas composition gives an understanding of their influence on etching results. After a description of the available equipment at our Institute we consider the development of optimized processes for the realization of etched vertical and smooth sidewalls. We discuss the influence of the plasma parameters mentioned above on etch rate, selectivity, uniformity anisotropy and surface quality with respect to a model of the underlaying processes. The chapter is completed with a list of the etch processes with best performance for various purposes.

Chapter 4 deals with grating demultiplexers as an example of a more advanced device that relies on high performance plasma etching. The design, fabrication and characterization of this device that is essential for future wavelength division multiplexed (WDM) transmission is reported. Tools for the simulation of the demultiplexer are developed and applied for design optimization. Special attention is paid to low polarization dependence of the devices. Packaged grating demultiplexers hybridized with receiver arrays are successfully used for a transmission experiment with four channels at 2.5 Gbit/s each. Temperature controlled grating demultiplexers are used for the very accurate determination of the refractive index of InP and its temperature dependence.

A part of the results of this work has been published during the coarse of the investigations. Selected publications are included in the text. A complete publication list is added at the end of the thesis. References are given at the end of each chapter.
1.5. References

[1.1] S. E. Miller
"Integrated optics: An introduction"

[1.2] T. M. Benson
"Etched-wall bent-guide structure for integrated optics in the III-V semiconductors"

[1.3] P. Buchmann and H. Kaufmann
"GaAs single-mode rib waveguides with reactive ion-etched totally reflecting corner mirrors"

"Self-aligned low-loss totally reflecting waveguide mirrors in InGaAsP/InP"

[1.5] T. Ushikubo, I. Asabayashi, and T. Ishida
"AlGaAs/GaAs directional coupler type 4×4 optical switch matrix"

[1.6] H. Appelman, J. Levy, M. Pion, D. Krebs, C. Harding, and M. Zediker
"Self-aligned chemically assisted ion-beam-etched Ga/(Al,Ga)As turning mirrors for photonic applications"

[1.7] Y. Chung, R. Spickermann, D. B. Young, and N. Dagli
"A low-loss beam splitter with an optimized waveguide structure"

"Low loss mirrors for InP/InGaAsP waveguides"
1. Introduction

"New compact polarisation insensitive 4x4 switch matrix on InP with digital optical switches and integrated mirrors"
Proceedings of the 19th European Conference on Optical Communication, ECOC'93, post-deadline papers, pp. 13–16, 1993

"A corner reflector InGaAs/GaAs strained layer single quantum well coupled laser array"
IEEE Photonics Technology Letters, Vol. 6, pp. 10-12, 1994

[1.11] H. Han, D. V. Forbes, and J. J. Coleman
"Self-aligned high-quality total internal reflection minors"

[1.12] Special issue on multiwavelength optical technology and networks

"New focusing and dispersive planar component based on an optical phased array"
Electronic Letters, 24, pp. 385-386, 1988

"Monolithic InP/InGaAsP/InP grating spectrometer for the 1.48-1.56 µm wavelength range"

"Grating spectrograph in InGaAsP/InP for dense wavelength division multiplexing"

"Demonstration of a 15x15 arrayed waveguide multiplexer on InP"

"Fabrication of 128-channel arrayed-waveguide grating multiplexer with 25 GHz channel spacing"
"Digitally tunable channel dropping filter/equalizer based on waveguide grating router and optical amplifier integration"

"InP-based 2.5 Gbit/s optically preamplified WDM receiver"

"Monolithic eight-wavelength demultiplexed receiver for dense WDM applications"

"16 channel phased array wavelength demultiplexer on InP with low polarisation sensitivity"

"Polarisation-independent InP arrayed waveguide filter using square cross-section waveguides"

"Polarization independent 8×8 waveguide grating multiplexer on InP"

"Polarisation compensated waveguide grating router on InP"

[1.25] E. Gini and H. Melchior
"Thermal dependence of the refractive index of InP measured with integrated optical demultiplexer"
1. Introduction

[1.26] E. Gini and H. Melchior
"Erratum: Thermal dependence of the refractive index of InP measured with integrated optical demultiplexers"

"Tunable phased-array wavelength demultiplexer on InP"
Electronics Letters, Vol. 31, pp. 32-33, 1995

"Integrated grating demultiplexer and pin array for high-density wavelength division multiplexed detection at 1.5 μm"

"High-performance InP reflection-grating wavelength multiplexer"

"Polymeric arrayed-waveguide grating multiplexer operating around 1.3 μm"

"High speed monolithic WDM detector for 1.5 μm fibre band"

[1.32] H. Bissessur, B. Martin, R. Mestric, and F. Gaborit
"Small-size, polarization-independent phased-array demultiplexers on InP"

[1.33] F. N. Timofeev, P. Bayvel, J. E. Midwinter, and M. N. Sokolskii
"High-performance, free-space ruled concave grating demultiplexer"
2. Integrated optical waveguide corner mirrors in InGaAsP / InP
2.1. Introductory overview

The advantages of corner mirrors have already been mentioned in section 1.2. In this chapter we describe our concept of corner mirrors that is based on the self-alignment of mirror facet and optical waveguides (Fig. 1.3). The key requirements for the realization of low-loss corner mirrors that will be discussed are listed below:

- optimized mirror design
- suitable fabrication technology
- adequate characterization technique
- compatibility for integration with other waveguide devices.

The losses of a corner mirror depend on the position of the plane, at which total internal reflection occurs. The orientation of the plane is fully determined by three variables: its horizontal and vertical angle and a shift parallel to the normal of the plane. A mirror plane, denoted "facet" in the following, is ideally vertical, with a horizontal angle of half of the deflection angle, and includes the point where the centerlines of the two connected waveguides intersect. We numerically studied the influence of deviations of the three variables from the ideal value on mirror losses using a method based on Fourier analysis and Fresnel reflection [2.1].

![Fig. 2.1 Calculated loss of a corner mirror on InP/InGaAsP rib waveguides as a function of facet shift and deviation of the horizontal and vertical angles from the ideal geometric-optical value. The results show that the loss critically depends on the facet shift and the horizontal angle of the facet.](image)
In order to give a feeling on the tolerances allowed, in Fig. 2.1 we show calculated losses for a waveguide structure that is typically for our laboratory. For each curve one variable is varied and the two others are kept at their ideal values.

With the concept of waveguide to mirror self-alignment, the horizontal angle and the facet shift are no longer the result of the relative alignment of two masks but accurately defined on one mask level only. The only variable not defined by the mask design remains the vertical facet angle. The fact, that facet angle deviations from verticality are less critical for mirrors with small deflection angles, lead to the development of corner mirrors with 45° deflection angle, as described in section 2.2.

Fig. 2.2 Process sequence for the fabrication of self-aligned corner mirrors. Alternatively, the waveguides can be etched prior to the mirror holes.
However, an optimized mirror design does not guarantee for low losses. Facet shifts due to imperfect pattern transfer, deviations in facet angle from verticality and surface roughness may be introduced during the fabrication. The process sequence for self-aligned corner mirrors is illustrated in Fig. 2.2. An optimized fabrication process must minimize the imperfections. We developed thin SiO$_2$ masks that can be structured with photoresist of 300 nm thickness, resulting in maximum resolution and fidelity in pattern transfer. According to its importance, the entire chapter 3 is dedicated to the development of dry etching processes with high selectivity to those masks and with vertical sidewalls of minimal roughness.

A detailed study using a special mask with 55 different corner mirrors was undertaken in order to investigate the influence on optical losses of waveguide widths, facet shifts, and geometry of the mirrors in the transition region of the waveguides in front of the facets. Results of this study are summarized in section 2.3.

In section 2.4 we present results of an interlaboratory comparison experiment that aimed the evaluation of corner mirror characterization techniques. A device fabricated at our Institute with a variety of corner mirrors was characterized in eight laboratories throughout Europe and the results were compared. Agreement within about ± 0.2 dB for the losses of corner mirrors has been found in the vast majority of cases. This value can be regarded as realistic spread in loss measurements based on the used characterization technique, i.e. the Fabry-Perot method [2.2].

Additional results and considerations on corner mirror mask design, optical waveguide structure and mirror measurement technique are given in section 2.5. Some examples of applications are presented in section 2.6. The flexibility and the compatibility of the fabrication process of corner mirrors with other integrated optical devices such as optical switches or amplifiers support their successful integration with these devices.
2.2. Low loss corner mirrors with 45° deflection angle for integrated optics: Paper A

E. Gini, G. Guekos, H. Melchior

Abstract
A new design of corner mirrors with 45° deflection angle for integrated optics is demonstrated. The mirrors have been fabricated on an InP/InGaAsP single heterostructure. The losses are as low as 0.3 dB per corner mirror. The fabrication process is described and is compatible with the fabrication of integrated optic devices.

1. Introduction
Integrated waveguides with corner mirrors are of interest to gain more freedom for the implementation of active waveguide devices, their interconnection and coupling with fibres. To be practically useful, such corner mirrors must have low optical losses and be compatible in their fabrication with other waveguide structures. The process must perfectly align vertical facets having smooth surfaces on the position of the waveguides while taking fabrication undercuts and positional tolerances into account. First corner mirrors on GaAs fabricated by reactive ion etching were reported by Buchmann et al [2.3]. To overcome alignment problems a self aligned process has been proposed by Niggebrügge et al [2.4]. Based on this technique, we have designed corner mirrors with 45° deflection angle (see top of Fig. 2.3). The first mask defines the waveguides and the mirror facet. This masking layer is kept in place while the second mask is applied to open the windows for the facet etching. Thus the first mask has to stand the etching of the waveguide ribs and the etching of the mirror hole. The order in which the two etching steps are carried out is not important. This mirror design allows easy crossing of waveguides with low crosstalk in switch matrices or separation of waveguides with lower losses than with corner mirrors with 90° deflection angle.
2. Integrated optical waveguide corner mirrors in InGaAsP / InP

![Mask layout and SEM picture of a corner mirror with 45° deflection angle.]

**Fig. 2.3**  *Mask layout and SEM picture of a corner mirror with 45° deflection angle.*

2. Mirror Loss Calculations

We have calculated the mirror losses by a method proposed by Besse et al [2.1]. The waveguide structure for the calculations is given in the inset of Fig. 2.4. As parameters we varied the shift $s$ of the facet from the ideal position and the angle $\alpha$ between the vertical and the mirror facet (see Fig. 2.5). The horizontal angle of the facet $\phi$ was chosen to be either 45° or 22.5°. Due to the selfaligned process, this angle can be expected to have a negligible deviation from the above values. The results of the calculation show that the mirror for 45° deflection ($\phi$ equal to 22.5°) is much less sensitive to the angle $\alpha$. However, the sensitivity to the facet shift $s$ is increased. These results are easily understood.
2.2. Low loss corner mirrors with 45° deflection angle for integrated optics

From Fig. 2.5 we have

\[
\frac{d}{s} = \frac{\sin(2\phi)}{\sin(\phi)}
\]  
(2.1)

Fig. 2.4  **Calculated reflectivity of mirrors with 45° and 90° deflection angle for TE polarization. Top: 90°, bottom: 45°**

The angle \( \alpha \) between the vertical and the facet causes an angle \( \beta \) between the deflected beam and the waveguide axis where

\[
\beta = 2 \times \arctan(\tan \alpha \times \sin \phi)
\]  
(2.2)

The beam displacement \( d \) from the waveguide after a mirror with shifted facet is larger for small deflection angles. The vertical angle between the beam reflected on a rotated facet and the waveguide axis is smaller for small deflection angles. Since the most critical parameter in the fabrication is the angle \( \alpha \), the 45° mirrors should give lower losses than the 90° mirrors.
2. Integrated optical waveguide corner mirrors in InGaAsP / InP

![Diagram of integrated optical waveguide corner mirrors]

**Fig. 2.5 Definitions of variables. Arrows of \( s \) and \( \alpha \) mark the positive sign direction.**

3. Fabrication Process

A 0.6 μm thick InP buffer layer and a 0.65 μm thick InGaAsP layer (\( \lambda_{\text{gap}} = 1.1 \) μm) have been grown on a semi-insulating InP substrate by MOVPE. For the first mask 50 nm SiO\(_2\) has been deposited by CVD and AZ 1350 positive photoresist was structured by UV contact lithography. The SiO\(_2\) was dry etched by CF\(_4\) RIE. With this mask the waveguides were dry etched by an H\(_2\)/CH\(_4\) process on a magnetron enhanced reactive ion etching apparatus. The second mask was applied with photoresist and the facets were deeply etched. After removal of the masks the device was cleaved for optical measurements. The optical measurements were done with a 1.3 μm TE polarized Fabry-Perot diode laser. Light was coupled into the waveguides through microscope objectives and the output was measured with a photodetector and imaged with an infrared camera. For the evaluation of the corner mirror losses, the insertion loss of a waveguide having four (respectively two) corner mirrors was compared with the best value of six straight reference waveguides. Initially the device was 19 mm long. It was cleaved into two pieces for the measurement of the coupling losses and the propagation losses.

4. Results

The losses of the waveguides and the corner mirrors are listed in Tab. 2.1. The values are for \( \lambda = 1.3 \) μm and TE polarization. The 90° mirrors were fabricated on the same chip for comparison.
2.2. Low loss corner mirrors with 45° deflection angle for integrated optics

<table>
<thead>
<tr>
<th>Waveguide width</th>
<th>Coupling loss</th>
<th>Propagation loss</th>
<th>45° mirror loss</th>
<th>90° mirror loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>[μm]</td>
<td>[dB]</td>
<td>[dB/cm]</td>
<td>[dB/mirror]</td>
<td>[dB/mirror]</td>
</tr>
<tr>
<td>6</td>
<td>11.2 ± 0.7</td>
<td>1.8 ± 0.3</td>
<td>0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>11.4 ± 0.7</td>
<td>1.8 ± 0.5</td>
<td>0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>12.2 ± 0.6</td>
<td>2.5 ± 0.9</td>
<td>1.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Tab. 2.1 Waveguide and corner mirror losses.

5. Discussion
The insertion losses were measured without AR coating. In addition we used the Fabry-Perot method [2.2] to control the loss values. We used a semiconductor laser with an external cavity for this measurements with a linewidth of less than 200 kHz [2.5]. The results confirm the values measured with the Fabry-Perot laser. For TM polarization the insertion loss was 0.7 dB lower but the mirror losses were the same as for TE within 0.1 dB. The device was also evaluated with this method with an HeNe laser at λ = 1.52 μm. For TE the mirror losses were 0.2-0.6 dB lower at λ = 1.52 μm and for TM the mirror losses were the same for both wavelengths.

6. Conclusion
We have shown integrated corner mirrors with losses as low as 0.3 dB/mirror. The main reason for this good performance is the reduced sensitivity of the losses to the verticality of the facet etching. This was reached by a new design with 45° deflection angle. The fabrication process is compatible with the fabrication of active integrated optic devices. The structure is very helpful for the crossing and separation of waveguides in photonic components.

This work was in part performed within the RACE Project 1033 (OSCAR). We acknowledge the support of the Swiss PTT and the Swiss National Research Foundation.
2.3. Low loss self-aligned optical waveguide corner mirrors in InGaAsP/InP: Paper B

E. Gini, and H. Melchior

European Conference on Optical Communication ECOC'92
September 1992, Berlin, Germany,
Proceedings, pp. 553–556

Abstract
Low loss corner mirrors on single mode optical waveguides have been fabricated in InGaAsP/InP. A variety of mirror designs using a self-aligned technique have been realized. Minimal measured losses were 0.4 dB per corner mirror at $\lambda = 1.52 \mu m$.

1. Introduction
Integrated waveguides with corner mirrors using total internal reflection are of interest to gain more freedom for the implementation of active optical waveguide devices, for their interconnection and for their coupling with fibres. To be practically useful, such corner mirrors must have low optical losses and be compatible in their fabrication with other waveguide structures. First corner mirrors on GaAs fabricated by reactive ion etching were reported by Buchmann et. al. [2.3]. Problems arise from the alignment of the facet to the waveguide. A solution using a self aligned process has been proposed by Niggebrügge et. al. [2.4]. The first mask defines the waveguides and the mirror facet. This masking layer is kept in place while the second mask is applied to open the windows for the facet etching. Based on this technique we have designed a number of corner mirrors, varying their facet positions, their waveguide widths, the deflection angles [2.6] and having different geometries in the transition regions of the waveguides in front of the mirrors.
2. Fabrication
The layers were fabricated by LP-MOVPE on a sulfur doped (100) orientated InP substrate. After a 1.0 µm InP buffer layer a 0.55 µm thick InGaAsP layer ($\lambda_{\text{gap}} = 1.1 \mu \text{m}$) and a 1.0 µm InP cap layer were grown. As first mask we used a 65 nm thick SiO$_2$ layer delineated by AZ 1350 photoresist. The second mask was defined with AZ 1350J photoresist. The InP was dry etched by a H$_2$/CH$_4$ process in a magnetron enhanced reactive ion etching apparatus. The etch depths of the waveguides and mirrors were 0.65 µm and 3.9 µm respectively. After removal of the masks the device was cleaved for optical measurements. Fig. 1-4 show the fabricated corner mirrors of different designs.

Light from a single mode fibre was coupled into the waveguides through microscope objectives and the output was measured with a photodetector and imaged with an infrared camera. The optical measurements were done at $\lambda=1.3 \mu \text{m}$ and at $\lambda=1.52 \mu \text{m}$. For the evaluation of the corner mirror losses at $\lambda=1.3 \mu \text{m}$ we used a semiconductor laser. The insertion loss of a waveguide having four (respectively two) corner mirrors was compared with the lowest insertion loss of 6 straight reference waveguides. At $\lambda=1.52 \mu \text{m}$ we used a HeNe laser and the Fabry-Perot method [2.2]. The internal loss of a waveguide having four (respectively two) corner mirrors was compared with the lowest internal loss of 6 straight reference waveguides.

3. Results
The experimentally determined propagation losses of the waveguides are listed below. The values are for $\lambda=1.3 \mu \text{m}$.

<table>
<thead>
<tr>
<th>Waveguide width</th>
<th>Propagation loss for both TE and TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 µm</td>
<td>0.5 ± 0.2 dB/cm</td>
</tr>
<tr>
<td>5 µm</td>
<td>0.5 ± 0.3 dB/cm</td>
</tr>
<tr>
<td>4 µm</td>
<td>0.6 ± 0.3 dB/cm</td>
</tr>
<tr>
<td>3 µm</td>
<td>0.7 ± 0.4 dB/cm</td>
</tr>
</tbody>
</table>
2. Integrated optical waveguide corner mirrors in InGaAsP / InP

Fig. 2.6 InGaAsP/InP optical waveguide corner mirror. The waveguide is opened at an angle of 90° in front of the mirror. Different facet positions were realized.

Fig. 2.7 Corner mirror where the waveguide is opened at an angle of 45° in front of the mirror. Different facet positions were realized.

Fig. 2.8 Corner mirror where the waveguide is symmetrically opened at angles of 45° in front of the mirror. Different facet positions and facet lengths were realized.

Fig. 2.9 Corner mirror with 45° deflection angle. Different facet positions were realized.
The losses of the corner mirrors for the different mirror designs, wavelengths and polarizations are given in Tab. 2.2.

<table>
<thead>
<tr>
<th>Corner mirrors</th>
<th>Rib width</th>
<th>Pol.</th>
<th>see Fig. 2.6</th>
<th>see Fig. 2.7</th>
<th>see Fig. 2.8</th>
<th>see Fig. 2.9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td>90°</td>
<td>90°</td>
<td>45°</td>
</tr>
<tr>
<td>$\lambda = 1.3 , \mu m$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 \mu m</td>
<td>TM</td>
<td>1.7</td>
<td>1.9</td>
<td>2.1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>3 \mu m</td>
<td>TE</td>
<td>1.7</td>
<td>2.4</td>
<td>2.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>4 \mu m</td>
<td>TM</td>
<td>1.1</td>
<td>1.6</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 \mu m</td>
<td>TE</td>
<td>1.1</td>
<td>1.6</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 \mu m</td>
<td>TM</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>5 \mu m</td>
<td>TE</td>
<td>1.2</td>
<td>1.5</td>
<td>1.4</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>6 \mu m</td>
<td>TM</td>
<td>1.2</td>
<td>1.3</td>
<td>1.2</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>6 \mu m</td>
<td>TE</td>
<td>0.9</td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$\lambda = 1.52 , \mu m$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 \mu m</td>
<td>TM</td>
<td>1.2</td>
<td>1.6</td>
<td>2.0</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>3 \mu m</td>
<td>TE</td>
<td>1.3</td>
<td>1.7</td>
<td>2.3</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>4 \mu m</td>
<td>TM</td>
<td>1.1</td>
<td>1.4</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 \mu m</td>
<td>TE</td>
<td>0.9</td>
<td>1.4</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 \mu m</td>
<td>TM</td>
<td>1.1</td>
<td>1.2</td>
<td>0.9</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>5 \mu m</td>
<td>TE</td>
<td>1.1</td>
<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>6 \mu m</td>
<td>TM</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>6 \mu m</td>
<td>TE</td>
<td>0.8</td>
<td>0.9</td>
<td>1.09</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

Tab. 2.2 Losses of the different corner mirrors.

4. Discussion

At $\lambda = 1.52 \, \mu m$ the corner mirrors showed lower losses than at $\lambda = 1.3 \, \mu m$. This is attributed to a lower sensitivity to the etched facet roughness. For all corner
mirror designs the losses decreased with increasing waveguide width. The polarization dependence of the mirror losses is small, at most 20%. The lowest losses are obtained with corner mirrors with 45° deflection angle.
For the corner mirrors with 90° deflection angle the lowest losses are obtained with the longest facets. The reason for this is the low lateral confinement of the guided mode (typical spot sizes viewed by the IR camera were 2 μm x 6 μm). The mirror losses as a function of facet position are given in Fig. 2.10. The ideal facet position seems to be where the waveguide centerlines intersect (zero shift position). We observe that the facet is shifted by -0.1 μm to -0.2 μm during fabrication due to dimension shrinkage by mask undercutting.

![Graph showing mirror losses for a given design as a function of facet position.](image)

*Fig. 2.10 Mirror losses for a given design as a function of facet position. The positive sign marks an outward shift. The real facet position is shifted by -0.1 μm to -0.2 μm during fabrication.*

5. Conclusions
We have realized corner mirrors with losses as low as 0.4 dB/mirror which, to the best of our knowledge is the lowest value for InGaAsP/InP double heterostructure singlemode waveguides reported so far. This loss is mainly attributed to scattering loss on the dry etched mirror facet. Alignment errors up to 1.5 μm can be tolerated.

We thank M. Ebnöther and P. Wägli for the SEM photographs. This work was in part performed within the RACE Project 1033 (OSCAR). We acknowledge the support of the Swiss PTT and the Swiss National Research Foundation.
2.4. Measurements of loss and mirror reflectivity in semiconductor optical waveguides: a European interlaboratory comparison experiment: Paper C


Technical Digest - Symposium on Optical Fiber Measurements, Boulder, pp. 113-116, September 1994

Abstract
The results of round-robin measurements of waveguide loss and integrated mirror reflectivity in several European laboratories in the frame of the COST 240 project are presented. The Fabry-Perot cavity contrast method was used on semiconductor waveguides. The results show a satisfactory agreement (at the ±0.5 dB/cm level) between all the laboratories, but also point out some aspects which must be taken into account to get meaningful data.

1. Introduction
Several aspects of the measurement procedure for integrated optical waveguides and components are at a far less evolved stage than for the optical fiber counterparts. The repeatability and reproducibility of measurements, the homogeneity and comparability of results from equivalent or similar methods or set-ups, even for basic parameters like waveguide loss, are just a few of these aspects. To address this problem, within the European Project COST 240 "Techniques for Modeling and Measuring Advanced Photonic Telecommunication Components" it was decided to organize the circulation of waveguide samples in a number of participating laboratories, to perform measurements and compare the results.

As a first test, it was agreed to measure the loss of waveguides fabricated on InGaAsP/InP chips, using the well-known method of Fabry-Perot resonances contrast in the cavity formed by the partially reflecting terminal facets [2.2]. The
choice of this technique was prompted by its sensitivity, non destructiveness and availability (in a few modifications of the basic configuration) at several participating laboratories.

2. Principle of the technique and experimental set-ups

In a Fabry-Perot resonator operating in a single transverse mode regime, the ratio $K$ between its maximum and minimum transmittance when changing the resonance conditions appears in the following relationship [2.2]:

$$L \alpha = \ln(R) + \ln\left(\frac{\sqrt{K} + 1}{\sqrt{K} - 1}\right)$$  \hspace{1cm} (2.3)

where $L$ is the geometrical length of the cavity (i.e. the waveguide in the present case), $\alpha$ the cavity attenuation and $R$ the mirror (facet) reflectivity, assumed equal for both ends.

The basic experimental set-up to use this technique for waveguide measurements is shown in Fig. 2.11; the actual implementations differ in several details, the most significant one being the way of changing the resonance conditions to scan several periods of the transmission characteristics, and hence to determine $K$. Two techniques are currently in use: a) a slow heating or cooling of the sample, by which the length of the optical cavity is changed by the combined action of thermal expansion and thermo-optic effect, while the wavelength of the narrow-linewidth source is kept fixed; b) small changes of wavelength of the source, while keeping constant the sample temperature and its optical length. AAR, DBP Telekom, EPFL and Thomson CSF used method a), while ETHZ, both TU Delft laboratories and CSELT used method b).

Other minor differences pertain to the source (gas or diode laser), the way of coupling light to the waveguide (lens or single-mode fiber) the type of control of the input or output polarization state. All the implementations in the participating laboratories use either HeNe lasers operating at 1.523 $\mu$m or diode lasers operating in the 1.55 $\mu$m range.
3. Sample structure

Semiconductor chips with stripe waveguides fabricated in the InGaAsP/InP material system were made available for this experiment; the high refractive index of these materials yields natural Fresnel reflectivities for the facets around 0.3, so that good contrast can be achieved without special sample preparation besides cleaving the I/O facets. A first sample with simple straight ridge guides, supplied by CSELT, was used for some initial essays; then a more complex chip, containing both straight guides and different types of integrated mirrors, supplied by ETHZ, was circulated among all the labs and extensively characterized. Its structure is shown in Fig. 2.12, and all data reported in this paper refer to this sample.
2. Integrated optical waveguide corner mirrors in InGaAsP / InP

- Device length: 9.0 mm
- No AR coatings
- Offset: 4.5 mm
- InP 0.63 µm
- InGaAsP 0.55 µm
- InP 1 µm

Fig. 2.12 Schematic structure of the layout and waveguide cross-section of the ETHZ-supplied chip. Groups 1 and 7 contain sets of straight waveguides 3, 4, 5 and 6 µm wide; group 2 contains pairs of 45° deviating mirrors; groups 3 to 6 contain pairs of 90° deviating mirrors; mirror waveguides have the same widths as straight guides. The facets have no intentional coating.

4. Measurement results and discussion

Measurements of Fabry-Perot contrast were performed on selected waveguides and mirrors on the chip, separately for TE and TM polarizations. From the measured values of K, the total cavity loss was calculated, and the corresponding values are shown in Fig. 2.13 for the TE polarization.
2.4. Measurements of loss and mirror reflectivity in semiconductor optical waveguides

Fig. 2.13 Distribution of the total cavity loss (propagation plus reflection loss at the facets) for TE polarization. The laboratories are listed in the order of measurement. The bar at left shows the uncertainty coming from a change of ±0.1 in $K$ at different total loss levels.

The data show a general agreement between the results of all laboratories, with some occasional discrepancies and more scattered data for particular guides; in two cases (Thomson-CSF and ETHZ data) the measurements were made after a new cleavage of one end (sample length reduced from 9 to 5.6 mm), so that the facets are not the same as for the other laboratories, and their quality may be different. Other differences can arise from cleaning of the sample in different solvents, which was performed in some laboratories to remove the mounting wax used to fix the chip on the holder after the measurements: residual contamination can alter both $R$ (if the facet is affected) and $\alpha$ (if the guide surface is contaminated); a possible example of this effect is the sequence of the results from AAR, CSELT and DBP Telekom for guides on one side of the chip. Some guides 6 $\mu$m wide exhibited multimode behavior, and in this case the contrast values $K$ depended more or less sensitively on the input coupling conditions, thus increasing the uncertainty.
To get the corresponding values of attenuation $\alpha$ (expressed in dB/cm) for the waveguides, in addition to the measured length $L$, calculated values of modal reflectivity were used for $R$; these were computed by a Fourier analysis and Fresnel reflection method [2.1] applied to the actual waveguide structure, and range between 0.315 and 0.319 (TE) or 0.247 and 0.250 (TM) according to the guide width; no experimental value for $R$ was available.

