InP-based photonic crystals:
Processing, Material properties and Dispersion effects

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# Contents

Contents iii
Acknowledgments vii
List of papers ix
Acronyms xiii

1 Introduction 1
   1.1 Background and Motivation 1
   1.2 Aim and Overview of the original work 4
   1.3 Outline of the thesis 5

2 Photonic crystals: general concepts 7
   2.1 Light propagation in periodic media 7
   2.2 Two-dimensional PhC lattice 8
   2.3 Planar Photonic Crystals 8
       High index contrast system 9
       Low index contrast system 9
   2.4 Light propagation in planar photonic crystals 10
   2.5 Computational methods 13
       Plane Wave Expansion 13
       Finite Difference Time Domain 14
   2.6 Leaky modes 15

3 Fabrication steps for photonic crystals 17
   3.1 Epitaxy 17
   3.2 Mask deposition 17
   3.3 Electron Beam Lithography 18
       Ebeam resists 18
       The Raith 150 E-beam lithography system 19
   3.4 Mask opening - Reactive Ion Etching 22
   3.5 Etching of the semiconductor material 22
3.6 Post-etching process steps ............................................. 23

4 Chemically Assisted Ion Beam Etching of InP-based photonic crystals 25
  4.1 Chemically Assisted Ion Beam Etching .............................. 25
  4.2 Feature size dependence of the etching ............................. 27
    A Physico-chemical model for InP etching ....................... 27
    Experimental characterization of the lag-effect ............... 29
    Roughness development ........................................... 32
    Impact on the optical properties ................................ 33
  4.3 Brief overview of some dry-etching processes .................... 33
  4.4 Conclusion ....................................................... 35

5 Optical properties of the fabricated photonic crystal mirror and cavities 37
  5.1 Internal Light Source method ...................................... 37
    Description of the investigated PhC structures ................. 39
  5.2 Optical losses ................................................... 40
    Intrinsic loss parameter ....................................... 41
    Extrinsic loss parameter ....................................... 42
    Optimization of vertical heterostructure waveguide .......... 43
  5.3 Impact of the feature size dependence of the etching on the optical properties of PhCs ........................................ 45
  5.4 Conclusion ....................................................... 47

6 Carrier lifetimes in etched photonic crystals 49
  6.1 Surface/Interface States ......................................... 49
  6.2 Carrier dynamics in semiconductor materials .................... 50
  6.3 Time resolved photoluminescence spectroscopy .................. 51
  6.4 Modification of carrier lifetimes ................................ 52
    Sample description ............................................... 52
    Influence of the mask material ................................ 52
    Evidence for accumulated sidewall damage ..................... 52
    Non-radiative sidewall recombination velocity ................ 53
  6.5 Modeling of the accumulated damage in CAIBE .................... 54
    Sputtering theory applied to photonic crystal etching ......... 54
    Influence of the hole shape ..................................... 56
  6.6 Conclusion ....................................................... 57

7 Lateral electron transport through photonic crystal fields 59
  7.1 Electron transport through a photonic crystal field .......... 59
    Modeling the carrier transport .................................. 59
    Simulation of current flow through InP-based photonic crystal field . 60
  7.2 Experimental .................................................... 64
Sample fabrication ........................................... 64
Current-Voltage measurements ............................... 65
Thermal effects due to carrier heating ...................... 65
7.3 Etching induced modification of surface potential .......... 66
Influence of dry etching on electrical properties of semiconductor surfaces ........................................... 67
7.4 Conclusion ................................................... 69

8 Some selected dispersion properties of photonic crystal based devices 71
8.1 Bloch modes in two-dimensional photonic crystals ............. 71
8.2 Negative refraction in Photonic crystals ........................ 75
Negative refraction in two-dimensional InP based photonic crystals 76
8.3 End-fire characterization ...................................... 77
8.4 Experimental investigations of negative refraction ............... 78
Light focusing .................................................. 78
Light Collection using Negative Refraction .................... 79
8.5 Fourier Optics ................................................. 80
Experimental set-up: principle of measurement .................. 81
Auto-collimation ............................................... 82
Visualization of the excited Bloch modes in the 2D PhC field ........ 83
8.6 Group velocity dispersion in photonic crystal waveguides ....... 83
PhC waveguides ............................................. 84
Slow light ..................................................... 85
Coupled cavity waveguides .................................... 85
Phase-shift technique ......................................... 87
Measurement results ........................................... 88
8.7 Conclusion ................................................... 89

9 Summary, conclusions and future work 91
9.1 Achievements ............................................... 91
9.2 Future work ............................................... 92

10 Guide to the papers ........................................ 95

General references ......................................... 99

Bibliography .................................................. 101
Abstract

Photonic crystals (PhCs) are periodic dielectric structures that exhibit a photonic bandgap, i.e., a range of wavelength for which light propagation is forbidden. The special band structure related dispersion properties offer a realm of novel functionalities and interesting physical phenomena. PhCs have been manufactured using semiconductors and other material technologies. However, InP-based materials are the main choice for active devices at optical communication wavelengths. This thesis focuses on two-dimensional PhCs in the InP/GaInAsP/InP material system and addresses their fabrication technology and their physical properties covering both material issues and light propagation aspects.

Ar/Cl$_2$ chemically assisted ion beam etching was used to etch the photonic crystals. The etching characteristics including feature size dependent etching phenomena were experimentally determined and the underlying etching mechanisms are explained. For the etched PhC holes, aspect ratios around 20 were achieved, with a maximum etch depth of 5 µm for a hole diameter of 300 nm. Optical losses in photonic crystal devices were addressed both in terms of vertical confinement and hole shape and depth. The work also demonstrated that dry etching has a major impact on the properties of the photonic crystal material. The surface Fermi level at the etched hole sidewalls was found to be pinned at 0.12 eV below the conduction band minimum. This is shown to have important consequences on carrier transport. It is also found that, for an InGaAsP quantum well, the surface recombination velocity increases (non-linearly) by more than one order of magnitude as the etch duration is increased, providing evidence for accumulation of sidewall damage. A model based on sputtering theory is developed to qualitatively explain the development of damage. The physics of dispersive phenomena in PhC structures is investigated experimentally and theoretically. Negative refraction was experimentally demonstrated at optical wavelengths, and applied for light focusing. Fourier optics was used to experimentally explore the issue of coupling to Bloch modes inside the PhC slab and to experimentally determine the curvature of the band structure. Finally, dispersive phenomena were used in coupled-cavity waveguides to achieve a slow light regime with a group index of more than 100 and a group velocity dispersion up to 10$^{-7}$ times that of a conventional fiber.

Keywords: Photonic crystals, indium phosphide, chemically assisted ion beam etching, lig effect, cavities, optical losses, carrier transport, carrier lifetimes, negative refraction, photonic band structure, photonic bandgap, Bloch modes, slow light, dispersion, coupled cavity waveguides.
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vii
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Audrey Berrier
Kista, April 2008
List of Papers

Publications included in the thesis


**Other journal publications and conference proceedings not included in the thesis**


## Acronyms, Notations and Symbols

### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D, 2D, 3D</td>
<td>One-, two-, three-dimensional</td>
</tr>
<tr>
<td>BZ</td>
<td>Brillouin zone</td>
</tr>
<tr>
<td>CAIBE</td>
<td>Chemically assisted ion beam etching</td>
</tr>
<tr>
<td>CBM</td>
<td>Conduction band minimum</td>
</tr>
<tr>
<td>CCW</td>
<td>Coupled-cavity waveguide</td>
</tr>
<tr>
<td>EFC</td>
<td>Equi-frequency contour</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite difference time domain</td>
</tr>
<tr>
<td>FIB</td>
<td>Focused ion beam</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>FSDE</td>
<td>Feature size dependent etching</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier transform</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
</tr>
<tr>
<td>GVD</td>
<td>Group velocity dispersion</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductively coupled plasma</td>
</tr>
<tr>
<td>ILS</td>
<td>Internal light source</td>
</tr>
<tr>
<td>I–V</td>
<td>Current–Voltage</td>
</tr>
<tr>
<td>LED</td>
<td>Light emitting diode</td>
</tr>
<tr>
<td>MOVPE</td>
<td>Metalorganic vapor phase epitaxy</td>
</tr>
<tr>
<td>PhC</td>
<td>Photonic crystal</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma-enhanced chemical-vapor deposition</td>
</tr>
<tr>
<td>PL</td>
<td>Photoluminescence</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethylmethacrylate</td>
</tr>
<tr>
<td>PWE</td>
<td>Plane wave expansion</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse magnetic</td>
</tr>
<tr>
<td>QW</td>
<td>Quantum well</td>
</tr>
<tr>
<td>W_n</td>
<td>n-missing row PhC waveguide</td>
</tr>
</tbody>
</table>
Notations

\begin{align*}
  a & \quad \text{PhC lattice period} \\
  c & \quad \text{Light velocity in vacuum} \\
  d & \quad \text{Hole diameter} \\
  \vec{E} & \quad \text{Electric field} \\
  f & \quad \text{Air-filling factor} \\
  \vec{H} & \quad \text{Magnetic field} \\
  h(t) & \quad \text{Depth of the straight portion of the hole} \\
  J & \quad \text{Ion density} \\
  \vec{k} & \quad \text{Wavevector} \\
  k_x & \quad \text{Propagation constant in a PhC waveguide} \\
  L(\lambda) & \quad \text{Mirror loss} \\
  L(t) & \quad \text{Hole depth} \\
  L_{\text{decay}} & \quad \text{Decay length of the electric field in the substrate} \\
  L_p & \quad \text{Optical penetration depth inside a PhC mirror} \\
  n & \quad \text{Refractive index} \\
  n_{\text{core}} & \quad \text{Refractive index in the core layer} \\
  n_{\text{clad}} & \quad \text{Refractive index in the cladding layer} \\
  n_{\text{eff}} & \quad \text{Effective refractive index of the planar waveguide} \\
  n_g & \quad \text{Group index} \\
  Q & \quad \text{Quality factor of a resonant cavity} \\
  q & \quad \text{Elementary charge} \\
  R & \quad \text{Mirror reflection} \\
  \vec{r} & \quad \text{Position vector} \\
  t & \quad \text{Transmission of a PhC structure} \\
  T & \quad \text{Mirror transmission} \\
  u & \quad \text{Normalized frequency (} = a/\lambda\text{)} \\
  u_{\text{B}} & \quad \text{Bloch function} \\
  W & \quad \text{Mirror spacing of a 1D cavity} \\
  v_g & \quad \text{Group velocity} \\
  V_{\text{bias}} & \quad \text{Self-induced bias in RIE} \\
  V_{-,+} & \quad \text{Electric potentials of the grids of the CAIBE system} \\
  Y & \quad \text{Sputtering yield} \\
  Y_{\text{InCl}_x} & \quad \text{Sputtering yield for In containing etching products, } x=0 ... 3
\end{align*}
Symbols

\( \theta_c \)  
Cone angle of a PhC hole

\( \alpha, \alpha_i \)  
Optical absorption coefficient

\( \alpha_c \)  
Clausing’s factor

\( \delta \)  
Depletion region width around the PhC holes

\( \varepsilon, \varepsilon' \)  
Dielectric constant

\( \varepsilon'' \)  
Loss parameter (imaginary part of complex \( \varepsilon \)

\( \varepsilon_{\text{int}} \)  
Intrinsic loss parameter

\( \varepsilon_{\text{ext}} \)  
Extrinsic loss parameter

\( \Gamma_{\text{core}} \)  
Confinement factor in the core layer

\( \lambda \)  
Optical wavelength

\( \mu' \)  
Magnetic permeability

\( \eta_{\text{in}} \)  
Coupling efficiency

\( \eta_{\text{out}} \)  
Collection efficiency

\( \omega \)  
Optical frequency

\( \phi, \phi_i \)  
Phase shift

\( \sigma \)  
Electric conductivity

\( \zeta \)  
Vertical field profile

\( \tau_{\text{PL}} \)  
Photoluminescence decay time

\( \tau_{\text{nonrad}}, \tau \)  
Carrier lifetime (non-radiative)

\( \nu_C \)  
Surface recombination velocity at the hole sidewalls

\( \theta_{\text{Cl}} \)  
Surface coverage (probability) for Cl at the etch plane

\( \theta_{\text{InCl}} \)  
Surface coverage (probability) for InCl at the etch plane
Chapter 1

Introduction

1.1 Background and Motivation

The major application areas for photonics are displays, lighting, healthcare including medical diagnosis/therapy, sensing, and communication to name a few. The European roadmap for photonics and nanotechnologies, Merging Optics and Nanotechnologies (MONA) a result of discussions among European academic and industrial organizations and released early 2008 [1], identifies nine fields in which nanophotonics will have a major impact in the coming years: sensors, data and telecom, data storage, flat panel displays, imaging, instrumentation, LEDs and lighting, optical interconnects and photovoltaics. On the road towards the development of novel technologies in these application areas, a strong research effort is devoted to new promising materials such as semiconductor quantum dots and wires, metallic nanostructures, carbon nanotubes, functionalized nanoparticles, metamaterials and high index contrast nanostructures. In this last material type, photonic crystals are highly promising candidates for their optical properties.

Photonic crystals (PhCs) are dielectric structures with a periodicity in the dielectric constant of the order of the wavelength of light. One-dimensional (1D) PhCs are historically called Bragg gratings/mirrors and have been studied for many years [2, 3], e.g., as mirrors in laser designs [4, 5] or for their dispersive properties [6]. Later the concept of periodic variation of the dielectric constant was extended to two and three dimensions. Subsequent to the first proposals of PhCs for inhibition of spontaneous emission [7] and photon localization [8], several types of two-dimensional (2D) and three-dimensional (3D) PhCs have been successfully fabricated and characterized. In such structures, the periodic dielectric potential can give rise to a photonic bandgap, similar to the situation for electrons in a semiconductor crystal in which case the periodic potential is that of the atoms constituting the crystal. It is for this reason that sometimes PhCs are also referred to as photonic bandgap materials. The existence of a band structure modifies the dispersion of light compared to an homogeneous material and provides new ways to manipulate
the flow of light. In an otherwise perfect crystal the local modification of the crystal lattice or basis will introduce "defects" in the crystal, giving rise to the presence of new states in the bandgap. Line or point defect resonators can be created in the crystal. Such an engineering of defects in the PhC lattice offers new ways to guide and confine light by the formation of waveguides [9-11], or cavities [12, 13].

![Images of PhC structures](image)

Figure 1.1: a) GaAs-based 1D PhC structure; Courtesy of F. Raineri (LPN); b) GaAs-based 1D PhC mirror in GaAs; Reprinted by permission from Elsevier [5]. Copyright 2001; c) InP-based 2D PhC structure fabricated at KTH; d) Si 3D PhC structure; Reprinted by permission from Macmillan Publishers Ltd:Nature [1-4], Copyright 1998; e) GaAs-based 3D PhC structure; Reprinted with permission from [10], American Institute of Physics, Copyright 2006.

Photonic crystals have the potential to play an important role in most of the domains identified by the MONA roadmap. They can bring compactness and improved sensitivity to sensors (chemical [15–17], biological[18]). Quantum cascade lasers with PhCs are sources of mid-infrared radiation which will allow integrated terahertz spectroscopy for chemical and biological sensing [19–21]. For data and telecom applications, efficient and compact waveguides, light sources and photodetectors among others are required. Dispersion engineering can enable new functionalities such as dispersion compensation, slow light, etc. PhC-based designs allow improved performances for light emitting devices: LEDs can make use of the light extraction enhancement provided by PhCs in order to increase their brightness and external quantum efficiency [22, 23] and cover markets for lighting and...
1.1. BACKGROUND AND MOTIVATION

displays. Similarly, telecom wavelength lasers can be made more compact [24] with low power consumption - low threshold - [25, 26]. Photodetectors use photonic crystal based designs to improve their quantum efficiency in the visible [17], at infra-red wavelengths [27-29].

PhC designs are potentially interesting for integration and for new functionality in components used in optical interconnects for local area networks and Fiber To The Home schemes [30], with wavelength multiplexing and reconfigurability as advantages. Slow light modes in PhCs can be a way to obtain optical delay lines. The significant mode dispersion close to band edges or close to mode cut-offs of coupled-cavity super-modes can slow down light, which is interesting for optical buffering and processing [31] and also for enhancing light-matter interactions [32, 33]. The steady increase of the storage density of data will soon require to beat the diffraction limit of light to perform memory read-out. New ways to improve imaging capabilities, which are not diffraction limited would be valuable towards that goal. Even though plasmonic materials have very good prospects, tailored PhC designs can to yield super-resolution [34].

![Schematic drawing of a two-dimensional photonic crystal indicating the type of vertical light confinement](image)

Figure 1.2: Schematic drawing of a two-dimensional photonic crystal indicating the type of vertical light confinement a) low index contrast, vertical heterostructure; b) high index contrast, membrane. The orientation of the x, y and z axis as used in this thesis are also shown.

The technology for manufacturing photonic crystals for operation at infra-red wavelength or in the visible spectrum is challenging, requiring high precision nanofabrication tools. Even though some successful attempts were reported based on top-down [35] or bottom-up approaches [36], 3D PhC structures are far from realistic applications due to the high level of complexity of their fabrication. Therefore, 2D PhCs with in-plane periodicity combined with a conventional slab confinement in the third direction are nowadays the dominant technological solution. Figure 1.2 shows a schematic drawing of a planar 2D PhC field with low index contrast or high index contrast vertical light confinement.

When this thesis work was initiated, the interest for photonic crystals was mainly focused on defect engineering and devices operating in the bandgap; examples of these include waveguides, cavities, couplers, etc., almost exclusively for telecom applications. Structures operating in the upper transmission bands started to raise
CHAPTER 1. INTRODUCTION

interest, especially for unconventional light propagation phenomena, such as superprism effect [37] or negative refraction [38]. Recently, it has been shown that modifications of the PhC lattice [39, 40] or a local alteration of the basis by, e.g., a variation of the hole radius $r$ [41] of the photonic crystal can enhance greatly the optical properties of PhC lasers and cavities.

For the broad range of applications mentioned earlier, the main driving force is the steadily increasing integration level of components and functionalities. The integration of active functionalities still relies on III-V materials. InP-based materials are the main choice for operation in the 1.3 to 1.7$\mu$m range. Research on conventional InP-based devices has now reached a certain degree of maturity and technology platforms/foundries are being started. However, nanophotonic devices including photonic crystals are still far from maturity. The challenges are even higher considering that most applications require devices with high quality, low loss, high compactness, robustness, and compatibility with electrical access. Functional devices would ideally be optically active, be electrically controllable and enable intelligent processing of light. Towards these objectives an in-depth understanding of the optical, electrical and dispersion properties of photonic crystals is indeed highly valuable. At the same time, knowledge and control of fabrication processes are closely linked to the performances of nanophotonics devices. Thus there is a need to understand and control fabrication techniques for a mature technology yielding devices with high reproducibility and quality. Fabrication of photonic crystal structures is challenging in terms of process accuracy and reproducibility affecting the optical properties of the devices including propagation loss. Concerning waveguiding and other passive waveguide functions, silicon nanowires have shown better performances. However, for active functionalities (light emission, optical signal processing, non-linear processes, etc) III-V materials are particularly well suited.

1.2 Aim and Overview of the original work

The awareness and control of fabrication and of the material properties are necessary for high performance PhC devices and integration of these, including electrical access. It is technologically crucial for device performance to understand the impact of processing on optical losses, on the electrical properties of the material - relevant in the context of electrically active devices - and on the optical properties of the material -relevant for optically active devices. Further, the knowledge of the dispersion properties of PhCs and how to engineer them is important for novel functional devices. Therefore there is a need for understanding the physics of fabrication-related issues, and how they affect losses and material properties in order to control and predict process outcomes.

The present thesis addresses the above mentioned issues in the context of planar photonic crystal etched by chemically assisted ion beam etching (CAIBE) in the InP/InGaAsP/InP material system.
1.3 Outline of the thesis

The performances of the chemically assisted ion beam etching (CAIBE) should be evaluated in terms of achievable aspect ratios, feature size dependence of the hole shape and depth. Knowledge about the physico-chemistry of the etching and a model for the etching characteristics are necessary to understand the capabilities of the process and origins of its limitations. This is the subject matter of Paper A and the obtained results are directly relevant for optimizing device performances. The impact of the etching characteristics on the optical properties of photonic crystal such as losses, reflectivity and quality factor for devices operating inside the bandgap, are addressed in Paper B and C.

Dry-etching, a necessary process step in PhC device manufacturing, is known to introduce damage in the etched material [42, 43]. Process induced damage and its impact on the electrical and optical properties of PhCs need to be evaluated. Further, the extent and nature of the created damage depends on the etched material, the etching technique and process parameters. In light of this, a method to assess the effect of sidewall damage on the electrical conduction in PhCs is proposed (Paper F). The optical properties of the PhC material will also be affected by the type of etching. Paper D and E present the experimental characterization of the variation of the carrier lifetime of InGaAsP quantum wells in PhCs as a function of the etch parameters. The origin for material damage is identified and a model is developed to predict the process dependent defect creation and the findings have important implications for active PhC devices.