The attenuation values of course exhibit the same trend as the total cavity loss, and the average level is $1.1 \pm 0.3$ dB/cm for TE polarization; as a comparison, it should be noticed that for this chip length an uncertainty of $\pm 0.1$ in the corresponding contrast ($K=2.8$) amounts to $\pm 0.16$ dB/cm, and increases to $\pm 0.5$ dB/cm when $K=1.75$. An uncertainty of $\pm 0.01$ in the adopted value of $R$ leads to a corresponding systematic error of $\pm 0.16$ dB/cm in the attenuation.

The results for TM polarization are similar, except for a larger spread, due to lower reflectivity, smaller $K$ values and higher loss ($\alpha = 2.4 \pm 0.6$ dB/cm).

The reflectivity of integrated mirrors was obtained by subtracting the average guide loss of the corresponding straight guides; mirror losses of $0.8 \pm 0.2$ dB and $1.0 \pm 0.3$ dB were obtained for TE and TM polarization respectively.

5. Conclusions

An extensive series of optical loss measurements has been performed by several laboratories on semiconductor waveguides by similar set-ups based on the Fabry-Perot fringe contrast method. Agreement within about $\pm 0.5$ dB/cm has been found in the vast majority of cases for guide attenuation, and within $\pm 0.3$ dB for integrated corner mirrors. It has been shown, on the other hand, that maintaining very carefully facet quality and cleanliness is extremely important, and that definitely single mode propagation is essential to achieve meaningful and reproducible results.
2.5. Additional results on corner mirrors

Only part of the knowledge accumulated during the development of low-loss corner mirrors is included in Paper A-C. In this section we present additional considerations and results.

Mask design

In our definition of the ideal position of a facet in section 2.1, we have neglected the Goos Hänchen shift. According to the Fresnel theory of reflection, the phase of an optical field is abruptly changed by total internal reflection. The phase change can be interpreted as a reflection at an imaginary facet, shifted outwards compared to the real interface, leading to a displaced reflected beam (Fig. 2.14).

![Figure 2.14](image-url) The change in phase of an optical field during total internal reflection can be interpreted as a reflection at an imaginary interface shifted by the distance $s$ behind the real interface. The reflected beam appears to be displaced by a distance $d$.

The phase shifts $\delta$ at total internal reflections for s and p polarized waves are [2.7]

$$\delta_s = -2 \tan^{-1}\left(\frac{\sqrt{\sin^2 \alpha - \left(\frac{n_2}{n_1}\right)^2}}{\cos \alpha}\right) \quad (2.4)$$

$$\delta_p = -2 \tan^{-1}\left(\frac{n_1}{n_2}\frac{\sqrt{\sin^2 \alpha - \left(\frac{n_2}{n_1}\right)^2}}{\cos \alpha}\right) \quad (2.5)$$
In our case the s and p polarizations are translated into TM and TE, respectively. In equations (2.6) and (2.7) we give the corresponding Goos Hänchen shifts $s$ of the facets.

\[
\begin{align*}
    s_{TM} &= \frac{\lambda}{2\pi n_1} \times \frac{1}{\sqrt{\sin^2 \alpha - (n_2/n_1)^2}} \\
    s_{TE} &= s_{TM} \times \frac{1}{(1 + (n_1/n_2)^2) \sin^2 \alpha - 1}
\end{align*}
\]

(2.6) \hspace{1cm} (2.7)

For $n_1$ the effective refractive index of the waveguide is used. With typical values of $n_1 = 3.3$ and $n_2 = 1$ (air) one obtains $s_{TM} = 120 \text{ nm}$ and $s_{TE} = 30 \text{ nm}$ for mirrors with $90^\circ$ deflection angle ($\alpha = 45^\circ$), and $s_{TM} = 90 \text{ nm}$ and $s_{TE} = 10 \text{ nm}$ for mirrors with $45^\circ$ deflection angle ($\alpha = 67.5^\circ$). The Goos Hänchen shift can, thus, be neglected in the practical mirror designs.

The width of the facet has also to be considered in the mirror design. The mirror losses decrease with increasing facet width until they reach a minimum value that remains constant for further increases in facet width. Experimental results are presented in Fig. 2.15.

![Fig. 2.15 Measured mirror loss for different f/w ratios. The inset shows the mirror layout and the definition of f. The waveguide structure is the same as in Fig. 2.12. For the ratio f/w = 3 the loss minimum is not yet reached for this waveguide structure.](image-url)
The data of Fig. 2.15 is for the same waveguide structure as shown in Fig. 2.12. The symmetrical opening of the waveguide in front of the facet varied as sketched in the inset of Fig. 2.15. Due to the small etching depth of 650 nm of this particular structure the lateral guiding is only moderate and the minimum for the mirror losses is not yet reached for a f/w ratio of three.

With increasing facet width, the transition region in front of the facet increases, too. This transition region causes only negligible losses, of the order of 0.02-0.2 dB, depending on the waveguide structure. The losses were calculated with the beam propagation method for the “butterfly” structure that results when reflecting the mirror at the facet (left hand side of Fig. 2.16). The calculated numbers were verified by measurements. For this purpose, the insertion losses of straight waveguides having 0, 2, 4 and 8 “butterflies” were compared. A mirror design that further minimizes the losses caused by the transition region in front of the facet was developed by W. Vogt at our Institute and is shown on the right hand side of Fig. 2.16. In this design, the opening of the waveguides are realized in such a way that small misalignments of the second mask do not result in deeply etched holes besides the waveguides.

![“Butterfly” structure](image1)

![Corner mirror with minimum length of enlarged waveguide](image2)

**Fig. 2.16** Left: “butterfly” structure on waveguides to calculate and measure the additional losses caused by the transition region in the front of the facet.
Right: mirror design by W. Vogt that minimizes the losses caused by the transition region in front of the facet.
Waveguide structure

The detailed geometry of the waveguide influences the dependence of the mirror losses on deviations of the facet from its ideal orientation. As mentioned above, when using the self-alignment concept, the shift of the facet and its horizontal angle are defined by the mask, thus the vertical angle is left as fabrication dependent parameter. The dependence of mirror losses on facet deviations from verticality was studied for waveguide structures with different optical mode sizes. Fig. 2.17 shows calculated mirror losses as a function of optical mode size in direction of waveguide thickness (1/e² intensity) for a facet deviation of 3° from verticality. The losses drastically increase for large core waveguides. This is explained by different vertical apertures of the waveguides. Waveguides with large optical mode sizes in thickness direction have small vertical apertures. The overlap of the reflected mode with the eigenmode of the output waveguide depends strongly on the vertical angle of the facet. For a waveguide with a small optical mode thickness and hence a large vertical aperture this dependence is weaker. Again, corner mirrors with 45° deflection angle are less critical than corner mirrors with deflection angles of 90°.

![Graph](image)

**Fig. 2.17** Calculated mirror loss as function of optical mode thickness for a facet deviation of 3° from verticality. The losses drastically increase for waveguides with large optical mode thicknesses. Corner mirrors with 45° deflection angle are less critical to facet deviations from verticality than corner mirrors with 90° deflection angle.
One should keep in mind, that it is a challenge to etch vertical facets. Deviations from verticality mainly contribute to the mirror losses. The development of etching processes for smooth vertical facets is reported in chapter 3 of this thesis. From these arguments we can conclude that it is more difficult to realize low-loss corner mirrors with large core waveguides. Nevertheless, we fabricated corner mirrors on n'/n+-waveguide structures in GaAs and InP, with optical mode sizes in thickness direction of 2.8 μm and 2.4 μm, respectively. The measured losses were 1.4 dB for mirrors with 90° deflection angle in GaAs, and 0.8-0.9 dB per mirror with 45° deflection angle in InP. The deviations from verticality were less than 1° in both cases. As an example, we show a corner mirror etched in GaAs in Fig. 2.18. For this material it is rather easy to obtain smooth vertical sidewalls with chlorine based plasma etching.

![Corner mirror in n'/n+-GaAs etched on system 1 (MIE 711, see chapter 3). The optical mode thickness is 2.8 μm, the etch depth is 7 μm. We measured a facet deviation from verticality of less than 1° and 1.4 dB loss per mirror. Process data: SiCl₄ flow = 4 sccm, Cl₂ flow = 22 sccm, Ar flow = 74 sccm, pressure = 14 μbar, RF power = 300 Watt, etch rate = 1200 nm/min.](image)

We want to mention that it is difficult to judge the results of mirror loss calculations. All numerical calculations are based on algorithms with some simplifications and the exact solution of the Maxwell’s equations is not known. However, as our results compare well with other methods used for the modeling
of corner mirrors [2.8] and good agreement was achieved in comparison with measurements, the conclusions drawn are assumed to be correct.

**Measurement technique**

Corner mirrors are characterized by their optical losses as a function of wavelength and polarization. A schematic view of our measurement setup is given in Fig. 2.19. This setup was used for the measurements reported in earlier figures or papers in this thesis. It is built from an optical source, an alignment stage and a photodetector. Different types of pigtailed lasers with a variety of wavelengths can easily be connected to a single mode fiber from which the output is taken on an optical bench. Piezo-controlled microscope objectives are used for the optical coupling of the light to the device. Illumination with visible light simplifies the alignment procedure. The transmitted light intensity is measured with a photodetector and a high gain transimpedance receiver.

![Schematic view of our measurement setup](image)

*Fig. 2.19 Schematic view of our measurement setup. SMF=single mode fiber, O=microscope objective, BS=beamsplitter, P=polarization filter, RM=revolving mirror, IR=infrared and visible camera, L=lamp, PD=photodetector.*

Commonly, the polarization is controlled by a filter in front of the device. For the measurement of polarization conversion or birefringence of waveguides a second polarization filter is added at the device output.

The insertion loss is measured as the ratio of the photo-currents with and without device. Mirror losses are determined by the comparison of the losses of straight
waveguides with the losses of waveguides having a number of mirrors. Besides the Fabry-Perot method described in section 2.4 we used the cut-back method for the determination of mirror losses. In this method a waveguide having several mirrors is continuously cut back and the insertion losses are determined for each device length and the corresponding number of mirrors. If mirrors are integrated in the cavity of semiconductor lasers, the losses can be determined by measuring the threshold current as a function of the number of laser in the cavity [2.9]. For all methods, a certain homogeneity of the losses over the device area is necessary. For the measurement of mirror losses it is advantageous to design waveguides having different numbers of mirrors (Fig. 2.20). In that case the mirror losses can be determined without cutting back the device.

Fig. 2.20 Layout of a mask used for the fabrication and characterization of corner mirrors. Beside straight reference waveguides, it contains waveguides having 2, 4, and 8 mirrors and waveguides with different numbers of "butterfly" structures.

Statistics of mirror loss

"Never believe in statistics that you did not manipulate yourself.” In spite of this citation attributed to Lord Rutherford, we think that we have fabricated so many corner mirrors that it is worth to present their statistics. As mentioned in the previous section, results of waveguide and mirror losses may differ from laboratory to laboratory despite the use of the same measurement method. The devices presented below were fabricated with a special mask with 55 different corner mirrors (see Fig. 2.12) and have been characterized by both the Fabry-Perot and the cut-back method. Fig. 2.21 shows the mirror losses of the corner mirrors used for the round-robin experiment described in section 2.4.
Fig. 2.21 Losses of corner mirrors, measured with the Fabry-Perot method for TE polarization at $\lambda = 1.52 \mu m$. The results of eight different laboratories compare well within 0.5 dB. Average mirror loss is 0.71 dB with a standard deviation of 0.31 dB.

Interesting is the comparison of the mirror losses, averaged per partner (Fig. 2.22).

Fig. 2.22 Losses of the corner mirrors from Fig. 2.21, averaged per partner.
The laboratories are listed in the order in which they performed the measurements. The spread of the values is only ±0.15 dB. The differences between the partners are thought to be caused by sample preparation and the amount of time spent to optimize the alignment of the device before measurements. Alcatel Alsthom Recherche presents the lowest values, indicating very careful characterization, and our work results in the "second place". This ranking can be completely different for individual corner mirrors.

The excellent low loss values are in part due to the pre-selection of the waveguides with the corner mirrors to be measured. In the following we present results that were obtained with all variants of corner mirrors, that were designed in order to study the dependence of the mirror losses on different parameters. Only for 10 corner mirrors the facet was oriented in the ideal position whereas for the other 45 mirrors, a part of the losses are due to intentional design deviations from ideality.

Mirrors on single-heterostructure waveguides

Mirror loss results for corner mirrors on single-heterostructure waveguides are summarized in Fig. 2.23 for TE polarization at \( \lambda = 1.3 \ \mu \text{m} \). On this chip a yield of 100% was obtained: none of 55 the waveguides with each having two corner mirrors was destroyed or damaged during fabrication.

![Graph showing mirror losses on single heterostructure waveguides for TE polarization at \( \lambda = 1.3 \ \mu \text{m} \). All 110 mirrors of 55 waveguides are represented.](image-url)
We measured less than 1 dB loss for more than 10 corner mirrors. The average loss per mirror was 1.48 dB with a standard deviation of 0.53 dB. These low losses are explained as follows. The single-heterostructure has the advantage of strong vertical guiding with an optical mode thickness of about 0.8 μm. Facet deviations from verticality are not very critical (see Fig. 2.17). In addition, the necessary etch depth for the mirrors is only 2 μm resulting in a reduced roughness of the facet.

Mirrors on double-heterostructure waveguides

In Fig. 2.24 we summarize the losses for corner mirrors on double-heterostructure waveguides measured for both polarizations at λ = 1.3 μm and λ = 1.52 μm. Optical mode thickness is about 1.0 μm. Due to the buried waveguide core, the minimum etching depth of the facet is 4 μm.

![Fig. 2.24 Mirror losses on double-heterostructure waveguides for both polarizations for λ = 1.3 μm and λ = 1.52 μm.](image)

On this chip, seven corner mirrors out of 55 pairs were damaged and exhibited losses higher than 3 dB. The averages of the losses without these damaged units are given in Tab. 2.3. The conclusions are the same as reported in section 2.3. The higher losses at λ = 1.3 μm are attributed to a higher sensitivity to facet roughness, indicating that scattering loss is a main loss mechanism.
2.5. Additional results on corner mirrors

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Wavelength [µm]</th>
<th>Loss/mirror [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>1.30</td>
<td>1.73</td>
</tr>
<tr>
<td>TE</td>
<td>1.30</td>
<td>1.84</td>
</tr>
<tr>
<td>TM</td>
<td>1.52</td>
<td>1.54</td>
</tr>
<tr>
<td>TE</td>
<td>1.52</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Tab. 2.3  Averaged mirror losses for the device presented in Fig. 2.24.

After this demonstration of the feasibility of low-loss corner mirrors we want to answer the question: "Ok, what are they good for?"
2.6. Applications of corner mirrors

In this section we describe OEIC waveguide devices that take advantage of integrated corner mirrors. We focus on our own contributions.

Polarization-insensitive optical switches and modulators
We describe the contributions to two published papers, [2.10] and [2.11] and will concentrate on the aspects concerning corner mirrors.

Since the state of polarization is not maintained in standard optical fibers, polarization-independent operation of the components used for optical communication is highly desirable. Switches and modulators customarily realized in (100) InGaAsP/InP material for operation in the 1.3 μm to 1.6 μm wavelength range operate only for TE polarized light [2.12].

Fig. 2.25 Layout of the polarization-insensitive Mach–Zehnder interferometer. The direction change is done with self-aligned low-loss corner mirrors. The waveguides in the Y–junction separate with half angle of 0.5°. The lengths of the electrodes are 5 mm.

This is, because for waveguides on commonly used (100) substrates and oriented perpendicular to the {011} cleavage planes, the linear electro-optic effect vanishes for TM polarization. In order to avoid this strongly polarization
dependent linear electro-optic effect, we realized Mach Zehnder Interferometric (MZI) optical modulators in InGaAsP/InP that maintain the (100) substrate orientation and (011) cleavage planes but place the waveguide at 45° to use the quadratic electro-optic effects only, such as to achieve a high degree of polarization insensitivity. The effect exploited are due to carrier depletion, band-filling, Franz-Keldysh and quantum confined Stark effects. The use of this orientation of the waveguides has become possible with the development of low loss corner mirrors with 45° deflection angle. The geometrical layout of the device is shown in Fig. 2.25.

The layer structure of the waveguide is shown in Fig. 2.26. It consist of a double heterostructure with a 0.6 μm InGaAsP core, a 1 μm buffer, and a 1 μm cladding layer. The InGaAsP composition is optimized for a wavelength of \( \lambda = 1.3 \) μm. The structure is doped to form a pin–junction. In reverse bias operation, changes in the refractive index at 1.3 μm are dominated by electro-refractive effects. Singlemode rib waveguides are used, with rib widths of 3 μm and electrode lengths of 5 mm.

![Fig. 2.26 The fabricated double-hetero waveguide structure. The light is laterally guided by etching a rib with a width of 3 μm. The lines showing the calculated mode form are drawn at constant light intensity, spaced by 10% each for TE polarization at \( \lambda = 1.3 \) μm.](image)

Epitaxial layer growth is by metal-organic vapor-phase epitaxy (MOVPE) on (100) InP \( n^+ \)-substrates. Rib waveguides are delineated by e-beam masks and mirrors defined by a two-mask process. Rib waveguides and mirrors are realized by magnetically-enhanced reactive-ion etching with a \( H_2/CH_4 \) mixture. Device fabrication is completed by the deposition of the Ti / Au electrodes, passivation and cleavage.
The MZI has been measured between microscope objectives at $\lambda = 1.3 \mu m$. Both the TE and TM polarizations are modulated (Fig. 2.27).

![Switching curves for the two polarizations](image)

*Fig. 2.27 Switching curves for the two polarizations. On/off ratio when measured with a singlemode fiber at the output was 17 dB.*

From the measured phase shift versus applied voltage curves the quadratic electro-optic coefficient $R_{\text{eff}}$ in

$$\Delta n_{\text{eff}} = R_{\text{eff}} \cdot E^2$$

was extracted. We determined $R_{\text{eff}} = 8 \times 10^{-15} \text{ cm}^2/\text{V}^2$ for the structure.

The on/off ratios achieved were $>12$ dB for both polarizations when measured between microscope objectives. As the extinction ratio in an MZI depends on the separation of the symmetric and antisymmetric modes, an even higher extinction ratio of 17 dB is achieved when measured between fibers. The mirror losses of these initial devices were around 3 dB/mirror. An improved version showed losses below 1 dB/mirror.

In conclusion, optical waveguide modulators that operate with both polarizations of light have been realized using rib-waveguide Mach–Zehnder interferometers that use polarization-insensitive electro-optic effects in InGaAsP / InP. In order
to achieve a high degree of polarization insensitivity while maintaining the preferred (100) substrate orientation and the \{011\} cleavage planes for fiber connection, these MZIs were placed at $45^\circ$ and the optical beams redirected by means of dry-etched waveguide corner mirrors.

The concept of the special orientation of the phase shifting waveguides was further pursued and applied to $2 \times 2$ optical switches [2.13]. More detailed studies of the physical effects involved resulted in an optimized rotation angle of $34^\circ$ relative to the [011] cleavage plane. Polarization insensitive matrices with four $2 \times 2$ optical switches were realized [2.14]. In these switch matrices the corner mirrors were replaced by waveguide bends because of the very small tolerances in differential loss.

**Compact $4 \times 4$ switch matrix with digital optical switches**

Another approach to a polarization insensitive switch is the digital optical switch (DOS) [2.15], [2.16]. It consists of one input waveguide from which the light can be switched into one of two output waveguides. By arranging the DOS’s in a tree structure, strictly nonblocking $N \times N$ switch matrices are achieved. The layout of a $4 \times 4$ matrix built by a tree structure is shown in Fig. 2.28. For the interconnection of the DOS’s, many crossings are necessary with a maximum of 9 crossings per individual waveguide.

![Schematic diagram of a 4x4 matrix with digital optical switches in a tree structure. Each Y represents a DOS. In the interconnect area up to 9 crossings for an individual waveguide are necessary.](image)

*Fig. 2.28* Schematic diagram of a $4 \times 4$ matrix with digital optical switches in a tree structure. Each Y represents a DOS. In the interconnect area up to 9 crossings for an individual waveguide are necessary.
The switch matrix in Fig. 2.28 has been realized by Alcatel Alsthom Recherche and the results are reported in [2.17]. In a very compact solution, 24 DOS were interconnected with 32 corner mirrors whose deflection angles were 45°. Design input for these corner mirrors came from the work reported in this thesis. For reasons of loss equalization, each light path includes two corner mirrors.

A self aligned process has been used to fabricate mirrors thanks to a dielectric/TiW metallic mask association. First, TiW was sputtered on the whole wafer and etched by a SF$_6$ plasma etching process in order to define the waveguide level. Then a SiO$_2$ layer was deposited on the wafer and opened to define mirror holes using a CHF$_3$ plasma etching process. At this step, the mirror etching was done with a Cl$_2$/CH$_4$/H$_2$ plasma etching process. Deviations of the facets from verticality were less than 1° and the facet surface profiles were smooth.

![Fig. 2.29 Interconnection region of the 4x4 switch matrix reported in [2.17]. A total of 32 corner mirrors are used to interconnect the DOS. Waveguide crossings take place at angles of 45° and 90° with minimum crosstalk. The mirror losses were close to 0.6 dB/mirror and 0.8 dB/mirror for TE and TM polarization, respectively.](image)

Fig. 2.29 shows the interconnection area of the realized switch matrix. Waveguide crossings take place at angles of 45° and 90° with minimum crosstalk.
The mirror losses were close to 0.6 dB/mirror and 0.8 dB/mirror for TE and TM polarization, respectively. Thanks to the corner mirrors it was possible to reduce the length of the device by a factor of two without any penalty in performance.

Mirrors that help for optical characterizations

It is difficult to make optical measurements of devices that have the optical inputs and outputs on one side of the chip only. A grating demultiplexer, as considered in chapter 4 is an example for such a device. Light has to be coupled simultaneously into all waveguides at the same facet.

---

**Fig. 2.30** Application of corner mirrors for easy optical characterization of grating demultiplexers between microscope objectives. The mirrors may be cut away for further processing. The comparison of losses of straight waveguides and waveguides having corner mirrors allows for preliminary evaluation of the quality of the etched grating.
In some cases the problem is solved by using tapered fibres instead of microscope objectives but active alignment is only possible for 2 to 3 channels. For the characterization of our demultiplexers we introduced corner mirrors that separate and direct the input and output waveguides to opposite facets. In this way the devices can be aligned easily between microscope objectives for optical measurements. For further processing, i.e. packaging, the mirrors may be cut away. The principle is illustrated in Fig. 2.30.

The introduction of waveguides having four corner mirrors allows for preliminary evaluation of the quality of the etched grating. Since the reflective grating and the mirror facets are etched with the same process at the same time, the mirror losses are used to estimate the grating losses. Based on this information, we decided if it was worth to continue the processing or to stop. A picture of a set of corner mirrors used to deflect the outputs of a grating demultiplexer is shown in Fig. 2.31.

![Image: SEM photograph of a set of corner mirrors that are used to deflect the outputs of a grating demultiplexer. The mirrors are used to simplify the characterization of the demultiplexer and are cut away during subsequent processing steps.]
2.7. Conclusions

Optical corner mirrors were thoroughly studied. Based on a waveguide to mirror self-alignment technique that eliminates the dependence of the facet position from the alignment of the second mask, the design has been optimized considering theoretical as well as experimental results. A special mask has been designed in order to study the influence of different parameters on mirror losses. A process sequence whose details are described in section 2.1 and 2.3 has been developed to fabricate corner mirrors that are compatible with the fabrication of other opto-electronic devices. Different measurement techniques were used to determine mirror losses and to confirm the measured values. The results achieved advance the state of the art. Corner mirrors were successfully integrated with other waveguide devices demonstrating the compatibility of the fabrication process. A number of applications of corner mirrors were listed that prove their advantages of compactness and polarization insensitivity.

The most critical parameter for the optical losses of the corner mirrors is the quality of the facet etching. The mirror losses were found to be dominated by two origins: facet roughness and deviations of the facet from verticality. The development of a dry etching process that minimizes these origins is the topic of the next chapter.
2. Integrated optical waveguide corner mirrors in InGaAsP/InP

2.8. References

[2.1] P. A. Besse, J. S. Gu, and H. Melchior
"Reflectivity minimization of semiconductor laser amplifiers with coated and angled facets considering two-dimensional beam profiles”

[2.2] R. G. Walker
"Simple and accurate loss measurement technique for semiconductor optical waveguides”

[2.3] P. Buchmann and H. Kaufmann

“Self-aligned low-loss totally reflecting waveguide mirrors in InGaAsP/InP”

[2.5] D. Syvridis, G. Guekos, P. A. Besse, and R. Dall’Ara
“Polarization selective widely tunable external cavity diode laser”

“Low loss corner mirrors with 45° deflection angle for integrated optics”

[2.7] M. Born
“Optik”
Springer-Verlag, Berlin, p. 43, 1985

“Modeling of self-aligned total internal reflection waveguide mirrors: an interlaboratory comparison”
Optical and Quantum Electronics, Vol. 27, pp. 935-942, 1995
[2.9] J. E. Johnson and C. L. Tang
"Precise determination of turning mirror loss using GaAs/AlGaAs lasers with up to ten 90° intracavity turning mirrors"

"Polarization insensitive waveguide modulator using InGaAsP/InP Mach–Zehnder interferometer"
Proceedings of the 18th European Conference on Optical Communication, ECOC'92, pp. 345-348, 1992

"Optical waveguide modulators and switches using InGaAsP/InP"
Proceedings of the 3rd European Workshop of COST 240: 'Innovative optical waveguide space switches', Athens, 1992

"InP/GaInAsP guided-wave phase modulators based on carrier-induced effects: theory and experiment"

"Polarization-insensitive low-voltage optical waveguide switch using InGaAsP/InP four-port Mach-Zehnder interferometer"

"Low-loss polarization-insensitive InP-InGaAsP optical space switches for fiber optical communication"

[2.15] Y. Silberberg, P. Perlmutter, and J. E. Baran
"Digital optical switch"
"Low driving voltage or current digital optical switch on InP for multiwavelength system applications"

"New compact polarisation insensitive 4×4 switch matrix on InP with digital optical switches and integrated mirrors"
Proceedings of the 19th European Conference on Optical Communication, ECOC '93, post-deadline papers, pp. 13–16, 1993
3. Dry etching techniques
3. Dry etching techniques

3.1. Introductory overview

Today, state-of-the-art integrated circuit manufacture depends on the mass replication of tightly controlled, micron-sized features in a variety of materials. Plasma etching has become central to this process because it is the only current technology that can do this job efficiently and with good reproducibility and high yield. Driven from the silicon based microelectronics industry, plasma etching has become the dominating process also for the patterning of III-V semiconductor based optoelectronic integrated circuits (OEIC). The alternative to plasma etching is the traditional wet chemical etching. Important properties of wet chemical etching and plasma etching are compared in Tab. 3.1.

<table>
<thead>
<tr>
<th></th>
<th>wet chemical etching</th>
<th>plasma etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>material selectivity</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>anisotropy</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>crystal damage</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>surface quality</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>homogeneity</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>mask undercut</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>minimal feature size</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>etch rate</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>reproducibility</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>equipment</td>
<td>simple</td>
<td>complex</td>
</tr>
</tbody>
</table>

Tab. 3.1 Properties of wet chemical etching and plasma etching.

All the devices presented in this thesis were fabricated using plasma etching. Much effort was put into the development of etching processes that fulfill the stringent requirements for the realization of plasma etched optical facets in InGaAsP/InP waveguide mirrors and demultiplexers.
In section 3.2 we give a short overview of the principles of plasma etching including a physical understanding of the parameters that influence the etching results. In section 3.3 we describe the actual equipment used and give some safety and health considerations. The development of dry etching processes for the fabrication of the main devices investigated in this thesis, namely InP based corner mirrors and grating demultiplexers are reported in section 3.4. Finally a list of the optimized processes for the etching of a variety of materials is presented together with the results obtained in section 3.5.
3.2. Principles of plasma etching

In this section we give an overview over the principles of plasma etching, with particular emphasis on process parameters at the disposal of operators. The more interested reader can find a detailed introduction to plasma etching in the excellent textbook of D. M. Manos and D. L. Flamm [3.1].

First we briefly describe the essential basic characteristics of the plasma environment. A plasma is an ionized gas with equal numbers of free positive and negative charges. The free charge is produced by the passage of current through the discharge. The extent of ionization is very small, typically only one charged particle per 1'000'000 neutral atoms and molecules. The positive charge is mostly in the form of singly ionized neutrals, the negative particles are predominantly electrons. Electrons are the main current-carriers since they are light and mobile. The energy transfer from electrons to the neutrals is inefficient due to the much larger weight of the neutrals. On account of this, the electrons have high energy (many electron volts equivalent to tens of thousands of degrees) permitting high temperature type reactions capable of creating free radicals in low temperature neutral gases. The coexistence of a warm gas and high temperature active species distinguishes the plasma reactor from conventional thermal processing.

Diffusion of charged particles to the walls tend to deplete the charge in the plasma. Electrons diffuse fastest and leave an excess of positive charge, and the plasma potential is positive relative to the walls. The resulting electrical field equalizes the charged fluxes and causes a decreased concentration of electrons near the surface creating a sheath. The plasma sheath appears as a dark region next to the surfaces contacting the plasma. The lower concentration of electrons in the plasma sheath reduces the number of electron-neutral collisions which excite species into states that relax by photoemission. As the plasma is a fairly good conductor, most of the potential drop appears across the sheath. Voltage drops across the sheath range from tens to thousands of Volts, depending on plasma parameters. Positive ions are accelerated through the sheath and strike the walls at near-normal incidence.

In these areas plasma etching can proceed in four basic mechanisms.

The first mechanism is sputter etching or sputtering (Fig. 3.1, a). Positive ions are accelerated across the sheath and strike the substrate with high kinetic energy. Some of this energy is transferred to surface atoms which are then ejected,
leading to material removal. This process is distinguished from the others in that the interaction is mechanical: differences in chemical bonding are important only

\[ \text{Ion} \]

\[ \text{Volatile product} \]

**a) Sputtering**

\[ \text{Neutral} \]

\[ \text{Volatile product} \]

**b) Pure chemical etching**

\[ \text{Neutral} \]

\[ \text{Ion} \]

\[ \text{Volatile product} \]

**c) Ion-enhanced energetic etching**

\[ \text{Neutral} \]

\[ \text{Ion} \]

\[ \text{Volatile product} \]

**d) Ion-enhanced inhibitor etching**

**Fig. 3.1** The four basic mechanisms of plasma etching (see text): 
a) sputtering where ions mechanically eject substrate material, 
b) purely chemical reaction with radicals forming volatile products, 
c) ion-enhanced energetic, where ion energy starts etching reactions, 
d) ion-enhanced inhibitor, where inhibitor species form a protective film. Ions disrupt this film on horizontal surfaces.
3. Dry etching techniques

in so far as they determine the bonding forces between surface atoms and the ballistics dislodging them.

The second mechanism, pure chemical etching (Fig. 3.1, b) occurs when active species from the gas phase encounter a surface and react to form a volatile product. High volatility is essential in order that the products do not coat the surface and cut off the chemical reaction. The role of the plasma is merely to supply etching species.

In the third, energy-driven mechanism (Fig. 3.1, c) neutral species cause little or no etching without ion bombardment. Ions supply kinetic energy, which disrupt the surface being etched allowing a variety of elementary processes to form volatile products. Since ions are accelerated across the plasma sheath and strike surfaces vertically, the etching induced is directional.

With the fourth mechanism, inhibitor-driven ion-assisted etching (Fig. 3.1, d), ion bombardment does not cause the etching reaction. Ions interact with "film-formers" that coat surfaces and cut off etching reactions. As the ions strike mostly on horizontal surfaces, these are kept free of films, while vertical feature sidewalls are being protected against chemical attack. The "film formers" may be generated during etching reactions or supplied from the plasma.

Investigators have used a wide variety and sometimes a confusing number of terms to refer to the processing at various etching pressures and sheath potentials. In the following we use the term plasma etching and dry etching as synonyms for the practice of etching or gasifying substrate material in a plasma. Note that ions are rarely the etchant, neutrals are responsible for almost all reactive etching at pressures above about 1 \( \mu \)bar. Sometimes plasma etching has been used to refer to etching at higher pressures (above 100 \( \mu \)bar), where ion energies are often low. Reactive ion etching (RIE) is commonly used to refer to plasma etching at pressures below 100 \( \mu \)bar. The term is misleading since etching by ions that react with and remove substrate material is rare, unless ion beam sources are used at much lower pressures. For such processes reactive ion beam etching (RIBE) is commonly used. Sputter etching refers to etching brought about by the physical effects of ion impact.

**Electrical considerations**

A schematic diagram of an electrical discharge and its simplified equivalent circuit are shown in Fig. 3.2. Each part of the discharge, sheath and plasma, is
3.2. Principles of plasma etching

represented by a parallel combination of resistors and capacitors [3.2]. Diodes are used in the sheaths to represent the differences in ion and electron mobilities which result in rectification of the applied voltage. Most of the operating characteristics of discharges can be understood in terms of the relative impedances of each of these components.

Fig. 3.2  Left-hand side: schematic diagram of an electrical plasma discharge. Positive ions, denoted by +, transverse the sheaths along the electric field lines $E_s$, and impact the electrode surfaces where the neutral etching reactions are enhanced. Right-hand side: equivalent circuit of an electrical discharge. Sheath and plasma are represented by a parallel combination of resistors and capacitors. The sheaths have diodes in parallel to account for voltage rectification due to the different mobilities of electrons and positively charged ions (according to [3.2]).

At low frequencies only the resistive components need to be considered. The impedance of the plasma body will be governed primarily by electron conductivity

$$\rho_e = \mu e N$$  \hfill (3.1)

with the mobility

$$\mu = \frac{e}{m_e v_e}$$  \hfill (3.2)

where $N$ is the charge density, $e$ the electronic charge, $m_e$ the electron mass and $v_e$ the electron momentum transfer collision frequency.
3. Dry etching techniques

The plasma body resistance is

\[ R_p = \frac{l_p}{\rho_e A} \]  

(3.3)

with \( l_p \) being the thickness of the plasma and \( A \) the area of the plasma. The sheath impedance is given by the ion conductivity, defined as in Eq. (3.1), except using ion mass and collision frequency:

\[ \rho_i = \mu_i eN = \frac{e}{m_i v_i} eN. \]  

(3.4)

The ion conductivity is roughly an order of magnitude smaller than the electron conductivity (see below, Tab. 3.2), thus the sheath resistance will always be higher than the plasma resistance.

At higher frequencies \( \omega \), the capacitive impedances \( Z_{S,P} \) of the sheath and plasma must be considered:

\[ Z_{S,P} = \frac{1}{\omega C_{S,P}} \]  

(3.5)

with

\[ C_{S,P} = \frac{\varepsilon_0 A_{S,P}}{l_{S,P}}. \]  

(3.6)

The change in impedance from primarily resistive to primarily reactive is around the plasma frequency. The electron plasma frequency \( \omega_{pe} \) applies for the plasma body while the ion plasma frequency \( \omega_{pi} \) applies for the sheath. To derive the plasma frequency we consider a body with equal numbers of each charge. For the separation of the negative and positive charges, energy is required and an electric field develops, which makes the separation progressively more difficult. By integrating the Maxwell equation

\[ \rho = \rho_i - \rho_e = \varepsilon_0 \text{div}E \]  

(3.7)
we get the electrical field $E$ as a function of the separation $x$

$$E = \frac{Q}{\varepsilon_0} = \frac{Ne}{\varepsilon_0}x$$

(3.8)

with the charge density $N$.

![Diagram](image)

**Fig. 3.3** By separating charged particles an electrical field develops that will force the particles back to each other.

The restoring acceleration

$$\frac{d^2x}{dt^2} = \frac{eE}{m_e} = \frac{Ne^2}{m_e\varepsilon_0}x$$

(3.9)

is proportional to the separation distance leading to a harmonic motion with the plasma frequency

$$\omega_{pe} = \sqrt{\frac{Ne^2}{m_e\varepsilon_0}}.$$  

(3.10)

The thermal energy of the electron is (by reason of the 1-dimensional motion)

$$\frac{1}{2}m_ev_T^2 = \frac{1}{2}kT_e$$

(3.11)

with the electron temperature $T_e$ and the thermal velocity $v_T$. 

---

69
3. Dry etching techniques

The length that an electron can move with its thermal energy is the Debye length $\lambda_D$:

$$\lambda_D = \sqrt{\frac{kT_e e_0}{N e^2}}.$$  \hspace{1cm} (3.12)

The same expressions result for the ions with the corresponding mass and temperature. The plasma frequency can be regarded as the inverse of the time it takes to move a Debye length at thermal velocity

$$\omega_{pe} = \frac{v_T}{\lambda_D}.$$ \hspace{1cm} (3.13)

Typical values for the plasma frequency are 1 MHz and 1 GHz for the ions and electrons, respectively. For frequencies below 1 MHz all impedances in Fig. 3.2 are predominately resistive and the sheath resistance is much higher than the plasma resistance. Thus we expect power dissipation to occur primarily in the sheaths. Ion accelerated by the field of the sheath can dissipate their energy in two ways: collisions with neutrals can result in ionization, excitation, chemical reactions and heating; collisions with the electrodes can result in any combination of surface damage, sputtering, secondary electron emission and heating with either implantation or reflection of the incident ion. Increasing the radio-frequency (RF) power will result in higher ion energies as they are accelerated to the full sheath potential, which is approximately the full applied voltage.

For frequencies higher than the ion plasma frequency, the sheath impedance changes from primarily resistive to primarily reactive. The ions can no longer respond to the instantaneous value of the field and displacement instead of conduction current dominates. The sheath capacitor becomes a current shunt. The power dissipation shifts from the sheaths to the plasma. The current in the plasma is primarily conducted by electrons, and hence the dissipation mechanisms must involve electron-neutral collisions: ionization, dissociation and excitation. Increasing the RF power results in an overall increase in radical, ion and excited state production. Simply spoken the RF power at low frequency determines the ion energy while the RF power at high frequency determines the ion concentration.
Microwave excitation above the electron plasma frequency can very efficiently couple power into bulk plasma processes such as molecular dissociation and can be used to create plasmas containing high concentrations of reactive species. In most cases specialized equipment is required.

By comparing the effects of excitation frequency we can conclude that at low frequency the ion energy is determined with the RF power while at high frequency the number of ions is determined. Ideally, both low and high frequency are used for independent determination of ion energy and density.

**Plasma Reactors**

Although plasma reactors have been constructed from opposed parallel plates in a vacuum chamber, a wide variety of more complex arrangements are used commercially. Reactors have been classified according to wafer capacity, the position of material relative to the plasma, pressure regime, electrode geometry and generator frequency. The most common type in use today is the parallel plate or planar reactor. A schematic view of an example is shown in Fig. 3.4.

![Fig. 3.4 Schematic view of a parallel plate reactor.](image)
3. Dry etching techniques

A simplified model of the configuration in Fig. 3.2, neglecting the plasma impedance results in the sheath voltage:

\[ V_{S1} = \frac{V_0}{1 + \frac{C_{S1}}{C_{S2}}(\sin \omega t - 1)}. \] (3.14)

Since the capacitance scales with area, see Eq. (3.6), the sheath voltages \( V_{S1}, V_{S2} \) scale inversely with the electrode areas \( A_1, A_2 \):

\[ \frac{V_{S1}}{V_{S2}} = \left( \frac{A_2}{A_1} \right)^2 \] (3.15)

The larger voltage drop across the sheath develops at the smaller electrode. A more detailed model [3.3] including the current and voltage relation to sheath thickness results in

\[ \frac{V_{S1}}{V_{S2}} = \left( \frac{A_2}{A_1} \right)^4. \] (3.16)

Parallel plate reactors are often made asymmetrical with wafers placed on the smaller electrode. A larger potential develops across the sheath at this electrode, which increases ion energy and improves the directionality of the etching process. In most cases the high-potential RF power lead is connected to the smaller electrode with the larger electrode grounded at common potential. The external circuit usually has a blocking capacitor so that a negative DC bias voltage appears between the small electrode (cathode) and ground. This DC voltage is roughly the same as the potential drop in the sheath between the plasma and the cathode. Related to the plasma frequencies derived above, three regimes of RF excitation frequency are distinguished: low frequency (< 2 MHz), high frequency (2-30 MHz, usually 13.56 MHz) and microwave excitation.

In order to feed process gases into the reactor a simple opening can be used. A more homogeneous distribution is achieved when using a shower head. The chamber pressure is controlled by a pumping system with a butterfly valve and with the inlet gas flows.
Magnetrons

Magnetic fields are used to enhance the degree of ionization by confining the plasma. A treatment of the influence of magnetic fields to plasmas can be found in [3.4]. Here, we give only a summary. We use bold letters for vectors.

The equation of motion of an electron of velocity $v$ in an electric field $E$ and magnetic field $B$ is

$$\frac{dv}{dt} = \frac{e}{m_e}(E + v \times B).$$ (3.17)

When $B$ is uniform and $E$ is zero, the electron drifts along the field lines with a speed $v_\parallel$ which is unaffected by the magnetic field, and orbit the field lines with a cyclotron frequency

$$\omega_c = \frac{eB}{m_e}$$ (3.18)

and at the Larmor radius

$$r_L = \frac{m_e v_\perp}{e B}.$$ (3.19)

The resulting motion is a helix. When $B$ and $E$ are uniform and $E$ is parallel to $B$, the particles are freely accelerated and the helix pitch increases continuously. When there is an electric field component $E_\perp$ perpendicular to $B$, a drift speed

$$v_D = E_\perp/B$$ (3.20)

develops in a direction perpendicular to both $E_\perp$ and $B$ and combines with the orbiting motion. The effect of the magnetic field is a confinement of charged particles in the direction of the electric field. The loss mechanism in a plasma due to collisions is changed. With a magnetic field, collisions between identical or like particles do not result in net transport. The inward displacement of one particle is exactly balanced by the outward displacement of the other. The main contributions to diffusive transport become collisions of charged particles with neutrals (see Fig. 3.5).
3. Dry etching techniques

Fig. 3.5 Influence of a magnetic field on diffuse transport mechanism. \( \lambda_m \) is the mean-free-path and \( r_L \) the Larmor radius of the ion.

The modified electron and ion mobilities are given by [3.5]

\[
\mu_{\perp} = \frac{\mu}{1 + (\omega_e/v)^2}
\]  

where \( \mu \) is the mobility in the absence of a magnetic field or parallel a magnetic field line as in Eq. (3.2), and \( v \) is the collision frequency for the species in question (electrons to neutrals):

\[
v = N\sigma v_T.
\]

The collision cross section \( \sigma \) of an argon atom with an electron with 10 eV energy is about \( 10^{-19} \) m\(^2\) [3.6].

Typical values for the plasma parameters of an argon plasma in a magnetron are given in Tab. 3.2. The ion mobility is only slightly reduced by the magnetic field. However, the mobility of the electrons, with their motion dominated by collisions with neutrals, is reduced by a magnetic field by several orders of magnitude. They become much more efficient in generating ions. The ion concentration is enhanced and the sheath length is reduced. This results in a higher flux of ions with lower energy to the substrate enhancing the etch rate and decreasing the bombardment damage [3.7].
### 3.2. Principles of plasma etching

<table>
<thead>
<tr>
<th></th>
<th>electron</th>
<th>Ar⁺ ion</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>10</td>
<td>0.04</td>
<td>eV</td>
</tr>
<tr>
<td>Temperature</td>
<td>77.300</td>
<td>310</td>
<td>K</td>
</tr>
<tr>
<td>Mass</td>
<td>9.11×10⁻³¹</td>
<td>6.7×10⁻²⁶</td>
<td>kg</td>
</tr>
<tr>
<td>Density</td>
<td>5×10¹⁶</td>
<td>2.7×10²⁰ (Ar⁰)</td>
<td>m⁻³</td>
</tr>
<tr>
<td>Thermal velocity</td>
<td>1.9×10⁶</td>
<td>440</td>
<td>m/s</td>
</tr>
<tr>
<td>Collision frequency with neutrals</td>
<td>51.3</td>
<td>0.06</td>
<td>MHz</td>
</tr>
<tr>
<td>Conductivity</td>
<td>27.4</td>
<td>0.32</td>
<td>l/Ωm</td>
</tr>
<tr>
<td>Mean-free-path</td>
<td>4.4</td>
<td>7.4</td>
<td>mm</td>
</tr>
<tr>
<td>Plasma frequency</td>
<td>2000</td>
<td>7.4</td>
<td>MHz</td>
</tr>
<tr>
<td>Debye length</td>
<td>0.1</td>
<td>0.007</td>
<td>mm</td>
</tr>
<tr>
<td>Cyclotron freq. at B = 0.02 Tesla</td>
<td>560</td>
<td>0.048</td>
<td>MHz</td>
</tr>
<tr>
<td>Larmor radius</td>
<td>0.38</td>
<td>6.4</td>
<td>mm</td>
</tr>
<tr>
<td>Mobility at B = 0</td>
<td>3420</td>
<td>40</td>
<td>m²/Vs</td>
</tr>
<tr>
<td>Mobility at B = 0.02 Tesla</td>
<td>28</td>
<td>24</td>
<td>m²/Vs</td>
</tr>
</tbody>
</table>

Tab. 3.2  Calculated plasma parameters for an Ar plasma at p = 0.01 mbar. We assumed a density of charged particles of 5×10¹⁶/m³.

### Parameters for plasma control

Plasma etching processes may be characterized by their rate, selectivity, uniformity, anisotropy and surface quality. Ideally one would like to know how to control etching properties by manipulating basic chemical and plasma variables. In many basic texts and literature on electrical discharges, the plasma is examined from a fundamental point of view as a function of certain quasi-dimensionless similarity variables (like the ratio of electric field to number density or the product of number density and a characteristic length of reactor geometry). Unfortunately these variables are generally not useful for controlling most plasmas. Instrumental parameters or discharge variables are used instead. Discharge variables include reactor pressure, RF input power and frequency,
temperature, flow rate, feed gas composition, reactor geometry and material. The influence of **RF power** and **frequency** have already been discussed. We will survey some effects of the other variables.

The range of useful **pressure** is limited by two effects. With increasing pressure the collision rate will increase but the average electron energy will eventually decrease because the existing field will have less time to accelerate the electrons between collisions. The number of electrons with appropriate energy for generating active species decreases and the etch rate too. The low pressure limit is given by the reduced collision frequency and concentration of active species. These limitations delineate the useful pressure range to the region from about 10 μbar to several millibars. It should be noted that the pressure has not only influence on the concentration of active species, but also on their lifetimes. With decreasing pressures the characteristic potentials across the sheaths and the voltage applied to a discharge increase. As DC bias is proportional to the peak applied voltage, it rises too (see Fig. 3.6). The rise in potential translates into higher ion energy. Sputtering does not take place for ion energies below a ion-specific threshold [3.8]. However, for energies above threshold the number of atoms removed per incident ion usually remain well below unity.

![Oxygen plasma graph](image)

**Fig. 3.6** Dependence of DC bias voltage on chamber pressure for an oxygen plasma at different RF power levels. The DC bias increases with RF power and decreases with pressure (O₂ flow = 50 sccm, System 3, see next section).
Low pressure favors higher ion bombardment energies which promote etching by damage-induced mechanisms. But ion energies that are too high are undesirable in that selectivity decreases with increasing ion energy. At higher pressures the energy flux to the substrate increases with pressure as the number of ions increases with pressure. The energy transfer from electrons to neutrals - the thermalization of electrons - is proportional to gas pressure, so the neutral gas temperature tends to increase with pressure while the electron temperature falls. It is found heuristically that the ion density ranges about an order of magnitude more or less independent of the operating pressure [3.1]. That means that the surface flux of ions relative to neutrals can be varied by several orders of magnitude by changing pressure alone. So pressure allows to determine whether etching will be chiefly chemical or predominately ion assisted. In kinetic limited reactions the pressure has a strong influence on the etch rate, as the delivery of etching species is proportional to the pressure.

The influence of temperature is manifold. First we should mention that only the surface temperature of the cathode is really controllable. The gas temperature is a complex function of local RF power dissipation, heat transfer and transport phenomena. The temperature at the surface of the sample has a dominant effect on the rate constants for chemical reactions and hence on selectivity, etch rates, surface morphology and the degradation of resist masks.

Elementary chemical reactions usually vary with temperature according to the Arrhenius expression

\[ R(T) = A(T) \exp\left(-\frac{E_A}{kT}\right) \]  

where \( A \) is a "pre-exponential" which varies only weakly with temperature and \( E_A \) is the activation energy. If Eq. (3.23) is the slowest, rate determining reaction, the etch rate depends exponentially on temperature. This material specific alteration of etch rate can be used to improve the selectivity of the process. For high temperatures, \( \exp\left(-\frac{E_A}{kT}\right) \) always approaches unity, decreasing selectivity of reactions with different activation energies.

The evaporation rate \( r_a \) of a material with molecular weight \( M \) from a surface is:

\[ r_a \sim \sqrt{\frac{kT}{M}} P_A \]  

(3.24)
with the temperature dependence of the vapor pressure $p_A$ according to Clausius Clapeyron

$$p_A = C_A \exp(-\Delta H/kT)$$  \hspace{1cm} (3.25)

where $\Delta H$ is the latent heat of vaporization. Ion-induced etching processes typically exhibit smaller temperature dependence than those of neutral processes. However, the influence of temperature on the etch rate is sufficient to require temperature control in order to achieve constant and reproducible etch rates.

With the **flow-rate** $F$ at constant pressure $P$, the residence time of the feedstock gases in the reactor which is proportional to $F/P$ is controlled, with minimal effect on other plasma parameters. The degree of dissociation increases with increasing time the feedstock gas spends in the plasma. Thus at high flow-rates or short residence times, the radical density will decrease with increasing flow-rate. At low flow-rates the radical density will establish a dynamic equilibrium such that it becomes flow-independent. A generalized flow-rate dependence of the etch rate for the case where the reactant is generated in the plasma is given in Fig. 3.7.

![Fig. 3.7](image)

*Fig. 3.7 Dependence of etch rate on flow rate in the case where the reactant is generated in the plasma. Two limiting cases are obvious (after [3.9]).*

Etch rates often decrease as more etchable substrate material is placed in a reactor. This **loading effect** is the result of gas phase etchant being depleted by reactions. The etch rate is usually proportional to etchant concentration, and if a significant portion of these reactive species are consumed in the etching
3.2. Principles of plasma etching

reactions, their concentration decreases with increasing surface area being etched. Most isotropic etchants exhibit this effect. Loading is not present in plasmas in which the principal etchant loss process is insensitive to the etching reaction or where ion bombardment flux, rather than etchant supply, controls the etch rate.

Two criteria for **gas composition** are rather obvious. First, the gas must contain constituents which could form a volatile compound with the material to be etched. Secondly, the expected volatile compound should be relatively stable, that is, it should have a reasonably large heat of formation. The latter condition, apart from providing a thermodynamic driving force for the etching reaction, ensures that the volatile compound, once formed, will not decompose easily into its constituents in the plasma. The gas composition has dramatic influence on the plasma chemistry but also the material of the chamber walls can influence the distribution of reactants by surface reactions. For particular etching processes, the role of gas composition is discussed in section 3.4.

Many processes use **gas additives** for the following purposes:

- oxidants, to increase etchant concentration or to suppress polymers,
- inert gases, to stabilize plasma, dilute etchant, and improve heat transfer,
- radical scavenger, to increase film-former and to improve selectivity,
- inhibitor former, to induce anisotropy and to improve selectivity,
- volatilizer, to form a more volatile product and to increase etch rate.

A summary of typical trends in plasma processing as a function of process parameter variation is given in Tab. 3.3 (after [3.10]). All of these trends are contradicted for particular processes; therefore while this table is useful, careful consideration of each particular system and the physical phenomena which take place are necessary for accurate prediction of the process trends.
3. Dry etching techniques

<table>
<thead>
<tr>
<th>Response Variables</th>
<th>Process Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF power</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>+</td>
</tr>
<tr>
<td>Loading</td>
<td>-</td>
</tr>
<tr>
<td>Selectivity</td>
<td>-</td>
</tr>
<tr>
<td>Roughness</td>
<td>+</td>
</tr>
<tr>
<td>Uniformity</td>
<td>0</td>
</tr>
</tbody>
</table>

+ positive correlation
- negative correlation
0 small or unpredictable correlation

Tab. 3.3 Typical trends in plasma etching processes.
3.3. Available plasma etching equipment

Four commercial plasma etching systems are available in our Institute. They are used for the patterning of III-V semiconductor compounds, the etching of titanium, silicon oxides and nitrides, polyimide, photoresist and PMMA, as well as to ash organic residues. The systems are described in the following together with their applications.

System 1: Materials Research Corporation's MIE-711 (ARIES-C)
The system has been installed in 1988 and is an upgrade of the equipment described in [3.11]. A schematic diagram is shown in Fig. 3.8.

The 22 liter rectangular stainless steel chamber contains a "band-type" post magnetron which is to be described in more detail below. The magnetron cathode is connected to an automatic tuning network which is used to match the varying...
impedance of the plasma to the 50 Ohm impedance of a water cooled 13.56 MHz generator capable of delivering 3000 Watt. The pumping station consists of a 450 l/s turbopump and a 40 m³/hour mechanical pump. A manually controlled high vacuum gate valve is used to throttle the gas flow through the process chamber. The station is equipped with a load lock which is separately pumped by a mechanical pump. Prior to every process the chamber is evacuated to a background pressure of less than $5 \times 10^{-6}$ millibar. From the pump exhaust the process gases and the etching products are fed through a scrubber to remove the toxic parts. The turbopump, the cathode and the tuning network are water cooled. For pressure measurements a low pressure cold cathode ionization gauge and a high pressure capacitance manometer are connected to the process chamber. Dry nitrogen is used to vent the chamber through a separate inlet valve.

A schematic diagram of the cathode assembly is shown in Fig. 3.9. It contains bar magnets which produce the magnetic field surrounding the cathode. Other bar magnets are located outside of the chamber on the hinged lid. These aid in producing a more uniform magnetic field near the surface of the cathode. The strength of the magnetic field is about 0.02 Tesla. The effect of the magnetic field has been described in the previous section. The area of the driven electrode which is shielded by SiO₂ pieces is 1200 cm².

Fig. 3.9  *The band type cathode of the magnetron system.*
The stainless steel cathode is loaded by a 4-inch silicon wafer which is hold by four wafer clamps. The samples are mounted on this wafer. For good heat transfer a vacuum oil with high thermal conductivity (Santovac 5) is used. Thermal contact between the silicon wafer and the cathode is enhanced by helium at a pressure of 10 millibar. Fig. 3.10 shows a cut through the cathode.

![Fig. 3.10 Cut through the magnetron cathode.](image)

The system has four gas lines. The types of gas and the maximum flows are listed in Tab. 3.4. In the fourth line either hydrogen or helium can be used. On this system chlorine based as well as CH₄/H₂ based chemistries are used. Procedures to switch from one chemistry to the other without any crosstalk have been developed. InP as well as GaAs based materials are etched in this system.

<table>
<thead>
<tr>
<th>Gas</th>
<th>max. flow [sccm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl₂</td>
<td>90</td>
</tr>
<tr>
<td>SiCl₄</td>
<td>6</td>
</tr>
<tr>
<td>CH₄</td>
<td>15</td>
</tr>
<tr>
<td>H₂</td>
<td>110</td>
</tr>
<tr>
<td>He</td>
<td>150</td>
</tr>
</tbody>
</table>

Tab. 3.4 Gas types and maximum flows for system 1 (sccm = standard cubic centimeter per minute).
3. Dry etching techniques

**System 2: Oxford PlasmaLab 80 plus**

The system has been installed in 1993. It is a parallel plate reactor as sketched in Fig. 3.4. The 14.2 liter aluminum chamber is pumped by a 150 l/s turbopump and a 25 m³/hour mechanical pump. Pressure is controlled by an automatic butterfly valve. The circular electrode with a diameter of 17 cm is covered with a graphite plate and is water cooled. RF power is delivered by a 13.56 MHz generator with 500 Watt maximum power. A capacitance manometer and a low pressure cold cathode ionization gauge are used for the measurement of process and background pressure, respectively. Four gas lines are installed. The gases and the maximum flows are listed in Tab. 3.5. For safety reasons the oxygen line is locked against the lines with hydrogen and methane. The system is used for the etching of InP and GaAs based materials.

<table>
<thead>
<tr>
<th>System 2</th>
<th>Gas</th>
<th>max. flow [sccm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>CH₄</td>
<td>50</td>
</tr>
</tbody>
</table>

*Tab. 3.5 Gas types and maximum flows for system 2.*

The etching system is computer controlled. We installed a number of standard processes and a user-friendly menu allows people to run their plasma etching processes without the need of profound technical knowledge. During process a selection of data, like gas flows, RF power and DC bias are logged for the analysis of plasma stability.