The potential of designing dispersion in PhC structures is experimentally demonstrated with examples such as negative refraction, flat lensing and auto-collimation. The understanding of the coupling to PhC Bloch modes is beneficial in order to decide how to make the best use of PhC structures both in the gap and in the transmission bands. Band structure related dispersion effects in PhC are investigated in Papers G, H and I. Paper G gives an experimental demonstration of light focusing using negative refraction. This paper also shows its potential application for light collection. Paper H is a theoretical and experimental analysis of the excitation of Bloch modes in a PhC field operating above the bandgap. In Paper I two designs of PhC-based coupled-cavity waveguides are optically characterized in the slow light regime. Group velocity dispersion and the group index are determined.

The rest of the thesis is organized as follows. The following chapter gives a general introduction to the concepts used to describe the optical properties of two-dimensional photonic crystals including an overview of some relevant computational methods. Chapter 3 presents the process steps used in this work for the fabrication of 2D photonic crystals, and includes a brief description of the methods involved. Chapter 4 gives a detailed description of chemically assisted ion beam etching and summarizes the results on the feature size dependence of the etching. Chapter 5 introduces the Internal Light Source characterization method and gathers the re-
results on the evolution of PhC losses as a function of the vertical confinement or the PhC hole shape and depth. The results on the influence of the PhC etching on the carrier lifetime measured by time-resolved photoluminescence are presented in Chapter 6. Chapter 7 details the results obtained on the electrical properties of PhC fields which provides an in-depth understanding of the electron transport as well as the process induced modification of the electrical properties of the PhC material. Chapter 8 describes the nature and behavior of Bloch modes as well as the anomalous dispersion regimes in 2D PhC fields. This chapter also summarizes the results on negative refraction, the observation of Bloch modes by Fourier optics and experimental measurements of slow light modes. Finally, Chapter 9 gives the main conclusions and discusses possible extensions of this work. A list of the appended papers together with their summaries is in Chapter 10.
Chapter 2

Photonic crystals: general concepts

Photonic crystals (PhCs) are electro-magnetic structures characterized by the spatial periodicity of the dielectric constant $\epsilon(\vec{r})$. The periodicity allows a mathematical description by in terms of a lattice which brings the analogy with the periodic arrangement of atoms in a crystalline material, hence the name "crystal". The period of the lattice in PhCs is of the order of magnitude of the wavelength of the "light", hence the term "photonic". Most commonly in PhCs, like in the present work, $\epsilon(\vec{r})$ is a periodic repetition of pockets of a material with dielectric constant $\epsilon_m$ in a background material with dielectric constant $\epsilon_b$. One could imagine some structures with more complicated functions for the permittivity $\epsilon(\vec{r})$ or permeability $\mu(\vec{r})$.

2.1 Light propagation in periodic media

Maxwell's equations describe the behavior of electro-magnetic waves in any given medium. For an electrically polarizable, non-magnetic, locally macroscopically isotropic and lossless material where we neglect free charges and currents we have, in SI units, in the linear regime [44]:

$$\nabla \cdot (\epsilon_0 \epsilon(\vec{r}) \vec{E}) = 0 \quad (2.1)$$

$$\nabla \times \vec{H} - \epsilon_0 \epsilon(\vec{r}) \frac{\partial \vec{E}}{\partial t} = 0 \quad (2.2)$$

$$\nabla \cdot \vec{H} = 0 \quad (2.3)$$

$$\nabla \times \vec{E} + \mu_0 \frac{\partial \vec{H}}{\partial t} = 0 \quad (2.4)$$

where $\vec{E}(\vec{r})$ is the electric field, $\vec{H}(\vec{r})$ is the magnetic field, $\epsilon_0$ is the permittivity in vacuum, $\mu_0$ the permeability in vacuum and $\epsilon(\vec{r})$ is the local relative permittivity.
By introducing time dependence of the fields as an harmonic oscillating function, into equations \ref{eq:1} to \ref{eq:2} we obtain after some algebra the following master equations for the $\vec{E}$-field and $\vec{H}$-field, respectively.

\begin{equation}
\hat{\tau} \vec{E}_\omega(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \vec{E}_\omega(\vec{r})
\end{equation}

\begin{equation}
\hat{\theta} \vec{H}_\omega(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \vec{H}_\omega(\vec{r})
\end{equation}

where $\omega$ is the cyclic frequency, $c$ the light velocity, $\hat{\tau} = \nabla \times \left(\frac{1}{c(\omega)} \nabla \times \right)$ and $\hat{\theta} = \nabla \times \left(\frac{1}{c(\omega)} \nabla \times \right)$.

### 2.2 Two-dimensional PhC lattice

The focus of this thesis is on two-dimensional (2D) air hole photonic crystals. We will provide here the concepts needed to describe 2D PhCs. We consider here 2D PhCs made from a triangular lattice of air holes in a dielectric material, i.e., an InP-based heterostructure. The lattice constant $a$ and the diameter of the holes $d$ are defined on Fig. 2.1. The air fill factor $f$, usually expressed in $\%$, is the ratio between the surface occupied by air to the total surface of the PhC. It is calculated from a unit cell and is given by $f = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{a}\right)^2 \approx 0.907 d^2/a^2$.

The reciprocal lattice is generated by the basis vectors $\vec{b}_1$ and $\vec{b}_2$ constructed from the real space basis vectors $\vec{a}_1 = (a, 0)$ and $\vec{a}_2 = a \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)$ and are given by $\vec{b}_1 = \frac{2\pi}{a} (1, \frac{-1}{\sqrt{3}})$ and $\vec{b}_2 = \frac{2\pi}{a} (0, \frac{1}{\sqrt{3}})$. Figure 2.1 shows the real and reciprocal space associated with the triangular lattice 2D PhC, as well as the main symmetry directions \Gamma M and \Gamma K, and the first Brillouin zone.

Introduction of simple defects in a 2D PhC lattice in the form of removed holes (or holes filled with a material different from the host matrix) allows the formation of waveguides [9], resonators [12, 45]. Recent works have shown that a local modification of the lattice (modification of $a$ to form photonic heterostructures [39], shift in position of lattice points [46]) or of the basis ([40, 47, 48]) of the photonic crystal can enhance the optical properties greatly.

### 2.3 Planar Photonic Crystals

By definition, two-dimensional crystals extend infinitely in the direction normal (vertical direction) to the plane of periodicity. Thus for optical devices based on PhCs, a confinement in the vertical direction is necessary. This confinement is obtained by a planar waveguide with the light confined in the core layer of higher refractive index. Several solutions for this material stacking are possible and are generally classified into high or low index contrast systems according to the magnitude of the refractive index difference $\Delta n$ between the core layer and the surround-
2.3. PLANAR PHOTONIC CRYSTALS

Figure 2.1: a) Schematic of a 2D PhC in real space. The circles represent the basis (hole) repeated at each lattice point. \( \vec{a}_1 \) and \( \vec{a}_2 \) are the primitive lattice vectors. The lattice constant \( a \) and hole diameter \( d \) are also shown; b) schematics of the reciprocal space corresponding to the lattice shown in a). \( \vec{b}_1 \) and \( \vec{b}_2 \) are the basis vectors of the reciprocal lattice. The first Brillouin zone is shown, as well as the symmetry points \( \Gamma \), \( K \) and \( M \).

High index contrast system

The high index contrast domain is commonly defined by the condition \( \Delta n \geq 2 \). The materials above and below the core layer may be made of different materials. Examples in this category are membranes [12, 49, 50], semiconductor-on-insulator structures where the core layer is asymmetrically bounded by air and a low index dielectric layer which could be oxides [51, 52], polymers [53, 54] or low index substrates (e.g., sapphire [55, 56]).

Low index contrast system

The most common way to fabricate PhC devices in the low index contrast system makes use of semiconductor heterostructures to confine the light in the vertical direction [57]. The devices and structures presented in this work are formed from an InP/GaInAsP/InP heterostructure slab waveguide. Figure 2.2 is a schematic
sketch of this vertical structure indicating the respective values of refractive index (at 1.55 μm) as well as the mode profile \( \zeta(z) \) of the the fundamental mode of the electric field \( \vec{E}(z) \) in the waveguide for TE polarization. The small difference in refractive indices does not allow for a strong vertical confinement, i.e., \( \zeta(z) \) extends deep into the substrate. This weak confinement of the mode profile has significant implications on the fabrication of PhC devices and on their optical properties. These issues will be given attention in Chap. 5.

### 2.4 Light propagation in planar photonic crystals

In cases for which we can define two distinct polarization states TE\( (E_z=H_x=H_y=0) \) and TM\( (H_z=E_x=E_y=0) \) the master equations for the z-component of the respective fields are given by:

\[
\frac{\partial}{\partial x} \left[ \frac{1}{\epsilon(\vec{r})} \frac{\partial}{\partial x} H_z \right] + \frac{\partial}{\partial y} \left[ \frac{1}{\epsilon(\vec{r})} \frac{\partial}{\partial x} H_z \right] + \frac{\omega^2}{c^2} H_z = 0
\]

\[
\frac{1}{\epsilon(\vec{r})} \left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right] E_z + \frac{\omega^2}{c^2} E_z = 0
\]

We can now introduce the periodicity of the dielectric function:

\[
\epsilon(\vec{r}) = \epsilon_m \left[ 1 + C \exp(-j\vec{G} \cdot \vec{r}) \right]
\]

with \( \vec{G} \) a reciprocal lattice vector such as \( \vec{G} = \sum_{i=1}^{n} m_i \vec{b}_i \) with \( n \) being the number of dimensions of the considered problem, \( m_i \) an integer and \( \vec{b}_i \) the basis vectors of the reciprocal lattice. In 1883 the mathematician Gaston Floquet [58] introduced a
2.4. LIGHT PROPAGATION IN PLANAR PHOTONIC CRYSTALS

Theorem to deal with linear differential equations with periodic coefficients in one-dimension, and much later a similar concept was developed by Félix Bloch [59] in three dimensions (3D) to solve the problem of the motion of electrons in a periodic potential. Therefore, solutions of the Maxwell's equations describing the propagation of electro-magnetic waves in a periodic dielectric medium are often referred to as "Floquet-Bloch waves" (FB waves) or simply "Bloch waves". Mathematically a FB wave, for example for TM polarization for which the electric field in the $\vec{z}$ direction is $\vec{E} = E\vec{z}$, can be expressed as,

$$\sum_{n=-\infty}^{\infty} V_n(\vec{k}) \cdot \exp(-j\vec{k}_n \cdot r)$$

(2.10)

with $\vec{k}_n = \vec{k}_0 + \vec{G}_n$ where $\vec{k}_n$ is the wavevector of the $n$-th component of the FB wave, $\vec{k}_0$ the wavevector of the first harmonic, $\vec{G}_n$ a reciprocal lattice vector, and $V_n(\vec{k})$ the Fourier coefficient function.

The diffraction properties of one- or two-dimensional gratings and the optics of the FB waves supported in such structures were analyzed in the late 80's [2, 3] using the powerful framework of wavevector diagrams. Such diagrams have been applied to anisotropic crystals and later to photonic crystal structures. They will be used in Chap. 8 to explain the physics of the dispersion related effects seen in 2D PhC structures.

The eigenvalues of the master equations 2.7 and 2.8 give the band structure $\omega(\vec{k})$ of the PhC and is also called the dispersion relation [60]. It is common to consider the band structure in the first Brillouin zone either in the full zone or along the main symmetry directions (Γ-M-K) only. Figure 2.3 displays an example showing the band structure for a triangular-lattice 2D PhC indicating the bandgap (sometimes called stopgap) and the first three bands are labeled. The master equations 2.7 and 2.8 are wavelength scalable. The properties of the PhC structures do not depend on the absolute wavelength of the light but rather on the ratio of the wavelength to the lattice periodicity. Thus it is meaningful to use the normalized frequency $\nu = a/\lambda$, as in Fig. 2.3 to describe the optical properties of PhCs.

In the first band close to the Γ point the wavevector of the light inside the structure is much smaller than the lattice constant: we are in the long wavelength limit (i.e., $\lambda$ is much larger than the PhC period). The light does not "feel" the periodic dielectric perturbation and the propagation is similar to that in an isotropic medium of refractive index $n_{eff}$, the effective refractive index of the structure. Away from this long wavelength limit, as $\lambda$ decreases the wave sees the periodicity: we enter the regime of Bragg reflection. Depending on the strength of the dielectric "potential" (that can be called "photonic strength"), the energy of the wave will be more or less distributed in between the Fourier components of the excited mode. In certain cases, a range of frequencies become forbidden for light propagation: we have a bandgap.
Fig. 2.3 compares the band structures for TE and TM polarized light for a PhC structure of $f = 30\%$, air holes in a background of refractive index $n = 3.24$. The band structure for TE shows the presence of a bandgap whereas there is no bandgap for TM. Another difference is that for TM the separation between the second and the third bands is larger.

![Band structure comparison](image)

Figure 2.3: Band structure for TE modes in a 2D triangular lattice along the main symmetry directions with air fill factor $f = 30\%$; b) Band structure for TM modes. The air light line is shown in the TM direction.

The relationship between the wavelength of light and its wavevector in air or in the background material is given by:

$$u = \frac{a \cdot k}{2\pi n}$$

where $n = n_{\text{mat}}$ or $n_{\text{air}}$ is the refractive index of the background material or of air ($=1$), respectively. These linear relations are called the light lines. On Fig. 2.3b, the light line corresponding to air is indicated in the TM direction only. Light lines are often useful to identify guided and leaky modes. A more detailed discussion is given in Sec. 2.6.

Fig. 2.3 also suggests that for a given PhC the band structure can be investigated by varying the wavelength of light and/or the lattice period $a$. In practice, the latter can be useful when the available wavelength range of the source is limited. This is called lithography tuning, and is applied in Chap. 5.

Modeling of the optical properties of 2D PhC devices with the InP/GaInAsP/InP vertical heterostructure is usually performed with 2D modeling tools. The refractive index of the background material is given the value of the refractive index for the heterostructure $n_{\text{eff}}$ and is obtained from the effective index approximation.

Defining the polarization of modes in a planar photonic crystal is not a straightforward issue. First of all, the conventions used in the "waveguide approach" and in the "2D PhC" are different. From the point of view of the vertical waveguide a field component is defined as transverse with respect to the interface of the waveguiding layers. In the 2D PhC case, the transverse direction is defined with respect to the
2.5. **Computational methods**

Different methods have been successfully used to solve the Maxwell’s equations and to model the optical characteristics of photonic structures. Here only a list of a few (most common) methods is given. In a sketchy picture, the methods can be divided in two main categories treating Maxwell’s equations either in real space as a function of time (where Finite-Difference Time-Domain (FDTD) is the dominant method) or in reciprocal space (frequency domain). In the frequency domain, methods are distinguished by the basis used for the expansion of the field. The first and most straightforward method is the Plane Wave Expansion method (PWE) using a basis of plane waves. It is a particularly successful method to obtain the PhC band structure. To address simple defects in PhC structures it is possible to use the supercell method. However other methods are more powerful to simulate complex structures. For instance, the Multiple Multipole Expansion method using a basis of spatial Bessel/Hankel functions [62], or Wannier functions is especially useful in the case of localized fields (i.e., cavities) [63]. Scattering/transfer matrix method is a widely used computational method for photonics. This method and has also been applied to photonic crystals, sometimes together with a modal expansion of the field. Modal methods can expand the eigenmodes on a Bloch mode basis (as in the freely available software CamFR [64] or on a Fourier basis (e.g., Fourier modal method [65]). In this thesis, PWE and FDTD are used, and a more detailed discussion of these two methods is given below.

**Plane Wave Expansion**

The Plane Wave Expansion method takes advantage of the periodicity of the structure and solves the Master equations 2.7 and 2.8 in the frequency domain. Two
CHAPTER 2. PHOTONIC CRYSTALS: GENERAL CONCEPTS

major implementations are available: a full vectorial calculation used by the MIT program MPB [66], or a more computationally effective method proposed by Ho [67]. When we introduce the periodicity of the lattice we can expand the field in terms of Bloch modes $\varphi_k(\mathbf{r}) = \exp(i\mathbf{k} \cdot \mathbf{r}) \tilde{u}_k(\mathbf{r})$ with $\tilde{u}_k(\mathbf{r})$ a vectorial function with the same periodicity as the PhC lattice. Owing to this periodicity, we can now expand $\tilde{u}_k(\mathbf{r})$ into a Fourier series. In order to solve the master equations 2.7 and 2.8 numerically one needs to expand all the coefficients and truncate the series to a finite number $N$ of plane waves. One possibility is to expand $1/\epsilon(\mathbf{r})$. However, for reasons of improved convergence Ho’s method first calculates the Fourier transform of the dielectric map $\epsilon(\mathbf{r})$, truncates it to the number of considered plane waves $N$, and then inverts it. In this thesis, the 2D PWE results were obtained using a Matlab implementation of Ho’s PWE method [67].

In the PWE method the simulated PhC fields are infinite in the 2D plane of periodicity and translation invariant along the vertical direction (i.e., infinitely long holes). It is possible to simulate structures with simple defects in the crystal lattice (such as cavities, waveguides) using the supercell approach. We define a unit cell for the crystal (much larger than the original unit cell of the PhC lattice) including the defect that we call "supercell" and then repeat this unit cell to cover the full space. In order to avoid artifacts arising from artificial coupling between the repeated defects the supercell should be sufficiently large. One understands immediately that this method is suitable to very simple geometries only.

Finite Difference Time Domain

In the FDTD method Maxwell’s equations are solved in time domain using finite difference operators to approximate the differentials. It is a powerful method, albeit often described as a "brute force" method, and is able to simulate any given geometry and does not rely on the periodicity of the structure. It is a widespread computational method to solve a large variety of electro-magnetic problems. It has been proposed in 1966 by Yee [68]. A grid (Yee’s grid) is used to discretize space. At each point of the grid the electric component of the field at time $t+1/2$ is calculated from the value of the magnetic field at time $t$, then the magnetic field at time $t+1$ is obtained from the electric field value at $t+1/2$, and so on. The discretization in time depends on the spatial grid size. For instance, in 2D the time step is expressed as:

$$\Delta t = \frac{\beta}{2} \frac{1}{\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}}}$$  

(2.12)

where $\Delta x$ and $\Delta y$ are the grid step sizes, $\alpha$ is the lattice constant (usually set to 1), $c$ the light velocity and $\beta$ a coefficient. The field can be excited by different sources such as point sources, plane waves or waveguide modes. The computational domain is surrounded by Perfectly Matched Layers (PML) [69] that are absorbing layers in order to avoid any spurious reflections at the boundaries. This is also called the "absorbing boundary conditions" since the field is arbitrarily set to decrease
towards zero over a boundary layer. FDTD calculations are very demanding in terms of computational power, especially for simulation of 3D structures.

In this thesis, only 2D calculations were performed with an infinite structure in vertical direction (i.e., infinitely long cylindrical holes) and a finite geometry in the 2D plane. The FDTD method can provide the spatial field distribution at any given time step for monochromatic excitation, or the spectral energy distribution (transmission, reflection, ...) by calculating the value of the Poynting vector at a given position in the structure excited by a pulse. It is possible to induce loss in the structure by the introduction of an imaginary part in the definition of the refractive index of one or more of the regions. For a more general reference about the FDTD method see Ref. [70]. In this work, we have used the freely available FDTD program F2P [71].

2.6 Leaky modes

![Diagram](image)

Figure 2.4: Comparison of the in-plane wavevector with the out-of-plane sphere defined by the wavevector in air

Modes supported by a PhC slab can suffer from losses if some Bloch harmonics are located inside the light cones. For a 2D PhC, modes can be guided in the slab or leaky into the cladding layers. In the case of the low index contrast system, leaky modes are radiative modes in air or in the substrate, which by definition introduce energy losses. If the in-plane wave-vector \( k_{\text{in}} \) of a given Bloch harmonic in the PhC slab is shorter than the norm of the corresponding wavevector in air \( k_0 \), it is possible for light to couple into radiative modes in air. The vertical component of the \( p^{th} \) Bloch mode component is expressed as:

\[
k_{\parallel}^2 = \sqrt{n_{\text{layer}} k_0^2 - (k_{\text{in}}^2 + pG^2)}
\]

(2.13)

where \( n_{\text{layer}} \) is the refractive index of air or of the substrate. From this equation one can see that if there exists an integer \( p \) such that \( k_{\text{in}} + p \frac{G^2}{k_0} < n_{\text{layer}} k_0 \) the
wavevector \( \vec{k}_2 \) will be real and this component of the Bloch mode will leak. The group of vectors in \( k \)-space, norms of which are equal to \( n_{layer} |\vec{k}_0| \), define the light cone. In order to find the leaky modes of the structure one should compare the position of the excited Bloch modes in \( k \)-space with respect to the light cones for air and for the substrate material. On Fig. 2.4, the mode of wavevector \( \vec{k}_{in-1} \) can couple into radiative modes in air, whereas the mode of wavevector \( \vec{k}_{in-2} \) will be evanescent in air. The influence of leaky modes on the optical properties of PhC devices is addressed in chapter 5.
Chapter 3

Fabrication steps for photonic crystals

The fabrication of semiconductor-based 2D PhCs involves several process steps, typically in clean room environment, and different process equipments are used. Each of the process steps should be precisely controlled and calibrated in order to obtain structures of desired quality. In this chapter the relevant process steps that were used for PhC device fabrication are described, following their sequence in a typical process flow.