**System 3: Oxford PlasmaLab 80 plus**

The system has been installed in 1993 and is identical with system 2 except of the gas delivery system. Five lines that can be used simultaneously are installed. The gases and the maximum flows are listed in Tab. 3.6. The system is used for the etching of silicon-oxides, silicon-nitrides, titanium for mask formation and for the ashing of photoresist and hydrocarbon deposits.
3.3. Available plasma etching equipment

<table>
<thead>
<tr>
<th>System 3</th>
<th>Gas</th>
<th>max. flow [sccm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>CHF₃</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>CF₄</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>C₂F₆</td>
<td>50</td>
</tr>
</tbody>
</table>

Tab. 3.6 Gas types and maximum flows for system 3.

System 4: Plasmatherm PK 12
The system has been installed in 1982 and has experienced several modifications. It is a parallel plate reactor system with a 13.2 liter aluminum chamber. A 300 l/sec diffusion pump is used for downpumping and a 370 l/min roots pump during process in conjunction with a 40 m³/hour mechanical pump. A maximum power of 400 Watt of a 13.56 MHz generator can be either switched to the bottom (loaded) or top electrode. Three gas lines are installed. The gases and the maximum flows are listed in Tab. 3.7. The system is used for the etching of GaAs, SiO₂, polyimides and for the ashing of photoresist and hydrocarbon deposits.

<table>
<thead>
<tr>
<th>System 4</th>
<th>Gas</th>
<th>max. flow [sccm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CF₄</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>CCl₂F₂</td>
<td>1000</td>
</tr>
</tbody>
</table>

Tab. 3.7 Gas types and maximum flows for system 4.
3.4. Process development

Plasma etching processes have been studied in order to develop an optimized process for the realization of integrated optical and microelectronic devices. The etching of InP and GaAs compound based materials, isolators and metals and the removal of organic residuals for cleaning purposes have been investigated. In this section we consider the development of etching processes that fulfill the needs for the realization of InP based corner mirrors and grating demultiplexers. The main requirement of such a process is a smooth vertical sidewall.

Test samples have been etched and evaluated in order to optimize process parameters. For each sample we routinely measured the etching depth by stylus force measurement (Alphastep 200) and inspected the etched surface quality by optical and scanning electron microscopy. A full characterization of an etching process includes the following essential parameters:

- chemistry
- rate
- selectivity
- uniformity
- anisotropy
- surface quality
- reproducibility
- compatibility with other process steps.

We discuss these parameters in the following with respect to our considerations towards an optimized process for the realization of InP based corner mirrors and grating demultiplexers.

Chemistry

Two chemistries are widely used for the dry etching of III-V compound semiconductors: halone based and more recently, hydrogen/hydrocarbon based chemistries. The choice amongst the two chemistries is influenced not only by process considerations but also from an equipment point of view. Most halons are toxic and very corrosive. Plasma etching processes with gases containing fluorine [3.12], chlorine [3.13], bromine [3.14] and iodine [3.15] are reported. The reactor must be kept rigorously free of oxygen and moisture. A load-lock system is
3.4. Process development

recommended and for environmental reasons a detoxification of the exhaust gases is advantageous. From our available equipment only system 1 (MIE 711) is suited for halone based chemistry. We investigated chlorine (Cl₂) and silicon tetrachloride (SiCl₄) based processes that are commonly used. The etching process is understood as a series of sequential steps [3.1]:

- ion and electron formation (which balance loss of charged species and are part of a more complex reaction set)

\[ e^- + \text{Cl}_2 \rightarrow \text{Cl}_2^+ + 2e^-, \] (3.26)

- etchant formation

\[ e^- + \text{Cl}_2 \rightarrow 2\text{Cl} + e^-, \] (3.27)

- adsorption of etchant on the substrate

\[ \text{Cl} + \text{Cl}_2 \rightarrow \text{InP}_{\text{surf}} + n\text{Cl} \] (3.28)

- chemical reaction to form product

\[ \text{InP} + n\text{Cl} \rightarrow \text{InCl}_x(\text{ads}) + \text{PCl}_y(\text{ads}) \] (3.29)

or ion enhanced etching to form product

\[ \text{InP} + n\text{Cl} \rightarrow \text{InCl}_x(\text{ads}) + \text{PCl}_y(\text{ads}) \] (ions) (3.30)

- product desorption either by evaporation or by ion-assisted desorption

\[ \text{InCl}_x(\text{ads}) \rightarrow \text{InCl}_x(\text{gas}), \] (ions)
\[ \text{PCl}_y(\text{ads}) \rightarrow \text{PCl}_y(\text{gas}) \] (3.31)

\[ \text{InCl}_x(\text{ads}) \rightarrow \text{InCl}_x(\text{gas}), \] (ions)
\[ \text{PCl}_y(\text{ads}) \rightarrow \text{PCl}_y(\text{gas}) \] (ions) (3.32)

The slowest step, usually removal of the group III halide product, will limit the etching rate (see below). The relative importance of the spontaneous [Eq. (3.29), (3.31)] and ion-assisted [Eq. (3.30), (3.32)] reactions depends on the etchant flux and substrate. At moderate pressure (~200 μbar), etching in chlorine is rapid,
spontaneous and crystallographic. However, at low pressure with intense ion bombardment (1-15 μbar), ion-enhanced reactions are more important.

Hydrogen/hydrocarbon mixtures were first reported in 1985 [3.16]. These noncorrosive gases are very useful not only from the point of view of safety but also because they can etch a wide range of InP-based semiconductors. Although an understanding of the etching mechanisms is still evolving [3.17], this chemistry is presently increasingly important in the fabrication of micro- and optoelectronic devices. The gases are neither hazardous nor corrosive and are well suited for the plasma etching of InP, GaAs, InAs, GaSb [3.18] and the entire range of InGaAsP quaternaries [3.19]. We will concentrate on CH₄/H₂ based gas mixtures, but also CH₄/He [3.20] and C₂H₆/H₂ [3.21] have successfully been used.

The following conclusions regarding the chemistry and mechanisms of plasma etching of InP in methane/hydrogen have been reached [3.17]. Hydrogen atoms are the primary reactants responsible for the volatilization of phosphorus, which desorbs as PH₃. Indium does not desorb to an appreciable extent as a result of interaction with hydrogen atoms or other excited species found in an hydrogen plasma alone; this is evidenced by the formation of indium droplets on the surface after removal of 20 nm of material at T<100°C [3.22]. In methane/hydrogen discharges, the primary reactant(s) responsible for indium volatilization is undoubtedly an organic radical. Organic ions are also possible, but their neutralization probability at the surface is high. The most likely candidate is the methyl radical, but ethyl and other radicals probably also play a role. At very low methane fractions the flux of organic radicals responsible for indium volatilization limits the etch rate; the system is thus under diffusion-limited control. On inert surfaces, organic radicals react only with each other to deposit a polymer film. The role of the ion-bombardment is to desorb lower-volatility organoindium hydrides and/or to provide the activation energy necessary to overcome barriers to the formation of volatile organoindium products.

**Etch Rate**

The demand for a sufficiently high etch rate is driven by economics, since it is often the limiting factor for the throughput. But high etch rates do not necessarily result in lower cost. Equipment size (footprint) and yield are major cost considerations in that the capital and operation costs of clean rooms are a large
fraction of the total expense. For the choice between two processes we considered
the etch rate only if the results are of the same quality.

For chlorine based InP etching the removal of the group III halide InCl$_3$ is often
the rate limiting step, due to the relative high latent heat of vaporization
$\Delta H = 34.5$ kcal/mol [3.23]. In order to increase product vapor pressure, the
samples are commonly heated (see Eq. (3.25)). In collaboration with the Swiss
PTT research laboratory, a chlorine based plasma etching process for InP was
developed for the fabrication of integrated optical corner mirrors. InP was etched
with SiCl$_4$ at temperatures between 200°C and 300°C in a magnetron ion etching
system. Smooth, vertical sidewall were obtained as shown in Fig. 3.11, with an
etch rate of 500 nm/min.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{corner_mirror SEM.png}
\caption{SEM picture of a corner mirror, etched with SiCl$_4$/Cl$_2$ at 240°C
(Swiss PTT research laboratory).}
\end{figure}

One should keep in mind that a controlled process at these temperatures is not
easily obtained and requires also a non-standard mask preparation. A detailed
description of the process and the results are given in [3.24] and [3.25].

For GaAs etching with chlorine containing gases, the etch rate is not limited by
the product evaporation due to the high vapor pressure of GaCl$_3$ (latent heat of
vaporization $\Delta H = 10.5$ kcal/mol [3.23]). Thanks to the high volatility of AlCl$_3$
at room temperature, the chlorine based chemistry is also suitable for the plasma
etching of Al$_x$Ga$_{1-x}$As structures. A high selectivity for the etching rates of GaAs
3. Dry etching techniques

and Al\textsubscript{x}Ga\textsubscript{1-x}As is obtained by adding fluorine containing gases. The aluminum reacts to the not volatile product AlF\textsubscript{3} that prevents underlaying structures from being etched [3.26].

The etch rate for InP for CH\textsubscript{4}/H\textsubscript{2} based processes is usually much lower than for halone based processes. Typical values are in the range of 10-60 nanometer per minute [3.16]-[3.19]. The etch rate is limited by the flux to the surface of hydrocarbon reactants responsible for In desorption. PH\textsubscript{3} is identified by mass spectrometry as the primary P-containing volatile product, while the primary In-containing volatile product remains unidentified [3.17]. We measured much higher etch rates, up to 500 nm/min, with the magnetron system 1 (MIE 711). This is explained by the higher concentration of ions and other active species. The etch rate increases with increasing RF power and total gas flow (Fig. 3.12).

![Fig. 3.12 Measured InP etch rate with CH\textsubscript{4}/H\textsubscript{2} on system 1 (MIE 711) as a function of total gas flow. The etch rate increases nearly linearly with total gas flow. CH\textsubscript{4} content = 15%, pressure = 87.5 \textmu bar, RF power = 1300 Watt.](image)

The dependence on methane content is observed to increase rapidly, go through a maximum, and decrease at methane levels above about 25%. Past the maximum the etch rate is not very reproducible (Fig. 3.13) and a deposition of polymers on the InP surface is observed.

90
Fig. 3.13 Measured InP etch rate with $\text{CH}_4/\text{H}_2$ on system 1 (MIE 711) as a function of $\text{CH}_4$ content. The etch rate increases with $\text{CH}_4$ content. Plasmas with more than 25% $\text{CH}_4$ tend to deposit nonvolatile products also on the InP surface. Total gas flow = 100 sccm, pressure = 100 \(\mu\text{bar}\), RF power = 1000 Watt.

Fig. 3.14 Measured InP etch rate with $\text{CH}_4/\text{H}_2$ on system 1 (MIE 711) as a function of chamber pressure. The etch rate is almost constant over a wide range of pressure. Total gas flow = 100 sccm, $\text{CH}_4$ content = 15%, RF power = 1300 Watt.
3. Dry etching techniques

The etch rate is almost constant over a wide range of pressure (Fig. 3.14). The small temperature dependence of the etch rate is an indication that the limiting step is not the desorption of the etching products from the substrate surface. We observed a strong loading effect for the etching with CH₄/H₂. The etch rate varied more than a factor of 3 between devices with very small areas to be etched and full 2-inch InP wafer etching.

**Selectivity**

Selectivity is the ratio of the etch rates of two different materials. Techniques for etching III-V compound semiconductor devices are sometimes complicated by the need to penetrate multiple layers of binary, ternary and quaternary alloys in a single structure. High selectivity is required at times, yet in other cases it is necessary to etch different III-V materials at the same rate. Most important is the selectivity to photoresist as mask material. It is an essential parameter in order to obtain minimum feature size. Mask shrinkage leads to reduced dimensions. In some cases this can be compensated by proper mask design [3.27] but generally other mask materials with better selectivity have to be used. This is the case for chlorine based processes where we measured selectivities to photoresist of about 2. With SiO₂ masks we obtained better results with a selectivity of about 10. We found chrome to be very stable against chlorine attack, but this metal is not easily removed after plasma etching.

Processes based on CH₄/H₂ do not etch either photoresist, nor metals and insulating layers as SiO₂ and SiNₓ. The plasma produces polymerizing radicals that form hydrocarbon films. The films are deposited on the masked areas and allow the use of very thin masks with highest resolution. We measured film deposition rates from 10% to 30% of the InP etch rate. However, very thin layers on the surface can work as unwanted mask. Residuals of solvents, photoresist developer or native oxides can occur on the surface. Careful sample cleaning before etching becomes important. A 5 second dip in hydrofluoric acid or a 30 second oxygen plasma treatment were found to reduce the risk of polymer formation on InP surfaces. Due to the usually high RF power of the CH₄/H₂ processes, photoresist is replaced by SiO₂ as mask material because of the much higher thermal stability of SiO₂. In spite of the polymer deposition, the SiO₂ mask is observed to be slightly eroded [3.28]. We confirmed this effect. The measured mask shrinkage was less than 0.3 μm for etching depths up to 10 μm.
The selectivity for CH$_4$/H$_2$ between different III-V semiconductor compounds seems to be dependent on the equipment and process parameters. With system 2 (Plasmalab 80 plus) the general trend of etch rates InP > InGaAsP > InGaAs > GaAs > AlGaAs [3.17] is confirmed with a ratio of approximately 3 between InP and InGaAs for the same process. However, with the magnetron system 1 (MIE 711) we did not observe any differences in etch rate between InP and InGaAsP quaternaries. Fig. 3.15 shows an etched sample that was masked with photoresist and consisted of an InP/InGaAsP/InP double heterostructure. No changes in sidewall angle and morphology are visible at the layer interfaces.

![InP/InGaAsP/InP double heterostructure etched with CH$_4$/H$_2$ on system 1 (MIE 711). No changes in sidewall angle and morphology are observed at the layer interfaces. The etch rate was the same for both materials. Photoresist with a thickness of 1.9 μm was used as mask. CH$_4$ flow = 12 sccm, H$_2$ flow = 108 sccm, pressure = 150 μbar, RF power = 1200 Watt.]

**Uniformity**

Nonuniformity in etch depth is the result of two effects: variations in the etch rate caused by reactor geometry and variations in the etch rate over the sample due to edge effects. Equipment suppliers try to maximize uniformity by proper reactor design. Variations in etch rate caused by reactor geometry can hardly be compensated by process parameter optimization. In some cases it helps to etch in several steps and to load the sample in different orientations into the reactor.
CH$_4$/H$_2$ plasma etching inherently tends to form a rather nonuniform distribution of etch rates across an InP wafer with fastest etching occurring at the wafer edge. On system 1 (MIE 711) we measured nonuniformities of more than ±10%. These were reduced to ±3% by placing unmasked InP pieces around the sample to be etched. Successful uniformity improvement by the introduction of a guard ring is also reported [3.29]. The edge effect can also be counteracted by an appropriate choice of process parameters. On system 2 (Plasmalab 80 plus) by process optimization we reached less than ±1% nonuniformity for the InP etch rate within the sample area 2 mm from the edge.

**Anisotropy**

We define the degree of anisotropy

$$A = 1 - \frac{R_h}{R_v}$$

where $R_h$ and $R_v$ are the horizontal and vertical etch rates, respectively. For isotropic etching, $R_h$ and $R_v$ are equal ($A=0$) whereas for ideal anisotropic etching, $R_h=0$ ($A=1$).

![Fig. 3.16 Definition of sidewall angle Φ, mask sidewall angle θ, horizontal etch rate $R_h$ and vertical etch rate $R_v$.](image)

The sidewall angle Φ of an etched structure is dependent on anisotropy and mask shrinkage. Mask shrinkage (neglected in Fig. 3.16) is a function of selectivity and mask sidewall angle θ. Consequently, for perfect pattern transfer a high degree of anisotropy as well as a high selectivity are mandatory. For the realization of corner mirrors and grating demultiplexers a sidewall angle of 90° is most important (and difficult to obtain). Non-vertical facets redirect light from
horizontal propagation on the chip, excite radiation modes and cause optical losses.

The anisotropic nature of CH\textsubscript{4}/H\textsubscript{2} etching is not yet fully understood. According to [3.17], an ion-enhanced energetic mechanism (see Fig. 3.1) is proposed. Ion bombardment is shown to provide anisotropy either by sputter removal of low-volatility products or by providing the activation energy necessary to surmount barriers to reaction to form volatile products. Sometimes we observed sidewall deposits, therefore an inhibitor mechanism cannot be rejected. In the absence of polymer growth around the mask edge, a small undercut can appear. Here the material is largely protected from direct ion bombardment and consequently a fully chemical etch component exists. The addition of a small flow of oxygen to CH\textsubscript{4}/H\textsubscript{2} resulted in the disappearance of the undercut [3.30]. The sidewall etch mechanism has therefore been eliminated. This may be explained in terms of the formation of a protective oxide layer. In addition, the oxygen in the gas phase inhibits the formation of unsaturated hydrocarbons and promotes the formation of lower carbon species. It is suggested that this leads to a lower polymer deposition rate and therefore more vertical wall profiles. For safety reasons we do not add oxygen to the process gases. Instead, we interrupt the etching several times and introduce an oxygen cleaning step. This procedure leads to more vertical sidewalls with less roughness, if the mask material is not etched by the oxygen plasma, i.e. if SiO\textsubscript{2} is used instead of photoresist. Alternatives would be the addition of less reactive oxygen source gases like N\textsubscript{2}O or CO\textsubscript{2} to the process gases.

During process optimization the sidewall angle \( \Phi \) was measured by SEM inspection with an accuracy of about \( \pm 1^\circ \) (see inset of Fig. 3.17). Typically variations from run to run are in the \( \pm 2^\circ \) range. But the sidewall also varies on a single substrate, depending on the etched feature. Etched gaps with small widths have larger sidewall angles, in some cases even more than 90°, compared to etched ribs. This effect is probably caused by ion scattering and back-reflection from the opposite sidewall [3.31]. In the magnetron system 1 (MIE 711) we additionally noticed an orientation dependent asymmetry of the etched profiles. The asymmetry can be explained by the influence of the magnetic field on the ion trajectories.

Fig. 3.17 shows the influence of the total gas flow rate on the sidewall angle. The multiple points at 20 sccm and 80 sccm give an indication about the total spread
in sidewall angle for system 1 (MIE 711), including the mentioned effects above. Higher gas flows tend to increase the sidewall angle.

![Graph showing measured InP sidewall angle as a function of total gas flow with CH\textsubscript{4}/H\textsubscript{2} on system 1 (MIE 711). CH\textsubscript{4} content = 15%, pressure = 87.5 \textmu bar, RF power = 1300 Watt.]

During optimization of a CH\textsubscript{4}/H\textsubscript{2} based process on system 1 (MIE 711) the following heuristic trends for the anisotropy have been observed: higher methane content leads to more vertical sidewalls but also to increased roughness. Methane contents between 10% and 15% give best results. The RF power showed similar influence as the methane content: high RF power gives better verticality but also at the prize of an enhanced sidewall roughness. Therefore a compromise between verticality and roughness is necessary. For too high RF powers, mask decomposition may occur by excessive heating.

On system 2 (Plasmalab 80 plus) we state a reduced run to run spread in sidewall angle and a better homogeneity. The addition of a small amount of argon further improved the smoothness and verticality of the etched structures.

**Surface quality**

Surface quality covers a wide range of things that can be influenced by many variables, including temperature, ion bombardment, etchant and crystallographic orientation. Sometimes etching leaves a finished surface smoothness similar to
the unetched film. Under other conditions etched surfaces may be unacceptably rough, pitted or covered with cones or spikes or substrate material. Contamination from sputtering, etch residues and electrical damage caused by contamination, radiation and charging may degrade surface quality.

Ion bombardment, ion bombardment in conjunction with coating formation, or energetic photons can modify the properties of the semiconductors being etched. The introduced damage can be classified as either intrinsic bonding (crystal) damage, impurity permeation, or surface film formation [3.32]. Crystal damage occurs to a maximum depth of 50 nm for ion energies below 400 eV. Such disorder showed significant recovery after 400°C, 30 s annealing [3.33]. Hydrogen diffusion into the InP during CH$_4$/H$_2$ etching leads to a drastic reduction of the electrically active zinc acceptors. This passivation is only observed for p-type doping and penetrates up to 500 nm into the InP. A similar anneal procedure as above restores the active carrier concentration [3.34], [3.35]. These two classes of damage are not very important in our case, since the damaged layers are very thin and can be restored or wet chemically removed. More important is the third class of damage, the formation of surface films. It takes place on both vertical and horizontal surfaces. The films locally change the etch rate leading to an increased roughness.

![InP ridge waveguide with smooth surfaces etched with Ar / Cl$_2$ / CH$_4$ on system 1 (MIE 711). Ar flow = 20 sccm, Cl$_2$ flow = 1 sccm, CH$_4$ flow = 2.5 sccm, pressure = 3 μbar, RF power = 700 Watt.](image)
For the realization of corner mirrors and grating demultiplexers the roughness on horizontal surfaces is not critical, but the roughness on vertical surfaces is one of the main reasons for scattering losses. Roughness amplitudes of less than 10 nm are targeted (see chapter 2). This is more easily achieved, if the no restriction for sidewall angles apply. As an example, Fig. 3.18 shows an optical InP ridge waveguide where special attention was paid to surface smoothness. As mentioned above it is much more difficult to obtain simultaneously vertical and smooth sidewalls.

For the characterization of deposited films on etched and masked surfaces we prepared InP samples in the following way (Fig. 3.19): the samples were half covered with silicon dioxide. 50 μm broad photoresist stripes with 50 μm spacing were overlaid.

![Photoresist stripes](image)

*Fig. 3.19 Sample preparation for the characterization of deposited films on etched and masked areas.*

Films were deposited during etching with CH₄/H₂ in system 1 and system 2. After photoresist removal with acetone that did not attack the films, a pattern as shown at the top left hand side in Fig. 3.20 resulted. The samples were analyzed by secondary ion mass spectroscopy (SIMS) at the Swiss Federal Laboratories for Materials Testing and Research (EMPA). Positive ion mass spectra were taken and for some selected masses a mapping of the signal intensity was made, that represents the local abundance of the corresponding elements on the sample surface [3.36].

The results can be summarized as follows: the mass spectra were dominated by the indium peaks at m/z = 113 and 115. Phosphorus (m/z = 31) and InP (m/z = 146) were not visible indicating a strong phosphorus depletion of the
surface. Many organic signals were found originating from polymers and possible contamination.

3.4. Process development

Fig. 3.20 Results of the SIMS surface characterization of CH$_4$/H$_2$ etched InP. All four parts show the same section of a sample. The bright areas show higher signal intensities than the dark areas.

Top left: schematic view of the periodically repeated pattern after processing.
Top right: map of the $^{115}$In$^+$ signal,
Bottom left: map of the $^{28}$Si$^+$ signal,
Bottom right: map of the m/z = 73 signal.
Signals between m/z = 200 and m/z = 300 could not be definitely associated. The spectra of the different samples were very similar, suggesting the same film composition in the two etching systems. This is astonishing, since we found big differences in the ability for removing the film after etching in the two systems. Films formed in system 1 could never be completely removed without lift-off by wet etching of the underlaying silicon dioxide mask, while films formed in system 2 were completely etched in an oxygen plasma. A possible explanation for this behavior is the higher temperature occurring in system 1 (MIE 711) due to the high RF power applied.

Fig. 3.20 shows the maps of the signals from $^{115}$In$^+$, $^{28}$Si$^+$ and m/z = 73 that was found representative for the hydrocarbons. The indium signal map (Fig. 3.20, top right) is interpreted as follows: indium is incorporated in the deposited films. The intensity on the previously masked SiO$_2$ is lower owing to the removal of the film by photoresist lift-off. In the region without SiO$_2$ mask, the indium signal is lower in the etched stripes. This may be caused by a thin shielding film cover that was created during etching. The silicon signal map (Fig. 3.20, bottom left) shows a very low intensity in the InP region. The source is suggested to be caused by SiO$_2$ mask erosion. The signal behavior in the SiO$_2$ masked region is easily understood. High intensity is measured in the stripes with native SiO$_2$ while low intensity appears where the SiO$_2$ has been covered by a film. The map of the hydrocarbon signal (Fig. 3.20, bottom right) looks like an inverted picture of the silicon map. In the SiO$_2$ region the hydrocarbon signal intensity is high where a film was deposited and low where the film was removed with the photoresist. In the InP region the intensity is unexpected high. Only small differences are seen between the stripes with and without photoresist. We attribute most of the signal to organic contamination generated during photoresist removal that may be stronger attached on the InP surface than on the SiO$_2$ and film surface. Differences between the native and the etched InP, originating from generated surface films during etching are covered up by this contamination.

In conclusion, the surface study confirmed the suppositions that the silicon dioxide mask is slightly eroded during CH$_4$/H$_2$ plasma etching, and that polymer films are deposited which contain indium. A quantitative characterization of the film composition and structure may give more insight and possibly explain the differences observed during film removal, but would require much effort.
3.4. Process development

Reproducibility
At first glance, reproducibility may appear to be more a matter of process control than an inherent process characteristic. However, etching equipment and processes sometimes have insidious memory or hysteresis effects that are difficult to control. The initial condition of the reactor can be influenced by accumulation of etch products, exposure to ambient atmosphere with moisture adsorption and surface modification brought about by reaction with chemical plasmas in the equipment. For CH$_4$/H$_2$ etching, reactions with the polymer-coated walls of the reactor are an important source of reactive species; thus periodic cleaning with an oxygen plasma and subsequent seasoning are necessary for reproducible results. Careful cleaning of the sample surface prior to etching was identified as critical procedure. Although we achieved state of the art results, the reproducibility has still to be improved for applications in industrial processes. This is only possible with a better knowledge of the basic chemical reactions and mechanisms during CH$_4$/H$_2$ plasma etching that would also enable a reliable modeling of the etching processes.

Compatibility with other process steps
Since the etching is not the only process used in the fabrication of OEIC's, it must not affect the other steps. Problems that may be encountered are: formation of masking layers on non-planar substrates, restrictions in the choice of mask material, cleaning steps that attack structured layers, excessive heating of the devices, and others. In most cases these are not issues of the etching process alone and can be solved individually by a proper design of the fabrication sequence.

To conclude, we can state that the development of plasma etch process is a complicated, time-consuming undertaking, with many performance trade-offs and compromises involved. The goal still remains a totally controllable process that uses a harmless chemistry, with tunable etch rate, infinite selectivity, perfect pattern transfer, smooth vertical sidewalls, mirrorlike surfaces, at moderate costs.
3. Dry etching techniques

3.5. Results

In this section we describe the processes with the best performance for each type of etching material. In order to obtain reproducible results the etching chamber was conditioned prior to the loading of the samples. Conditioning consisted of a dummy run of about 20 minutes. A decrease in DC bias of more than 30 Volts compared to initial values indicated the necessity of chamber cleaning (change of chamber shields for system 1, one hour oxygen plasma for system 2).

The variation in etch rate are due to the loading effect. The lowest etch rate corresponds to full 2-inch wafer etching while the highest etch rate is measured for small samples or for wafers with a high percentage of masked area.

**InP and InGaAsP with system 1 (MIE 711)**

![Etched corner mirror in an InP/InGaAsP/InP doublehetero structure. The same etch rate for InP and InGaAsP is measured. The deviation from verticality is less than 3°. The triangle was masked with low resolution photoresist, the waveguide with high resolution SiO₂.](image)

The mirrors presented in Fig. 2.3 and Fig. 2.6 - Fig. 2.9 are etched with the same process. The sidewalls deviation from verticality is always less than 3° with a
3.5. Results

weak roughness of 20-40 nm that is observed by SEM. Preferred mask material is SiO₂, but the process is also suited for photoresist masks with more than 1 μm thickness (see Fig. 3.15). The film deposited on the masked areas is difficult to remove. Best results are obtained with mask lift-off. Process data are listed in Tab. 3.8. The process is very sensitive to any residual contamination of the surface to be etched.

<table>
<thead>
<tr>
<th>CH₄ flow</th>
<th>12</th>
<th>sccm</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ flow</td>
<td>108</td>
<td>sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>150</td>
<td>μbar</td>
</tr>
<tr>
<td>RF power</td>
<td>1200</td>
<td>Watt</td>
</tr>
<tr>
<td>DC bias</td>
<td>-290</td>
<td>Volt</td>
</tr>
<tr>
<td>Etch rate</td>
<td>80-300</td>
<td>nm/min</td>
</tr>
</tbody>
</table>

Tab. 3.8 Process data for the etching of InP/InGaAsP with system 1 (MIE 711).

InGaAsP with system 2 (Plasmalab 80 plus)

Fig. 3.22 Part of an etched reflective grating in InP and a waveguide profile. Compared to system 1 the surface is smoother. However, the sidewall is bowed due to a small mask undercut.
3. Dry etching techniques

The grating in Fig. 4.4 is etched with the same process. On system 2 the optimized process for the fabrication of corner mirrors and grating demultiplexers showed some differences, compared to system 1. The etched sidewalls are smoother, but suffer from a bowing due to a small mask undercut. For best verticality, after the etching of every 500 nm, the process is interrupted and an oxygen cleaning step of 2-3 minutes duration is introduced. Either SiO₂ or photoresist can be used as mask material. Polymer deposit on masked surfaces can easily be removed with an oxygen plasma. The process is very homogeneous and well suited for the fabrication of rib waveguides with a nonuniformity of less than ±1.5%.

<table>
<thead>
<tr>
<th>Process Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄ flow</td>
<td>12 sccm</td>
</tr>
<tr>
<td>H₂ flow</td>
<td>60 sccm</td>
</tr>
<tr>
<td>Ar flow</td>
<td>6 sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>85 µbar</td>
</tr>
<tr>
<td>RF power</td>
<td>225 Watt</td>
</tr>
<tr>
<td>DC bias</td>
<td>-440 Volt</td>
</tr>
<tr>
<td>Etch rate</td>
<td>15-35 nm/min</td>
</tr>
</tbody>
</table>

Tab. 3.9 Process data for the etching of InP/InGaAsP with system 2 (Plasmalab 80 plus).
AlGaAs with system 1 (MIE 711)

**Fig. 3.23** Plasma etched GaAs/AlAs Bragg mirror for a vertical cavity surface emitting laser (VCSEL). The etch rates are the same for GaAs and AlAs. Smooth vertical sidewalls were obtained. The sample has been stain etched in order to distinguish the different layers.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl$_2$ flow</td>
<td>16.5</td>
<td>sccm</td>
</tr>
<tr>
<td>SiCl$_4$ flow</td>
<td>3</td>
<td>sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>2.7</td>
<td>µbar</td>
</tr>
<tr>
<td>RF power</td>
<td>300</td>
<td>Watt</td>
</tr>
<tr>
<td>DC bias</td>
<td>-100</td>
<td>Volt</td>
</tr>
<tr>
<td>Etch rate</td>
<td>800</td>
<td>nm/min</td>
</tr>
</tbody>
</table>

**Tab. 3.10** Process data for the etching of GaAs based materials with system 1 (MIE 711).

For this process, the obtained selectivity of two relative to photoresist is too low for a good pattern transfer. SiO$_2$ (selectivity $= 10$) or chrome (selectivity $> 40$) are the preferred mask materials.
3. Dry etching techniques

**SiO$_2$ with system 3 (Plasmalab 80 plus)**

![Plasma etched SiO$_2$ strip. The SiO$_2$ is mainly used as mask material. The large thickness of 1 µm for this sample has been used order to show the etch profile.](image)

**Fig. 3.24** Plasma etched SiO$_2$ strip. The SiO$_2$ is mainly used as mask material. The large thickness of 1 µm for this sample has been used in order to show the etch profile.

**Tab. 3.11** Process data for the etching of SiO$_2$ with selectivity $\approx 7$ relative to photoresist.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar flow</td>
<td>61</td>
<td>sccm</td>
</tr>
<tr>
<td>CHF$_3$ flow</td>
<td>13</td>
<td>sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>130</td>
<td>µbar</td>
</tr>
<tr>
<td>RF power</td>
<td>375</td>
<td>Watt</td>
</tr>
<tr>
<td>DC bias</td>
<td>-500</td>
<td>Volt</td>
</tr>
<tr>
<td>Etch rate</td>
<td>50</td>
<td>nm/min</td>
</tr>
</tbody>
</table>

With system 3 we were able to substantially increase the performance of our previous SiO$_2$ etching process. The process listed in Tab. 3.11 replaced a SiO$_2$ patterning process that was run on system 4 (Plasmatherm PK 12) based on CF$_4$. The selectivity relative to photoresist has been increased by a factor of twenty and
the sidewall angle increased from 30° to nearly 90°. The improvement is due to the presence of hydrogen in the plasma that works as a radical scavenger. Fluorocarbon polymer films form on the surfaces not exposed to ion irradiation (i.e. the sidewalls) and induce anisotropy. The most critical parameter during process optimization was the Ar / CHF₃ gas flow ratio.

Thanks to the involatility of group III fluorides, this chemistry is used for the selective etching of SiO₂ layers on III-V semiconductors.

**Removal of organic residuals with system 3 (Plasmalab 80 plus)**

A variety of processes are run for the stripping of photoresist and the removal of organic residuals from a wafer surface. The process parameters are not critical and are selected according to individual requirements. Typical values are listed in Tab. 3.12. This process is also used for polymer removal and chamber cleaning of system 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ flow</td>
<td>100</td>
<td>sccm</td>
</tr>
<tr>
<td>Pressure</td>
<td>130</td>
<td>µbar</td>
</tr>
<tr>
<td>RF power</td>
<td>150</td>
<td>Watt</td>
</tr>
<tr>
<td>DC bias</td>
<td>-325</td>
<td>Volt</td>
</tr>
<tr>
<td>Etch rate</td>
<td>material dependent</td>
<td></td>
</tr>
</tbody>
</table>

*Tab. 3.12 Typical process data for the removal of organic residuals on system 3 (Plasmatherm 80 plus).*
3. Dry etching techniques

3.6. Conclusions

We gave an overview of the principles of plasma etching. The influence of important process parameters such as RF power, pressure and gas composition on the etching results has been described. We developed dry etching processes for the available equipment that push the limits of dry etching. SiO₂ masks have been defined with accurate pattern transfer and high selectivity to photoresist. InP has been etched with H₂/CH₄ gas mixtures resulting in smooth facets with a deviation of less than 1° from verticality. Etch rates were up to 250 nm/min and no mask undercut appeared. These processes are essential for the successful fabrication of corner mirrors and grating demultiplexers. However, there is still room for improvements of the reproducibility and maturity of the used techniques in order to fulfill the very stringent process requirements for integrated optical devices.
3.7. References

[3.1] D. M. Manos and D. L. Flamm (Editors)
"Plasma Etching"

[3.2] W. C. Dautremont-Smith, R. A. Gottscho, and R. J. Schutz, in
"Semiconductor materials and process technology handbook"
edited by G. E. McGuire
Noyes publications, New Jersey, pp. 191-328, 1988

[3.3] H. R. Koenig and L. I. Maissel
"Application of RF discharges to sputtering"

[3.4] F. F. Chen
"Introduction to plasma physics"
Plenum, New York, pp. 70-74, 1974

"Principles of Plasma Physics"

"The diffusion and drift of electrons in gases"
Wiley, New York, p. 611, 1974

"Advantages of magnetron etching"

[3.8] C. M. Melliar-Smith and C. J. Mogab, in
"Thin film processes"
edited by J. L. Vossen and W. Kern

"Flow rate effects in plasma etching"

[3.10] H. H. Sawin
"A review of plasma processing fundamentals"
3. Dry etching techniques

“High rate masked etching of GaAs by magnetron ion etching”

“Reactive-ion etching of GaAs and InP using CCl₂F₂/Ar/O₂”

“Directional reactive-ion-etching of InP with Cl₂ containing gases”

“Controlled beam dry etching of InP by using Br₂-N₂ gas”
Proceedings of the 7th International Conference on Indium Phosphide and Related Materials, IPRM’95, pp. 561-564, 1995

“Vapor etching of GaAs and AlGaAs by CH₃I”

“A novel process for reactive ion etching of InP, using CH₄/H₂”

“Reactive ion etching of InP using CH₄/H₂ mixtures: Mechanisms of etching and anisotropy”

“Methane/hydrogen-based reactive ion etching of InAs, InP, GaAs, and GaSb”

“Methane/hydrogen metal organic reactive ion etching of GaInAsP compounds”
3.7. References

[3.20] E. Andideh, I. Adesida, T. Brock, C. Caneau, and V. Keramidas
"Short-period gratings for long-wavelength optical devices"

"1.5 μm GaInAsP/InP buried-heterostructure laser diode fabricated by
reactive ion etching using a mixture of ethane and hydrogen"

"Hydrogen plasma etching of semiconductors and their oxides"

"Temperature dependence of InP and GaAs etching in a chlorine plasma"

"Etching of InP with SiCl₄ for smooth surfaces and vertical sidewalls at
temperatures between 200°C and 300°C in a modified magnetron ion
etching system"
Proceedings of the 5th International Conference on Indium Phosphide
and Related Materials, IPRM'93, pp. 533-536, 1993

[3.25] Generaldirektion PTT:
J. Schneider
"Temperature-dependent reactive ion etching of InP with chlorine-based
gases for vertical sidewalls"
Report No. VM25.040C, 28.2.1991,
J. Schneider, M. Moser, and K. Affolter
"Modification of a magnetron ion etching system for etching at
temperatures from ambient to about 250 °C"
Report No. VM25.048C, 3.8.1992, and
J. Schneider, M. Moser, and K. Affolter
"Low loss corner mirrors in InP/InGaAsP/InP for integrated optics
etched with chlorinated gases"
3. Dry etching techniques

"Reactive ion etch characteristics of thin InGaAs and AlGaAs stop-etch layers"

[3.27] E. Gini and H. Melchior
"Low loss self-aligned optical waveguide corner mirrors in InGaAsP/InP"
Proceedings of the 18th European Conference on Optical Communication, ECOC'92, pp. 553-556, 1992

"SiO₂ mask erosion and sidewall composition during CH₄/H₂ reactive ion etching of InGaAsP/InP"

[3.29] K. Janiak and U. Niggebrügge
"Investigation of macroscopic uniformity during CH₄/H₂ reactive ion etching of InP and improvement using a guard ring"
Proceedings of the 87th International Conference on Indium Phosphide and Related Materials, IPRM'96, pp. 111-114, 1996

"Reactive ion etching of low-loss mirrors in InP/InGaAsP/InP heterostructures using CH₄/H₂/O₂ chemistry"
Proceedings of the 6th International Conference on Integrated Optics, ECIO'93, 1993

"The influence of ion scattering on dry etched profiles"

"Damage effects in dry etching"

"Electrical and structural changes in the near surface of reactively ion etched InP"
[3.34] T. R. Hayes, W. C. Dautremont-Smith, H. S. Luftman, and J. W. Lee
"Passivation of acceptors in InP from CH₄/H₂ reactive ion etching"

[3.35] J. Singh
"Reactive ion etching of zinc doped InP using methane and hydrogen:
Assessment of the degree and extent of changes in surface carrier concentration"

[3.36] B. Keller and M. Wolfensberger
"Oberflächenuntersuchung von InP-Proben"
EMPA Untersuchungsbericht Nr. 15840982
3. Dry etching techniques
4. InP Grating demultiplexers and their applications
4.1. Introductory overview

In this chapter we present our results on multiplexers/demultiplexers. The motivation for the development of these devices came from the ESPRIT project MOSAIC. The objective of this project was the development of advanced optoelectronic circuits creating high functionalities for future communication systems. We were engaged in the development and realization of multichannel WDM receivers for a multiwavelength transmission system testbed.

Towards this end we developed and realized grating demultiplexers in InP. The choice of this demultiplexer type and material was strongly influenced by the following two system specifications:

- Wavelength matching of the transmitter and wavelength filter channels is mandatory
- Transmission is over standard single mode fibre with erbium-doped fiber amplifiers.

In order to fulfill the first specification one must very accurately control the refractive index of the material. An active control of the refractive index that corresponds to tunability is of great help. This specification was the main reason to select InP as material because of its high temperature coefficient of the refractive index. The possibility for the integration with other optical or electrical components is an additional advantage.

The second specification was translated into the necessity of polarization independence and a high coupling efficiency to single mode fibers. Since no polarization independent demultiplexers in InP were reported at the time of the start of the project, this was also a challenging feature. High coupling efficiencies to single mode fibres are achieved for large optical mode sizes. With no optical mode transformers this implies the use of low contrast waveguides that are not suited for small radii waveguide bends. Due to this fact we selected a reflective grating as dispersive element that avoids the use of waveguide bends and hence minimized the needed chip area. The free spectral range should cover the EDFA window which is about 30 nm. Consequently the working order of the demultiplexer must be below 50.

After the decision on InP as material and on a grating type device the following problems were encountered: theoretically, the optimization of the grating design in terms of polarization dependence, aberration reduction, size, filter
transmission curve and crosstalk. Practically, the fabrication of the etched gratings was the most challenging factor. A grating demultiplexer has many technological features in common with corner mirrors: instead of one mirror facet that reflects light from one waveguide into another, a grating is built from several hundred of small mirrors that not only reflect light but also work as dispersive elements due to the correlated positions of the individual mirrors. For this device too, the results obtained depend strongly on the masking and etching technique used for the fabrication of the gratings. At our Institute we have developed a plasma etching technique which is well suited for the realization of smooth vertical facets, so that we optimistically started the realization of grating demultiplexers.

The chapter is structured as follows:

In section 4.2 we present our concept of the grating demultiplexer. The design, fabrication, characterization and packaging of a WDM filter module are reported. Special attention is paid to achieve a polarization insensitive device.

Section 4.3 describes the simulation of the grating demultiplexer. The optimization in terms of grating blazing, size, resolution, image quality and filter transmission curve are concerned. A ray-tracing method was developed and applied for the calculation of focal properties of the grating. Simulated behavior of the grating is compared with experimental data.

In section 4.4 we present results obtained in a WDM experiment for which a grating demultiplexer was hybridized with a 4-channel receiver array in order to form a multichannel WDM receiver. Four channels with 2.5 Gbit/s each were successfully transmitted and received with state of the art sensitivity. Additional results from grating demultiplexers are given in section 4.5. They include the expansion of the free spectral range with e-beam written gratings and the enhancement of WDM receiver sensitivity by optical preamplification.

The grating demultiplexer modules realized were used for the measurement of the refractive index on InP and its thermal dependence with a very high degree of accuracy. The measurements and the results of this application are reported in section 4.6.
4.2. Polarization independent InP WDM multiplexer/demultiplexer module: Paper D

E. Gini, W. Hunziker, and H. Melchior
to be submitted to IEEE Journal of Lightwave Technology

Abstract
We report the design, fabrication, packaging and characterization of a polarization independent integrated optical InP multiplexer/demultiplexer module. The device is based on a vertically etched diffractive grating and separates four channels with 4 nm spacing in the 1.55 μm window. An n/n⁺-InP layer structure with very low birefringence results in a shift of the passbands between TE and TM polarization of less than 0.1 nm. With a self-aligned flip-chip mounting technique light is optically coupled from the input and output waveguides to an array of lensed single mode fibers with a coupling efficiency of more than 80%. The packaging includes temperature control that allows fine tuning of the channel passbands over 5 nm. Optical crosstalk is always better than -17 dB and fiber to fiber losses of 15 dB are achieved. The module has been successfully implemented in a 4 × 2.5 Gbit/s WDM transmission system.

1. Introduction
Integrated wavelength division multiplexers and demultiplexers are important for cost effective implementation of wavelength division multiplex (WDM) technology in fiber optical communication networks. They couple sources emitting at different wavelengths into the same optical fibre and separate the signals after transmission towards different detectors.

Depending on the dispersive element employed, two main types of monolithic wavelength demultiplexers are distinguished: reflection grating devices and devices using phased arrays of curved waveguides (phasars). The reflection grating type devices are usually operated at low order, offering typically more than 50 nm free spectral range for the demultiplexing of a high number of wavelength channels [4.1], [4.2]. However, the losses of these devices depend critically on the quality of the vertically etched mirror grating. Arrayed curved waveguides (phasars), a concept first published in 1988 [4.3], have become
increasingly popular due to their more simple and tolerant technology [4.4.1]. They are usually operated at orders higher than 100th with reduced free spectral ranges of less than 15 nm. Taking into account their specific advantages, both types of devices are being pursued in InP as well as in SiO₂/Si. The choice of the material is dependent on the desired functionality and performance of the multiplexers and demultiplexers. Silica based devices usually offer lower losses [4.5] and higher coupling efficiencies to single mode fibers, while InP based materials are chosen with regard to the integration with amplifying [4.6] and detecting [4.7] devices. Due to the birefringence of conventional InGaAsP/InP waveguides, these demultiplexers may exhibit significant TE/TM shifts. Different approaches have been used to eliminate these shifts: layer structures with large cores and low refractive index contrasts [4.8], waveguides with square cross-section [4.9], special designs of grating orders [4.10], and birefringence compensation [4.11].

An advantage of InP is its high temperature coefficient of the refractive index [4.12], [4.13] that allows for the control of the channel wavelengths allocations over a range of about 5 nm. Additional tuning is possible by carrier injection [4.14].

We propose a grating multiplexer/demultiplexer (MUX/DEMUX) with a large core n⁻/n⁺-InP waveguide structure with the following advantages: easy and homogeneous growth, very low birefringence, high coupling efficiency to optical single mode fibers and accurate control of the refractive index. Dry etching techniques were developed to fabricate smooth grating facets with less than 1° deviation from verticality. For practical use packaged modules are required. Simple stand alone reversible multiplexer/demultiplexer units were realized with fibers attached and temperature control for wavelength fine tuning.

2. MUX/DEMUX design

The MUX/DEMUX is based on a curved reflective diffracting grating in a so-called Rowland configuration [4.15] (Fig. 4.1). Light emitted from a source on the Rowland circle is focussed by the curved grating onto the same circle with a reflection angle that depends on wavelength. The grating curve is a circle with the double radius of the Rowland circle. The grating points are constructed by the projection of constant distances d on the tangent at the pole onto the grating circle.
The relation between the grating constant $d$, the angles between the circle diameter pointing through the grating pole and the input and the output beam, $\alpha$ and $\beta$, respectively, the working order $m$, the wavelength $\lambda$, and the refractive index $n_{\text{eff}}$ of the medium in the circle are given by [4.16]:

$$d \times (\sin \alpha + \sin \beta) = \frac{m \times \lambda}{n_{\text{eff}}} \quad (4.1)$$
In the integrated version a channel input waveguide feeds light into a slab waveguide region at the Rowland circle. Output waveguides collect the diffracted light at locations corresponding to their design wavelengths. We designed a demultiplexer for 4 channels with 4 nm separation. Actual channel allocations are at 1548 nm, 1552 nm, 1556 nm and 1560 nm. With $\alpha = 45$ degrees and a Rowland circle radius of $R = 2$ mm the 4 nm spaced output channels are separated by 15 $\mu$m. Bent channel waveguides with 10 mm radius separate the light to 250 $\mu$m spacing at the chip facets. In order to minimize the chip size needed for this separation, the first output waveguide is laterally spaced by 366 $\mu$m from the input waveguide. The resulting angles $\beta$ range between 37.5 and 38.3°. Identical single mode input and output waveguides are used in order to form a reversible MUX/DEMUX.

Based on the coordinates of the input and output waveguides the grating was stigmatically corrected according to [4.17]. The input and the two output points for $\lambda = 1548$ nm and $\lambda = 1556$ nm were selected as stigmatic points. The correction also considered a material dispersion for InP of $10^{-4}$/nm [4.18]. The grating was blazed for $\lambda = 1556$ nm.

The choice of the working order $m$ of the grating follows from a trade-off between a desirable large free spectral range (FSR) and technological requirements for the definition of the grating by lithography. Since $\text{FSR} = \frac{\lambda_0}{m}$, a low working order is preferred for a large FSR. On the other hand, the grating constant $d$ is proportional to the working order. An order of $m = 30$ has been selected, resulting in a grating constant of 11.16 $\mu$m. This leads to relaxed technological requirements while still maintaining the FSR of 50 nm, compatible with the bandwidth of optical amplifiers.

The mask layout is shown in Fig. 4.2. Two mask levels are necessary. The first mask defines the planar waveguide section with the grating and the channel waveguides. The second mask defines the openings for the deeply etched grating. Both masks include alignment features needed for flip-chip mounting and for fiber coupling.
4. InP Grating demultiplexers and their applications

Fig. 4.2 Mask layout of the four channel InP MUX/DEMUX. A first mask defines the waveguide parts that couple light from the input through a planar waveguide section to the vertically etched grating and separates the outputs to a spacing of 250 µm. The grating and the fiber alignment regions are deeply etched (dark, second mask). Chip size is 3 mm × 10 mm.

3. Waveguide design

A simple n'/n+-InP layer structure has been developed that fulfills the following requirements: in order to minimize the polarization sensitivity a vertically monomode planar waveguide structure with low birefringence, low-loss channel waveguides with high coupling efficiency to single mode fibers, and good reproducibility with accurate control of the refractive index. The problems of lattice matching, layer composition and homogeneity arising from quaternary InGaAsP structures are eliminated.

The actual structures of the planar and channel waveguides are shown in Fig. 4.3. The guiding film is a 3.2 µm thick undoped InP layer. The index contrast to the substrate is due to n-type doping of the substrate. The plasma effect reduces the refractive index by [4.19]:

\[
\Delta n = \frac{N \times e^2 \times \lambda^2}{8 \times \pi^2 \times n \times \epsilon_0 \times m_{\text{eff}} \times c^2}
\]

(4.2)

where \( N \) is the donor concentration, \( e \) the elementary charge, \( n \) the refractive index of InP at the wavelength \( \lambda \), \( \epsilon_0 \) the permittivity of free space, \( m_{\text{eff}} \) the effective mass of the electrons and \( c \) the speed of light.
4.2. Polarization independent InP WDM demultiplexer module

Fig. 4.3  Slab and rib waveguide structures of the n'/n⁺-InP WDM demultiplexer. The refractive index of InP is taken from [4.18] for λ=1560 nm, the substrate value is calculated according to [4.19] for N=3.2x10¹⁸/cm³. The rib waveguide is etched to a depth of 1.2 μm. Shown are the calculated optical intensity distributions of the slab waveguide for both polarizations. For the singlemode rib waveguide the lines show equal optical field intensities spaced at 10% for TE polarization.

The contribution from the holes is neglected and m_eff is taken as 0.075 m_e. The effects of bandfilling and bandshrinkage are considered according to [4.19]. The influence of variations of doping level and layer thickness on the MUX/DEMUX passband centers has been calculated. The results are given in Tab. 4.1. The corresponding values for the effective refractive index of the slab waveguide show a birefringence of always less than 4 x 10⁻⁴, resulting in a maximum TE/TM shift of 0.16 nm. Large variations in layer thickness and substrate doping are allowed for wavelength deviations of less than 0.5 nm. For this single binary layer structure a sufficient homogeneity in thickness is easily guaranteed.

The structure of the single mode channel waveguides is shown on the right hand side in Fig. 4.3. The width of the ribs is 5 μm and the etch depth is 1.2 μm. The optical mode has a relatively large and rather circular shape that is not critically dependent on fabrication tolerances. A large circular shape is essential for high efficiencies when coupling to single mode fibers.
4. InP Grating demultiplexers and their applications

<table>
<thead>
<tr>
<th>Layer thickness [μm]</th>
<th>Substrate doping [10¹⁸/cm³]</th>
<th>Polarization</th>
<th>λ [nm]</th>
<th>λ(TE)-λ(TM) [nm]</th>
<th>n_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>3.2</td>
<td>TE</td>
<td>1560.00</td>
<td>0.13</td>
<td>3.1586</td>
</tr>
<tr>
<td>3.2</td>
<td>3.2</td>
<td>TM</td>
<td>1559.87</td>
<td></td>
<td>3.1583</td>
</tr>
<tr>
<td>2.9</td>
<td>3.2</td>
<td>TE</td>
<td>1559.48</td>
<td>0.16</td>
<td>3.1576</td>
</tr>
<tr>
<td>2.9</td>
<td>3.2</td>
<td>TM</td>
<td>1559.32</td>
<td></td>
<td>3.1572</td>
</tr>
<tr>
<td>3.5</td>
<td>3.2</td>
<td>TE</td>
<td>1560.41</td>
<td>0.10</td>
<td>3.1594</td>
</tr>
<tr>
<td>3.5</td>
<td>3.2</td>
<td>TM</td>
<td>1560.31</td>
<td></td>
<td>3.1592</td>
</tr>
<tr>
<td>3.2</td>
<td>2.0</td>
<td>TE</td>
<td>1560.28</td>
<td>0.09</td>
<td>3.1592</td>
</tr>
<tr>
<td>3.2</td>
<td>2.0</td>
<td>TM</td>
<td>1560.17</td>
<td></td>
<td>3.1589</td>
</tr>
<tr>
<td>3.2</td>
<td>4.0</td>
<td>TE</td>
<td>1559.88</td>
<td>0.14</td>
<td>3.1584</td>
</tr>
<tr>
<td>3.2</td>
<td>4.0</td>
<td>TM</td>
<td>1559.74</td>
<td></td>
<td>3.1581</td>
</tr>
</tbody>
</table>

Tab. 4.1 Influence of layer thickness and substrate doping level on center passband wavelength of InP MUX/DEMUX

4. Fabrication

A 3.2 μm thick undoped InP guiding layer was grown by low-pressure MOVPE on a 3.2×10¹⁸/cm³ sulfur doped (100) oriented InP substrate. Measured background doping level was below 10¹⁵/cm³. For deep etching the waveguides and both the slab and the grating areas were masked with 150 nm SiO₂ and covered with photoresist that leave openings over the grating and the fiber alignment areas. The SiO₂ was patterned using UV contact lithography and plasma etched with a mixture of Ar and CHF₃. Deep etching of the grating to a depth of about 6 μm was done by Ar/H₂/CH₄ reactive ion etching. Special attention was paid to achieve smooth and vertical sidewalls. Process data for the best results are summarized in Tab. 4.2. A SEM photograph of a part of the grating is shown in Fig. 4.4. During the etching of the grating the alignment indentations for flip chip mounting (see below) were formed too. After removal of the photoresist the areas outside of the waveguides were dry etched to a depth of 1.2 μm using the same process conditions as for the grating. The gratings were covered with a reflection coating of 2 nm titanium and 80 nm gold by means of angled electron-beam evaporation. After cleavage the waveguide facets were
4.2. Polarization independent InP WDM demultiplexer module

antireflection coated with 176 nm SiO and 24 nm Al$_2$O$_3$ resulting in a residual reflectivity of less than 1%.

Fig. 4.4 SEM photograph of dry etched reflective grating. The facet angle deviates less than 1 degree from verticality.

| Gas flows: | H$_2$ | 60 sccm |
|           | CH$_4$ | 12 sccm |
|           | Ar     | 6 sccm  |
| Chamber pressure |     | 85 µbar  |
| RF power density (13.56 MHz) | | 1 Watt/cm$^2$ |
| DC self bias |     | -445 Volt |
| Table temperature | | 10° C |
| Etching rate |     | 30 nm/min |

Tab. 4.2 Process data for the plasma etching of the grating
A drawback of the large core waveguide structure is its strong dependence of the gating reflection loss on the facet angle (Fig. 4.5). A deviation of only two degrees from verticality already results in an additional loss of 10 dB. This demonstrates the stringent requirements for the etching technique used to form the grating.

![Gold coated Grating](image)

**Fig. 4.5** Calculated grating losses as a function of the facet angle. Even a deviation from verticality of only 1° causes 4 dB additional loss.

5. Packaging

For the optical connection of the input and the four output waveguides to an array of five single mode fibers a self aligned flip-chip technique [4.20] is used. An illustration of the principle is shown in Fig. 4.6. The turned over MUX/DEMUX chip penetrates in the coupling region in the same V-grooves of a silicon motherboard that are used to hold the fiber array. The center of the fibers and the InP channel waveguides are self-aligned by these V-groove sidewalls. The relative position is defined by alignment indentations formed in the same process step as the waveguides. The position of the alignment indentations is calculated with:

\[
a = \frac{r}{\sin \phi} - \frac{h}{\tan \phi}
\]

where \(a\) is the horizontal distance of the indentations from the center of the waveguide, \(r\) the radius of the fiber, \(h\) the distance of the center of the waveguide
mode measured from the wafer surface and $\phi$ the sidewall angle of the etched V-grooves. For the fiber radius $r=62.5 \, \mu m$, $\phi=54.74$ degrees and $h=2 \, \mu m$, a distance of 75.1 \, \mu m results for the position of the alignment indentations.

For efficient coupling, the optical fields of the channel waveguides and the optical fiber should be the same in size and shape. The optical field of a single mode fiber is circular with a beam radius of about 5 \, \mu m. In comparison, the optical field of our channel waveguides is elliptic with dimensions of about 6.2 \, \mu m \times 3.4 \, \mu m at $1/e^2$ of the maximum intensity (see Fig. 4.3, right hand side).

The overlaps between the channel waveguide mode and Gaussian beams with different radii were calculated. The results are presented in Fig. 4.7. Calculated coupling efficiencies are better than 80\% (-1dB) for beam radii between 1.5 \, \mu m and 3 \, \mu m. The fiber mode was adapted in size by lensing the fibers with a process described in [4.21]. Measured coupling efficiencies from waveguides to a set of lensed fibers producing different beam radii are also given in Fig. 4.7. For beam radii between 2.0 \, \mu m and 2.5 \, \mu m coupling efficiencies between 70\% and 80\% were measured. An additional advantage of the large mode of our channel waveguide design are rather large alignment tolerances.