3.1 Epitaxy

The InP/GaInAsP/InP vertical waveguide is grown by metal-organic vapor phase epitaxy (MOVPE) on an InP substrate. The growth precursors are trimethylindium, trimethylgallium, arsine AsH$_3$ and phosphine PH$_3$ and the growth is conducted at a temperature of 680°C. The thickness of the top InP cladding is 200 nm (unless otherwise stated). The core layer is made of Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ with $x = 0.24$ and $y = 0.52$ lattice matched to the InP substrate. The refractive index of this material at $\lambda = 1.55$ $\mu$m is $n = 3.35$ and its absorption edge at $\lambda_{edge} = 1.22$ $\mu$m. Some samples had a 10-nm InGaAsP quantum well (QW) for carrier lifetime measurements, with an emission wavelength of $\lambda = 1.14$ $\mu$m. The thickness of the core layer is 420nm, unless otherwise specified. All the layers are undoped. For internal light source measurements (chap.5), two QW with emission wavelengths around 1.47 $\mu$m and 1.55 $\mu$m are embedded into the InGaAsP core layer.

3.2 Mask deposition

The SiO$_2$ mask is deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD).
Table 3.1: Process parameters for the PECVD processes for SiO$_2$ deposition

<table>
<thead>
<tr>
<th></th>
<th>Process C</th>
<th>Process P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substrate temperature</strong></td>
<td>230°C</td>
<td>300°C</td>
</tr>
<tr>
<td><strong>Plasma power</strong></td>
<td>15 W</td>
<td>20 W</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>700 mT</td>
<td>800 mT</td>
</tr>
<tr>
<td><strong>Deposition rate</strong></td>
<td>1 nm/s</td>
<td>1.2 nm/s</td>
</tr>
<tr>
<td><strong>Refractive index</strong></td>
<td>1.47-1.49</td>
<td>1.51-1.52</td>
</tr>
<tr>
<td><strong>Gases and flows</strong></td>
<td>5% SiH$_4$ in He: 40 SCCM</td>
<td>2% SiH$_4$ in N$_2$: 740 SCCM</td>
</tr>
<tr>
<td></td>
<td>N$_2$O: 200 SCCM</td>
<td>N$_2$O: 425 SCCM</td>
</tr>
</tbody>
</table>

Chemical vapor deposition (CVD) is a process in which gaseous species react on a substrate to form a thin solid film [72]. In plasma enhanced CVD most of the energy required to generate chemically reactive species is provided by the plasma. Thus PECVD allows deposition of thin films at relatively low process temperatures.

The plasma is generated at a frequency of 13.56 MHz. In this thesis work we used two types of deposition processes as listed on Table 3.1. The conformality of the deposited films can be tailored to some extend by adapting energy and angular distribution of the ions. The gases we used to form SiO$_2$ thin films are silane (SiH$_4$) and dinitrogen oxide ("laughing gas") N$_2$O. Details about the PECVD processes used in this thesis are found in Table 3.1.

### 3.3 Electron Beam Lithography

The pattern definition of nanostructures is a critical step for device generation. Although alternative methods have been proposed (deep-UV lithography [73], nanoimprint lithography [74], self assembly [75]), electron beam (e-beam) lithography is still by far the dominant method owing to its flexibility. In the present work, two e-beam systems were used: a Raith 150 e-beam system at the KTH Nanophysics department and a LEICA e-beam system at the Laboratory for Physics and Nanostructures (CNRS-LPN, Marconis, France).

**Ebeam resists**

The dose is the amount of electrical charges received by the resist per unit area. It is usually expressed in $\mu$C/cm$^2$. The critical dose corresponds to the minimal dose required by the resist in order for the exposed regions to be removed completely by the developer. When electrons penetrate into a material, they are subjected to forward and backward scattering. These depend on the material (nature of substrate and resist), the sample thickness and the acceleration voltage of the electrons. Some of the incident electrons are scattered with a very large angle and are responsible
3.3. **ELECTRON BEAM LITHOGRAPHY**

for the exposure of the resist in areas away from the actual beam position. This is called the proximity effect (PE) defined as pattern specific linewidth variations [76]. The magnitude of this effect depends on the acceleration voltage – an operation at 100 keV allows a diminution of the PE due to a larger penetration depth of the electrons in the substrate material. In this case, the large angle scattering occurs further away from the substrate/resist interface and the probability that they get scattered/absorbed in the material before reaching the resist is much higher. This is not the case for lower acceleration voltages, at 25 keV for instance, for which case the PE can be very important. Work at very low beam energies can be a solution to reduce scattering but it suffers from a main drawback in terms of the resist resist thickness.

![Chemical structure of PMMA](image1.png) ![Chemical structure of ZEP](image2.png)

**Figure 3.1:** a) Chemical structure of PMMA; b) Chemical structure of ZEP.

Many e-beam resists are available, differing in terms of resolution, sensitivity or resistance to dry-etching. However some of them are predominantly used due to their high sensitivity or their resistance to dry etching. In this work, two types of positive resists were used: PMMA and ZEP 520-A.

Poly-methyl-methacrylate (PMMA) (Fig.3.1a) is conventionally adopted for its high sensitivity allowing very fine structures to be patterned. ZEP-520 A, provided by Nippon Zeon Co, has the structure presented in Fig.3.1b [77]. It consists of a virtual 1:1 copolymer of α-chloromethacrylate and α-methylstyrene which exhibits a positive resist behavior upon electron beam exposure. The high-sensitivity is attributed to the α-chloromethacrylate groups, whereas the resistance to dry-etching is due to the α-methylstyrene groups. The glass transition temperature of ZEP is 145°C. We chose here to hard bake the resist at 180°C and p-xylene was used as the developer.

**The Raith 150 E-beam lithography system**

An e-beam lithography system is a computer-controlled Scanning Electron Microscope (SEM) provided with a beam blanker and a pattern generator unit. In some cases an interferometric stage for exposure of patterns over a large sample area is also available [76]. A schematic drawing of the Raith 150 e-beam system is provided on Fig. 3.2. The SEM chamber is maintained under high vacuum (range of 10^-7 mBar).
Figure 3.2: Schematics for the Raith 150 system. Reproduced with permission from A. Holmberg’s PhD thesis [78]

Figure 3.3: Schematics illustrating the procedure for writing field alignment.
3.3. ELECTRON BEAM LITHOGRAPHY

The SEM column is a Gemini column, specially built to provide high performance at low accelerating voltages. The column is equipped with a Schottky field-emission electron source of the hot-cathode type (a tungsten tip with a zirconium oxide collar). The vacuum in the electron gun chamber ("gun vacuum") is in the $10^{-8}$ mBar range. The pattern generator is a unit controlling the beam blanker and the deflection of the beam by sending voltage signals to the scan coils. The displacement of the sample with respect to the column is adjusted by a laser-interferometer controlled stage, which in the Raith system we used has a resolution of 5 nm. The movement of the stage allows stitching of writing fields when exposing large areas (i.e., larger than what is achievable by deflection of the e-beam). In the Raith 150 system, the writing field length is limited to the range 60 $\mu$m to 1400 $\mu$m. However, a trade-off should be made depending on the requirements in the accuracy of patterning. A large writing field area allows to expose extremely stitching sensitive patterns (such as PhC areas) without moving the stage. However, large writing field areas should be avoided if distortion sensitive patterns are present far from the central area. In the case of stitching, smaller writing fields will also provide better results.

The writing speed depends on several parameters such as the available e-beam current (dose), the maximum frequency of operation of the DAC controlling the beam deflection (10 MHz, step displacement) and the settling time which is the time the e-beam needs each time it moves to a new position on the sample (5 ms in the Raith system we use). The pattern design needs to be divided into small rectangular and triangular units that the system will expose following parallel lines. This is a problem for circular features; thus the holes are approximated by polygons. Typical hole diameters for PhC operating at near infrared ($\lambda$ around 1.5 $\mu$m) are in the range of 100 to a few 100 nm.

The parameters of the exposures performed with the Raith 150 system at KTH are an acceleration voltage of 25 keV, apertures of 7.5 $\mu$m for PhC holes (e-beam current $\approx$ 10-20 pA) and of 20 to 60 $\mu$m for large areas (ebeam current $\approx$ 3 nA), a working distance of approximately 5 mm, a writing field size of 100 $\mu$m and a step size of a few nm.

Before exposure one should correct for focus, astigmatism and beam alignment, as in any conventional SEM system. In the case of exposure over large areas, a writing field alignment (WFA) procedure has to be performed. It is a "learning" procedure aimed at calibrating the orthogonality and scaling factor of the deflection axis to the high precision sample stage. The stage is assumed correct and the deflection system is adjusted to it. One chooses a small feature that is placed at the center of the given writing field (WF) corresponding to the center of the column for zero deflection. Then the system moves the stage in order to position the feature at one of the WF corners. The system then deflects the electron beam to scan over an area at the WF corner (see Fig. 3.3), the generated image is used to indicate to the system the actual position of the feature within the scan area. This is repeated over positions 2 and 3. Since the stage is considered as the reference, the WFA procedure will fail if the stage drifts with time. It is therefore crucial to make sure
at regular intervals that the feature is still at the center of the writing field. If the deflected beam does not find the exact position it will result in stitching errors.

3.4 Mask opening - Reactive Ion Etching

Reactive ion etching (RIE) is a widespread technique used in microelectronics. Generally, a capacitively coupled radio-frequency (RF) plasma is composed of a source operating at 13.56 MHz and two planar electrodes in a vacuum chamber. The system is self-biased, which means that the ion energy cannot be independently controlled. It depends on the RF power, the operating pressure and gas composition. The etching of the SiO$_2$ mask is performed by Fluorine based RIE. The reactive gas is usually CHF$_3$. CF$_4$ can also be used, however in this case the etch selectivity of the SiO$_2$ over the resist is rather poor. One solution is to add H$_2$ to the CF$_4$ plasma. The presence of hydrogen increases the polymerization processes (C-H bonds) thus increasing the selectivity. The parameters of the process used in this thesis are a power of 45 W, a bias $V_{bias}$ of -300V, and a process pressure of 15 mT. The gas composition was H$_2$ (10 SCCM)/CF$_4$ (28 SCCM).

3.5 Etching of the semiconductor material

The patterns defined by e-beam lithography and transferred to the hard mask need to be now transferred to the semiconductor material by highly anisotropic etch processes. Dry-etching methods are ideally suited for this purpose. All the PhC structures presented in this thesis were etched using Ar/Cl$_2$ CAIBE. The implementation of this particular etching technique as well as the study of its characteristics and implications on the properties of the fabricated PhC represent a significant part in this thesis work. A detailed presentation of CAIBE and its characteristics is presented in the next chapter.

Most of the alternative techniques for PhC fabrication are also dry-etching based and are listed on Table 3.2. An equipment-specific comparison of the main dry etch techniques used in the context of PhC etching is presented in the next chapter. Wet chemical etching is excluded in most of the cases due the isotropy of the etching and the impossibility to obtain high aspect ratio for the PhC holes. However high aspect ratios can be obtained by an electro-chemistry method of pore etching [97].

Table 3.2 lists out most of the reported InP etching techniques for PhC fabrication and compares their reported performances. The values for the aspect ratios given in Table 3.2 refer to the total depth of the holes down to the tapered bottom. Depending on the hole shape the aspect ratio of the straight portion of the hole will be smaller than that given in the table. Typically the approximately straight portion corresponds to about 70% of the total depth. However, this estimate has to be taken cautiously. RIE is more limited in achievable aspect ratios than other processes with more dense plasmas such as ICP. Highest reported AR are provided by CAIBE (≈18-20). Process induced damage is an important issue when manu-
facturing active devices. It is reasonable to expect that high bombarding energy will create more damage. However the nature of the created defects will also depend on the type of dry-etch chemistry. The most material damaging fabrication technique is Focused Ion Beam etching, which bombards the sample with gallium ions accelerated to a high energy (typically 15 to 30 keV for sputtering, of the order of 100 keV for implantation regimes).

### Table 3.2: Comparison of etching techniques for InP-based PhC fabrication

<table>
<thead>
<tr>
<th>Technique</th>
<th>Chemistry</th>
<th>Performance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIE</td>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>AR=2</td>
<td>[79]</td>
</tr>
<tr>
<td></td>
<td>CH&lt;sub&gt;4&lt;/sub&gt;/Ar/He</td>
<td>AR=2</td>
<td>[80, 81]</td>
</tr>
<tr>
<td>ECR-RIE</td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;/Ar</td>
<td>AR=8, cylinder-conical</td>
<td>[82]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>AR=2, cylindrical</td>
<td>[83]</td>
</tr>
<tr>
<td>ICP-RIE</td>
<td>SiCl&lt;sub&gt;4&lt;/sub&gt;/Ar</td>
<td>AR=14, cylinder-conical</td>
<td>[84], [85]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>AR=10</td>
<td>[86]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;/O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>AR=16, cylinder-conical</td>
<td>[87]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;/N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>AR=8</td>
<td>[88]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;/Ar/N&lt;sub&gt;2&lt;/sub&gt;/He</td>
<td>AR=16, cylindrical</td>
<td>[89]</td>
</tr>
<tr>
<td></td>
<td>Cl&lt;sub&gt;2&lt;/sub&gt;/Xe</td>
<td>AR=5, cones</td>
<td>[90]</td>
</tr>
<tr>
<td></td>
<td>H&lt;sub&gt;2&lt;/sub&gt;/Xe</td>
<td>AR=13, conical</td>
<td>[91], [92]</td>
</tr>
<tr>
<td>CAIBE</td>
<td>Ar/Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>AR=18-20, cylinder-conical</td>
<td>[81, 93, 94]</td>
</tr>
<tr>
<td>FIB</td>
<td>–</td>
<td>low AR</td>
<td>[95, 96]</td>
</tr>
</tbody>
</table>

#### 3.6 Post-etching process steps

After the PhC is etched, depending on the devices and measurement configuration, additional process steps are usually necessary. If one needs to access the PhC structures electrically (case of lateral conduction (Chap. 7)), one should define electrical contacts. We use conventional optical lithography to pattern areas for the contacts, then we evaporate a metal layer (Ni/AuGe/Ni/Au for n-contact to InP) and use a lift-off technique to isolate the contact pads. An annealing step in neutral atmosphere (N<sub>2</sub>) around 450°C is necessary to achieve a good, ohmic contact between
the metal layer and the semiconductor by alloying. If the photonic crystal devices are to be measured by an in-plane coupling technique, such as the end-fire method described in Sec. 8.3, other process steps are usually necessary. The optical coupling via the cleaved facet of the sample requires good optical quality. In order to achieve this it is preferable to thin down the substrate to a thickness of about 100 μm by a lapping technique. Then the samples are be cleaved at a suitable length and mounted on an appropriate holder for measurements.
Chapter 4

Chemically Assisted Ion Beam Etching of InP-based photonic crystals

Several techniques have been used for etching PhCs in InP-based materials as described in the preceding chapter. Argon-chlorine chemically assisted ion beam etching (Ar/Cl₂ CAIBE) is one of the most successful processes for high aspect ratio etching. The awareness and control of fabrication and understanding of the material issues for photonic crystals are necessary for high performance PhC devices. The characterization of the etching is therefore necessary. The quality of etching of photonic crystals is very critical as it directly influences their optical properties in terms of losses. In addition, etching characteristics such as etch depth, roughness and shape invariably depend on the feature size. This chapter presents the results obtained in Paper A. We introduce the CAIBE technique, present the experimental results on the feature size dependence of the etching and develop a physico-chemical model for the etching mechanism. The phenomenon behind the feature size dependence of the etching is explained and its implications in terms of the optical properties of PhCs is discussed.

4.1 Chemically Assisted Ion Beam Etching

CAIBE is an etching technique relying on the bombardment of a sample with a chemically inert ion beam under a reactive gas atmosphere in a high-vacuum chamber. In the experiments reported here, the neutral gas is argon and the reactive species Cl₂. Chlorine is injected via a gas ring over the sample and argon ions are extracted from a remote plasma. It allows independent variations of the ion energy and density. CAIBE was performed with a Nordiko 3000 ion beam etching system, equipped with a two-grid ion gun (Fig. 4.1). In this system, the plasma is generated by inductive coupling of the RF power (13.56 GHz) through a dielectric window by
CHAPTER 4. CHEMICALLY ASSISTED ION BEAM ETCHING OF INP-BASED PHOTONIC CRYSTALS

way of a flat coil antenna. The substrate holder can be rotated with respect to the ion beam axis. It allows the variation of the sample orientation by tilting the sample holder.

A set of two perforated grids is used to extract the ions from the plasma and accelerate them towards the sample. The positive grid, as well as the walls of the plasma chamber, are at the potential $V_+$. The negative grid is isolated from the chamber and has a negative potential $V_-$ kept at -100 V. The distance between the two grids is approximately 1 mm. The ions extracted from the plasma impinge on the positive grid with low energy (a few eV). The ions diffusing through the openings of the positive grid are then accelerated by the potential difference between the grids and acquire an energy $qV_+$. Unless otherwise specified, the ion energy is kept at 400 eV. Since the sample holder is grounded, this is the energy with which the ions bombard the sample. The ion beam is collimated with the help of a diaphragm of diameter 5 cm. Apart from the diaphragm, an electron gun is also used to neutralize the ions in the beam and reduce thereby the beam divergence generated by Coulomb repulsion between ions. The base pressure in the chamber is in the range of $10^{-8}$ to $10^{-7}$ Torr maintained by a turbo-molecular pump backed by a mechanical pump. The process pressure is in the $10^{-4}$ Torr range.

Chlorine based CAIBE takes advantage of the high chemical reactivity of halogen chemistries in etching III-V materials. However, the etching of InP-based materials has some peculiarities due to the much lower sputtering rate for Indium and to the low saturation vapor pressure for its chlorinated compounds [98]. In the Ar/Cl$_2$ CAIBE process, the preferential removal of phosphorus by argon sputtering is compensated by the chemical etching of indium by chlorine. Chlorine reacts with indium on the surface to form InCl$_x$ compounds [99, 100]. The description of the chlorinated reaction products is enhanced at an elevated temperature. According to Ref. [101], a process temperature above 225°C results in good anisotropy. In the present case a radiative heater is provided to heat the sample. The influence of temperature on InP etching is described in Ref. [102].

![Schematic diagram of the Nordiko 3000 CAIBE system.](image-url)
4.2 Feature size dependence of the etching

The dependence of the etching outcome as a function of the PhC hole diameters is a very important factor affecting the optical properties of the PhC devices. The dependence of the characteristics of the etching as a function of the feature size has been noticed for most of the dry-etching techniques [103, 104] used in semiconductor processing. This is usually referred to as the "lag-effect" where the etch rate decreases as the feature size (e.g., trench width, hole diameter) reduces. This can be positively used in devices with adiabatic coupling such as tapers [105]. However, its origin and importance depend on the process conditions. The feature size dependence of CAIBE should be experimentally characterized so that it can be taken into account when simulating PhC devices and make predictions of the fabrication outcomes.

Some models for the etching of large pattern areas in GaAs-based materials [106, 107] have been developed. However, the etching of PhC holes differs from the etching of micrometer-sized trenches due to the size of the openings (in the range of some 100 nm) and the typical aspect ratios. A predictive model based on the physics of the etching is necessary.

A Physico-chemical model for InP etching

As mentioned earlier, the sputtering yield of phosphoricous atoms is very high, therefore we assume that the limiting process is the removal of In atoms. Ion beam etching of InP produces a local Indium enrichment of the surface, which will chemically react with the surrounding chlorine molecules to form InCl₅. The desorption of indium chlorides is very low at room temperature. This desorption is enhanced by temperature and by ion bombardment. This external energy also enhances surface diffusion and helps in the migration of In at the etched surface to form clusters together with nonvolatile InCl₅.