Fig. 4.6  Self-aligned optical coupling between single mode fiber and channel waveguide. The turned over InP MUX/DEMUX chip and the fibers are aligned by the same V-grooves etched in the silicon motherboard. The position of the InP chip is defined by the position of the alignment indentations formed in the same process step as the waveguides.
Fig. 4.7 Measured coupling efficiencies from $n/n^+$-InP channel waveguides to a set of lensed fibers producing different beam radii (dots). The solid line are calculated overlaps with Gaussian beams.

For the coupling to a Gaussian beam with 2 $\mu$m beam radius a 0.6 $\mu$m displacement results in a penalty of around 0.5 dB, a displacement of 1 $\mu$m in any direction is allowed for 1 dB additional loss. Further improvements are possible with the use of integrated optical mode adapters or elliptical lenses, but the higher expense in fabrication and packaging has to be compared with the already achieved high coupling efficiency.

The device was flip-chip mounted on a silicon motherboard with wet etched V-grooves. An array of five lensed fibers was inserted in the V-grooves and the distance to the device was adjusted for maximum transmission. The radius of the fiber lenses were chosen to transform the fiber mode into beams with radii between 2.3 $\mu$m and 2.4 $\mu$m. The silicon motherboard was mounted on a copper block with a NTC thermocouple in the vicinity of the device and a Peltier thermoelectric cooler. The MUX/DEMUX is finally enclosed in an aluminum housing with dimensions of 4 cm $\times$ 4 cm $\times$ 2 cm. A photograph of the completed MUX/DEMUX module is shown in Fig. 4.8.
6. Results

Optical measurements were performed with a tunable external cavity semiconductor laser source. Output spectra of the four channels are superimposed in Fig. 4.9. The channel spacing and the absolute values of the wavelengths were determined for 18 devices fabricated in 6 different batches. The mean channel spacing was 3.95 nm with a standard deviation of 0.07 nm. The mean deviation of the center of the passbands from the design values was +0.3 nm with a spread of ±0.5 nm. This corresponds a difference in refractive index of less than 0.001 from the design values and proves the very accurate control of the effective refractive index of the slab waveguide. The FWHM of the WDM channels were 1.4 nm. Measured crosstalk was always less than -17dB. The background level is thought to be caused by stray-light from the grating collected by the output waveguides. The background can be further reduced by improving the smoothness of the etched grating facets.
Measured fiber to fiber transmission curves of a InP MUX/DEMUX for the polarization with the lowest attenuation. The channel spacing is 4 nm and the crosstalk is better than -17 dB. The background level is thought to be caused by stray-light from the grating collected by the output waveguides.

Transmission curves of one WDM channel for TE and TM polarization. The shift between the two curves is within the wavelength resolution (0.1 nm) of the optical measurement system. Also shown is the theoretical transmission curve.
The transmission peaks of the next grating order were found between 1500 nm and 1512 nm in full agreement with the calculated free spectral range of 50 nm.

The polarization dependence of the passband wavelengths is illustrated in Fig. 4.10. The TE and TM transmission curves of a single channel are equal to each other within the measurement resolution of 0.1 nm. The curves are compared with a theoretical transmission curve obtained by overlap calculation of the optical input and (identical) output field distribution with wavelength dependent lateral offsets. The measured curves are in good agreement with the calculations.

Fiber to fiber losses of the MUX/DEMUX were between 15 dB and 17 dB with the losses for TM about 2 dB higher than for TE polarization. This is attributed to different grating losses for the two polarizations. The grating loss is caused by non-verticality of the facets and by roughness. The contributions to the overall losses are estimated as follows:

- Fiber coupling loss: 1.5 dB/facet, 3 dB
- Excess mounting loss: 0.75 dB/facet, 1.5 dB
- Propagating loss: 2 cm × 1 dB/cm, 2 dB
- Channel to slab coupling: 2 × 0.5 dB, 1 dB
- Grating loss: 8-10 dB

The temperature dependence of the refractive index [4.12], [4.13] is used for the fine tuning of the MUX/DEMUX. The relative precision in effective refractive index needed for an accuracy of 0.1 nm in demultiplexer passband wavelength is 6×10⁻⁵. Typical variations of the effective refractive index are at least one order of magnitude larger. The possibility of tuning is important to solve this problem. Due to the large temperature coefficient of the refractive index of InP, tuning over a range of several nanometers is possible. Fig. 4.11 shows the wavelengths of maximum transmission of a MUX/DEMUX measured between 15° C and 55° C. The wavelengths were found to vary linearly with temperature with a coefficient of 0.1 nm/K over more than 5 nm. The channel spacing remains constant. The tunability of InP devices is tenfold larger when compared with SiO₂ based devices which typically have a temperature coefficient of 0.01 nm/K [4.22]. However, for InP based devices temperature control is needed for passband allocation stabilization.
Fig. 4.11 Dependence of the passband center wavelengths on temperature. The wavelengths are found to vary linearly with temperature with a coefficient of 0.1 nm/K.

The device was tested in a transmission experiment. Hybridized with a 4-channel receiver array WDM detection was successfully demonstrated [4.23]. Sensitivities as good as -13 dBm per channel at 4 × 2.5 Gbit/s were achieved. Due to the large FSR of 50 nm the MUX/DEMUX is well suited for applications in systems with erbium doped fiber amplifiers.

7. Conclusions
We have realized a fully packaged InP MUX/DEMUX module based on an etched reflective grating in InP for the use in WDM fiber optical links. The device separates 4 channels with 4 nm spacing in the 1.55 μm window. An n⁻/n⁺-InP waveguide structure allows for precise control of the refractive index and of the absolute values of the channel wavelength allocations. The device was optically coupled to an array of five single mode fibers using a self-aligned flip-chip mounting technique on a silicon motherboard. A coupling efficiency of 80% from the channel waveguides to lensed single mode fibers was demonstrated. The polarization shift of the filter passbands was less than 0.1 nm. Fiber to fiber losses of 15 dB and crosstalk better than -17 dB were achieved. The package included temperature controls that allowed for tuning of the channel passbands over a
range of 5 nm. The utility of these modules has been proven in a $4 \times 2.5$ Gbit/s WDM system experiment.

This work was carried out in part within the European ESPRIT Project MOSAIC and financially supported by the Swiss Federal Office for Education and Science, Berne.
4.3. Design of demultiplexers

The gratings used for demultiplexers have to be carefully designed and optimized for the targeted performance of the device. Not only theoretical limitations (for example for resolution and aberrations), but also technological constraints (for example chip size and photolithographic limitations) have to be considered. In this section we discuss some of the key aspects for demultiplexer optimization.

Waveguide optimization

The waveguide structure was optimized in terms of polarization dependence and losses. The main loss contributions are grating losses, fiber coupling losses and propagation losses. The thickness of the waveguide is an important parameter for the sensitivity of the grating losses on facet deviations from verticality: the thicker the waveguide the stronger the influence of non-vertical grating facets (the same is true for corner mirrors, see Fig. 2.17). From this point of view, thin optical modes are favored but on the other hand, a thin mode leads to an enhanced polarization sensitivity of the demultiplexer. Tab. 4.3 lists calculated polarization shifts and excess grating losses for waveguide structures with different mode thicknesses. For example, an optical mode thickness of 1 μm is not very sensitive on non-vertical facets, but its polarization shift exceeds the targeted channel spacing of 4 nm.

<table>
<thead>
<tr>
<th>Mode thickness at 1/e² [μm]</th>
<th>1.0</th>
<th>1.5</th>
<th>1.9</th>
<th>2.4</th>
<th>3.2</th>
<th>4.0</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ(TE-TM) shift [nm]</td>
<td>4.28</td>
<td>1.17</td>
<td>0.61</td>
<td>0.27</td>
<td>0.11</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>Excess grating loss, facet 1° off [dB]</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>4.2</td>
<td>5.4</td>
<td>7.1</td>
</tr>
<tr>
<td>Excess grating loss, facet 2° off [dB]</td>
<td>3.9</td>
<td>4.5</td>
<td>7.1</td>
<td>8.6</td>
<td>12.4</td>
<td>17.0</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Tab. 4.3  Calculated polarization shifts and excess grating loss for grating facet deviations from verticality for different optical mode thicknesses (1/e² intensity).
From the TE/TM shift, we calculated the polarization penalty with the help of the filter transmission curve with 1.4 nm FWHM. In Fig. 4.12 we compare the resulting excess losses of the demultiplexer originating either from polarization shift or from grating facets with 1° deviation from verticality, as a function of optical mode thicknesses.

For thin optical modes the excess loss is mainly due to the polarization shift, while for thick optical modes the influence of non-vertical grating facets becomes dominant. The optimum mode thickness is around 2.5 μm. If the facet deviations from verticality are less than 1°, the optimum is shifted towards thicker modes. In addition, a thicker optical mode is favored due to usually lower propagation losses and higher coupling efficiency to single mode fibers. Our realized demultiplexers have optical mode thicknesses of 3 μm, where the polarization penalty can be fully neglected.

**Blazing of the grating**

A grating generally diffracts light into many orders. Their output angles $\beta$ are solutions of Eq. (4.1) for the corresponding order $m$. The power distribution
among the orders depends on the profile of the grating facets. For many applications it is desirable that all the power is diffracted into one single order only. This is achieved by blazing the grating.

In this case the facets of the grating are oriented in such a way, that the incident light is reflected in a direction that coincidences with the direction of a diffraction order of the grating. The grating facets form a sawtooth profile. The fact that the diffraction angle is wavelength dependent leads to the conclusion, that blazing at a fixed working order is only possible for one wavelength.

Our grating is blazed for the wavelength $\lambda=1556$ nm. Each grating facet was individually oriented in respect to the position of the input waveguide and the output waveguide for $\lambda=1556$ nm in such a way that the input and the output beam form the same angle $\delta$ with the normal of the grating facet, see Fig. 4.13. From Fig. 4.1, we see that this is the case for

$$\delta = \frac{\alpha - \beta}{2}. \quad (4.4)$$
In the general case where $\alpha$ and $\beta$ are unequal, one facet will partially shadow the adjacent facet and thereby reduce the effective facet width. For our demultiplexer the difference between the input angle $\alpha$ and the output angles $\beta$ was optimized in respect to minimize the area needed for the separation of the output channel waveguides to a pitch of 250 $\mu$m and is always less than 7.5°.

Rounding of the grating corners will further reduce the effective facet width and contribute to crosstalk. A simple approximate formula for the peak intensity $I_p$ of the diffracted light at the output is [4.24]

$$I_p = I_0 \left( \frac{d_1}{d_0} \right)^2$$

(4.5)

where $I_0$ is the peak intensity at the input and $d_1$, $d_0$ are defined in Fig. 4.13. The factor results from decreased fraction of incident light that may be properly diffracted and the increased divergence of the diffracted light. The rounding of the inner corner of the grating facet was compensated by an "overhang" of 5° relative to the connection line between two adjacent facets, which originally was designed to be parallel to the reflected beam. From Fig. 4.13 we get for the effective facet width

$$d_1 = d_0 - \tan\delta \times \left( \frac{m \lambda}{2 n_{\text{eff}}} \right) - r \times (1 - \sin\delta)$$

(4.6)

For our grating design, the angle $\delta$ is always smaller than 3.7°. Assuming corner roundings with a radius of 0.5 $\mu$m we achieve

$$I_p > 0.83 \times I_0.$$  (4.7)

The shadowing of the grating facet and the corner roundings contribute each about one half to the total reduction in peak intensity.

**Grating size**

The size of the grating determines the resolution of the demultiplexer. We use the term resolution for the smallest change of wavelength that the demultiplexer can resolve. The term resolving power is used for the gratings "ability to resolve" and is defined as the ratio between the operating wavelength and the resolution at that
wavelength. One gets the following expression for the resolving power of a grating [4.25]:

$$\frac{\lambda}{\Delta \lambda} = mN$$

(4.8)

where \(m\) is the working order and \(N\) the number of illuminated grooves of the grating. The number of illuminated grooves is determined by the expansion angle \(\varphi_a\) of the beam and the distance between the channel waveguide and the grating pole (Fig. 4.14). To a first approximation:

$$N = 2R\varphi_a/d$$

(4.9)

where \(R\) is the radius of the Rowland circle and \(d\) the grating constant, see Fig. 4.1. Using Eq. (4.1) for the grating constant, we obtain for the resolving power

$$mN = 2R\varphi_a n_{\text{eff}}(\sin \alpha + \sin \beta) / \lambda_{\text{vac}}.$$  

(4.10)

As expected, the resolving power is proportional to the size of the grating, determined by the Rowland radius \(R\). The values of \(\varphi_a\) and \(n_{\text{eff}}\) are dependent on the structure of the input channel waveguide. We have chosen a \(n^-/n^+\)-InP waveguide structure with a rib width of 5 \(\mu\)m in order to achieve low birefringence and high coupling efficiency to single mode fibers. For the calculation of the expansion angle \(\varphi_a\) we approximated the optical mode by a Gaussian beam of effective width \(w_e\) (1/e² of intensity), for which the relation

$$\varphi_a = \frac{4\lambda}{\pi w_e}$$

(4.11)

is valid. For our waveguide structure we get \(w_e \approx 5.6 \mu\)m and \(\lambda = \lambda_{\text{vac}} / n_{\text{eff}} \approx 0.5 \mu\)m, resulting in \(\varphi_a \approx 6.5^\circ\). According to Eq. (4.10), the input and output angles \(\alpha\) and \(\beta\) should be maximized. For reasons of grating efficiency, the difference between the input and output angles should be minimized, as stated above. We fixed \(\alpha\) at 45° because grating aberrations also increase with the angle \(\alpha\) [4.26].
4.3. Design of demultiplexers

For a targeted resolution of $\Delta \lambda = 1$ nm which is sufficient for the 4 nm spaced channels, a theoretical Rowland radius of

$$R = \frac{\lambda^2}{\Delta \lambda} \times \frac{1}{2R \phi_n n_{\text{eff}} (\sin \alpha + \sin \beta)} \approx 2.2 \text{ mm}$$

(4.12)

is necessary. We fixed $R$ at 2 mm. Since the width of the chip is not limited by the grating size, we have written the gratings with an opening angle of

$$\phi_g \geq 3\phi_n.$$  

(4.13)

That angle is far enough to diffract all the light emerging from the input waveguide.

The resolving power is not dependent on the working order $m$ of the grating. This can be seen from Eq. (4.10). An increase of $m$ leads to a decrease in $N$ by the same factor. We have optimized the working order by considering photolithographic limitations. For a low working order and hence a small grating constant the optical losses of the grating increase due to the rounding of the corners of the grating [4.27]. On the other hand, a high working order results in a small free spectral range for the demultiplexer which reduces the maximum number of channels of the demultiplexer.

Fig. 4.14 Definitions of the expanding angle of the waveguide mode $\phi_n$. The grating is written with an opening angle $\phi_g$. Also shown is the orientation of the coordinates for the evaluation of the PSF. All waveguides axis are directed to the grating pole.
Image quality

The performance of the grating was studied by evaluating the quality of the diffracted optical image by means of the point spread function (PSF) of the grating [4.28].

The PSF of the grating takes the following form:

\[ I(x,y) = \frac{1}{C^2} \times \left| \sum C_i \times \left[ \frac{2\pi i}{\lambda} (\overline{AP_i} + \overline{P_iB}) \right] \right|^2 \]  

(4.14)

For the grating shown in Fig. 4.14 with a point source located at point A, its image is calculated around point B. The summation includes all grating points \( P_j \). The field amplitudes at the grating points are \( C_j \). The PSF is normalized with

\[ C = \sum C_i. \]  

(4.15)

We considered the problem to be only two-dimensional, which means that the vertical beam profile is assumed not to change as it propagates. A similar expression was used in [4.29] to calculate the PSF of Rowland gratings. It was assumed that the contribution of each grating groove that falls within the beam expansion angle \( \varphi \) is the same, \( C_i = \text{constant} \). As a result of this assumption the PSF has the form of a squared sinc curve:

\[ y = \left( \frac{\sin x}{x} \right)^2 \]  

(4.16)

In our calculation, we approximate the optical field amplitudes at the grating points by a Gaussian curve which gives a better matching with the real distribution. The PSF then becomes also Gaussian without any fringes. A comparison of the two PSF for a Rowland grating is shown in Fig. 4.15. The widths of the PSF's are comparable for the two amplitude distributions.
4.3. Design of demultiplexers

Fig. 4.15 PSF $I(x, y=0)$ for an input beam with 7° expansion angle for a Rowland grating. Solid: Gaussian amplitude distribution at the grating, dotted: rectangular amplitude distribution at the grating according to [4.29], resulting in a $\text{sinc}^2$ curve for the PSF.

Fig. 4.16 PSF $I(x, y=0)$ for an input beam with 15° expansion angle. Solid: stigmatically corrected grating, dotted: Rowland grating. The Rowland grating suffers increasingly from spherical aberration. The linewidth is reduced in respect to the calculation with $\varphi_a=7^\circ$ due to the higher resolving power.
For small angles $\varphi_a$ the difference between a Rowland grating and a stigmatically corrected one is small. However, for larger angles (corresponding to waveguides with small widths) the aberrations for the Rowland grating become important. The image of the Rowland grating suffers from spherical aberration that increase with the fourth power of the numerical aperture [4.16]. The effect of the aberration on the PSF is a reduced intensity in the focal point (see Fig. 4.16). The width of the PSF is narrower for larger angles $\varphi_a$ due to the higher resolving power of the grating.

The aberration correction of our grating was performed according to [4.17] and is summarized in the following. The construction starts with the selection of two stigmatic points $D_1$ and $D_2$ for which all aberrations vanish. The grating line is then found at the intersection points of two families of confocal ellipses with the parameter $t$. These two families of ellipses have one common focus at the demultiplexer input, the other two foci are located at the stigmatic points $D_1$ and $D_2$ (see Fig. 4.17). The distance of the focal points $2c_i$, their long axis $2a_i(t)$ and their short axis $2b_i(t)$ are defined by

$$2c_i = |\overrightarrow{ID}_i|$$
$$2a_i(t) = r_i + \lambda_i t$$
$$b_i(t) = \sqrt{a_i(t)^2 - c_i^2}.$$  \[4.17\]

Equations (4.18) and (4.19) describe the grating line of a mounting with two stigmatic points using a polar coordinate system $(r, \varphi)$ with the origin at the input point I and with its axis along the vector $\overrightarrow{ID}_1$.

$$\cos \varphi(t) = \frac{SQ \pm \sqrt{Q^2 + R^2 - S^2}}{Q^2 + R^2}$$
$$\sin \varphi(t) = \frac{SR \pm \sqrt{Q^2 + R^2 - S^2}}{Q^2 + R^2}$$
$$r(\varphi(t), t) = \frac{b_1(t)^2}{a_1(t)^2 - c_1 \sin \varphi(t)}.$$  \[4.18\]
with the angle $\varphi_2 = \angle(D_1D_2)$ and

\[
\begin{align*}
Q &= b_1(t)^2 c_2 \cos \varphi_2 - b_2(t)^2 c_1 \\
R &= b_1(t)^2 c_2 \sin \varphi_2 \\
S &= b_1(t)^2 a_2(t) - b_2(t)^2 a_1(t).
\end{align*}
\]

(4.19)

Fig. 4.17 Construction of the grating line for a grating with two stigmatic points (after [4.17]).

Another approach to improve the grating image quality is to appropriately tailor the grating “constant” to eliminate higher order aberrations. An example of aberration elimination up to the fifth order is reported in [4.30]. The interested reader is referred to [4.31] for a more general treatment of aberration theory.

The focal properties of the grating were checked by calculation of the PSF in the y-direction. Fig. 4.18 compares the results for PSF $I(x=0,y)$ for a Rowland grating and our stigmatically corrected grating design. For an angle $\varphi_a$ of 7° we observe a shift of the focal plane away from the grating for the Rowland design. For $\varphi_a = 15^\circ$ the effect is more pronounced and the intensity of the maximum is decreased. The depth of focus is several tens of microns and decreases with increasing angle $\varphi_a$. 
Fig. 4.18  PSF $I(x=0, y)$ for different gratings. Solid: stigmatically corrected grating, dotted: Rowland grating. The aberrations of the Rowland grating not only decrease the intensity but also shift of the focus away from the grating. The effect is more pronounced for larger angles $\phi_a$.

Fig. 4.19  Surface plot of the PSF of the four channel demultiplexer. Note the different scales for the x and y-axis.
A two-dimensional surface plot of the PSF at the location of the output waveguides of the demultiplexer is shown in Fig. 4.19.

Waveguide channels whose axis are not directed towards the pole of the grating have second-order aberrations which lead to excess image distortion. In our design all the waveguides are pointing to the pole of the grating and thus the second-order diffraction aberration is eliminated (Fig. 4.14). However, we did not correct for the diffraction according to Snell’s law at the interface between the slab waveguide and the channel waveguides. The effective refractive indices differ by about 0.002. This results in a beam deflection at the interface between the slab and channel waveguide of less than 0.04°, which can be neglected.

**Filter transmission curves**

The grating can be regarded as an imaging apparatus that projects the optical field of the input waveguide to a wavelength-dependent location around the output waveguide. The theoretical transmission curve was calculated as the overlap integral of the image of the input field and the eigenmode of the output channel waveguide. As an approximation we assume the same field distributions for identical input and output waveguide structures. The translation of the wavelength into a lateral displacement of the field is according to the linear dispersion of the grating, which, for our grating design is

\[
\frac{d\lambda}{ds} = 0.27 \text{ nm/\mu m.} \quad (4.20)
\]

This approach was used to calculate the theoretical transmission curve of the filter in Fig. 4.10 from the two-dimensional eigenmode field distribution of the channel waveguides.

More correctly, the image field distribution \( F_g \) in the focal plane is the convolution of the PSF defined in Eq. (4.14) with the input field \( F_i \). If we neglect the vertical beam profile changes, we get

\[
F_g(x) = F_i(x) \otimes I(x) = \int_{-\infty}^{\infty} F_i(x - t) \times I(t) dt \quad (4.21)
\]

In Fig. 4.20 different optical field distributions are shown: a Gaussian profile with \( w_e = 5.6 \ \mu m \), the calculated field of our waveguide structure and the convolution
of this field with the PSF of our grating. The Gaussian profile differs from the other two by a more rapid decay of the field at larger distances from the waveguide axis.

Theoretically more correct, the transmission $T$ of the filter is the overlap integral of the output waveguide eigenmode, which is identical with the input field $F_i$, and $F_g$. Again, the displacement $s$ is translated into a wavelength variation according to Eq. (4.20).

$$T(s) = \frac{\iint |F_i(x, z) \times F_g(x - s, z) dx dz|^2}{\iint |F_i(x, z)|^2 dx dz \times \iint |F_g(x, z)|^2 dx dz}$$  \hspace{1cm} (4.22)

Fig. 4.20  Amplitude distributions of different fields. Dotted: Gaussian profile, dashed: field calculated from our waveguide structure, solid: convolution of the calculated field with the PSF of our grating (solid line in Fig. 4.15).

The filter transmission curves for four practically important different waveguide field profiles are shown in Fig. 4.21:

i) overlap of two Gaussian profiles with $w_e=5.6 \, \mu m$, 

146
ii) overlap of calculated identical input and output fields $F_i$,
iii) overlap of $F_i$ with $F_g$, and
iv) two-dimensional overlap of the identical input and output eigenmodes of the waveguide structure, as calculated for Fig. 4.10.

The Gaussian profile again shows a rapid decay. The transmission curves that are based on eigenmode calculations of the waveguide structure do not differ very much. Their FWHM vary between 1.38 nm and 1.52 nm (see inset of Fig. 4.21). In the best case, the crosstalk of the demultiplexer is the value of the transmission curve at $\Delta \lambda = \pm 4$ nm. With our grating design and waveguide structure, values from -53 dB to -58 dB result. Grating imperfections arising during fabrication increase the crosstalk above this theoretical limit.

The flattening of filter transmission curves is considered in section 4.5.

![Fig. 4.21](image)

*Fig. 4.21* Calculated transmission curves for different input and output field distributions. Dotted: Gaussian-gaussian, dashed: eigenmode-eigenmode, solid: convolution of eigenmode with PSF-eigenmode, dash-dotted: eigenmode-eigenmode (two-dimensional). For the eigenmode based calculations, the FWHM is between 1.38 nm and 1.52 nm, the crosstalk level is always less than -53 dB.
Limitation of data rate for WDM transmission

The demultiplexer is an interferometric device in that light propagates different paths with different lengths to interfere at the output. The interference image at the output needs time to build up. This time depends on the maximum difference between the light paths. We calculated the building-up of the output signal of the filter under the assumption that the input signal is switched on immediately. A rise time of 5.3 picoseconds results for an expansion angle of 7°. This rise time allows a data rate of approximately 90 Gbit/s for WDM transmission, far beyond the highest presently considered rates. Light from channel waveguides with reduced widths expand with increased angles in the slab waveguide region (see Eq. (4.11), Fig. 4.14). More grating points are illuminated and therefore the maximum light path difference is larger. In Fig. 4.22 the calculated signal response in time is shown for the input beam expansion angles $\phi_a$ of 7° and 15°.

![Graph showing calculated time response of the grating demultiplexer.](image)

**Fig. 4.22** Calculated time response of the grating demultiplexer. The rise time from 10% to 90% of maximum intensity are 5.3 ps and 11.2 ps for 7° and 15° expansion angle, respectively.

The “speed” of an optical filter and its resolution are correlated. A fundamental limit is given by the Heisenberg uncertainty relation

$$|\Delta E| \times |\Delta t| \geq \frac{\hbar}{4\pi}$$  \hspace{1cm} (4.23)
where $h$ is Planck's constant, $\Delta E$ is the energy uncertainty, and $\Delta t$ the measuring time. For a wavelength filter $\Delta E = h\Delta v$. As a rough estimate, we calculate $\Delta v$ from the FWHM of the our filter:

$$\Delta v = \frac{c \times \text{FWHM}}{\lambda^2} = 175 \text{ GHz}$$

(4.24)

for FWHM = 1.4 nm at $\lambda = 1550$ nm. The resulting quantum theoretical value for $\Delta t$ is 0.5 ps. This is one order of magnitude shorter than the 5.3 ps of our filter.

**Polarization effects**

Up to now we have simulated the grating by a scalar theory with geometrical optics and perfectly conducting facets. This simplified model can not explain polarization effects. As a general rule, it is often accepted that scalar theory can be applied when the groove spacing is greater than five times the wavelength. In the case where geometrical dimensions approach the wavelength, anomalies may occur. Examples for anomalies are altered power distributions among the various orders and strong polarization dependences of the grating efficiencies. The problem is to solve Maxwell's equations with real boundary conditions that also include light polarization that lead for example to Brewster angle effects. With the help of computers, the calculation of grating efficiency has been developed to the stage where is can be applied with confidence to a wide range of physical situations. Reviews on vector theories of diffraction gratings are given in [4.32] and [4.33]. Although our demultiplexers have groove spacings of more than five times the wavelength, we observe polarization effects. Here we will give a simplified explanation of its origins.

In a classical picture the free electrons in the metallized grating facets are accelerated by the electrical field of the incident light and they re-emit it as reflected light. The electrical vector of the incident light oscillates parallel to the grooves for TM polarization. In this direction the electrons can freely follow the electrical field while for TE polarization they are disturbed by the grating grooves. According to that picture we may conclude that the grating efficiency should be higher for TM polarization. However, we observe a reduced efficiency for TM polarization. This effect can be explained by the planar structure of the device. A grating facet is about 7 $\mu$m wide, while the length of the "grating lines" is less than 5 $\mu$m. Contrary, the demultiplexers with vertically even more
confined doublehetero layer structures showed higher grating efficiencies for TM polarization. This may be caused by observed vertical striations introduced during the etching of the grating facets.

We can conclude that not only theoretical difficulties limit the prediction of grating efficiencies but also the lack of complete input data, for example the microscopic surface morphology.

Nowadays its possible to predict the efficiency of a grating with its anomalies, but there still remains the inverse diffraction problem: that is, given the efficiency, deduce the groove profile. This may tell us whether the types of grating that are used at present are the most efficient, or whether there exists an entirely different shape of groove that would give higher efficiencies over a greater range of wavelengths. In other words: “It is one thing to be able to describe how a given grating behaves, but it is another to understand how gratings work.”
Abstract

Fully packaged 4-channel WDM receiver modules with InP reflective grating WDM filters and pin-JFET receiver arrays are demonstrated. Channel allocations are 1548 nm, 1552 nm, 1556 nm, 1560 nm. Measured module sensitivity for a BER of $10^{-9}$ at 2.5 Gbit/s is as good as -13 dBm.