The model presented here is a 1D model that calculates the time evolution of the position of the bottom of the hole with respect to the top surface of the material (i.e., the etch depth). It is based on an earlier model developed for GaAs [106] and is modified to the case of InP PhC etching. We refer to the bottom of the holes as the "etch plane". The etch rate depends on the sputtering yield \( Y_{tot} \) for In and its chemical compounds, the ion energy \( E \) and the ion density of the beam \( N_{ions} = J/q \) according to:

\[
H = \frac{Y_{tot} \sqrt{\gamma EN_{ions}}}{\rho_{In}} \quad (4.1)
\]

where \( \gamma \) is a coefficient depending on the geometry of the etching chamber and \( \rho_{In} \) the volume density of In atoms in the InP crystal.

The etch rate depends on chlorine supply via the total effective sputtering yield \( Y_{tot} \) for In removal and is given by the sum of the contributions of In and its chemical compounds as follows:
\[ Y_{tot} = \sum_{x=0}^{3} Y_x S_{InCl_x} \]  

(4.2)

Here \( Y_0 \) is the sputtering yield for In, \( Y_x \) the sputtering yield for InCl\(_x\), and \( S_{InCl_x} \) a probability factor. \( S_{InCl_x} \) is a function of the InCl\(_x\) surface coverage \( \theta_{InCl_x} \) and \( r \) is the redeposition probability.

The arrival of chlorine molecules at the etch plane is crucial to form Indium chlorides. However the diffusion of chlorine molecules towards the bottom of the holes is impaired by collisions with the sidewalls. Cl\(_2\) molecules sticking to the surface when released do not have the memory of their incoming direction. This is schematically illustrated on Fig. 4.2. Intuitively one sees that as the path to reach the etch plane increases, the probability of one entering Cl\(_2\) molecule to reach the bottom reduces. This is characterized by the Clausing’s factors \( \alpha_c \) \([108, 109]\) giving the probability of transport of a gas molecule through a tube of aspect ratio \( AR \) under molecular flow conditions (Fig. 4.2 b). The removal of the etched products out of the holes and the associated redeposition process is also dependent on the gas conductance of the holes. The redeposition on the sidewalls may influence the evolution of the hole shape, which is not considered in the present 1D model. The redeposition probability \( r \) is expressed as a percentage of the etch products inside the holes remaining at the etch plane.

![Figure 4.2: Schematic drawing of a PhC hole under Ar ion flux and chlorine atmosphere illustrating the behavior of the Cl\(_2\) molecules on their way to the etch plane: they can stick to the sidewalls (A), be re-emitted from the sidewalls (B), reach the etch plane and react with In (C), be redeposited on the sidewalls in the form of Indium chlorides (D) or finally exit the holes as InCl\(_x\) (E); b) evolution of the Clausius factor \( \alpha_c \) as a function of the hole aspect ratio.](image)
4.2. FEATURE SIZE DEPENDENCE OF THE ETCHING

The surface coverage of the chlorinated products \( \theta_{1nCl} \), at time \( t \) are calculated by solving the rate equation given below for the presence of chlorine atoms at the etch plane.

\[
\frac{dN_{Cl}}{dt} = 2k_S\alpha_c \nu_{Cl_2}(1 - \theta_{Cl}) - \left( \sum_{x=1}^{3} Y_{InCl_x}\theta_{Cl}^x \right) \frac{J\sqrt{\gamma E}}{q}. \tag{4.3}
\]

The term \( 2k_S\alpha_c \nu_{Cl_2}(1 - \theta_{Cl}) \) describing the arrival of chlorine at the etch plane depends on the Clasing factors, and hence on the hole aspect ratio defined as etch depth \( L(t) \) divided by the hole diameter \( d \). The obtained value for \( \theta_{1nCl}(t) \) is inserted in Eqs. 4.2 and 4.1 in order to calculate \( H(t) \) and the etch depth at next time step \( L(t+1) \), which allows the calculation of \( \alpha_c(t+1) \) used to solve Eq. 4.3 in a new iteration run. More details on the physico-chemical model are given in Paper A. Lag-curves or plots of the etch depth \( L(d) \) as a function of the hole diameters calculated using this model are presented on Fig. 4.3. \( Ar/Cl_2 \) CAIBE yields smaller etch depth for small hole diameters, an observation that is qualitatively similar to other etch processes. However, when the etch depth is smaller than about 1 \( \mu \)m no appreciable lag effect occurs. As the etching time is increased the lag-effect becomes prominent even at larger hole diameters.

**Experimental characterization of the lag-effect**

To investigate the CAIBE lag effect experimentally, we patterned PhC fields with varying hole diameters and periods following the fabrication steps described in Chap. 3. Samples were etched by \( Ar/Cl_2 \) CAIBE for different durations ranging from 10 to 60 min. The fabricated samples were inspected by SEM (top-views and cross-sections) and hole dimensions were measured. The graph of the measured etch depth as a function of the hole diameter is presented on Fig. 4.4.

![Graph showing etch depth vs. hole diameter for different times](image_url)

**Figure 4.3:** Lag curves calculated using the 1D physico-chemical model.
Figure 4.4: a) Experimentally measured hole etch depth as a function of hole diameter for process times varying from 10 to 60 min.

Figure 4.5: Scanning electron microscope picture of a cross-section of etched holes. Three zones are defined: in the first zone the hole sidewalls are almost straight, in zone Z2 they start to deviate from verticality. In the third zone Z3 is they are tapered.
4.2. FEATURE SIZE DEPENDENCE OF THE ETCHING

The performances of our CAIBE etching are visible on Fig. 4.5 where, for 60 min etching, the obtained etch depths are 5 \( \mu m \) for hole diameters \( d \geq 300 \text{ nm} \) and in excess of 3 \( \mu m \) for \( d \geq 200 \text{ nm} \) (Fig. 4.4).

Zone Z1 in Fig. 4.5 indicates the portion of hole exhibiting nearly vertical sidewalls. In the second portion the sidewalls are sloped, whereas the bottom most portion is tapered and the hole shape is irregular. If the application requires minimizing the exposure time of the material to the energetic ions, one could choose shorter etch times and still get appreciable etch depth.

![Figure 4.6: a) Variation of the etch depth as a function of the aspect ratio of the holes as calculated by the model presented in the previous section; b) Experimentally obtained etch depth as a function of increasing aspect ratio for the different process times.](image)

For the shortest etch duration, there is no appreciable lag-effect. However, as the etching time increases the influence of the hole diameter on the final depth becomes more pronounced. Replotting the data as a function of the aspect ratio (Fig. 4.6), we can define a critical aspect ratio in the range 20-25 where the lag limiting mechanism dominate the etch rate of the holes. The value of the critical aspect ratio is a measure of the performance of the etching process in terms of anisotropy and it also gives information about the limiting mechanism. For instance, reactive ion etching processes are characterized by a much higher process pressure and the lag-effect is much more serious than for CAIBE. The aspect ratio is limited in RIE to about 2 (Paper A). The lag-effect is also seen on Fig. 4.6 – at a given etch depth it gives the range of physically achievable aspect ratios. The steepness of the curves indicates the importance of the lag-effect. For an etch depth around 1 \( \mu m \) (the lowest curve corresponding to an etch time of 10 min), a large variation of aspect ratio is possible indicating a small lag-effect. As the etch time increases, the aspect ratio varies with the etch depth – a clear sign of the presence of lag-effect. The calculated curves converge for aspect ratios > 40. This region is not experimentally valid as other limitations should be taken into account. However, this region corresponds to very small hole diameters, and are not of consideration for PhC operating at optical telecommunication wavelengths.
CHAPTER 4. CHEMICALLY ASSISTED ION BEAM ETCHING OF INP-BASED PHOTONIC CRYSTALS

Roughness development

Surface roughness is often an important criteria in semiconductor processing. In PhC etching two different types of roughness can be distinguished:

- bottom roughness
- sidewall roughness

![SEM cross-sections of PhC holes indicating the dependence of the bottom roughness with hole diameter (top pictures) and etch time (bottom pictures).](image)

The impact of the feature size is not solely limited to its influence on the etch depth. The development of the roughness at the bottom of the holes is also affected and possibly the sidewall roughness as well.

The roughness at bottom of the holes, was systematically investigated. It was previously mentioned that ion sputtering of InP gives rise to In enrichment of the etched surface. The excess In atoms are able to migrate at the surface and form clusters, together with InCl₄ compounds. These etch resistant clusters will act as micro masks initiating the formation of cones/whiskers at the bottom of the holes. A balance between continuous sputtering and supply of new material determines the stability of the clusters. If the formed clusters can be sustained long enough the roughness will be appreciable. For this to happen a critical amount of material is required. This depends on the hole size and explains why roughness is present inside the larger holes but absent for the smaller holes (Fig. 4.7).

At the initial stages of the etching, when the aspect ratio is low and the exposed surface at the bottom is large, we can see that the roughness is considerable. As the etching proceeds, the clusters are continuously sputtered while less material can migrate to the top of the grass like features to maintain the critical size of the
4.3. BRIEF OVERVIEW OF SOME DRY-ETCHING PROCESSES

cluster. The whiskers are thus gradually etched away. As the aspect ratio increases, it is also found that the bottom of the hole becomes more conical.

In the case of sidewall roughness, one can observe sidewall corrugation on micrometer-sized patterns etched by Ar/Cl$_2$ CAIBE. However, inside the PhC holes, sidewall roughness may be reduced owing to the confinement of the structure and the limitation of ricochet ion bombardment. It is then reasonable to believe that the rms value of the roughness would depend on the hole diameter. The investigation of the hole sidewall roughness is an interesting topic for further investigations.

Impact on the optical properties

The third and more device-relevant aspect of the feature size dependence of CAIBE etching is the development of the hole shape and depth. Fig. 4.5 indicates that Ar/Cl$_2$ CAIBE does not result in perfectly cylindrical holes. However, the top section of the hole is nearly cylindrical. The tilt angle of the sidewall in the middle portion (zone 2) decreases when the etch depth is increased from 2 to 5 µm. Having in mind the negative impact of a large value of the slope of the sidewalls on the optical loss [110], this observation justifies the efforts invested into increasing the etch depth. It is shown in Paper C that the optical properties of PhC devices such as the quality factor of cavities and the mirror properties improve with hole diameter, given a constant air fill factor $f$. This knowledge is relevant for the design of structures exploiting the maximum potentialities of the etching process. Further discussions focusing on the optical properties are given in Chap. 5, Sec. 5.3.

4.3 Brief overview of some dry-etching processes

In this section we give a brief description of the most commonly used dry-etching techniques used for PhC etching [111]. The dry etching techniques can be divided in two main classes: plasma etching where a potential is applied between the substrate table and a top electrode to accelerate bombarding ions, and ion beam systems where a set of grids is used to extract ions from the plasma to form a directed ion beam. Plasma can be produced by different techniques (Fig. 4.8) such as capacitively coupling, inductively coupling and microwave heating and are described briefly below.

- Capacitively Coupled Reactive Ion Etching (RIE). The plasma is created by applying RF power in a parallel plate configuration. The energy of the ions is set by the voltage difference between the electrodes. The ion density is low (around $10^{10}$ cm$^{-3}$) and the process pressures are in the range 50-500 mTorr. Ion density and ion energy are inherently coupled.

- Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE). RF power is coupled to the plasma chamber using coils. Often the plasma chamber is remote from the sample chamber. A high plasma density can be produced (around $10^{12}$ cm$^{-3}$). A separate RF source is used to accelerate the
bombarding species resulting in an independent control of the ion density and ion energy. The pressure range of the process is 1-50 mTorr.

- **Electron Cyclotron Resonance Reactive Ion Etching (ECR-RIE).** The plasma is generated based on resonant wave-plasma interaction: microwaves are launched into a magnetized chamber containing the etching gases and accelerates electrons. Plasma densities are comparable to ICP. As in ICP-RIE a separate RF supply accelerates the ions towards the substrate. This results in an independent control of the ion density and ion energy. The process pressure range is from 1 to 10 mTorr.

Ion beam techniques are classified according to the nature of the ions directed at the sample to be etched and the chemical gases present in the atmosphere surrounding the sample. Except for FIB, the processes described below are broad beam etching techniques.

- **Chemically Assisted ion Beam Etching (CAIBE)** has the inert gas in the plasma and a reactive gas is injected over the sample. For details see Sec. 4.1.

- **Reactive Ion Beam Etching (RIE)** uses a plasma of reactive gases. Equipment is an ion beam source with remote plasma chamber and extraction grids as described in Section 4.1.

- **Ion Beam Etching (IBE)** is obtained from the generation of a plasma of inert gases. It is also referred to as ion milling.

![Figure 4.8](image)

**Figure 4.8:** a) capacitively coupled RIE; b) inductively coupled RIE (ICP-RIE); c) Electron-cyclotron resonance RIE (ECR-RIE); d) inductively coupled ion beam etching.
4.4. CONCLUSION

- **Focused Ion Beam (FIB)** is obtained by forming a focused beam of Ga ions. Contrary to all the previous methods which use a mask to pattern the substrate, FIB is a serial etching process where the features are etched one after the other without mask. The energy of the bombarding ions is very high (some tens, typically 15 to 30, of keV for sputtering and of the order of 100 keV for implantation regimes).

A low process pressure is advantageous for the transport of species in and out the holes and the desorption of the etch products from the sample surface. One can then expect that the lag effect is less significant for low pressure processes, hence larger aspect ratios may be achieved. In terms of material damage, it is advantageous to reduce the ion energy. Therefore decoupled systems are preferable.

4.4 Conclusion

In this chapter we discussed the characteristics of Ar/Cl\textsubscript{2} CAIBE in the context of PhC etching. The removal of In atoms (i.e., the etch rate) is limited by the transport of molecular chlorine inside the holes, which reduces the etch rate at large aspect ratios. A physico-chemical model dependent on the process parameters was developed to predict etching outcomes. The modeled lag-curves clearly reproduce the experimental trends as a function of time and hole diameter. The lag-effect was characterized experimentally: aspect ratios in the range of 20 were achieved. A comparison with CH\textsubscript{4}/Ar/H\textsubscript{2} RIE shows that the achievable aspect ratios are tenfold higher for Ar/Cl\textsubscript{2} CAIBE. Holes as deep as 5 \( \mu \)m are achievable for hole diameters larger than about 300 nm. The roughness at the bottom of the holes is due to micro-masking by Indium chloride clusters and depend on hole size and etch-duration.
Chapter 5

Optical properties of the fabricated photonic crystal mirror and cavities

This chapter presents the optical characterization of the fabricated PhC mirrors and cavities, which is relevant for improving the device performance. In the low index contrast system losses depend on the overlap between the PhC holes and the vertical mode profile of the light. Therefore the reduction in the loss level can be realized by two means: (1) by the optimization of the vertical structure to modify the mode profile at a given hole shape; or (2) by optimizing the hole shape by a deeper etch depth or improved sidewall verticality. The optimization of the vertical structure is the topic of Paper B. The influence of the etching characteristics and of the dependence with feature size is dealt in Paper C.

5.1 Internal Light Source method

The internal light source (ILS) measurements presented in this work were carried out during a visit at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland within the framework of the European Network of Excellence on Photonic Integrated Components and Circuits. The photoluminescence (PL) from two GaInAsP quantum wells (QWs) embedded in the core layer of the planar waveguide is used as the built-in light source. The emission of the QWs covers the wavelength range about 1400-1550 nm. Figure 5.1 shows a spectrum of the QW emission collected in the direction normal to the substrate. The guided light collected at the output cleaved facet suffers from reabsorption $a(\lambda)$. Hence the spectrum of the guided light collected at the output facet will be modified with respect to the PL spectrum obtained from the sample surface.

The PL light is excited by focusing a He-Ne laser ($\lambda = 633$ nm) on the sample surface. The excitation spot is at a distance $d$ from the cleaved facet. Part of the PL signal generated at the excitation spot is guided along the planar waveguide. The light beam collected from the cleaved facet is guided through a multimode
CHAPTER 5. OPTICAL PROPERTIES OF THE FABRICATED PHOTONIC CRYSTAL MIRROR AND CAVITIES

fiber to a spectrum analyzer. The objective aperture limits the collected rays to an incidence angle of 6° compared to the normal direction to the facet, so that, in a first approximation, only the light exiting the cleaved facet at normal incidence is detected. Fig. 5.2 shows a schematic drawing of the principle for ILS. The reference intensity spectrum is given by:

\[ I(d, \lambda) = I_0(\lambda) \exp(-\alpha(\lambda)d) \]  \hspace{1cm} (5.1)

In the case of the characterization of a PhC structure light travels from the excitation spot to the cleaved facet through the PhC field. The distance between the PhC field under test and the cleaved facet is denoted \( d' \). Since the guided signal is reabsorbed by the QWs \( d \) and \( d' \) should be small in order to maximize the intensity of the collected signal. \( d \) should, however, be at least 100 \( \mu \)m in order that the light radiated into the air and into the substrate does not interfere in the measurements. \( d' \) should be larger than 30 \( \mu \)m to limit the influence of the multiple

![Figure 5.1](image1.png)

Figure 5.1: Photoluminescent spectrum of the quantum wells collected from the top of the sample.

![Figure 5.2](image2.png)

Figure 5.2: Schematic diagram of the experimental configuration for the excitation and collection of light.
5.1. INTERNAL LIGHT SOURCE METHOD

reflections between the PhC structure and the cleaved facet. Typically, \(d\) and \(d'\) are equal to 100 \(\mu\)m and 60 \(\mu\)m, respectively. The spectrum of the light collected at the cleaved facet after traveling through the PhC field is expressed as:

\[
I(\lambda) = I_0(\lambda) \exp(-\alpha(\lambda) \tilde{d}) T(\lambda) \exp(-\alpha(\lambda) d')
\]

with \(\tilde{d}\) the distance between the excitation spot and the PhC field and \(T(\lambda)\) the transmission spectrum of the PhC structure (mirror or cavity).

The determination of the absolute transmission \(t(\lambda)\) through the PhC structure requires a reference measurement. The reference intensity \(I_0(\lambda)\) is measured in an unpatterned region of the sample located near the PhC field under test. The excitation spot is placed at the same distance \(d\) from the cleaved edge as for the PhC measurement. The measured intensity \(I_{PhC}(\lambda)\) for the PhC structure is given by Eq. 5.2 with \(T(\lambda) = t(\lambda) \exp(\alpha(\lambda) W_{PhC})\). Here \(W_{PhC}\) is the width of the PhC structure such that \(\tilde{d} + W_{PhC} + d' = d\) and assuming that the absorption \(\alpha(\lambda)\) in the PhC region is identical to that in the unpatterned region. As a consequence, the ratio \(I_{PhC}(\lambda)/I_0(\lambda)\) yields the absolute transmission spectrum \(t(\lambda)\) of the PhC structure.

**Description of the investigated PhC structures**

![Figure 5.3: Scanning electron microscope top view picture of a one-dimensional cavity with PhC mirrors. The cavity width \(W\) is defined from hole center to hole center and is indicated by an arrow.](image)

Two types of PhC structures were used in this work: one-dimensional cavities and PhC mirrors. The PhC mirrors are composed of four or eight rows of holes oriented in the \(\Gamma M\) direction. The lateral width of the PhC mirrors is 40 \(\mu\)m and that of the cavities 20 \(\mu\)m. To form cavities one uses two four-row PhC mirrors separated by a distance \(W\) which is greater than \(\sqrt{3} \frac{a}{2}\) as seen on Fig. 5.3. To characterize fully the optical properties of the PhC it is desirable to explore as much of the band structure as possible (from the dielectric band through the bandgap up to the air band). However, the bandwidth of the QW emission is limited to about 150 nm.
5.2 Optical losses

In terms of PhC Bloch modes, out-of-plane scattering can be understood as a coupling between components of the Bloch mode and radiative modes of the planar waveguide. By definition, radiative modes are not confined in the core layer: the vertical component of the wavevector $k_z$ is real in air and/or substrate. The leaky Bloch mode components are those located inside the light cone of the air and/or of the substrate. The existence and type of out-of-plane radiative modes can be determined from a wavevector diagram as shown on Fig. 2.4 on Chap. 2.

For a given lattice period $a$ and air fill factor $f$, the optical loss in a 2D PhC is expected to be minimum if the air holes are infinitely deep and perfectly cylindrical [112, 113]. Even in this hypothetical case, the structure may not be lossless: the presence of the air holes alters the confinement properties of the planar waveguide structure. All the PhC modes lying between the substrate light cone and the air light cone are coupled to radiative modes that decay exponentially (imaginary $k_z$) in the air and are radiating (real $k_z$) below the core layer. In other words, these modes are radiated into the substrate and are evanescent in air. All the PhC modes lying above the air line are radiated both into the air and into the substrate. A PhC Bloch mode needs to have all its energetic components outside the substrate cone in order to be completely lossless.

However, besides the intrinsic sources of losses of the ideal 2D PhC, the fabrication of 2D PhC structures introduce extrinsic losses. Extrinsic losses include the extra out-of-plane scattering resulting from a non-ideal hole shape and/or depth. To minimize out-of-plane scattering, it is essential that the depth of the PhC holes is large enough to overlap completely with the vertical profile of the guided mode [113]. A large etch depth is, however, still not sufficient. The holes should also be as cylindrical as possible [114]. Fluctuations of the hole position or the hole diameter as well as sidewall roughness are further sources of loss [115]. 2D FDTD simulations model out-of-plane losses by the introduction of an artificial conductivity inside the holes proportional to $\epsilon''$ expressed by $\sigma(\lambda) = \frac{2}{\pi} \epsilon''$. In order to model and characterize losses in PhC structures one introduces intrinsic and extrinsic loss parameters, as described in the following sections.
5.2. **OPTICAL LOSSES**

**Intrinsic loss parameter**

If material absorption is neglected, the intrinsic loss is purely radiative. The radiation from the holes of a PhC can be viewed as the radiation from an electric dipole placed in each hole. Using a perturbative approach [112] and supposing that the emission of the dipoles is incoherent, a scaling law for $\epsilon''_{\text{int}}$ can be formulated by Eq. 5.3.

$$
\epsilon''_{\text{int}} = \frac{4\pi^2 h_{\text{core}} \eta_{\text{core}} S_{\text{hole}}}{\lambda^3} (\Delta\epsilon)^2 \eta_{\text{core}}(\lambda)
$$

(5.3)

where $S_{\text{hole}} = \pi d^2$ is the cross-sectional area of the hole, $u$ is the normalized frequency, $f$ is the air fill factor, $\Delta\epsilon = \epsilon_{\text{core}} - \epsilon_{\text{clad}}$, and $\Gamma_{\text{core}}(\lambda)$ is the confinement factor inside the core layer. The latter is given by,

$$
\Gamma_{\text{core}}(\lambda) = \frac{\int_{\text{core}} \xi^2(z) \, dz}{\int_{-\infty}^{+\infty} \xi^2(z) \, dz}
$$

(5.4)

$\Gamma_{\text{core}}(\lambda)$ is a decreasing function of the wavelength. For a given material system and slab structure, according to Equation 5.3 the intrinsic losses become more significant as the air fill factor increases. In order to get absolute values for $\epsilon''_{\text{int}}$ one compares it with $\epsilon_{\text{int}}$ calculated by 3D FDTD.

The dependence of $\epsilon''_{\text{int}}$ on the geometry of the vertical structure comes from the factors $h_{\text{core}}$ and $\Gamma_{\text{core}}$. As the cladding thickness increases the profile of the mode becomes more symmetrical and the confinement factor increases. Therefore there is a small increase of $\epsilon''_{\text{int}}$ as the top cladding layer thickness increases. A similar argument explains its evolution as a function of the core thickness. Figure 5.4 displays the variation of $\epsilon''_{\text{int}}$ as function of cap layer thickness and core thickness.
**Extrinsic loss parameter**

Extrinsic losses are caused both by the irregularities due to fabrication (e.g., sidewall roughness, deviations in the lattice period or in the hole diameter) and by a non-perfect hole shape. Considerable work has been dedicated to the optimization of the fabrication techniques in order to reduce $\epsilon''_{\text{ext}}$. Below, we focus on the impact of the hole depth and shape on the extrinsic loss parameter.

![Graph showing theoretical dependence of extrinsic loss parameter $\epsilon''_{\text{ext}}$ on cone angle $\theta$ for different hole depths ranging from 1.2 µm to 3.5 µm. These curves were calculated for a hole diameter $d=300$ nm. The limit case of the conical holes is represented by the linear boundary where all the curves meet.](image)

Figure 5.5: Theoretical dependence of the extrinsic loss parameter $\epsilon''_{\text{ext}}$ on the cone angle $\theta$, for different hole depths ranging from 1.2 µm to 3.5 µm. These curves were calculated for a hole diameter $d=300$ nm. The limit case of the conical holes is represented by the linear boundary where all the curves meet.

Using the same perturbative approach as for the calculation of $\epsilon''_{\text{int}}$, in the case of a cylindrical hole with finite etch depth $|z_0|$ (Fig. 5.6) a semi-analytical expression for $\epsilon''_{\text{ext}}$ can be calculated [114]:

$$\epsilon''_{\text{ext}} = (1 - \epsilon_1)^2 \frac{8\pi^2}{3\lambda^3} n_1 \Gamma(z_0, \lambda) L_{\text{decay}} S_{\text{hole}}$$

(5.5)

where $L_{\text{decay}} = \frac{\lambda}{2\pi} \cdot \frac{1}{\sqrt{n_{\text{eff}}^2 - n_{\text{clad}}^2}}$ being a measure of the effective height of the radiating volume [112] and $\Gamma(z_0, \lambda)$ is the fraction of the electric field that is located under the depth $|z_0|$ of the holes. $\Gamma(z_0, \lambda)$ is an increasing function of the wavelength $\lambda$ and is given by:

$$\Gamma(z_0, \lambda) = \frac{\int_{z_0}^{\infty} \xi^2(z) dz}{\int_{-\infty}^{\infty} \xi^2(z) dz}$$

(5.6)
5.2. **OPTICAL LOSSES**

The simple cone and the cylindro-conical hole are hole shapes that have been used earlier for modelling the loss [110]. In the cylindro-conical model, the hole profile depends on three parameters: the total etch depth $|z_0|$, the cone angle $\theta_c$, and the length $|z_b|$ of the cylindrical section. Using the perturbative approach, it has been shown that a truncated cylindro-conical hole induces always more optical loss than a cylindrical hole with comparable etch depth [110, 114].

To estimate the influence of the geometry of the vertical structure, we assume a constant cylindrical section $|z_b| \approx 600\, \text{nm}$. Fig. 5.5 displays the calculated dependence of the extrinsic loss parameter $\epsilon''_{\text{ext}}$ on the cone angle $\theta_c$ for various etch depths $|z_0|$ varying from 1 $\mu$m to 5 $\mu$m and for a hole diameter $d = 300$ nm. One can distinguish three regimes. For larger values of $\epsilon''_{\text{ext}}$, the loss parameter decreases with the cone angle $\theta_c$; we are in the conical regime. As $\theta_c$ decreases $\epsilon''_{\text{ext}}$ will first decreases and be limited by the total hole depth $|z_0|$ (flat regions in Fig. 5.5 – it is the cylindrical hole regime. In between those two extreme cases it is the truncated cone regime.

**Optimization of vertical heterostructure waveguide**

As described in the previous sections, the total loss level of a PhC structure in, e.g., the InP/InGaAsP/InP system is the sum of an intrinsic and of an extrinsic contribution. Although the main dependence of the extrinsic contribution is on the hole geometry, the design of the vertical structure does have an influence due to a modified mode profile.

The intrinsic contribution depends as well on the vertical refractive index profile as seen in Eq. 5.3. Qualitatively, the intrinsic losses decrease if the core layer thickness decreases as illustrated on Fig. 5.4. If the mode profile is more spatially

![Figure 5.6: Schematic diagram illustrating the truncated cone model indicating the parameters $z_b$ and $z_0$.](image-url)
extended one foresees that the overlap of the mode profile with the conical part of the holes will be larger, thus inducing an increase of the extrinsic losses.

Fig. 5.7 a and b illustrate the influence of the reshaping of the mode on influence on the loss level as the vertical structure is varied. Since the variations of $\int_{\text{int}}$ and $\int_{\text{ext}}$ are opposite an optimized value can be found. It has to be stressed that this optimization is possible given a certain hole shape and depth. In this study we consider $d=4 \mu m$ and $\theta_c=0.5^\circ$. Lowest values for $\epsilon''$ are found for a cap layer of 200 to 300 nm and a core thickness of 470 to 670 nm. For this range of values, the mode profile is a compromise between a nicely symmetric shape with respect to the vertical waveguide and a peak position close enough to the sample surface to reduce overlap with the conical bottom of the holes.

In Paper B the loss level of the fabricated PhC structures is reduced by a factor of 2 with respect to that reported in Ref. [93]. This is attributed both to the optimization of the vertical confinement and to a reduction in $\epsilon''_{\text{ext}}$ due to higher quality of the etching in terms of shape and etch depth. The impact of the quality of the etching on the PhC optical properties is studied in Paper C and described in next section. As the optimization of the vertical structure presented here is valid for a fixed vertical hole geometry, if one strives towards lower possible loss levels, one should choose a vertical structure with an intrinsic loss level as small as possible and find process parameters or post-processing techniques to come as close as possible to the ideal cylindrical shape.

![Figure 5.7: Variations of the $\epsilon''$ for $f=38\%$, $u=0.32$, $d=300 \mu m$, $\lambda = 1550 nm$; a) as a function of the cladding thickness for a core layer thickness of 434 nm ; b) as a function of the core thickness for a top cladding layer thickness of 200 nm.](image-url)
5.3 Impact of the feature size dependence of the etching on the optical properties of PhCs

The impact of the hole shape and depth is investigated for PhC structures operating inside the bandgap. The structures used in this work are one-dimensional cavities (Fig. 5.3). The intensity spectrum of the resonant light in the cavity given by the Airy function is expressed as:

\[ t(\lambda) = \frac{T^2 \exp(-\alpha(\lambda) W)}{\left| 1 - RT \exp(2i\phi) \exp(-\alpha(\lambda) W) \right|^2} \]  \hspace{1cm} (5.7)

where \( \alpha(\lambda) \) is the intensity related absorption coefficient, \( \phi \) the single-trip phase inside the cavity is given by \( \frac{2\pi n_{ef f}(W+L_p)}{\lambda} \) where \( L_p \) is the penetration depth that takes into account the phase shift at transmission and reflection at the mirrors. \( T \) and \( R \) are the transmission and reflection coefficients of the mirror, respectively.

![Figure 5.8: A typical measured cavity resonance after background correction and normalization. The peak is fitted using the Airy function Eq. 5.7.](image)

The measured transmission through an eight-row mirror is subtracted from the measured spectrum for the cavities. The absolute peak level \( I(\lambda_{peak}) \) is then normalized to \( I_0(\lambda_{peak}) \) from the unpatterned region. Figure 5.8 displays an example of a cavity peak fitted by the Airy function.

The optical quality of the fabricated cavities is evaluated by the quality factor defined by \( Q = \lambda_{peak}/\Delta\lambda \) where \( \Delta\lambda \) the full-width at half maximum of the resonance and by the intrinsic properties of the PhC mirrors - reflectivity and losses. This analysis is described in Paper C and the main conclusions are summarized here.

The lag-effect phenomenon, described in Chap. 4 and Paper A, induces a dependency of the hole shape and depth with the hole diameter. As a consequence
Figure 5.9: Variation of the product $Q \times d^2$ as a function of the hole depth.

Figure 5.10: a) PhC mirror reflectivity as a function of hole depth; b) PhC mirror losses as a function of hole depth.
larger hole diameters will correspond to a better hole shape. Two competing mechanisms are at play: on one hand Eq. 5.5 suggests that increased hole diameters are detrimental; on the other hand with increased depth the hole profile is improved. Therefore it is a priori not obvious which effect will dominate in practice. As seen in Eqs. 5.3 and 5.5 optical losses are proportional to the hole area. Therefore, assuming a direct proportionality of the quality factor to the loss parameters, we can separate the contribution of the hole diameter \( d \) and of the etch depth by plotting the product \( Q \times d^2 \) as a function of the hole depth (Fig. 5.9). A very clear increase of the \( Q \times d^2 \) product as a function of the etch depth is seen. The impact of the fabrication process is directly obtained from this plot. For small hole diameters where the achievable etch depth is intrinsically limited by the lag-effect (Fig.4.4), the maximum achievable \( Q \) value is obtained from Fig. 5.9. The extraction of the properties of the PhC mirror also confirm this trend. Figure 5.10 shows the evolution of reflectivity and mirror losses. Two regimes can be identified: in the first regime up to an etch depth of about 3.5 \( \mu \)m the important parameter is the hole depth and the improvement in the optical properties is appreciable. In the second regime, the holes are deep enough to ensure complete overlap with the mode profile and the shape (angle \( \theta_e \)) is more important in determining the losses. However this change in \( \theta_e \) is slow, which is reflected in the observed slower variation of reflectivity and losses with hole depth.

5.4 Conclusion

We have presented the internal light source method to characterize the optical properties of planar photonic crystal structures. This method was applied to the investigation of the optical properties of one-dimensional PhC mirrors and cavities. The optical losses were empirically characterized using the \( \epsilon'' \) model for the intrinsic and extrinsic losses. Optical losses depend on the optical confinement of the vertical mode profile in the core layer, as well as on the extent of overlap of the mode profile with the holes. Two ways to improve the loss level were presented. For a given hole shape the vertical structure can be optimized in order to reduce the total loss level. An optimized vertical structure was proposed and the reduction of losses was experimentally demonstrated. The second way is, given a vertical structure, to modify the hole shape and depth. The impact of the processing induced modification of the hole shape and depth was addressed, and the benefit of deeply etched holes for improved optical properties were experimentally established.
Chapter 6

Carrier lifetimes in etched photonic crystals

The influence of PhC fabrication steps on the optical properties of the material are addressed. The photoluminescence decay time of an InGaAsP/InP QW is used as a figure of merit. The integration of active functionalities such as gain, tuning or switching imposes strong requirements on the material properties. Light emitting devices demand very long lifetimes (typically of the order of ns), whereas optical switching operating at high speed would benefit from a material where the carriers recombine very quickly (typically few tens of ps or less). Dry etching techniques, a necessary step to fabricate PhCs, is known to introduce material damage which is typically material and process dependent. Thus it is necessary to characterize the creation of defects and their influence on the optical properties of the material. The surface recombination velocities in the etched PhCs are determined and the variation with etch-duration is discussed. A qualitative model based on sputtering theory is presented to explain the experimental results. This chapter summarizes Paper D and Paper E.

6.1 Surface/Interface States

The nature of the extrinsically induced surface states is very much dependent on processes acting on the semiconductor surface like molecular adsorption or external defect creation. It is well known that ion beam etching can generate defects that could act as non-radiative recombination centers [116]. In the etching of photonic crystals, although the ion beam is not directed at the sidewalls continuous bombardment occurs at the sidewalls causing accumulated material damage. In this chapter, we evaluate the effect of this damage on the material properties experimentally, and discuss its possible origins.
6.2 Carrier dynamics in semiconductor materials

We have evaluated process induced damage using steady-state and time-resolved photoluminescence (PL) methods. These techniques are non-destructive and relatively straightforward (no need for sample preparation) [117]. When above bandgap light is shone onto a semiconductor sample, photons are absorbed and excite electrons from the valence to the conduction band. The PL intensity is expressed by

$$I(\lambda) = \alpha(\lambda) \cdot f_e \cdot f_h$$

with $\alpha(\lambda)$ the absorption coefficient, $f_e$ and $f_h$ the Fermi distribution function of electrons and holes, respectively. Several phenomena occur after absorption of the light – carriers (electrons and holes) are generated and relax rapidly from non-thermal distribution to thermal equilibrium [118]; the carriers will recombine either radiatively or non-radiatively through deep levels, Auger recombination or surface states. The principal concern in this study is the non-radiative recombination of the carriers. The time-resolved PL spectroscopy is an appropriate technique to provide information on the temporal evolution of a population of carriers in the material.

The evolution of carrier concentration, for example for electrons, is given by the rate equation:

$$\frac{dn}{dt} = G - R_n + G_n$$

(6.1)

where $G$ is the optical generation rate of electrons, $G_n$ the thermal generation rate due to emission from traps and $R_n$ is the recombination rate depending on $\sigma$ the capture cross section of the defect centers, $N_d$ the concentration of defects and $n$ the carrier concentration. After the optical pulse has passed ($G = 0$), and if we neglect thermal generation in the bands ($G_n = 0$), we can write $\frac{dn}{dt} = - (\sigma \cdot N_d \cdot n)$. The integration of this equation gives an exponential decrease for the carrier concentration, i.e., $n(t) \propto \exp(t/\tau_n)$ where $\tau_n$ is the lifetime for electrons. Carriers can recombine either radiatively or non-radiatively with the total recombination lifetime $\tau$ being expressed as:

$$\frac{1}{\tau_n} = \frac{1}{\tau_{n\text{rad}}} + \frac{1}{\tau_{n\text{nonrad}}}$$

(6.2)

Similar equations can be written for holes by replacing indices $n$ by $p$. The variation of the carrier concentration after optical illumination is then given by,

$$n(t) = n_0 \cdot \exp(-t \cdot \left(\frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{nond}}}\right))$$

(6.3)

$$p(t) = p_0 \cdot \exp(-t \cdot \left(\frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{nond}}}\right))$$

(6.4)

where $n_0$, $p_0$ are the optically generated initial carrier concentrations for electrons and holes, respectively. The photoluminescence intensity is proportional to the product of the electron and hole concentrations,

$$I(t) = I_0 \cdot \exp(-t \cdot \left(\frac{2}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{nond}}} + \frac{1}{\tau_{\text{pnon}}}ight))$$

(6.5)
where \( I_0 = n_0 \cdot p_0 \) and the inverse of the PL decay time is

\[
\frac{1}{\tau_{PL}} = \frac{2}{\tau_{rad}} + \frac{1}{\tau_{n_{nonrad}}} + \frac{1}{\tau_{p_{nonrad}}} \tag{6.6}
\]

If the non-radiative recombination of one type of carriers (e.g., electrons) is dominant, the PL decay time is simplified into:

\[
\frac{1}{\tau_{PL}} = \frac{1}{\tau_{n_{nonrad}}} \tag{6.7}
\]

As discussed in Paper D and E, we consider that the non-radiative recombination of electrons is dominant (Paper F).

### 6.3 Time resolved photoluminescence spectroscopy

![Schematic diagram of Time Resolved Photoluminescence set-up](image)

Figure 6.1: Schematics illustrating the Time Resolved Photoluminescence set-up.

The time resolved photoluminescence measurements were performed at room temperature using an experimental set-up according to the schematic sketch shown on Fig. 6.1. The temporal resolution of the set-up is 5 ps. The measurements were performed at 1.14 \( \mu \)m, close to the QW PL peak position. The photoluminescence of the sample was excited by an optically pumped self-mode-locked Ti:Sapphire laser (central wavelength \( \lambda = 790 \text{ nm} \)) focused onto a spot of diameter less than 10 \( \mu \)m. The pulse width is 130 fs and the repetition rate 76 MHz. This gives an average power of 0.6 mW, corresponding to a very low photo-pump level of 0.8 kW/cm\(^2\). The energy density at the sample surface is 16 \( \mu \)J/cm\(^2\). The emitted PL light is collected towards a spectrometer and a synchroscan streak camera for operation at the selected wavelength. A beam splitter is used to send part of the pump signal to the streak camera for synchronization.
6.4 Modification of carrier lifetimes

Sample description

The MOVPE grown structure was a 500 nm of undoped InP with a 10 nm InGaAsP quantum well in the middle. The patterns were designed as 30x30 µm² PhC fields framed by a 35 µm wide trench. Several samples (sets), each containing eight PhC fields with different lattice parameters, were prepared. The lattice parameter a ranges from 290 to 320 nm and the hole diameter d from 100 to 200 nm (f=15% to 40%). The PhCs patterns were generated as described in Chap. 3. All the samples were etched by CAIBE but the etch duration was different, ranging from 45 s to 50 min.

Influence of the mask material

The processing of the SiO₂ mask material (deposition, pattern definition and transfer) influences the carrier lifetimes. Defect creation and migration, or migration of existing surface defects, is process and material dependent. Different categories of defects can be created. A first category of material damage is located at the interface between dielectric layer and semiconductor due to structural defects inside the silicon dioxide layer and native oxides of semiconductor which are of unclear stoichiometry. A second category is the generated defects at the interface that can be mobile and can propagate deeper into the material. The third category of defects is due to damage that can be induced by bombardment of ions and energetic reactive species. The defect rich region may extend down to about 100 nm below the sample surface. The nature and extent of the defects depends on the properties of the mask material (condition for deposition, stoichiometry, etc.) and have a clear effect on the optical properties of the processed samples [119].

Evidence for accumulated sidewall damage

Figure 6.2 shows representative PL decay curves as a function of the process time for a PhC field with a lattice period a=510 nm and hole diameter d=210 nm. As the etching time increases, the holes get deeper and their shape evolves. When the QW is etched through we record a clear decrease in the decay time, from 2 ns to 800 ps. This is expected due to the sudden exposure of the QW surface (sidewalls). As the etching proceeds, we note that the PL decay time continues to decrease down to about 70 ps for 50 min etching and for etch durations longer than 30 min the decay time varies much more slowly (Fig. 6.2). For all the fabricated structures the overall behavior of the carrier lifetime with etch-time presents first a strong decrease as soon as the quantum well is etched through, and then as the holes become deeper the carrier lifetime is much less sensitive to the increase of etching times as described in Paper D. For a given etch time and lattice period, the carrier lifetime decreases at higher air fill factors. This is due to the variation of the sidewall area. To remove
the geometrical dependence and characterize the build-up of damage with time, we
determine the sidewall recombination velocity in the next section.