1. Introduction

Wavelength division multiplexing (WDM) is capable of increasing the throughput capacity of optical fiber transmission lines. To receive the individual channels, these systems employ WDM receivers, which optically demultiplex the different channels before detecting them with photodetectors. Different types of WDM filters are reported [4.2], [4.34] among them WDM's with monolithically integrated SOA’s and photodetectors [4.1], [4.35]. InP based OEIC receiver arrays are reported that integrate pin photodiodes with electronic preamplifiers using JFET, HBT or HEMT technologies. Here, we report a pigtailed WDM receiver module, hybrid integrated from a pigtailed InP WDM filter using a curved mirror grating and a pigtailed OEIC 4-channel receiver based on the monolithic integration of pin photodiodes with JFET transimpedance amplifiers. This hybridization is flexible and allows individual optimization of the devices for wavelength tunability, good sensitivity, high speed, low crosstalk, with no thermal coupling, while minimizing the complexity of the fabrication technology.
2. Module Description and Fabrication

The 4-channel WDM receiver module is shown in Fig. 4.23. It consists of an InP WDM filter and a monolithically integrated pin-JFET receiver array. The reflective grating filter is designed for 4 channels with 4 nm spacing. Polarization insensitivity and high coupling efficiency to single mode fibers are obtained with a n'/n+-InP layer structure grown by MOVPE [4.36]. Temperature control with a Peltier element allows the tuning of the channel allocations. The device is flip-chip mounted on a silicon motherboard and the waveguides are coupled to an array of lensed fibers [4.20].

Fig. 4.23 Functionality of the module (top left). Block diagram of monolithic 4-channel pin-JFET receiver array with adjustable feedback elements (top right). Layout of the InP WDM filter (bottom). The filter is flip-chip mounted on a silicon motherboard and optically coupled to an array of lensed fibers.

The monolithic integrated receiver front-end array consists of pin photodiodes and three stage JFET transimpedance amplifiers. The block diagram is shown in Fig. 4.23. The circuit design includes adjustable JFET feedback elements to overcome fabrication tolerances. The fabrication of the OEIC front-end array is
4.4. Packaged 2.5 Gb/s 4-channel WDM receiver module

based on an InGaAs/InP layer structure grown by MOVPE on semiinsulating substrate. Details of the fabrication process are described in [4.37]. A compact, lateral approach compatible with metal flat packs used for MMIC's is chosen for fiber-photodiode coupling. Four fibers are mounted in silicon V-grooves with a pitch of 250 μm corresponding to the photodiode pitch. After beveling the fiber ends at an angle of \(-42^\circ\) to totally reflect the light downwards on the photodiodes the silicon-fiber array is placed horizontal on the OEIC receiver chip. Finally the pigtailed receiver array is packaged in a fully connectorized metal flat-pack. The WDM-receiver module is realized by splicing the individual output fibers of the WDM to the receiver input fibers with an additional coupling loss below 0.1 dB.

3. Module Characteristics

A summary of the optical performance is given in Fig. 4.24. The losses of the InP WDM filter are measured between point A and B in the fibers. FWHM is 1.6 nm. The shift of the transmission curves for TE and TM polarization is less than 0.1 nm [4.36]. The difference in loss between TE and TM polarization is < 2 dB. Crosstalk is better than \(-17\) dB. Best coupling efficiency to an array of five lensed fibres is estimated to be 80%. Measured channel spacings are 3.9 nm ± 0.2 nm. The channel allocations deviate less than 0.5 nm from the design values.

![Fig. 4.24 Transmission curves of pigtailed InP WDM filter. The losses are measured between the points A and B. The maxima of transmission are at \(\lambda = 1548.2, 1552.1, 1556.0,\) and 1559.7 nm. About 1.5 dB of the differences in losses may be caused by different coupling efficiencies to the fiber array.](image-url)
Temperature control allows simultaneously tuning of the four channel allocations over more than 5 nm with a tuning coefficient of about 0.12 nm/K.

The performance of the WDM receiver module is summarized in Tab. 4.4. The photodiode responsivity is 0.8 A/W and the fiber to photodiode coupling loss is 0.2 dB or less for all channels. The transimpedance amplifiers offer a transimpedance gain between 1.7 and 1.8 kΩ with a 3 dB down bandwidth of 1.7 GHz corresponding to an excellent gain-bandwidth product of 2.9 THZ·Ω per channel. Sensitivity for a BER of $10^{-9}$ at a bitrate of 2.5 Gbit/s is determined by eye diagram measurements. It varies between -13.1 dBm and -9.3 dBm at point A and -28 dBm and -27.7 dBm at point B. The equivalent input noise current density of the receiver within a bandwidth of 1.7 GHz is around 2.8 pA/√Hz corresponding to an optimum internal receiver sensitivity of -30.7 dBm for 2.5 Gbit/s data transmission. Fig. 4.25 shows the 2.5 Gbit/s eye diagrams recorded at the output of the 4-channel receiver array for an average input power of -6 dBm into the WDM filter.

Fig. 4.25 2.5 Gbit/s eye diagram recorded at output of pin/JFET 4-channel receiver array for an average optical input power of -6 dBm into the WDM filter.
4.4. Packaged 2.5 Gb/s 4-channel WDM receiver module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Ch. #1 1548 nm</th>
<th>Ch. #2 1552 nm</th>
<th>Ch. #3 1556 nm</th>
<th>Ch. #4 1560 nm</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity of PD</td>
<td>( \lambda = 1550 \text{ nm} )</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>A/W</td>
</tr>
<tr>
<td>Transimpedance gain</td>
<td>( V_{\text{Control}} = -1.5 \text{ V} ) Bitrate = 2.5 Gb/s</td>
<td>1.8</td>
<td>1.8</td>
<td>1.7</td>
<td>1.8</td>
<td>k\Omega</td>
</tr>
<tr>
<td>Equivalent input noise current density</td>
<td>( B_w = 1.7 \text{ GHz} )</td>
<td>2.9</td>
<td>2.7</td>
<td>2.8</td>
<td>2.8</td>
<td>pA/\sqrt{\text{Hz}}</td>
</tr>
<tr>
<td>Internal sensitivity based on noise</td>
<td></td>
<td>-30.4</td>
<td>-30.7</td>
<td>-30.7</td>
<td>-30.7</td>
<td>dBm</td>
</tr>
<tr>
<td>Sensitivity at point B</td>
<td>Bitrate = 2.5 Gb/s</td>
<td>-28.0</td>
<td>-27.9</td>
<td>-27.9</td>
<td>-27.7</td>
<td>dBm</td>
</tr>
<tr>
<td>Sensitivity at point A</td>
<td>( V_{\text{Control}} = -1.5 \text{ V} )</td>
<td>-11.3</td>
<td>-9.2</td>
<td>-13.1</td>
<td>-10.4</td>
<td>dBm</td>
</tr>
</tbody>
</table>

Tab. 4.4  Performance Characteristics of WDM Receiver Module

4. Conclusions

In conclusion we have demonstrated a rugged, packaged, polarization insensitive WDM receiver with four channels at the wavelengths 1548 nm, 1552 nm, 1556 nm, and 1560 nm. For 2.5 Gb/s data transmission per channel the sensitivity is as good as -13 dBm for the best channel. Although there is still room for a reduction of the WDM losses the high functionality module is suitable for WDM system implementations.

This work was in part performed within the ESPRIT Project MOSAIC. We acknowledge the support of the Swiss Federal Office for Education and Science, Berne. We thank the Swiss PTT for lending a tunable laser source.
4.5. Additional results on grating demultiplexers

Electron-beam writing of gratings
The demultiplexer gratings were generally defined by ultraviolet (uv) contact lithography with commercial available chrome masks together with the waveguides and alignment indentations.

<table>
<thead>
<tr>
<th>Process step</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. InP layer growth</td>
<td>LP-MOVPE, 3.2 µm</td>
</tr>
<tr>
<td>2. SiO₂ deposition</td>
<td>PE-CVD, 300 nm</td>
</tr>
<tr>
<td>3. Alignment mark definition</td>
<td>2 nm Ti, 38 nm Au, lift-off process</td>
</tr>
<tr>
<td>4. E-beam writing of grating</td>
<td>external (IBM Rüsslikon) PMMA coating, e-beam writing, PMMA developing</td>
</tr>
<tr>
<td>5. Grating transfer</td>
<td>SiO₂ RIE through PMMA mask, PMMA removal</td>
</tr>
<tr>
<td>6. SiO₂ mask definition (waveguides)</td>
<td>500 nm photoresist coating, uv-contact lithography, SiO₂ RIE through resist mask, resist removal</td>
</tr>
<tr>
<td>7. Photoresist mask definition (for deep etching)</td>
<td>1.5 µm thickness, uv-contact lithography</td>
</tr>
<tr>
<td>8. Grating fabrication</td>
<td>H₂/CH₄/Ar vertical plasma etching through resist mask, resist removal</td>
</tr>
<tr>
<td>9. Waveguide fabrication</td>
<td>H₂/CH₄/Ar plasma etching through SiO₂ mask, SiO₂ removal, clean</td>
</tr>
<tr>
<td>10. Grating metallization</td>
<td>2 nm Ti, 80 nm Au, lift-off process</td>
</tr>
<tr>
<td>11. Facet formation</td>
<td>cleaving</td>
</tr>
<tr>
<td>12. Facet AR coating</td>
<td>177 nm SiO₂, 23 nm Al₂O₃</td>
</tr>
</tbody>
</table>

Tab. 4.5 Process sequence for the fabrication of demultiplexers with e-beam written gratings.
As an alternative, we used electron-beam (e-beam) direct writing for the
definition of the grating, taking advantage of the enhanced resolution of this
technique. This implied some additional fabrication steps. The modified process
sequence for the fabrication of demultiplexers with e-beam written gratings is
described in Tab. 4.5. The definition of the grating and the waveguides was done
in two process steps. The grating was written in collaboration with IBM
Rüsslikon. In order to properly align the grating with the waveguides we used
specially designed alignment marks that are placed onto the chip prior to the e-
beam writing of the grating. A misalignment of less than 0.5 μm was routinely
achieved with this technique.

For the optimization of grating quality, the coordinate system for e-beam writing
was rotated to form an angle of about 45° with the grating facets. Facets which
are almost parallel to the e-beam system coordinates, show visible steps that are
due to the digitalization of the data (see Fig. 4.26).

Fig. 4.26 PMMA test structure for the evaluation of the quality of the e-beam
writing. Here, the grating facets form a small angle with the e-beam
system coordinates (xy). The digitalization results in visible steps in
the grating facets. This effect vanishes if the data is digitalized in a
coordinate system (x’y’) that forms an angle of around 45° with the
grating facets.

The scanfield of the e-beam was about 410 μm. The mechanical alignment of the
scanfields to each other results in "stitching errors", that are very critical for the
demultiplexer grating and should be less than 50 nm. The demultiplexer grating
has a total length of over 2 mm and was written in several steps. For the reduction
of sensitivity to stitching errors the center of the first scanfield was chosen at the grating pole. The first interface is then at an opening angle of 2.8° of the grating, where the light intensity is already less than 30% of the maximum.

In order to gain e-beam time, the grating facets were written with highest resolution whilst the additional parts were written with reduced resolution. The working order of the e-beam gratings was reduced from 30th to 10th, resulting in an enhanced free spectral range of 134 nm and a reduced grating constant of 3.7 μm. The results for the demultiplexers with e-beam gratings are comparable with the conventional demultiplexers, without a notable increase in loss. This demonstrates that the realization of demultiplexers with a larger number of channels is possible, at the prize of a more complicated process sequence. A photograph of a realized e-beam written grating is shown in Fig. 4.27.

![E-beam written grating in InP after deep facet etching. The working order is 10th with a grating constant of 3.7 μm. Etch depth is 5.5 μm.](image)

**Fig. 4.27** E-beam written grating in InP after deep facet etching. The working order is 10th with a grating constant of 3.7 μm. Etch depth is 5.5 μm.

**Demultiplexers with shifted gratings**

In order to enhance flexibility and mask area utilization, a part of the demultiplexers were designed to allow for the fabrication of lithographic as well as e-beam written gratings. For this purpose the lithographic grating pattern was shifted by 3 μm in vertical and by 3 μm in horizontal direction as shown in Fig. 4.28. The shift was introduced to allow for a small misalignment of the e-beam grating in respect to the waveguide mask without any overlap of the two
4.5. Additional results on grating demultiplexers

gratings. Demultiplexers with shifted lithographic gratings were simulated using the ray-trace method described in section 4.3. The calculations predicted a shift of the filter passbands of 1.6 nm towards shorter wavelengths and a shift of the focal line of 1.4 µm towards the grating. While the shift of the focal line decreased the grating efficiency by less than 0.01% (see Fig. 4.18) the wavelength shift was fully confirmed by measurements with -1.7 nm ± 0.3 nm.

![Diagram](image)

**Fig. 4.28** Mask layout of a demultiplexer foreseen for e-beam grating. A lithographic grating that is shifted by 3 µm in vertical and horizontal direction is added on the mask and is effective when no e-beam writing is performed.

**Demultiplexer characterization in additional working orders**

The blazing of the grating is effective for an output angle that corresponds to a fixed wavelength for a given working order. Additional wavelengths values solve the grating Eq (4.1) for our demultiplexers with fixed values for the angles α, β and the grating constant d, if Eq (4.25) is fulfilled:

\[ \frac{m \lambda}{n_{\text{eff}}} = \text{constant} = \frac{30 \times 1556 \text{ nm}}{3.17} \]  

(4.25)
4. InP Grating demultiplexers and their applications

The response of the demultiplexer is hence "periodic" with a wavelength spacing according to the (variable) FSR. The losses only slightly change for the different orders. With the light sources available at our Institute we characterized demultiplexers in the wavelengths range from 1.2 \( \mu m \) to 1.6 \( \mu m \) according to the working orders 39 to 30. Channel allocations were also calculated by means of the ray-trace method. A comparison of the calculated and experimental values for a device with shifted lithographic grating is presented in Tab. 4.6.

<table>
<thead>
<tr>
<th>Working order</th>
<th>( \lambda_{\text{calc}} ) [nm]</th>
<th>( \lambda_{\text{meas}} ) [nm]</th>
<th>( \lambda_{\text{calc}}-\lambda_{\text{meas}} ) [nm]</th>
<th>FSR_{meas} [nm]</th>
<th>( \lambda_0/(m+1) ) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1554.4</td>
<td>1554.6</td>
<td>-0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>1507.1</td>
<td>1507.3</td>
<td>-0.2</td>
<td>47.3</td>
<td>47.1</td>
</tr>
<tr>
<td>32</td>
<td>1462.8</td>
<td>1462.8</td>
<td>0.0</td>
<td>44.5</td>
<td>44.3</td>
</tr>
<tr>
<td>33</td>
<td>1421.3</td>
<td>1421.2</td>
<td>0.1</td>
<td>41.6</td>
<td>41.8</td>
</tr>
<tr>
<td>34</td>
<td>1382.3</td>
<td>1382.7</td>
<td>-0.4</td>
<td>38.5</td>
<td>39.5</td>
</tr>
<tr>
<td>35</td>
<td>1345.7</td>
<td>1345.6</td>
<td>0.1</td>
<td>37.1</td>
<td>37.4</td>
</tr>
<tr>
<td>36</td>
<td>1311.2</td>
<td>1311.1</td>
<td>0.1</td>
<td>34.5</td>
<td>35.4</td>
</tr>
<tr>
<td>37</td>
<td>1278.8</td>
<td>1278.6</td>
<td>0.2</td>
<td>32.5</td>
<td>33.7</td>
</tr>
<tr>
<td>38</td>
<td>1248.1</td>
<td>1247.8</td>
<td>0.3</td>
<td>29.8</td>
<td>32.0</td>
</tr>
<tr>
<td>39</td>
<td>1219.2</td>
<td>1218.5</td>
<td>0.7</td>
<td>29.3</td>
<td>30.5</td>
</tr>
</tbody>
</table>

Tab. 4.6 Comparison of calculated and experimental data for the channel "1556" of a device with shifted lithographic grating. Excellent agreement is obtained for the channel allocations and good estimates the free spectral range result with Eq. (4.26).

Excellent agreement is obtained for the channel allocations which strongly depend on the accuracy of the input data for the refractive index. Also added are the values for the free spectral range. The formula

\[
\text{FSR} = \frac{\lambda_0}{m + 1}
\] (4.26)
becomes more inaccurate at shorter wavelengths because the dispersion of InP is not considered.

The measurement of blazing efficiency over the entire FSR as in [4.38], was not possible since the FSR is only partly covered with channels in our demultiplexers. Blazing efficiency was checked on test devices which had output waveguides at the positions of $\lambda=1556$ nm in other working orders (Fig. 4.29). However, the power level at these outputs was too low for the distinction from stray light.

Fig. 4.29  Demultiplexer layout with output waveguides at locations of other working orders for $\lambda=1556$ nm for the measurement of the blazing efficiency. The power level at these outputs was too low for distinction from stray light.
Grating metallization

For the enhancement of the grating reflectivity, the grating facets were coated with metal. An evaluation of most suitable metals was made by calculating the reflectivity of an InP/metal interface for plane waves. We used the Fresnel relation for normal incidence:

\[
R = \frac{(n_{\text{InP}} - n)^2 + k^2}{(n_{\text{InP}} + n)^2 + k^2}
\]

where \(n\) is the real part and \(k\) the imaginary part of the refractive index of the metal and \(n_{\text{InP}}\) the refractive index of InP. A list of the considered metals is given in Tab. 4.7. The reflectivity was calculated for \(\lambda = 1.55 \, \mu\text{m}\).

<table>
<thead>
<tr>
<th>Metal</th>
<th>n</th>
<th>k</th>
<th>R</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver (Ag)</td>
<td>0.469</td>
<td>9.32</td>
<td>94.1%</td>
<td>0.27 dB</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>0.559</td>
<td>9.81</td>
<td>93.6%</td>
<td>0.29 dB</td>
</tr>
<tr>
<td>Aluminium (Al)</td>
<td>1.44</td>
<td>16.0</td>
<td>93.4%</td>
<td>0.30 dB</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.606</td>
<td>8.26</td>
<td>90.7%</td>
<td>0.42 dB</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>3.38</td>
<td>6.82</td>
<td>52.1%</td>
<td>2.83 dB</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>5.31</td>
<td>7.04</td>
<td>44.6%</td>
<td>3.51 dB</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>3.69</td>
<td>4.66</td>
<td>32.0%</td>
<td>4.95 dB</td>
</tr>
<tr>
<td>air</td>
<td>1</td>
<td>0</td>
<td>27.1%</td>
<td>5.67 dB</td>
</tr>
</tbody>
</table>

Tab. 4.7 List of refractive index and calculated reflectivity \(R\) at InP/metal interface for plane waves at \(\lambda = 1.55 \, \mu\text{m}\).

The values for the refractive indices at \(\lambda = 1.55 \, \mu\text{m}\) (0.8 eV) were taken from [4.39], except for titanium [4.40]. For InP we took \(n = 3.17\). From Tab. 4.7 we see that silver, aluminum, and gold have the highest reflectivity. We selected gold because it is well suited for e-beam evaporation and exhibits good long term stability. A 2 nm thick titanium layer is used for adhesion enhancement. A gold thickness of about 80 nm was empirically found to be sufficient for an enhancement of 5 dB for the grating reflectivity.
Flattening of filter transmission curve

A problem encountered with demultiplexers is that their spectral passbands are "peaked"; a transmission maximum occurs at the filter center and throughput decreases as the wavelength moves away from the central wavelength. To avoid system penalties, all signal wavelengths and filters throughout a network have therefore to be very precisely aligned. This places very stringent requirements on the design and operation of both the wavelength-specific sources and filters.

Different approaches to improve the filter transmission curve are reported: flattening of the input waveguide mode form of the demultiplexer \([4.41]\), concatenation of filters \([4.42]\), and the use of multimode output waveguides \([4.43]\). The last method was applied to some of our demultiplexers in order to give the transmission curve a more rectangular form.

![Graph showing calculated and measured filter transmission curve](image)

**Fig. 4.30** Calculated and measured filter transmission curve for 5 \(\mu m\) input and 8 \(\mu m\) output waveguides. Compared with 5 \(\mu m\) single mode output waveguides the FWHM is increased from 1.4 nm to 1.9 nm. The differences between simulation and measurements are thought to be caused by the higher propagation losses of the first order mode and by the bent output waveguides.
We used multimode output waveguides with rib widths of 8 µm. The simulated and measured transmission curves are shown in Fig. 4.30. The calculated FWHM was 2.1 nm while we measured 1.8-1.9 nm. The incomplete agreement with the measured transmission curve is thought to be caused by higher propagation losses of the first order mode and asymmetries may be introduced by the bent output waveguides.

With multimode output waveguides the device is no more suited to be inserted between single mode fibers. This is not a disadvantage in applications where the light is directly coupled into photodetectors. We realized such demultiplexers for system experiments. With the help of a corner mirror at the input channel waveguide, the input and output facets of the demultiplexer are separated. The multimode output waveguides are end-fire coupled to an array of receivers with top-illuminated pin photodetectors. The layout of these demultiplexers is shown in Fig. 4.31.

![Fig. 4.31 Layout of demultiplexers with multimode output waveguides for direct coupling to photodetector arrays. A corner mirror is used to separate the input and output facets.](image)

Besides the FWHM, the optical characteristics were comparable with the demultiplexers with single mode output waveguides. We measured losses of 14.8-16.1 dB for TE polarization, the losses for TM were about 3 dB higher. For the MOSAIC project, we packaged a module including the demultiplexer, a 4-channel receiver array and temperature control. A schematic view of the package is shown in Fig. 4.32. This module exhibited a 6 dB worse sensitivity at 2.5 Gbit/s than the one reported in section 4.4. Two main reasons were found to cause the worse performance: the receiver array was actively aligned with an angle of 90° in respect to the demultiplexer and glued with uv-curing glue. The stability of this mounting was only moderate. The second problem was the
thermal coupling between receiver array and demultiplexer. The receiver array could not efficiently be cooled and its heat dissipation destabilized the demultiplexers passband allocations.

Fig. 4.32 Schematic view of the realized package for the demultiplexer and a photoreceiver array.

Improvement of crosstalk
The separations of the output waveguides of the demultiplexer at the focal line are 15 µm. The waveguide modes are only weakly confined and coupling between the waveguides may occur. Such coupling will increase the crosstalk. In order to check the waveguide coupling, we fabricated demultiplexers with deeply etched groves between the output waveguides. These groves prevent any waveguide coupling. The results showed that the contribution from the coupling between the output waveguides to the crosstalk can fully be neglected.

Measurement technique
Two methods were applied for the measurement of the optical transmission curves of demultiplexers. The first method is to launch light from a power controlled tunable laser (HP8168C) into the demultiplexer and to detected it at the output waveguides. The second method is faster and is based on broadband light sources and a spectrum analyzer (HP70951A). Light from a high power superluminescent diode (SLD) [4.44] or the spontaneous emission of erbium doped fiber amplifiers (EDFA) was coupled through the demultiplexer into the spectrum analyzer. The transmission curves of the channels were evaluated as the difference between the source spectrum and the spectrum at the demultiplexer output. Power spectra of the used sources that cover the range from 1.2 µm to 1.6 µm are shown in Fig. 4.33.
Measurement of birefringence of planar waveguide structures

The effective refractive index of a planar waveguide structure depends on polarization. Our demultiplexer is an instrument that translates the difference in effective refractive index into a difference in wavelength that can be measured with a high degree of accuracy. With the chosen \(n^-/n^+\)-InP layer structure we achieved a birefringence (difference between effective refractive index for the two polarizations TE and TM) of less than \(3 \times 10^{-4}\) corresponding to a wavelength shift of less than 0.15 nm. For InP/InGaAsP/InP doublehetero layer structures the birefringence is larger. In order to check modeling software and to characterize layer structures that are used for optical switches, we fabricated demultiplexers with our mask set on two doublehetero layer structures. The first structure was designed for low birefringence while the second was targeted to a TE/TM shift of 4 nm. A possible application of a demultiplexer with the second layer structure is a TE/TM splitter. The results of these experiments are summarized in Tab. 4.8.

Taking into account fabrication tolerances, good agreement was obtained for measured and calculated effective indices. Based on these results we can conclude that the simulation software is accurate within the measurement accuracy and the homogeneity of layer growth is sufficient for the use of doublehetero structures.
4.5. Additional results on grating demultiplexers

<table>
<thead>
<tr>
<th></th>
<th>Structure 1</th>
<th>Structure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP cap thickness</td>
<td>1000 nm</td>
<td>1000 nm</td>
</tr>
<tr>
<td>InGaAsP core thickness</td>
<td>760 nm</td>
<td>450 nm</td>
</tr>
<tr>
<td>InGaAsP core bandgap</td>
<td>1.11 μm</td>
<td>1.26 μm</td>
</tr>
<tr>
<td>Grating working order</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>Wavelength allocation $\lambda_0$</td>
<td>1540 nm</td>
<td>1520 nm</td>
</tr>
<tr>
<td># of characterized demultiplexers</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Calculated TE/TM shift</td>
<td>1.1 nm</td>
<td>4.0 nm</td>
</tr>
<tr>
<td>Measured TE/TM shift</td>
<td>1.0±0.2 nm</td>
<td>3.8±0.3 nm</td>
</tr>
<tr>
<td>Calculated birefringence</td>
<td>2.4×10^{-3}</td>
<td>8.6×10^{-3}</td>
</tr>
<tr>
<td>Measured birefringence</td>
<td>(2.2±0.5)×10^{-3}</td>
<td>(8.1±0.6)×10^{-3}</td>
</tr>
<tr>
<td>$n_{eff}(TE)$ at $\lambda_0$</td>
<td>3.247</td>
<td>3.294</td>
</tr>
</tbody>
</table>

Tab. 4.8 Summary of results of characterized demultiplexers based on InGaAsP/InP doublehetero layer structures.

The main problem with quaternary InGaAsP layers is the reproducible fabrication of layers with accurate absolute values of the refractive index, corresponding to only a few nanometers tolerance in bandgap wavelength.

System experiments with optically preamplified WDM receiver
The system measurements presented in section 4.4 were extended. In order to improve the sensitivity of the WDM receiver module, two erbium doped fiber amplifiers (EDFA) with a total gain of 40 dB were placed in front of the four channel WDM receiver. In principle, optical preamplification before the photodetection offers a way to overcome the limitation of sensitivity by thermal noise of the electronic receiver. The sensitivity of direct detection using optical preamplification and a pin photodiode is in the same range as by coherent detection and much better than by direct detection using avalanche photodiodes. The combination of EDFA's with pin receivers is most effective in the 1.55 μm window and for high data rates where the noise caused by spontaneous emission of the optical amplifier can be eliminated by narrow optical filtering.
The measurement setup with two cascaded EDFA’s offering 40 dB optical gain is depicted in Fig. 4.34.

![Measurement setup for the measurements with optically preamplified WDM receiver module. Channel allocations were 1548 nm, 1552 nm, 1556 nm, and 1560 nm, data rate was 2.5 Gbit/s.](image)

It should be noted that the demultiplexer is the only filter used after the EDFA’s with the twofold function of channel separation and “stripping” of the amplified spontaneous emission (ASE) from the EDFA’s. The results for the channel 2 are shown in Fig. 4.35.

![Recorded bit-error rates on channel 2 of a 4-channel WDM/receiver module with optical preamplification. The data sequence was a 2.5 Gbit/s 2^{15}-1 non-return to zero (NRZ) pseudo random bit sequence (PRBS). The sensitivity for a BER of 10^{-9} was -41.2 dBm compared to -9.8 dBm without optical preamplification.](image)
The optical preamplification improves the sensitivity for a bit-error rate (BER) of $10^{-9}$ from -9.8 dBm to -41.2 dBm at 2.5 Gbit/s, including an optical isolator in front of the EDFA's with 1 dB insertion loss. This improvement corresponds to an increase of repeaterless transmission span of 150 km. The measured sensitivity is only 3 dB worse than the best reported results for a single channel optically preamplified receiver applying narrow optical filtering [4.45]. The gain of the optical preamplifiers overcomes both the electrical noise of the receiver and the insertion loss of the InP demultiplexer and decreases the loss differences between the four channels.