Non-radiative sidewall recombination velocity

It is usual to express the non-radiative recombination velocity \( \nu \) in the case of one
type of carriers and one type of defect as \( N_d \cdot \sigma \cdot v_{th} \), where \( N_d \) is the defect density,
\( \sigma \) is the capture cross-section of the defects and \( v_{th} \) is the thermal velocity of the
carriers. The product \( \sigma \cdot v_{th} \) is the capture rate. In the following we note the
surface recombination velocity as \( \nu_S \) at the etched hole sidewalls. For a triangular
PhC, we define as a parameter the ratio of the length of the PhC sidewalls \( S \) over
the surface \( A \) of the emitting region per unit cell and is given by,

\[
\frac{S}{A} = \frac{\pi d}{\frac{\sqrt{3}}{2} a^2 - \frac{\pi}{4} d^2}
\] (6.8)

where \( a \) is the lattice period, and \( d \) the hole diameter. In the etched areas, non-radiative
recombination at the sidewalls reduces the carrier lifetime \( \tau_0 \) of the unprocessed material according to,

\[
\frac{1}{\tau} = \frac{1}{\tau_0} + \nu_S \frac{S}{A}
\] (6.9)

Then we can plot \( \tau^{-1} \) as a function of \( S/A \) for different etching durations and
\( \nu_S \) can be obtained from the slope and \( \tau_0 \) from the intercept (Fig. 6.3a).

Fig. 6.3 shows the variation of the surface recombination velocity as a function of the etch duration. The increase of \( \nu_S \) is the signature of accumulation of material
damage during etching. In the next section we present a physical model based on
sputtering theory to explain this evolution.
6.5 Modeling of the accumulated damage in CAIBE

Sputtering theory applied to photonic crystal etching

When an ion strikes a surface at normal incidence, the angular distribution of the ejected material in the 2D plane normal to the etched surface generally follows a cosine distribution (according to the linear cascade theory), with the maximum of sputtering probability at an angle $\beta=0$ with respect to the surface normal. This angle is called "polar angle". If the impinging ion strikes the surface along the surface normal, due to the rotational symmetry around the incident axis, the sputtering distribution is independent of the azimuthal angle $\varphi$ (rotational angle around the surface normal).

However, as soon as the incidence angle $\alpha$ (measured from the surface normal) starts to increase, the 3D distribution of sputtered material will be modified (Fig. 6.4). The first effect is that the symmetry with respect to the azimuthal angle is broken and we can divide the space into two semi-spaces defined as "forward" and "backward" with respect to the direction of incoming ion, as indicated on Fig. 6.4. We can define the azimuthal distribution in a plane parallel to the etching plane, where the probability of sputtering in the forward space is enhanced, and the probability in the backward space reduced. As $\alpha$ increases, the maximum in the polar distribution of the sputtered species is close to the direction of specular reflection as indicated on Fig. 6.4. Combining the azimuthal and polar distributions it is possible obtain the 3D probability map for the ejected species [120]. Since the sputtering yield depends on $\alpha$, the integrated probability of sputtering over the 3D space has to be normalized with respect to the respective sputtering yield. At low energies (<500 eV) the sputtering yield for Ar$^+$ ions is first independent of the incident angle and then decreases with $\alpha$ due to the reduced efficiency of momentum transfer [121].
Figure 6.4: a) Schematic drawing illustrating the sputtering process indicating the direction for the incoming ion, the polar and the azimuthal angles; b) example of a polar distribution of the sputtered species; c) example of an azimuthal distribution of the sputtered species.

Figure 6.5: Calculated number of sputtered species reaching the quantum well (line). Also shown by open circles is the surface recombination velocity as a function of the dry-etch time on the right axis.
Influence of the hole shape

As discussed in Sec. 4.2, the holes etched by Ar/Cl₂ CAIBE have a tapered bottom. SEM inspections show that the top portion of the holes is almost straight whereas the bottom part is more conical. The SEM inspections also show that the hole shape varies as the holes are etched deeper, with an increase of the depth of the straight portion. Following this, in Paper E we use the cylinbro-conical hole shape model and its evolution with time is sketched on Fig. 6.6a. The depth of the straight portion is \( h \). During each time step, the increase in etch depth \( \Delta L \) is calculated using the model described in section 4.2. We express the time dependent \( h \) as:

\[
h(t + 1) = h(t) + \gamma(t + 1) \times \Delta L(t + 1)
\]

(6.10)

where \( \gamma(t) \) is a time dependent coefficient increasing with the time step \( i \).

![Figure 6.6: a) Temporal evolution of the hole shape in the cylinbro-conical model; b) Illustrations for different hole shape models: conical, truncated-cone and cylindrical hole shapes.](image)

The cone angle is defined from the depth of the conical part of the hole \( (L(t) - h(t)) \). Different models can be proposed to model the development of the hole shape particular to a given etching technique. Models can be conical hole shape, cylinbro-conical with the adjustment of the depth of the straight portion, truncated cylinbro-conical, or cylindrical hole shape (Fig. 6.6b). From the considerations of sputtering angle in the previous section, one can speculate that an etching process developing with a cylindrical hole profile will result in a larger amount of accumulated damage since the QW would become closer to the direction for high sputtering probability as etch depth increases. The case of the truncated cylinbro-conical would be intermediate as both the bottom of the hole and the sloped sidewalls would contribute. In the case of a pure cone, one can expect a similar variation with etch depth as for the cylinbro-conical model, but the absolute number of sputtering events would be larger due to the larger sputtered area at a given etch depth. In the following we restrict ourselves to the case of the cylinbro-conical hole shape with varying \( h \) as in Eq. 6.10.
At each point P of the hole sidewall, we use the calculated sputtering map to get the number of secondary species sputtered in the direction of the quantum well and then sum up the contributions from the whole surface of the hole (varied point P). Fig. 6.5 shows the dependence of the number of sputtering events at the quantum well region as a function ofetch depth and etch time scaled to surface area density. Just after the QW is etched through, the number of sputtered species reaching the QW is very large. The sputtering directed at the QW decreases together with the cone angle \( \theta_c \) and is very low as we reach the backward semi-space. If the number of created defects is proportional to the number sputtering events, this trend will also indicate the variation of the accumulated damage at the sidewalls.

![Graph](image)

Figure 6.7: Evolution of the straight portion \( h \) and of the cone angle \( \theta_c \) as a function of the hole depth for the cylindro-conical model.

The variation of \( h \) and of the cone angle \( \theta_c \) of the sloped portion as a function of the etch depth. At the beginning of the etching, \( \theta_c \) is large and the sputtered species from the sloped etch plane will reach the quantum well from the forward semi-space. As \( L \) increases, \( h \) increases and \( \theta_c \) decreases, which modifies the respective angle from the impact point to the QW. As the cone angle decreases, the QW appears more and more in the backward semi-space, and the probability of sputtering the QW sidewalls reduces. However, if \( h \) is time dependent the cone angle will decrease more slowly and the slope of the number of sputtering events as function of etch depth is higher.

### 6.6 Conclusion

In this chapter we have investigated the modifications of the carrier lifetimes in an InGaAsP quantum well due to PhC manufacturing processes. The influence of the processing of the mask material was discussed. However, the major impact is...
on the carrier lifetimes originates from the dry-etching of the semiconductor. As soon as the quantum well is etched through a dramatic decrease in the lifetime is observed, which is further reduced by additional etching. For membranes which do not require deep etching a tailoring of the carrier lifetimes can be obtained by adjusting the etching time. An experimental measure of the sidewall damage is obtained by the extraction of the non-radiative sidewall recombination velocity. The non-linear variation with etch time suggests that the mechanism for damage creation is dependent on the hole shape and depth. A qualitative model based on sputtering theory and ejection probabilities is used to explain the evolution of the bombardment at the QW sidewalls as the hole shape is modified. A good qualitative agreement is obtained with the experiment.
Chapter 7

Lateral electron transport through photonic crystal fields

Investigations of transport of carriers in PhCs is necessary to achieve electrically-driven control of PhCs. Such access to PhC devices is relevant for applications such as lasers [24], LEDs [22, 23], or tunable devices, where on-chip electrical control can provide versatility and easier integration of the devices. One possible way to tune the optical properties of PhC devices is to modify the refractive index of the background material by temperature control [122, 123], or by an optically induced carrier plasma effect [124, 125]. Recently, electrically driven thermal tuning was achieved in the case of a Si membrane [126]. In this chapter we present investigations of carrier transport through InP-based two-dimensional PhC fields (Paper F). We also investigate thermal effects due to carrier heating. Finally we propose an experimental method based on the variation of conductance of the PhC structure with inter-hole distance to determine the sidewall surface potential.

7.1 Electron transport through a photonic crystal field

Modeling the carrier transport

Simulations of the current flow through PhC fields were performed using the commercial software ISE TCAD$^{TM}$ [127]. This is a widely used tool for simulating electronic and optoelectronic devices. It comprises of an editor for structure design (Mdraw), a mesh-generating unit (creating a tensor mesh), a calculating unit DESSIS, and a data processing unit for plots and single value extraction. The calculating tool DESSIS includes mathematical models of different physical effects in semiconductors, a set of nonlinear solvers, a parameter extractor as well as other device-specific packages.

Carrier transport in semiconductor is based on three fundamental equations. They are (i) the continuity equations including drift-diffusion for electrons, (ii) the
continuity equation for holes, and (iii) the Poisson equation. They are given by,

\[ \nabla \cdot (D_n \nabla n - n p_n \nabla \phi) - \frac{\partial n}{\partial t} = -(G - R_n) \] (7.1)

\[ \nabla \cdot (D_p \nabla p + pp_p \nabla \phi) + \frac{\partial p}{\partial t} = (G - R_p) \] (7.2)

\[ \Delta \phi = \frac{\rho}{\varepsilon_0}, \] (7.3)

respectively. In the above equations \( n \) is the electron concentration, \( p \) the hole concentration, \( \phi \) the potential, \( \mu_{n,p} \) the carrier mobility, \( D_{n,p} = \frac{\mu_{n,p}}{q} \mu_{n,p} \) the diffusion coefficients using Boltzmann’s statistics. The generation coefficient \( G \) is set to zero since we do not generate \( e - h \) pairs (no illumination). The recombination term \( R_{n,p} \) is given by the Shockley-Read-Hall model. The charge density \( \rho \) is given by, assuming full ionization, \( \rho(\vec{r}) = q(n(\vec{r}) - p(\vec{r}) - N_D^+ + N_A^-) \) where \( N_D^+ \) is the donor concentration and \( N_A^- \) the acceptor concentration [128].

### Table 7.1: Mobility models for InP in ISE

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Equations/values</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low field mobility</td>
<td>( \mu = \mu_{\text{max}} \left( \frac{T}{T_0} \right)^{1.5} )</td>
<td>Arora model [129]</td>
</tr>
<tr>
<td>( \mu_{\text{max}}^{\text{electrons}} )</td>
<td>( 4.5 \times 10^{-3} \text{cm}^2/\text{V s} )</td>
<td></td>
</tr>
<tr>
<td>( \mu_{\text{max}}^{\text{holes}} )</td>
<td>( 1.5 \times 10^{-2} \text{cm}^2/\text{V s} )</td>
<td></td>
</tr>
<tr>
<td>High field dependent mobility</td>
<td>( \mu_{\text{high}} = \mu \frac{1}{\sqrt{1 + (\frac{\mu}{\mu_{\text{sat}}} - 1)^2}} )</td>
<td>Gaughey Thomas Model [130]</td>
</tr>
</tbody>
</table>

Calculations are performed on the discretized forms of the partial differential Eqs. 7.1, 7.2 and 7.3. The discretization method used here is the Finite Volume Method (also called box integration method) [131, 132] which uses a finite difference scheme. The initial conditions are determined from the electron concentration in the material at room temperature, given the doping level. Boundary conditions are defined by either a constant value (Dirichlet) or a zero flux through the boundary (Neumann) which is also called reflective boundary condition. A further set of equations may be used to account for heat generation but was not incorporated into our present model. The physical models and model parameters for mobility are material specific and the ones used in our simulations are given below.

### Simulation of current flow through InP-based photonic crystal field

The aim of these simulations was to obtain the behavior of an electron flux through a perforated material. Simple models for the properties of InP were implemented
using the default parameters and models for the electrical properties of InP within ISE. The dielectric constant is $\epsilon = 12.4$. The values and expressions for the mobility used in the simulations can be found on Table 7.1. Models for surface recombination were not used in the present calculations.

![Graph](image)

Figure 7.1: (a) Variation of the electron drift velocity with applied electric field; (b) Variation of the electron mobility with electrical field; Curves are calculated with the Caughey-Thomas model.

The high field mobility is modeled using the Caughey-Thomas model [130]. The electron drift velocity saturates at the velocity $v_{sat}$ and its dependence on the electrical field is shown on Fig. 7.1. The high field value of electron drift velocity reaches $10^7$ cm s$^{-1}$. However the model used here does not take into account the overshoot appearing around 5 to 20 kV/cm [133].

![Diagram](image)

Figure 7.2: Schematic drawing of the simulated structure indicating the geometry and the boundary conditions where $V_{var}$ is the varying potential.

The flow of current has been simulated through a PhC field with the following dimensions: width $W=2.8$ μm, length $L=10$ μm and thickness $t=1$ μm (Fig. 7.2). The simulations use flat band conditions at the surfaces (i.e., surface potential is zero). The PhC field is connected by two 20 μm long conducting InP channels, terminated by contacts where the potential is set to a constant value (Dirichlet boundary condition). At the channel boundaries and at the outer edges of the PhC field, Neumann conditions are used.
Figure 7.3: Simulated current-voltage characteristics for PhC fields with different air fill factors scaled to the experimental geometry.

Figure 7.4: Resistance of a simulated structure as a function of the total channel length (both sides of the PhC field). The cut-back method allows the determination of the resistance of the PhC field from the intercept. The values for the resistance were normalized to the experimental geometry and mobility.
7.1. ELECTRON TRANSPORT THROUGH A PHOTONIC CRYSTAL FIELD

Full calculations of the I-V characteristics are performed for air fill factors between 10% and 75%. The simulated current values are scaled after calculation to the experimental geometry for purpose of comparison of the current levels. The resistance of the structures with different channel lengths are plotted as a function of the total channel length (Fig. 7.4) and the PhC resistance is determined from the intercept. The PhC resistance increases with air-fill factor as discussed in Paper F.

Figure 7.5 gives the electron density map for a PhC field of \( f=20\% \) and of \( f=60\% \) under low field conditions. The flow is "laminar" in the direction of current flow, which means that the integrated value along the direction normal to the flow is constant and there is no preferential path for the electrons. However, the local electron density in between the holes is much higher in the case of \( f = 60\% \). This is related to the dependence of the voltage at which saturation appears, which is discussed in Sec. 7.2.

The situation under high field conditions is quite different, as can be seen from Fig. 7.6. When the applied electric field is high enough, the electrons reach their sa-

![Figure 7.5: Electron current density maps in the low field regime \( (V=2V) \) a) \( f=20\% \); b) \( f=60\% \). Note that the scale bars for the current density are different for a) and b).](image)

![Figure 7.6: Electron current density map in the high field regime for \( f=60\% \).](image)
7.2 Experimental

Sample fabrication

Figure 7.7: Scanning electron microscope (SEM) top view of a) the full structure including the contact pads and, b) close view showing a PhC field; also seen are part of the conducting channels.

Figure 7.8: Experimental current-Voltage characteristics for PhC fields with different air fill factors.

The PhC samples were fabricated on a 500 nm thick n-doped \( (1.5 \times 10^{17} \text{cm}^{-3}) \) InP layer grown by MOVPE on a semi-insulating (Fe-doped) InP substrate. The structures are designed as a triangular-lattice \( (a \text{ varying from 450 to 850nm and } f \text{ from 10 to 50\%}) \) PhC field patterned in a conducting channel provided with two contact pads is shown on Fig. 7.7. Identical structures without PhC field were used as references. A 20 \( \mu \text{m}-\text{wide deeply-etched trench ensures electrical isolation of the conducting channel from the surrounding material. Measurements using unconnected pads did not show any conduction thus ruling out any parasitic surface...} \)
7.2. EXPERIMENTAL

conduction. The geometrical parameters of the conducting channel are: width $W=9 \mu m$, length $L=40 \mu m$, and thickness of the conducting layer $t=340 nm$. The latter value was calculated accounting for the depletion regions at the bare InP surface [134] and at the interface with the semi-insulating substrate [135].

Current-Voltage measurements

Current voltage (I-V) measurements on the PhC structures were performed using a probe station connected to a HP 4156A semiconductor parameter analyzer. Experiments were performed in dark in order to avoid carrier generation or modification of the electrical properties by light. Figure 7.8 displays the I-V characteristics obtained from the 40 $\mu$m long PhC field with $a=450$ nm with different filling factors in the range [-20V;20V]. The linearity of the characteristics close to the origin is a sign of ohmic behavior. As described in Paper F, the evolution of the resistance of the PhC field depends on the period $a$ and hole size.

In the perspective of PhC devices for applications at telecommunication wavelengths (1.5 $\mu$m), a PhC with $a=450$ nm and $f=30\%$ is typical. In that case, the increase in resistance due to the presence of the PhC field is threefold, from 3k$\Omega$ to about 9k$\Omega$ (Paper F). At higher applied voltages, the current level through the PhC saturates. Figure 7.8 indicates that the experimental data is qualitatively well reproduced by the simulations. This allows us to attribute the saturation to a high-field effect. Consistently, shorter fields showed current saturation at lower biases (not shown).

Thermal effects due to carrier heating

![Optical microscope picture of a fabricated waveguide structure indicating the W3 PhC waveguide, the ridge waveguides and the contact pads.](image)

Figure 7.9: Optical microscope picture of a fabricated waveguide structure indicating the W3 PhC waveguide, the ridge waveguides and the contact pads.

In order to evaluate the temperature change in our structures under current flow, we have measured the wavelength shift of Fabry-Perot fringes using the end-fire method (Sec. 8.3). 100 $\mu$m long W3 PhC waveguides (i.e., three-missing rows
forming a waveguide along [1K direction] with two access ridge waveguides were fabricated. Metallic contact pads were provided on the two sides of the PhC waveguide section (Fig. 7.9). We measure the transmission spectrum through the waveguide as a function of the current injected across the PhC waveguide.

Figure 7.10a displays Fabry-Perot fringes, originating from the cavity formed between the cleaved facets of the sample. A clear red shift with increasing current level is observed. This wavelength shift is translated into a refractive index variation using a Fabry-Perot model. From Ref. [136], we estimate the temperature dependence of the effective refractive index of InGaAsP as \( \frac{dn}{dT} = 1.75 \times 10^{-4} \text{K}^{-1} \), from which we calculate the temperature increase in the structure (Fig. 7.9b). The change in temperature is small (some degrees) up to 3 mW and even at 10 mW the total change is less than 30 K. The increase in saturation velocity with temperature is negligible and does not affect the I-V characteristics in that temperature range [28]. These results show that the low index contrast scheme for 2D PhC devices could be favorable in terms of heat dissipation. On the other hand, this method can be useful for thermal tuning of PhC membrane structures, since the changes can be much larger. One could also imagine to provide conventional waveguides with small W3 PhC sections to realize local heating.

7.3 Etching induced modification of surface potential

According to the Spicer-Bardeen model [137, 138] the defect states at the interface/surface, caused by the presence of adatoms or by missing atoms, can pin the Fermi level \( E_F \). The position of the Fermi level at the surface/interface is determined by the energy level of the defect (in the case of a single dominating level) or by the distribution of states. In the case of a single dominant "level", the Fermi level is pinned very close to it. In the case of a high density distribution of states,
the pinning of the Fermi level is such that the net charge of the states is zero (Bardeen limit). In either case the Fermi level at the surface can be different from that in the bulk resulting in a band-bending, hence the presence of a depletion region (Fig. 7.11).

Figure 7.11: Sketch of the band diagram for a $n$-type semiconductor indicating the corresponding band bending due to the Fermi level pinning at the surface/interface. The surface potential $V_S$ is also shown.

Therefore a modification of the distribution of the charged levels at the interface, induced by processing, will result in a modification of the surface potential and the depletion region width $W$. The surface potential $V_S$ is given by:

$$V_S = -\frac{(E_{surf}^C - E_{bulk}^C)}{q}$$  \hspace{1cm} (7.4)

where $q$ is the elementary charge, and $E_{surf}^C$ and $E_{bulk}^C$ are the conduction band (edge) energies at the surface and in the bulk, respectively.