The high performance of our configuration is in part due to the large free spectral range of the demultiplexer. Only the wavelengths corresponding to the working order 30 lie within the spectrum of the EDFA. For demultiplexers with smaller FSR, the multiple passbands of each channel are transparent to a part of the ASE power which degrades both the noise performance and the dynamic range of the receiver. Our results still compare well with the reported sensitivity of -39.6 dBm at 2.5 Gbit/s [4.46], where an 8-channel phasar demultiplexer with an FSR of 6.5 nm and an additional tunable filter with 1.3 nm passband were used.
4.6. The refractive index of InP and its temperature dependence measured with optical demultiplexers

We used the grating demultiplexer modules for the measurement of the refractive index on InP and its thermal dependence with a very high degree of accuracy. The measurements and results of this application were reported in [4.12], [4.13], and [4.47], which are summarized in this section.

Abstract

The temperature dependence of the refractive index of InP in the wavelength range from 1.2 to 1.6 μm has been determined with a relative accuracy of 2×10⁻⁴. The refractive indices are determined from the measured transmission wavelengths of an n/n⁺-InP optical demultiplexer at different device temperatures. The refractive index of InP is found to depend linearly on temperature with a temperature coefficient between 2.3 and 1.9×10⁻⁴/K. The measured absolute value and the dispersion of the refractive index of InP are in agreement with data from the literature.

1. Introduction

The precise knowledge of material parameters, such as the refractive index, is the basis for the design and manufacture of integrated optical devices. Especially for devices where the wavelength dependence scales with the refractive index, such as distributed feedback lasers or optical wavelength demultiplexers, accurate values are desired. Among the published data for InP, [4.18] give results with an accuracy of 7×10⁻³. Recently, data was reported with an accuracy of better than 10⁻³ [4.48]. The temperature dependence of the refractive index impacts the performance of electro-optic devices. By studying the thermal behavior of vertical cavity surface-emitting lasers the temperature dependences of the refractive indices of GaAs and AlAs have been determined [4.49], [4.50]. However, InP data for the thermal dependence of the refractive index [4.51] with a high degree of accuracy are missing. Very recently, more accurate data for the wavelength λ=1.56 μm has been presented [4.48].

We determined the thermal dependence of the refractive index of InP by measuring the transmission wavelengths of an n/n⁺-InP integrated optical demultiplexer as a function of device temperature. The method is also suitable for very accurate measurements (in the 0.01% range) of the effective index of planar
4.6. Thermal dependence of the refractive index of InP

waveguide structures. From measurements at different wavelengths, data for the material dispersion are extracted.

2. Measurement principle

The temperature dependence of the refractive index of InP is measured with a temperature controlled integrated optical InP demultiplexer. The layout of the device is shown in Fig. 4.36 and the working principle is as follows: light from an input channel waveguide is fed into a planar waveguide structure where it spreads out and is diffracted by a deeply etched reflective grating. The curved grating [4.17] focuses the light onto a focal line with a reflection angle that depends on the wavelength. Four laterally spaced waveguides are placed at the focal line. The input and output channel waveguides are separated to 250 μm spacing and coupled to an array of five lensed single mode fibers. At a fixed temperature T, maximum transmission from the input to a given output channel is achieved if Eq (4.28) is fulfilled [4.16],

\[ d(T) \times (\sin \alpha + \sin \beta_i) = \frac{m \times \lambda_{\text{max}}(T)}{n_{\text{eff}}(T)} \]  

(4.28)

where d is the grating constant, \( \alpha \) and \( \beta_i \) the input and output angles on the grating, respectively, m the working order, \( \lambda_{\text{max}} \) the wavelength for maximum transmission, and \( n_{\text{eff}} \) the effective refractive index of the planar waveguide structure. The grating constant d of the realized device is 11.16 μm, the angle \( \alpha \) is 45° and the angles \( \beta_i \) range between 37.5 and 38.3° for the four output waveguides. These values are defined by a mask used for the etching of the grating and the channel waveguides.

The planar waveguide structure consists of a sulfur doped InP substrate (N=3.2\times10^{18}/cm^3) and a 3.2 μm thick nominally undoped InP guiding layer (background doping level <10^{15}/cm^3) grown by low-pressure metal-organic vapor phase epitaxy (Fig. 4.36, bottom right). The refractive index change of the substrate due to the doping is calculated according to [4.19] considering the plasma effect and the effects of bandfilling and bandshrinkage. We get a Δn of -0.025 with 10% variations depending on wavelength and temperature. More details about the design and performance of the demultiplexer are described in [4.36].
The integrated demultiplexer is mounted onto a silicon motherboard for fiber array connection. The motherboard is fixed with conductive epoxy onto a small copper block on top of a Peltier element (Fig. 4.37). The temperature is measured with a NTC thermistor placed in the copper block in the vicinity of the device. After every temperature change 10 minutes were allowed for temperature homogenization. The temperature hysteresis between heating and cooling was less than 1 K.

The optical measurements were performed with a tunable external cavity laser source. Light from the output fibers was directed to a photodiode and monitored by an optical spectrum analyzer with a resolution of better than 0.1 nm (Fig. 4.36, bottom left). The wavelengths $\lambda_{\text{max}}$ with maximum transmission were determined for each output channel for the orders $m = 30$ to $m = 39$ in the temperature range from 10 to 60°C.
4.6. Thermal dependence of the refractive index of InP

Temperature control

Fiber array
Demultiplexer
Si motherboard
NTC
Copper block
Peltier element

Fig. 4.37 Schematic view of the package of the InP demultiplexer. The temperature is controlled with a Peltier element and a NTC thermistor in a hole in the copper block in the vicinity of the demultiplexer. The total size of the aluminum housing is 4 cm x 4 cm x 2 cm. A photograph of the module is shown in Fig. 4.8.

3. Results

From the wavelengths with maximum transmission \( \lambda_{\text{max}} \), the effective refractive index \( n_{\text{eff}} \) of the planar waveguide was calculated using Eq. (4.28). The thermal expansion of the grating constant \( d \) was taken into account with a temperature coefficient of \( 4.56 \times 10^{-6} / \text{K} \) [4.52]. It accounts for about 5% of the observed wavelength shifts. The data was corrected for material dispersion. The effective indices are found to vary linearly with the temperature. It is assumed that the variation of the refractive index of InP is the same as for the effective index of the planar waveguide structure as the carrier effects depend only slightly on temperature. Fig. 4.38 shows the linear temperature coefficients in the wavelength range from 1.2 to 1.6 \( \mu \text{m} \). Reference [4.48] report a value of \((2.02 \pm 0.02) \times 10^{-4} / \text{K}\) at \( \lambda = 1.56 \mu \text{m} \), measured with a grating coupling technique. Their data is not corrected for the thermal expansion of their device [4.53]. This fact completely explains the disagreement with our measurements.
4. InP Grating demultiplexers and their applications

Fig. 4.38 Measured linear temperature coefficient of the refractive index of InP in the wavelength range from 1.2 to 1.6 μm. The line is a quadratic least-squares fit: $y = 8.36 \times 10^{-4} - 8.194 \times 10^{-4} \lambda + 2.6 \times 10^{-4} \lambda^2$ where $\lambda$ is in [μm]. The open box is data from Ref. [4.48].

With Eq. (4.28) the effective refractive index of the planar waveguide structure, $n_{\text{eff}}$, was calculated from the wavelengths with maximum transmission, $\lambda_{\text{max}}$. The refractive index of InP was calculated from $n_{\text{eff}}$ by solving [4.54]

$$
2\pi \sqrt{n^2 - n_{\text{eff}}^2} \frac{t}{\lambda} = \tan^{-1} \left( \sqrt{\frac{n_{\text{eff}}^2 - n_s^2}{n^2 - n_{\text{eff}}^2}} \right) + \tan^{-1} \left( \sqrt{\frac{n_{\text{eff}}^2 - 1}{n_s^2 - n_{\text{eff}}^2}} \right) \tag{4.29}
$$

where $n_s = n + \Delta n$ is the substrate refractive index, $n$ the refractive index of undoped InP and $t$ the thickness of the undoped InP layer. Equation (4.29) is only valid for TE polarization, but for our layer structure the difference to TM polarization can be neglected. We estimate the accuracy of our values in the order of 0.0005. This is based on our accuracies of temperature (0.5 K), wavelength (0.1 nm), angles $\alpha$, $\beta$, and grating constant $d$ on the masks (0.03%). Errors in $\Delta n$ of 20% and in
layer thickness $t$ of 0.1 $\mu$m result in errors of only 0.0002 and 0.0003 in $n$, respectively. The derived refractive indices for InP for a temperature of 25°C are given in Fig. 4.39. The values are compared with the calculated curve from [4.18] and [4.48]. The difference to [4.18] are between 0.001 and 0.003 and lie within the accuracy of their fit of 0.007. We can not explain the offset of 0.009 relative to [4.48], also far more than their reported uncertainty of 0.0002 which may be underestimated [4.55].

![Graph](image)

**Fig. 4.39** Measured refractive indices of InP in the wavelength range from 1.2 $\mu$m to 1.6 $\mu$m at 25°C (boxes). The dotted line is calculated with $n^2 = 7.255 + 2.316/(1-0.3922\mu m^2/\lambda^2)$ according to [4.18], the dashed line is calculated with $n^2 = 7.283 + 2.337/(1-0.387\mu m^2/\lambda^2)$ according to [4.48]. Our measurements are best fitted with $n^2 = 7.233 + 2.34/(1-0.382\mu m^2/\lambda^2)$ (solid line).

4. Conclusion
We have determined with a high degree of accuracy the temperature dependence and the absolute value of the refractive index of InP in the wavelength range from 1.2 to 1.6 $\mu$m by means of an integrated optical demultiplexer in InP. The values
4. InP Grating demultiplexers and their applications

...presented are very suitable for the design of integrated optical components including filters in InP. The results compare well with values from the literature. The method allows for a very accurate measurement of the effective refractive index of planar waveguide structures.

This work was in part performed within the ESPRIT project MOSAIC. We acknowledge the support of the Swiss Federal Office for Education and Science, Berne. We thank the Swiss PTT for lending a tunable laser source.
4.7. Conclusions

Grating demultiplexers in InP were successfully realized. Based on an etched reflective grating the devices separate 4 channels with 4 nm spacing in the 1.55 μm window. An n-/n⁺-InP waveguide structure was developed that combines the advantages of low birefringence for polarization independence, large optical mode size for high coupling efficiency to a single mode fiber, and accurate control of the refractive index for precise filter passband allocations. Dry etching techniques were optimized to fabricate smooth grating facets with less than 1° deviation from verticality. A self-aligned flip-chip mounting technique was adapted for optical coupling to an array of single mode fibers. The demultiplexers were packaged including temperature control to ease handling for system transmission experiments.

We discussed the key aspects for grating design that allow for the optimization of targeted performance of the demultiplexer. Simulation of various demultiplexers with ray-tracing resulted in good agreement with experimental data.

Hybridized polarization insensitive multichannel WDM receiver modules were used to demonstrate four channel 2.5 Gbit/s WDM data transmission showing high functionality. Potential improvements were demonstrated with e-beam writing of gratings and optical preamplification.

Filter modules were used to determine with a high degree of accuracy the temperature dependence and the absolute value of the refractive index of InP in the wavelength range from 1.2 μm to 1.6 μm. The values achieved are very suitable for the design of integrated optical components. The method allows for very accurate measurement of the effective refractive index of other planar waveguide structures which was illustrated for different doublehetero waveguide structures.
4. InP Grating demultiplexers and their applications

4.8. References

"Monolithic InP/InGaAsP/InP grating spectrometer for the 1.48-1.56 μm wavelength range"

"Grating spectrograph in InGaAsP/InP for dense wavelength division multiplexing"

[4.3] M. K. Smit
"New focusing and dispersive planar component based on an optical phased array"

"Demonstration of a 15×15 arrayed waveguide multiplexer on InP"

"Fabrication of 64×64 arrayed-waveguide grating multiplexer on silicon"

"Digitally tunable channel dropping filter/equalizer based on waveguide grating router and optical amplifier integration"

"Monolithic eight-wavelength demultiplexed receiver for dense WDM applications"

"16 channel phased array wavelength demultiplexer on InP with low polarisation sensitivity"
"Polarisation-independent InP arrayed waveguide filter using square cross-section waveguides"

"Polarization independent 8×8 waveguide grating multiplexer on InP"

"Polarisation compensated waveguide grating router on InP"

"Thermal dependence of the refractive index of InP measured with integrated optical demultiplexers"

"Erratum: Thermal dependence of the refractive index of InP measured with integrated optical demultiplexers"

"Tunable phased-array wavelength demultiplexer on InP"
Electronics Letters, Vol. 31, pp. 32-33, 1995

[4.15] H. A. Rowland
"Preliminary notice of the results accomplished in the manufacture and theory of gratings for optical purpose"
Philosophical Magazine, Vol. 13, pp. 469-474, 1882

[4.16] M. C. Hutley
"Diffraction Gratings"

"On the theory of planar spectrographs"

"Refractive index of InP"
4. InP Grating demultiplexers and their applications

"Carrier-induced change in refractive index of InP, GaAs, and InGaAsP"

"Self-aligned optical flip-chip OEIC packaging technologies"
Proceedings of the 19th European Conference on Optical
Communication ECOC'93, pp. 84-91, 1993

[4.21] W. Hunziker, E. Bolz, and H. Melchior
"Elliptically lensed polarization maintaining fibres"

[4.22] M. Teshima, M. Koga, and K. Sato
"Multiwavelength simultaneous monitoring circuit employing
wavelength crossover properties of arrayed-waveguide grating"

"Packaged 2.5 Gb/s 4-channel WDM receiver module with InP grating
demultiplexer and pin-JFET receiver array"
Proceedings of the 21th European Conference on Optical
Communication, ECOC'95, pp. 207-210, 1995

[4.24] K. A. McGreer
"Diffraction from concave gratings in planar waveguides"

[4.25] M. Born
"Optik"

[4.26] G. R. Harrison
"The production of diffraction gratings: II. The design of echelle gratings
and spectrographs"

"Quantitative analysis of integrated optic waveguide spectrometers"
IEEE Photonics Technology Letters, Vol. 6, pp. 242-244, 1994

"On the concave grating spectrograph, especially at large angles of
incidence"
Journal of the Optical Society of America, Vol. 22, pp. 245-264, 1932
4.8. References

[4.29] M. Wu and Y. J. Chen
"Design considerations for Rowland circle gratings used in photonic integrated devices for WDM applications"

"Design of a multistripe array grating integrated cavity (MAGIC) laser"

[4.31] W. T. Welford
"Aberration theory of gratings and grating mountings"
Progress in Optics, Vol. 4, pp. 241-280, 1965

[4.32] R. Petit (Editor)
"Electromagnetic theory of gratings"
Springer, Berlin, 1980

[4.33] D. Maystre
"Rigorous vector theories of diffraction gratings"
Progress in Optics, Vol. 21, pp. 1-67, 1984

"Low-loss phased array based 4-channel wavelength demultiplexer integrated with photodetectors"

"A WDM receiver photonic integrated circuit with net on-chip gain"

[4.36] E. Gini and H. Melchior
"Polarization Independent InP Grating Spectrograph for Fiber Optical Links"
Proceedings of the 7th European Conference on Integrated Optics, ECIO'95, pp. 279-282, 1995

[4.37] M. Blaser and H. Melchior
"High performance monolithically integrated InGaAs/InP pin/JFET optical receiver front-end with adaptive feedback control"
4. InP Grating demultiplexers and their applications

"8-channel optical demultiplexer realized as SiO\textsubscript{2}/Si flat-field spectrograph"

[4.39] E.D. Palik (Editor)
"Handbook of optical constants of solids"

"Landolt-Börnstein, Numerical data and functional relationships in science and technology"

"Use of multimode interference couplers to broaden the passband of wavelength-dispersive integrated WDM filters"

"Eight-channel flat response arrayed-waveguide multiplexer with asymmetrical Mach-Zehnder filters"

"Phased-array wavelength demultiplexer with flattened wavelength response"

"High power superluminescent diodes for 1.3 μm wavelengths"

"2.5 and 10 Gb/s transmission experiments using a 137 photon/bit erbium-fiber preamplifier receiver"
4.8. References

"Performance of an eight-channel pin/HBT OEIC photoreceiver array module in an optically-preamplified WDM system experiment"

"The refractive index of InP and its temperature dependence in the wavelength range from 1.2 µm to 1.6 µm"

"Accurate index measurements of doped and undoped InP by a grating coupling technique"

"Thermal dependence of the refractive index of GaAs and AlAs measured using semiconductor multilayer optical cavities"

"Erratum: Thermal dependence of the refractive index of GaAs and AlAs measured using semiconductor multilayer optical cavities"

[4.51] V. B. Bogdanov, V. T. Prokopenko, and A. D. Yasko
"Refractive index of indium phosphide in the 0.96-13 µm wavelength range"
Optics and Spectroscopy, Vol. 60, pp. 68-69, 1986

"The thermal-expansion parameters of some Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ alloys"

"Response to comment on ‘Accurate index measurements of doped and undoped InP by a grating coupling technique’"

[4.54] T. Tamir (Editor)
"Integrated Optics"

"Comment on 'Accurate index measurements of doped and undoped InP by a grating coupling technique’"

5. Conclusions and outlook
5. Conclusions and outlook

5.1. Conclusions

We have successfully realized compact plasma etched devices for integrated optics in InP. Two devices were profoundly investigated: optical corner mirrors and grating wavelength demultiplexers. Key issues for the implementation of photonic integrated circuits into fiber-optic systems have been identified:

- polarization independence
- low optical losses.

These key issues had to be resolved while being compatible in their fabrication process with other InP based components for further integration.

Corner mirrors based on total internal reflection were found to have low polarization dependence and our work concentrated on the reduction of optical losses. The essential developments to achieve this goal were:

- the use of a self-alignment technique for the definition of the mirror mask
- corner mirrors with 45° deflection angle for the reduction of loss sensitivity on non-vertical facets
- the optimization of the fabrication process, especially plasma etching.

The plasma etching technique is of such importance that we reviewed the principles in order to gain a physical understanding of the influence of plasma parameters on etching results. The realization of reflecting facets with smooth vertical sidewalls at the correct positions requires high selectivity and anisotropy for the etching process. The optimized etching process resulted in facets with less than 1° deviation from verticality. Corner mirrors with losses in the 0.3 dB range were fabricated. We successfully integrated corner mirrors with more complex integrated optical devices which take advantage of their compactness, polarization insensitivity and compatibility in fabrication.

The developed plasma etching technique was applied to realize more advanced devices, such as grating wavelength demultiplexers. With a theoretical model the design of a demultiplexer based on a vertically etched diffractive grating was optimized in terms of resolution, aberrations and efficiency. A demultiplexer separating four channels at four nanometer spacing in the 1.55 μm EDFA
window has been developed. We realized fully packaged modules with the main characteristics:

- small size package, including self-aligned optical coupling to single mode fibers and temperature control
- 15 dB fiber-to-fiber losses
- channel spacing and absolute allocations at designed wavelengths
- less than 0.1 nm wavelength shift between TE and TM polarization
- less than -17 dB optical crosstalk
- fine tuning of the channel passbands over a range of 5 nm
- well suited for high performance optically preamplified WDM receivers.

We reached the goals that were set by European research projects on optical communication systems. All specifications were fully achieved. From a scientific point of view, optimized designs were achieved. However, it is economics that will decide, if these devices will find wide applications in future fiber-optic communication systems.
5. Conclusions and outlook

5.2. Outlook

The realized corner mirrors and grating demultiplexers in InP represent state of the art. Nevertheless we should note that there exist alternative devices with the same functionality and specific advantages. The decision which device is best suited for the integration in a photonic circuits depends on its purpose, targeted performance and available fabrication facilities. We will shortly discuss the advantages and drawbacks of some alternative devices.

Waveguide bends are an alternative to corner mirrors. Their design is less straightforward than for corner mirrors since a number of degrees of freedom have to be considered, like minimum radius, adiabatic or circular curvature and offsets. Tools for waveguide bend simulation are still evolving while for corner mirrors accurate results are obtained by a number of algorithms [5.1]. In order to reduce space consumption, the trend leads towards small radii. Waveguide bends with radii as small as 100 µm have already been reported [5.2], [5.3]. However, for such bends high contrast waveguide structures are needed that may raise the problems of compatibility and polarization sensitivity. The advantage of waveguide bends are their easy fabrication with enlarged tolerances that result in homogeneously distributed loss. This advantage favors waveguide bends for the realization of devices that rely on the same loss level for each light path, for example Mach-Zehnder interferometers [5.4].

If we compare phasars with grating demultiplexers, astonishly we find the same arguments as for the comparison of waveguide bends with corner mirrors. An additional difficulty for phasar simulation is the accurate calculation of the effective refractive index of bent waveguides, depending from material indices, 3-dimensional waveguide structure, and bending radius, whereas for the grating demultiplexer only a planar structure has to be calculated, with known analytical solutions. Interestingly, new phasars are reported that also take advantage of chip size reduction by light reflection [5.5].

We can conclude that the devices presented in this thesis have potential advantages over the alternatives. The devices are theoretically well understood but suffer from the lack of a well developed processing technology so that high performance is not routinely achieved.

For high yield high performance devices further improvements of the processing technology are necessary, especially on plasma etching. A new generation of high density plasma equipment and sources is being developed and enters into the
market. The 2.4 billion US dollar global plasma etch market is expected to reach 5.3 billion US dollars by the year 2000 [5.6]. Over 99% of this market is based on the silicon industry, but for sure we can rely on an improved quality of plasma etched III-V compound semiconductors in the future.

In the longer term one may think of emerging, completely new techniques. I want to mention the replacement of device structuring by layer growth and successive etching by new growth techniques, where the semiconductor structure is completely formed during growth. Although new techniques in this direction are being studied [5.7], they are far from being practical. Even if this vision seems to be only a dream, we should remember that big progress can only be made on big problems.
5.3. References

"Modeling of self-aligned total internal reflection waveguide mirrors: an interlaboratory comparison"
Optical and Quantum Electronics, Vol. 27, pp. 935-942, 1995

[5.2] J. S. Gu
"Numerical analysis of directionally varying optical waveguides"
Diss. ETH Nr. 9341, 1991

[5.3] H. Bissessur, P. Pagnod-Rossiaux, R. Mestric, and B. Martin
"Extremely small polarization independent phased-array demultiplexers on InP"

"Low-loss polarization-insensitive InP-InGaAsP optical space switches for fiber optical communication"

"Compact polarization independent InP reflective arrayed waveguide grating filter"

[5.6] P. Singer
"New frontiers in plasma etching"

"InGaAs/GaAs quantum well lasers with dry-etched mirror passivated by vacuum atomic layer epitaxy"
List of symbols and constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Magnitude</th>
<th>SI-Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>electron charge</td>
<td>$1.6022 \times 10^{-19}$</td>
<td>As</td>
</tr>
<tr>
<td>$m_e$</td>
<td>electron rest mass</td>
<td>$9.1096 \times 10^{-31}$</td>
<td>kg</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>free-space dielectric constant</td>
<td>$8.8542 \times 10^{-12}$</td>
<td>As/Vm</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant</td>
<td>$1.3806 \times 10^{-23}$</td>
<td>Nm/K</td>
</tr>
<tr>
<td>h</td>
<td>Planck’s constant</td>
<td>$6.6263 \times 10^{-34}$</td>
<td>Nms</td>
</tr>
<tr>
<td>c</td>
<td>speed of light in free-space</td>
<td>$299'792'458$</td>
<td>m/s</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength in free-space</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td></td>
<td>K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>input angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$</td>
<td>output angle</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
List of Publications

[1] E. Gini
   “Photoionisationsmodelle einfacher Gasnebel”
   Master’s thesis, ETH Institute of Astronomy, August 1986

   “Plasma etched optical corner mirrors and grating demultiplexers in
   InGaAsP/InP”

   “Low loss corner mirrors with 45° deflection angle for integrated optics”

   “Polarization insensitive waveguide modulator using InGaAsP/InP Mach
   Zehnder interferometer”
   Proceedings of the 18th European Conference on Optical
   Communication, ECOC’92, Berlin, pp. 345-348, 1992

   “Low loss self-aligned optical waveguide corner mirrors in
   InGaAsP/InP”
   Proceedings of the 18th European Conference on Optical
   Communication, ECOC’92, Berlin, pp. 553-556, 1992

   “Low coupling losses between InP/InGaAsP optical amplifiers and
   monolithically integrated waveguides”

    H. Melchior
   “Polarization-insensitive low-voltage optical waveguide switch using
   InGaAsP/InP four port Mach-Zehnder interferometer”
   Technical Digest of the Conference on Optical Fiber Communication /
   International Conference on Integrated Optics and Fiber
   Communication, OFC/IOOC’93, San Jose, Vol. 4, pp. 32-33, 1993
"Measurements of loss and mirror reflectivity in semiconductor optical waveguides: a European interlaboratory comparison experiment"
Technical Digest - Symposium on Optical Fiber Measurements, Boulder, pp. 113-116, 1994

"High-speed low-loss InP space switch matrix for optical communications systems, fully packaged with electronic drivers and single-mode fibers"

"New 1×2 multi-mode interference couplers with free selection of power splitting ratios"

"Low absorption InP/InGaAs-MQW phase shifters for optical switching"

"Polarization independent InP grating spectrograph for fiber optical links"

"Packaged 2.5 Gb/s 4-channel WDM receiver module with InP grating demultiplexer and pin-JFET receiver array"
"Thermal dependence of the refractive index of InP measured with integrated optical demultiplexers"

"Erratum: Thermal dependence of the refractive index of InP measured with integrated optical demultiplexers"

[16] E. Gini and H. Melchior
"The refractive index of InP and its temperature dependence in the wavelength range from 1.2 μm to 1.6 μm"

"Low-loss polarization-insensitive InP/InGaAsP optical space switch matrix for optical communication systems"

[18] P. A. Besse, E. Gini, M. Bachmann, and H. Melchior
"New 2×2 and 1×3 multi-mode interference couplers with free selection of power splitting ratios"

"Low-loss polarization-insensitive InP/InGaAsP optical space switches for fiber optical communication"

"Passively Q-switched microchip laser at 1.3 and 1.5 μm using semiconductor saturable absorber mirrors"
Advanced Solid State Lasers topical meeting, ASSL'97, Orlando, 1997
Curriculum vitae

Emilio Gini
born on September 20th, 1961
Citizen of Davos GR, Switzerland
married, children

1968 - 1974 Primarschule in Davos
1974 - 1977 Sekundarschule in Davos
1977 - 1980 Mittelschule Davos (SAMD)
1980 Matura Typus C
1980 - 1986 Studies in Physics at the
Swiss Federal Institute of Technology, Zürich
1986 Diploma thesis in Experimental Physics at the Institute of
Astronomy, Swiss Federal Institute of Technology, Zürich
1988 Licence for instructor in Physics/Mathematics at the
Swiss Federal Institute of Technology, Zürich
1988 - 1997 Work on the presented thesis and on related topics with
emphasis on plasma processing and MOVPE layer growth of
III-V compound semiconductors in the group of Prof. Dr.
H. Melchior as part of the Institute of Quantum Electronics,
Swiss Federal Institute of Technology, Zürich
Acknowledgments

I would like to express my profound gratitude to Prof. Dr. H. Melchior for offering me a position in his research group. His challenges were always accompanied with his scientific advice and constant support, but I also honored the opportunity of collaboration in a variety of European research projects in the field of optical communication.

In addition it's my pleasure to thank

Prof. Dr. P. Günter for the interest he shows in my work and his readiness to co-examine this thesis,

Prof. Dr. G. Guekos for his understanding, encouragement and fruitful discussions,

Dr. M. Bachmann for letting me win the Carambole games,

Dr. W. Vogt for his always friendly face,

R. Bauknecht for sharing the hotel rooms with me during conferences in order to save money,

Dr. J. Schmid for drinking the wine with me that was necessary to solve some mysteries,

Dr. W. Hunziker for switching into the “100% yield mode” for the mounting of critical devices,

Dr. P.-A. Besse for the advices how not to calculate,

Dr. J. Wieland for his invitations to various festivities on the Zürichsee beach,

Dr. M. Blaser for the honor start within his running team,

M. Ebnöther for the hours he spent in dark rooms for me,

P. Wägli for his art to let small things appear great,

Ch. Holtmann for some bright illuminations,

R. Krähenbühl, R. Staub, Dr. A. Steiner and P. Stillhard for all the nights we spent while playing cards and having good and bad ideas,

A. Müller for his efforts to bring some order in the measurement equipment,
L. Glasl, P. Pfammatter and V. Bürgisser for the arrangements in hotels and bowling cellars,
and all the collaborators of the “Melchioric” group, which transformed the working place into a social village and made the last ten years pass so fast.

Above all, I want to thank my wife Doris for her courage to marry a physicist, und am Mario und da Graziella fürs “Paaapii” schraia wenn i haichumma.

Emilio Gini

Zürich, February 1997