**Influence of dry etching on electrical properties of semiconductor surfaces**

Many different techniques have been used to characterize dry etched materials, such as current-voltage and capacitance-voltage characterization, measurements of metal-semiconductor contacts and $p-n$ junctions. However, the adaptation of such methods to investigate structures such as photonic crystals is not straightforward. Measurements of the conductivity of etched wires to assess the sidewall damage [139] is promising. We propose here a similar method to characterize the electrical modification at the hole sidewalls. The I-V characteristics of the PhC fields can give information on the sidewall surface potential, electrical conductivity and on the electrical field dependence of carrier transport.

Chemically assisted ion beam etching of the material to form PhC holes will modify the surface potential at the sidewalls of the etched holes. This will result in a different depletion region width ($\delta$) around the holes as compared to the bare
(unprocessed) surface potential. The value of δ is process-related and has to be determined. Fig 7.12 illustrates the variation of δ due to a modification of the surface potential. The figure also displays the extreme case where the adjacent depletion regions touch resulting in a pinch-off condition. If we consider the PhC field, we can define an electrical fill factor $f_{ele}$ defined as the ratio of the non-conducting region (air + depletion region) over the total surface of the PhC, and is given by:

$$f_{ele} = \frac{\pi \cdot (d + 2\delta)^2}{\pi a^2}$$  \hspace{1cm} (7.5)

Figure 7.12: Schematic drawing of the top view of PhC fields indicating the depletion region δ around the holes. For a given period and hole diameter, depending on δ the total amount of conducting material (darker shade) will be reduced.

Figure 7.13: Comparison of the conductance versus inter-hole distance in the case of the simulations and of the experiment.
7.4. CONCLUSION

The simulated data gives the conductance of the PhC field without any contribution of sidewall depletion and the PhC air fill factor used in the simulations $f_{simu}$ is the geometrical value and is smaller than the electrical fill factor $f_{elec}$. For a given conductance, the air fill factor difference $\Delta f$ between measured and simulated data gives the increase of the effective radius due to the presence of the depletion region around the holes. Another, more intuitive method to determine $\delta$ is to plot the conductance as a function of inter-hole distance (Fig. 7.13). This is discussed in detail in Paper F. Using this, $\delta$ can be determined hence the sidewall surface potential. The determined value of $\delta$ is 42 nm ± 5 nm. The value for the surface potential is calculated using Poisson equation using the obtained value of $\delta$ for depletion region width:

$$V_S = \frac{e N_D \delta^2}{2 \epsilon_r \epsilon_0}$$

where $e$ is the elementary charge, $N_D$ is the doping concentration, $\epsilon_r$ the relative permittivity for InP and $\epsilon_0$ the permittivity in vacuum. From this equation we obtain $V_S = 0.12$ eV below the CBM. This value is in agreement with the defect level associated to a P-vacancy [140, 141].

7.4 Conclusion

The electron transport through photonic crystal fields was studied. The dependence of the electrical properties such as resistance and saturation current level as a function of the geometrical parameters of the PhC were reported. The I-V characteristics are linear at low voltage but the current saturates at higher voltage. Full current transport simulations allowed us to confirm that the experimentally observed current saturation is due to saturation of the electron drift velocity and that it depends on the geometrical parameters of the PhC. The spectral shift of the Fabry-Perot fringes of PhC waveguide structures was used to estimate the temperature changes due to carrier heating. The modified Fermi level pinning at the etched hole sidewalls is estimated around 0.12 eV below the conduction band minimum. This pinning which is close to the conduction band is beneficial for electron transport.
Chapter 8

Some selected dispersion properties of photonic crystal based devices

Owing to the wide range of their diffraction properties, photonic crystals are very interesting structures to study and control light propagation. The presence of a band structure (including a bandgap) opens new possibilities to tailor the dispersion either of propagating modes in the transmission bands or of the guided modes. Waveguide modes were reported to exhibit multi-refringence [142, 143] or slow-light [126], whereas modes in the transmission bands of defect-free PhCs (mainly just above the bandgap) are appropriate for unconventional effects such as negative refraction [38], ultra-refraction [144], auto-collimation [145, 146], superprism [37, 147] and super-lensing [34, 148]. Band edge modes have demonstrated low group velocities sometimes referred to as heavy photons [149] and have been used to achieve lasing [150].

This chapter introduces the properties of Bloch modes in 2D PhCs, negative refraction and slow light regimes. Sections 8.4 and 8.5 discuss the experimental results on negative refraction (Paper G) and the observation of equi-frequency contours by Fourier optics (Paper H) respectively. Section 8.6 describes the investigation of slow light PhC structures focusing on group velocity dispersion and group index (Paper I).

8.1 Bloch modes in two-dimensional photonic crystals

As noted earlier in Chap. 2 the optical field excited in a photonic crystal is a sum of Bloch modes that can be expanded using a basis of plane waves. In the present chapter we will focus more on the representation of this optical field in the reciprocal space. In the folded zone scheme, which is by far the most common representation, one plots all the (eigenmode) solutions to Eqs. 2.7 and 2.8 in the first Brillouin zone as displayed on Fig. 8.1.
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

Figure 8.1: Band structure for $r/a=0.26$, folded into the first Brillouin zone.

Figure 8.2: Bands calculated by PWE are shown in the first Brillouin zone for $r/a=0.26$ a) second band TM; b) third band TM; c) second band TE; d) third band TE.
8.1. BLOCH MODES IN TWO-DIMENSIONAL PHOTONIC CRYSTALS

Figure 8.2 show detailed views of the second and the third bands, for TE and TM polarizations. It is seen from the figure that the second band for TM is more rounded over a larger range of frequencies than that for TE. The third bands (b and d) have a more complex shape. Equi-frequency contours (EFC) or wavevector diagrams can be obtained from the intersection of the calculated band structure with a plane at a given frequency. Such information provides detailed knowledge on the shape of the dispersion curve in the reciprocal space. Figure 8.3(a and b) shows examples of the EFCs for TE and TM polarizations showing that the modes of the second band in TM are more close to circles, similar to the case of an isotropic medium. However, contrary to the case of a homogeneous medium, the radius of the EFC decreases with increasing frequency, a phenomenon which is called anomalous dispersion.

Figure 8.3: Equi-frequency contours for a PhC field with $r/a=0.26$: a) second band TE polarization in the first Brillouin zone; b) second band TM polarization in the first Brillouin zone; c) second and third band in full reciprocal space; TM polarization; $u=0.310$; d) second and third band in full reciprocal space; TM polarization; $u=0.310$. In c) and d) the features corresponding to the second and the third bands are shown.

Even though the representation of the band structure in the first Brillouin zone is instructive, viewing the bands in the full reciprocal space is more useful to understand the propagation of Bloch modes. In a homogeneous medium of refractive
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

index $n_{eff}$ the wavevector diagram is a circle of radius $k = \frac{2\pi}{a} \cdot u \cdot n_{eff}$ around the origin. In the presence of periodicity, the Floquet-Bloch theorem states that, for every point on this circle, an infinite number of higher-order wavevectors will appear. This is equivalent to say that the circle will be translated according to the reciprocal lattice vectors $\tilde{G}$ and will be repeated in the full reciprocal space [2]. In the cases where $|\tilde{k}| > |G|/2$ the circles will intersect each other. The presence of the periodicity in the dielectric constant will also cause the distortion of the shapes of the EFC at the points of intersection creating stop bands at those points. Fig. 8.3d displays the situation where the circles are not very much distorted and it is easy to imagine them around each reciprocal lattice point. However, the presence of a small gap at the intersection points separates the $k$-vectors into the second and the third band (indicated on the figure). In the case of TM polarized light, the gaps at the intersection points are more pronounced and the separation between the second and the third bands is larger. Fig. 8.3c and d) display the EFC for the second and third band. These graphs provide knowledge about the wavevectors permitted to exist in the PhC slab, but do not inform us about the weight of their respective spatial harmonics $V_n(\tilde{k})$ (i.e., about the magnitude of the different Fourier coefficients in the plane wave expansion of the Bloch modes Eq. 2.10). The Fourier coefficients $V_n(\tilde{k})$ depend on the photonic strength of the crystal, which is determined by the dielectric map $\epsilon(\tilde{r})$ [151, 152].

![Figure 8.4](image)

Figure 8.4: FT-FDTD calculation showing the excited Bloch modes a) for point source excitation in middle of PhC slab; b) for an excitation from a ridge waveguide.

The Fourier Transform (FT) of the optical field existing in a PhC structure can be expressed as the product of the Bloch mode solution in the full reciprocal space by a function determining the excitation of the modes. To illustrate this concept, Fig. 8.4 compares the FT of the FDTD field map of a PhC structure excited by a point source placed at the center of the field with that obtained for an excitation
by a ridge waveguide in proximity (in plane). In the case of the point source excitation the Bloch modes are equally excited in all directions about the origin whereas the ridge waveguide excites only a limited number of Bloch modes in the direction of propagation. The comparison of Fig. 8.4a| and b| with Fig. 8.3c| and d| indicates that Bloch modes belonging to both the second and third bands are excited. The modes excited outside the values calculated from PWE are evanescent modes. Calculations for a PhC field of shorter length show that the distribution of excited Bloch modes is similar but with an additional broadening in $\Delta \tilde{k}$.

8.2 Negative refraction in Photonic crystals

![Wavevector diagram illustrating negative refraction](image)

Figure 8.5: Wavevector diagram illustrating negative refraction; Group velocity diagram illustrating, at the interface, the refraction on the same side as the normal to the interface is also shown.

Negative refraction effects have attracted a lot of attention in the recent years, especially after Pendry's proposal of the concept for a "perfect, flat lens" [153]. The negative refraction properties of PhCs defined by the introduction of an effective negative refractive index in analogy to a homogeneous material are in essence fundamentally different from those of metamaterials (left-handed materials). For such materials the dielectric permittivity $\varepsilon$ and/or the magnetic permeability $\mu$ are made negative by an artificial arrangement of materials with different properties, taking advantage of electric or magnetic resonances [154, 155]. The diffractive properties of 1D gratings have been explored in the mid 80's and anomalous refraction was demonstrated experimentally in the visible range [3, 156]. Negative refraction was experimentally demonstrated for left-handed materials at microwaves frequencies [157]. The experimental demonstration of negative refraction in 2D PhCs was reported at microwave frequencies [158, 159] and at optical wavelengths (Paper H). Subwavelength imaging has been demonstrated for both left-handed materials [160] and PhCs in the microwave region [161]. Negative refraction effects in PhCs have been proposed for directional emission imaging [162] or for field-of-view expansion...
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

[163]. In the following, we will introduce the concept of negative refraction in PhC structures, then present experimental results of light focusing by a PhC field and explore its application for light collection.

Figure 8.6: Values for the refractive index in the second band for a PhC with parameters \(r/a=0.26, \epsilon=10.5\); TM polarization

Negative refraction in two-dimensional InP based photonic crystals

When operating above the bandgap (in other contexts referred to as inside the air band), some of the transmission bands have their highest frequency modes around the \(\Gamma\) point. Two of the transmission bands are shown in the first Brillouin zone on Fig. 8.2. The group velocity \(\vec{v}_g\) is defined by the gradient of the dispersion band \(\vec{v}_g = \nabla_{\omega}(\vec{k})\) and is thus oriented along the inward normal to the EFC (i.e., on Fig. 8.3 oriented in the direction of increasing \(u\)). The group velocity \(\vec{v}_g\) indicates the direction of the energy flow. For strong enough modulations of the dielectric constant, equi-frequency contours become rounded around certain points of symmetry (\(\Gamma\) point in our case) and one can draw an analogy with the dispersion relation of an isotropic medium. We can use a wavevector diagram to describe light propagation from a homogeneous isotropic material to a PhC field as illustrated on Fig. 8.5. If we apply the \(k_{//}\) conservation rule we find the Bloch modes that can be excited with the incoming wavevector \(\vec{k}_{//}\). The solution in the PhC is that which has a wavevector allowing the propagation inside the PhC. At the interface light is refracted on the same side of the normal to the interface. This phenomenon is called negative refraction.

In the region close to the top of the second band, the EFCs in the first BZ are close to circles (Fig. 8.3 a). In this particular situation, it is tempting to ascribe to the PhC an effective refractive index value \(n_{PhC}^{attr}\) by comparing the slope of the band to the air light cone, as shown on Fig. 8.6. It has to be underlined that defining such an effective refractive index should only be seen as a practical aid and is not to be confused with the refractive index of a homogeneous material.
8.3. END-FIRE CHARACTERIZATION

Following this we can find a frequency interval where the effective refractive index is -1. The value $n_{P_{\text{HC}}}^{\text{eff}} = -1$ corresponds to an EFC intersecting with the light cone. For purposes of superlensing operating in air, a configuration having $|n_{\text{iso}} = 1|/|n_{P_{\text{HC}}}^{\text{eff}} = -1|/|n_{\text{iso}} = 1|$ is often chosen since it allows the better performance by avoiding reflection losses.

8.3 End-fire characterization

The end-fire method, also called fiber-to-fiber, is a technique particularly suited for optical characterization of planar photonic components/devices and here it is applied to characterize PhC devices. A photograph of the end-fire set-up is shown on Fig. 8.7. External light is provided by a tunable laser emitting in the wavelength range 1480-1580 nm. Typically, optical access to the PhC structure is provided by ridge waveguides (about 1.2 μm wide) at the input and output. The total sample length is typically of the order of 1 mm, in order to enable cleaving at both ends.

Figure 8.7: Photograph of an end-fire set-up. Courtesy of Prof. Bozena Jaskorzynska

Light is injected into the input ridge waveguide by focusing light at the input cleaved facet via a lensed fiber and the transmitted light is collected from the other facet either by a microscope objective into a fiber, or directly via a fiber. Measurements presented in this chapter were performed on three different end-fire set-ups. One at KTH (Sec. 8.4), the second at EPFL (Sec. 8.5), and the third one at LPN (Sec. 8.6). The set-up at KTH employs a ×63 microscope objective focusing the collected light onto a multimode fiber with a core diameter of 64 μm. This fiber is connected to an InGaAs photodiode. A fraction of the output light is directed at an infrared Vidicon camera by means of a beam splitter, and enables optical alignment and coupling. Experiments consisting of imaging the output light profile are also performed using the image on the Vidicon camera. The set-ups at EPFL
and LPN use two micro-lensed fibers and the alignment is performed by monitoring
the output signal level, which is a very delicate procedure.

8.4 Experimental investigations of negative refraction

Light focusing

The experiment described in this section is a demonstration of the phenomenon of
negative refraction in periodic dielectric structures. The negative refraction behavior
of 2D PhC fields as described earlier in this chapter are applied here to focus
light and we refer to such a lens as a flat lens. The experimental device is formed
by a $1.2 \mu m$-wide ridge waveguide with a 8-row TM oriented PhC field at its output.
The PhC is formed by a triangular lattice of air holes with $a=480nm$ and $r=125nm$
etched in the standard vertical heterostructure waveguide InP/InGaAsP/InP. The
sample is cleaved at a distance $d=17 \mu m$ from the input edge of the PhC field.

![Figure 8.8: a) Scanning electron microscope view graph of the fabricated PhC flat
lens; b) Schematic drawing of the modified end-fire set-up for the light focusing
experiment.](image1)

![Figure 8.9: Beam profiles of the light collected after the cleaved facet a) without
PhC field; b) with the PhC field showing a point of best focus.](image2)
8.4. EXPERIMENTAL INVESTIGATIONS OF NEGATIVE REFRACTION

Figure 8.8a is a SEM picture of the fabricated device. The wavelength of operation is $\lambda=1480\,\text{nm}$, corresponding to a normalized frequency of $\nu=0.324$. The shape of the output beam after the cleaved facet is recorded on the Vidicon camera as the collecting microscope objective is moved outwards from the point of focus on the cleaved facet (Fig. 8.8b). The measured full width at half maximum (FWHM) of the output beam in the presence of the PhC flat lens is compared to the reference case without any PhC field on Fig. 8.9: light focusing is clearly evidenced for the PhC lens. The experimental results are consistent with 2D FDTD simulations, as discussed in Paper G.

Light Collection using Negative Refraction

The ability to focus light at the exit of a PhC field in the regime of negative refraction can be potentially interesting for integrated optics to enhance the collection efficiency of a ridge waveguide. In order to demonstrate this principle experimentally the position of the output ridge for the PhC field was varied. A SEM top view of a fabricated device is shown on Fig. 8.10.

![SEM top view of the fabricated device for light collection.](image)

Figure 8.10: SEM top view of the fabricated device for light collection.

![Measured transmission at the output of the ridges located at three different distances $d$ from the PhC lens. The transmission through a ridge collector without PhC field is shown for purpose of comparison.](image)

Figure 8.11: Measured transmission at the output of the ridges located at three different distances $d$ from the PhC lens. The transmission through a ridge collector without PhC field is shown for purpose of comparison.
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

As we vary the wavelength, the size of the respective EFC is modified. As a consequence for a given range of angles of incident light at the input, the refraction angles will be altered. Then, the position of the point of best focus will depend on the wavelength. Figure 8.11 indicates that the level of light collection by the output ridge waveguide is much higher than in the case without PhC lens. As expected from the wavevector diagrams, the collected intensity is wavelength dependent: the PBF gets closer to the PhC lens as $\lambda$ increases. The measured transmission spectra are in very good agreement with those obtained by 2D FDTD simulations (Paper G).

8.5 Fourier Optics

Probing experimentally the photonic band structure and exploring anomalous dispersion effects has been an exciting research topic for many years, both in terms of novel experimental techniques and for demonstration of particular effects. Different methods have been shown to provide details about the photonic band structure:

- **Angle-resolved Surface Coupling** techniques for experimental investigation of the band structure using reflectivity [164], or photoluminescence measurements [165].

- **Scanning Near-field Optical Microscope (SNOM)** characterization under continuous wave [166], or pulse [167] excitation.

- **Fourier Optics techniques** uses the optical Fourier transform of out-of-plane diffracted light [168, 169] to investigate the band structure.

The surface coupling techniques with angle-resolved detection are well adapted to probe the available Bloch modes in the structure. For a long time restricted to Bloch modes with a component inside the light cone, the investigation of modes below the light line was recently reported [170]. However, in this case, the excitation and coupling to Bloch modes is dependent on the method itself and cannot be varied: in particular, the local excitation of Bloch modes in a given device design cannot be determined. Moreover, the method is time consuming since every angle ($k$-value) has to be measured separately. Similar arguments apply to SNOM based methods, where every spatial point has to be scanned. The advantage of the Fourier optics method is the immediacy of the results. Here we apply the principle of the real-time momentum space imaging provided by Fourier optics together with the end-fire technique to couple light into planar PhC structures. This method is more appropriate to study different configuration of excitation/coupling, especially those typically required in devices. One drawback of the technique is that one needs a field area sufficiently large (as well as a large numerical aperture objective) to be able to gather a sufficient part of out-of-plane radiation to form a clear signal at the Fourier plane. The measurements were carried out during a visit at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland within the framework...
8.5. FOURIER OPTICS

of the European Network of Excellence on Photonic Integrated Components and Circuits.

Experimental set-up: principle of measurement

Fourier optics measurements rely on the inherent properties of lenses to map the far field diffraction pattern of the samples at the back focal plane. It can be shown [171] that the far field diffraction pattern is the angular spectrum of the diffracted light, in other words its Fourier Transform. The back focal plane, for that reason, is called the Fourier plane. If one records the light intensity map at the Fourier plane it is possible to obtain information on the diffraction angles of the out-of-plane radiated light. Figure 8.12 shows the configuration of the optics to image the structure in real space and in Fourier space. An important advantage is that one can easily switch from the real space configuration to the Fourier space by inserting lens L3.

Figure 8.12: Configuration of the optics for observation in (a) real space and (b) in the Fourier plane.

Figure 8.13: Schematic sketch showing a thick lens and the definition of the primary principal surfaces and the Fourier plane.
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

Coupling of light into the PhC structure is performed in-plane and uses an end-fire configuration with lensed fibers at the input and output of the access ridge waveguides. The output signal was used for alignment purposes. The out-of-plane radiated light is collected by a microscope objective of large numerical aperture (NA=0.90). The microscope objective is modeled as a thick lens for which the primary principal surface is a sphere centered at the front focal point (Fig 8.13). Therefore the relationship between the norm of the in-plane wavevector $k_i$ and the corresponding distance at the back focal plane of the objective is given by,

$$k_i = k_0 \sin(\vartheta) = \frac{2\pi d}{\lambda_0 f}$$  \hspace{1cm} (8.1)

where $k_0$ is the wavevector in air, $\vartheta$ the angle of out-of-plane scattering defined from the surface normal, $d$ is the distance from the origin in the Fourier plane, and $f$ the focal length of the microscope objective.

The image on the CCD camera is a direct magnification of the in-plane wavevector space, imaged by the two pairs of lenses L1/L2 and L3/L4. Since the back focal plane of lens L2 is an image of the Fourier plane, we can perform optical filtering of the image by blocking the ray path of some spatial frequencies. In a similar fashion, the back focal plane of lens L1 can serve to delimit the part of the structure we wish to characterize.

Figure 8.14: Measurement with TE polarized light ($\lambda=1530\text{nm}$): a) Real space image showing auto-collimation; b) corresponding Fourier plane image superposed on to the EFC calculated by PWE.

Auto-collimation

A light beam is called collimated when its spatial divergence is close to zero. In the context of PhC devices, a beam is said to be auto-collimated when the light propagating in the PhC field forms a collimated beam, which is to say that the group velocity vectors are parallel to each other. Since $v_g$ is normal to the EFC, this implies that the EFC is flat (perpendicular to the direction of propagation).
This situation is illustrated on Fig. 8.14 where a) is the real space image and b) the Fourier plane image together with the calculated EFC.

Visualization of the excited Bloch modes in the 2D PhC field

![Visualization of the excited Bloch modes in the 2D PhC field](image)

Figure 8.15: Comparison of the equi-frequency contours calculated by PWE with a) the experiments ($\lambda=1500\,\text{nm}$); b) the FT-FDTD calculations showing the excited profiles for $u=0.310$.

The imaging of the Fourier plane allows us to see the evolution of the excited Bloch modes in the PhC field, as a function of the wavelength. As discussed in Paper H, the Bloch modes of significant weight correspond to the second band and are located in the Brillouin zones adjacent to the first Brillouin zone. In that case, the light that radiates out of the structure is the weak Bloch harmonics located in the air light cone (i.e., in the first zone). The experimental curvature of the excited part of the EFC is well fitted by PWE as shown on Fig. 8.15 and in Paper H. The comparison with FT-FDTD simulations reveals that the experimentally observed EFCs correspond to what is expected in terms of coupling into the Bloch modes.

The curvature of the band structure is also interesting to characterize as a function of the normalized frequency for a given direction in reciprocal space. The variations in the slope of the dispersion curve $\omega(\vec{k})$ influences the propagation of light. In regions close to band edges, modes become flat and the propagating light is slowed down. Investigation of such structures by Fourier optics would be very valuable. Below, we discuss the phase shift technique to investigate slow light structures.

### 8.6 Group velocity dispersion in photonic crystal waveguides

As we have seen earlier in this chapter, photonic crystals provide exciting opportunities to tailor light dispersion. Such applications were already investigated in
one-dimensional grating structures where band edge effects were used for dispersion compensation [172]. In this section we will turn our attention to dispersion in PhC waveguides focusing on coupled-cavity waveguides (CCW). The unusual dispersion achieved by these waveguides can be applied for non-linear applications such as soliton propagation [173] or wavelength conversion (like second harmonic generation [174, 175]), pulse compression, optical delay lines [31]. Here we present our results on the experimental measurements of the group velocity dispersion close to mode cut-off at band-edge for waveguide modes.

**PhC waveguides**

Line-defect waveguides are formed in a PhC lattice by removing a certain number of rows along a particular direction of propagation. PhC waveguides are identified by the number of missing rows $n$ and called $W_n$. For such waveguides, the band structure (including the allowed modes of the waveguide) is usually shown projected along the waveguiding direction. Examples of band structures for $W1$ and $W3$ are shown on Fig. 8.16.

![Figure 8.16: Dispersion diagram calculated by PWE for a) W1 and b) W3 with $f=40\%$. The x-axis shows the wavevector $k$ along the propagation direction. The badgap is indicated by an arrow in a).](image)

W1 waveguides have two modes in the photonic bandgap; however, over a certain range of frequencies, it operates as a monomode waveguide. In contrast, the dispersion diagram for W3 appears much more complex with several modes being present. Depending on the wavevector, the confinement of the waveguide modes can have different origins: the refractive-like region is obtained when the modal dispersion is linear, whereas bandgap effects affect modes close to the band edges where the modal dispersion becomes highly non-linear [142].
8.6. GROUP VELOCITY DISPERSION IN PHOTONIC CRYSTAL WAVEGUIDES

Slow light

Light propagating in a medium of refractive index $n$ travels with a velocity $v = c/n$. The slowing down of the light is thus achieved by modifications of the refractive index of the material. This can be achieved (i) by material dispersion (i.e., electromagnetically induced transparency EIT [176]) or (ii) by structural dispersion, e.g., in PhCs, where slow light appears close to band edges where the gradient of the dispersion curve (i.e., the group velocity) tends to zero.

The coupling into slow light modes is difficult due to reflections and modal mismatch at the interface between a normal waveguide and a slow light structure. In the approach adopted in Paper I, the coupling was improved using a tapered section at the entrance of the slow light structure [105]. Other solutions have also been proposed, for example by engineering the interfaces [177].

Coupled cavity waveguides

Coupled cavity waveguides are formed by a succession of in-line cavities forming a waveguide [178]. When cavities are close to each other, light is transferred from one cavity to the other and forms so-called supermodes. The spacing between cavities determines the wave function overlap, hence their coupling. In case of low coupling (equivalently, for cavities with high quality factors), light will stay longer in each cavity before neighboring cavities are excited. Therefore this situation leads to a low group velocity in the CCW. In order to experimentally determine this dependence we studied two CCW designs: the first one with weakly coupled cavities in a W1-based design (W1-CC) and a second one based on a W3 design having a larger cavity mode overlap (W3-CC).

The PhC waveguides were fabricated as described in Chap. 3. The geometrical PhC parameters are $a=450\,\text{nm}$ and $f=40\%$. PhC structures are inserted in between two 500 nm long ridge waveguides. W1-CC is formed by eight two-missing-hole cavities and with single-hole mirrors (hence a period $3a$) as seen on Fig. 8.17a. In order to improve light coupling into W1, a tapered transition (mode converters) from W3 to W1 [105] was provided. The reflections at the cleaved faces were suppressed by an anti-reflection coating. The second structure is a W3 based CCW with cavities formed by regular constrictions from W3 to W1 with a period of $2a$ and is 120 row long (Fig. 8.17b).

The dispersion relations for the respective CCW calculated by PWE are shown on Fig. 8.18. The wavelength range of interest is also shown indicating the studied mode cut-off for both of the designs. Inverse of the slope of the dispersion curve $d\omega/dk$ gives the group index $n_g$. The Group Velocity Dispersion (GVD) is the first chromatic derivative of the group velocity. In the context of optical communication, one usually characterizes the group velocity dispersion by the group delay dispersion parameter $D$ [44],

$$D = \frac{1}{L} \frac{d\tau}{d\lambda}$$

(8.2)
Figure 8.17: SEM micrographs of the fabricated CCW devices a) W1-CC with indication of the W3, taper, W1 and CCW sections; b) close view of the interface between the ridge waveguide and the W3-CC.

Figure 8.18: Dispersion diagrams for coupled-cavities designs (f=40%) a) W1 CC; b) W3-CC with f=40%. The gray shaded regions are the investigated wavelength range.
8.6. GROUP VELOCITY DISPERSION IN PHOTONIC CRYSTAL WAVEGUIDES

where $L$ is the length of the studied structure, $\tau$ is the time delay and $\lambda$ is the wavelength.

Phase-shift technique

Several methods have been reported to measure group velocities in regions of flattened dispersion. The Fabry-Pérot method relies on the measurement of oscillations originating from reflections at the extremities of the PhC waveguide. Closely spaced oscillations indicate a larger group index, hence a smaller group velocity [179]. However, very close to the mode cut-off, this method becomes difficult to implement since the group indices become too high. Interferometric methods based on an integrated Mach-Zender scheme provide information about the phase change in the PhC waveguide [180]. Measurement of the time-of-flight of femtosecond pulses is a direct method to determine time delays and group velocities [149, 181]. However, the interpretation of the results is rather involved since the pulse can be reshaped depending on the bandwidth of the waveguide mode. Large $n_g$ values are also difficult to measure when the pulse bandwidth is broader than that for constant $n_g$. Another method is the real-space observation of slow light behavior of PhC waveguides using time-resolved Scanning Near-field Optical Microscopy with an heterodyne detection scheme [182].

The method used in this work is the phase-shift method. The modulation phase-shift method consists in measuring the phase shift $\phi$ between a reference signal $P_{in} = \cos(\omega t)$ and the same signal transmitted through the PhC waveguide (which is now phase shifted) $P_{out} = \cos(\omega t + \phi) = \cos(\omega(t + \tau))$; here $\omega$ is the angular frequency of the modulation and $\tau$ the group delay. It is a commonly used method to measure GVD in optical fibers. The measurement set-up is also an end-fire configuration. At the input the optical source is modulated by an electro-optic (LiNbO$_3$ based) Mach-Zender modulator, two lensed-fibers couple the light in and out of the structure, and the output signal is amplified. A network analyzer with a phase comparator records $\phi = f(\lambda)$ (Fig. 8.19).

The value of the group delay dispersion $D$ introduced by the PhC waveguide is expressed in ps/nm$^{-1}$,km$^{-1}$ as:

$$D = \frac{1}{L} \frac{d\tau}{d\lambda} \approx \frac{1}{2\pi f_{mod}} \frac{\Delta \phi}{\Delta \lambda}$$  \hspace{1cm} (8.3)

where $L$ is the length of the CCW and $f_{mod}$ the modulation frequency. The dispersion parameter $D$ is linked to the curvature of the dispersion diagram by the expression [44]:

$$D = -\frac{2\pi c}{\lambda^2} \frac{d^2 k}{d\omega^2}$$  \hspace{1cm} (8.4)

For data extraction we use $\Delta \lambda = 1.5$ nm for W1-CC and 3 nm for W3-CC. Measurements through simple ridge waveguides constitute the reference signal for normalization.
CHAPTER 8. SOME SELECTED DISPERSION PROPERTIES OF PHOTONIC CRYSTAL BASED DEVICES

Measurement results

The measurement of the phase shift allows to extract the value of the group index \( n_g \) according to the relation [44],

\[
\Delta n_g = D \cdot c \cdot \Delta \lambda \quad (8.5)
\]

For the W1-CC design, the GVD is of the order of \( 10^7 \text{ps.mm}^{-1}.\text{km}^{-1} \), and a peak at \( 35 \times 10^7 \text{ps.mm}^{-1}.\text{km}^{-1} \) with \( n_g \) up to 180, whereas the W3-CC design yields a GVD up to \( 15 \times 10^7 \text{ps.mm}^{-1}.\text{km}^{-1} \) and \( n_g \) up to 70. The CCW design with a stronger coupling (W1-CC) results in a weaker overlap between the coupled cavities, therefore the light propagation is slower and the group indices larger. However, even though the GVD and group index are lower, the W3-CC design is more flexible to tailor the dispersion to specific needs. Depending on the application, large GVD values can be beneficial or detrimental. A positive use of the large GVD values obtained in this work is dispersion compensation after propagation in optical fibers. As a stand-alone device for slow light operation, such large GVDs can deform pulses of 1 ps or less causing bandwidth problems, and may require a trade-off between GVD and \( n_g \). In order to overcome this issue, chirped structures have been proposed to obtain high \( n_g \) with relatively low GVD [183].

The large group velocity dispersion of PhC based CCW find a natural application in pulse reshaping. It has been demonstrated for 1D PhC structures in a 40 Gb/s optical transmission system [184]. Another promising application is the enhancement of non-linear effects. In that perspective 2D PhC may provide an advantage due to the larger degree of freedom in design.

The value for \( n_g \) measured in the present work (180), to the author’s knowledge, is the largest \( n_g \) value experimentally measured. The use of a W3 waveguide with a tapered section towards a W1 provides efficient coupling into the W1-CC slow light structure, enabling the measurement of such high group indices.

![Figure 8.19: Schematic drawing of the phase-shift measurement set-up.](image)
8.7 Conclusion

In this chapter we presented some selected dispersion properties of photonic crystal based devices. Concepts relevant to Bloch modes and their excitation in two-dimensional photonic crystals such as the equi-frequency contours, photonic strength and Bloch mode coupling functions were discussed. The phenomenon of negative refraction was experimentally demonstrated and applied for light collection of integrated optics devices. Fourier optics measurements allowed the observation of out-of-plane radiative Bloch modes. The experimentally obtained EFCs together with the calculated ones from PWE and from Fourier Transformed FDTD field maps is shown as necessary to understand and identify the excited Bloch modes. The wavelength dependence of the EFCs provides a measure of the slope of the bands and is in good agreement with the simulations. Finally, the dispersion in coupled cavity waveguides was characterized using the phase-shift technique. The group index dispersion was measured for waveguide modes near cut-off. We reported a group index value up to 180 and a GVD of $35 \times 10^7 \text{ps.nm}^{-1}\text{.km}^{-1}$ for a design based on weakly coupled cavities. A larger coupling between cavities was shown to reduce both group index and GVD values.
Chapter 9

Summary, conclusions and future work

This thesis has addressed (i) the physics and technology involved in the fabrication of InP-based photonic crystals, (ii) the optical properties of devices such as mirrors, 1D cavities, and slow light structures, (iii) special phenomena for light propagating in transmission bands above the bandgap (negative refraction and auto-collimation) and in slow light structures. In addition, the work also emphasizes the importance of material properties. In particular, the impact of the dry-etching on material properties such as surface Fermi level pinning, carrier lifetime and sidewall surface recombination velocities were investigated.

9.1 Achievements

The quality of the etching of PhCs (hole shape and depth) was improved as indicated by a reduction of the loss level by 50% compared with the values reported at the beginning of this thesis. This was achieved by optimizing the vertical structure and by improving the etched holes (hole shape and depth) in Paper B. Experimental characterization of the feature size dependence of the etching (lag-effect) was performed (Paper A) and its implications on optical losses was demonstrated (Paper C). A model using the physico-chemistry of Ar/Cl₂ CAIBE that qualitatively reproduced the experimentally obtained lag-curves (dependence of etch depth on hole size) as a function of the etching time was developed (Paper A). A comprehensive understanding of the physics behind CAIBE etching of InP-based PhCs was provided in Paper A and Paper E.

The modifications of the material properties by Ar/Cl₂ CAIBE were investigated and experimental evidence for accumulated sidewall damage while dry-etching photonic crystal holes was obtained (Papers D and E). The non-radiative sidewall recombination velocities were determined and the variation with etch-duration is
qualitatively explained by a sputtering model taking into account the evolution of the hole shape during etching.

From the investigations of electron transport across PhCs, a method to determine the process-induced modification of the sidewall surface potential was demonstrated and its consequence on the electron transport was highlighted (Paper F). Surface Fermi level pinning at the hole sidewalls was found to be at 0.12 eV below the conduction band minimum. The measured I-V characteristics of photonic crystal fields provide information on resistance and current levels, which is useful for devices. Simulations of electron transport were performed to explain the observed I-V characteristics.

A few selected dispersive phenomena such as slow light, auto-collimation, and negative refraction were investigated. In Paper G, negative refraction at optical communication wavelengths was experimentally demonstrated. Focusing of light by a PhC lens was shown and the potential of this effect for light collection was explored. The curvature of the transmission bands were experimentally determined by imaging the EFCs by Fourier optics (Paper H). By varying the wavelength, the slope of the second band was determined from the imaged EFCs. Importantly, this work also provides a theoretical framework to understand the distribution of the excited Bloch modes in the PhC. The dispersion characteristics of super modes in PhC-based coupled-cavity waveguides were measured and a group index up to 180 at the mode cut-off was demonstrated. The results also suggest how the group velocity dispersion can be changed by altering the inter-cavity coupling.

9.2 Future work

Considering the current status of the field of photonic crystals including the present thesis work, some research areas/directions that are both interesting and challenging can be identified:

**Active PhC devices**

The efficiency of light emitting PhC devices (LED and lasers) is an important issue. In LEDs, PhCs are promising for light extraction. For lasers, it is important to find methods to reduce non-radiative surface recombination. In general, for active functionalities including tuning, electrical access is a major concern. The electrical study presented in this thesis should be pursued by the investigation of the role of the material (InGaAsP) and structure (membranes), of the configuration (other contact geometries) as well as the etching process (chemistry) and/or technique (ICP, ECR, ...). A scheme for local modification of the etched sidewalls could be developed to provide efficient electron and hole transport through the PhC fields. This would allow the formation of effective $p$--$n$ junctions.
9.2. *FUTURE WORK*

Physics of light propagation in the transmission bands

The exploration of band structure related effects in higher bands could bring a deeper understanding of the physics of light propagation in periodic media. Phenomena such as negative refraction, super-resolution or super-lensing should be investigated further for potential device applications. The interaction of ultra-short pulses with the photonic crystal medium can lead to a deeper understanding of dispersion engineering, and may lead to the discovery of a new range of applications.

Light-matter interaction

The photonic crystal patterning induces modification in the dispersion relation with interesting regions at the band edges or at mode cut-offs, resulting in a local enhancement of the optical density of states which is in certain cases divergent. This is an ideal situation for enhancing light-matter interactions. Dispersion of coupled-cavity systems or at the edges of transmission bands can be studied together with quantum dot containing materials for novel effects. The interaction of material non-linearities with the photonic bands is another potentially promising track. Enhanced non-linear effects using PhC structures are attractive for second or third harmonic generation.

Processing

On the processing side, challenges are still present: the actual loss level should be reduced by improvement of the hole profile towards more cylindrical hole shapes. A reduction of the sidewall roughness and hole to hole fluctuations would also allow a more precise control of the light and would potentially allow the demonstration of new phenomena. Such a development is also relevant for on-chip laser mirrors. New methods for sidewall passivation could be investigated, taking advantage of the process evaluation methods discussed in this thesis. As far as material damage is concerned, ways to control the amount of damage would present a new dimension to tailor the carrier lifetimes to the requirements of the application (either long lifetimes for light emission or ultra-short for optical switching).
Chapter 10

Guide to the papers

PAPER A: Characterization of the feature size dependence in \( \text{Ar/Cl}_2 \) chemically assisted ion beam etching of InP based photonic crystal devices

This paper presents a detailed analysis taking into account the different physical mechanisms in \( \text{Ar/Cl}_2 \) chemically assisted ion beam etching of InP-based photonic crystal structures and provides insights on the underlying mechanisms. The feature size dependence of the etching in terms of etch depth (often known as lag-effect), hole shape and roughness development are experimentally characterized. It is found that the achievable aspect ratios are significantly higher (around 20 to 25) than in the case of Reactive Ion Etching (around 2). A one-dimensional physico-chemical model taking into account the molecular conductance of the hole is developed and the results are shown to be in rather good agreement with the experiments.

Author contribution: carried out the experiments (sample design, CAIBE, SEM, optical measurements), developed the model, major parts of the data analysis and writing.

PAPER B: Minimization of out of plane losses in planar photonic crystals by optimizing the vertical waveguide

This paper evaluates the impact of the design of the vertical heterostructure InP /InGaAsP /InP on the optical losses of CAIBE etched photonic crystal devices. PhC mirrors and 1D cavities are characterized by the Internal Light Source technique. Optical losses are evaluated in the framework of the \( \epsilon^* \) model (which amounts to attributing a complex dielectric constant to the air holes). It is demonstrated that by a proper choice of the vertical structure, the total loss (which is the sum of the intrinsic and extrinsic contributions) can be minimized. This together with the improvements in the hole shape allows a reduction in the loss parameter \( \epsilon^* \) from 0.08 to 0.04.
Author contribution: part of sample design and fabrication (CAIBE, SEM analysis), optimization of the CAIBE process, part of data analysis, part of writing.

PAPER C: Impact of the feature size dependent etching on the optical properties of photonic crystal devices

This paper analyzes the impact of the feature size dependence of the etching of photonic crystal holes on the optical properties of one-dimensional cavities formed by two PhC mirrors. The optical characterization was performed using the Internal Light Source method. The quality factor of the 1D PhC cavities is shown to increase from 70 to more than 200 when hole depth increases from 2.3 to 4.3 μm. The determined intrinsic properties of the PhC mirror, its reflectivity and loss show consistent improvement with each depth. It is also found that this dependence shows two regimes: a large variation for depths smaller than 3.5 μm and a slower dependence for larger etch depth.

Author contribution: carried out the experiments (sample design, CAIBE etching, SEM analysis, ILS measurements), major part of analysis of data, major part of writing.

PAPER D: Evidence of accumulated sidewall damage in dry etched InP-based photonic crystals

Evidence for accumulated damage is provided by investigating the effect of etch duration on the carrier lifetime of an InGaAsP quantum well inside InP-based photonic crystal (PhC) structures. It is found that, once the quantum well is etched through, additional etching reduces the carrier lifetimes - from 800 to 70 ps. The observed variation of carrier lifetime with etch-duration is qualitatively understood by taking into account possible origins of accumulated damage and its development. The results suggest a new method for tailoring the carrier lifetimes in PhC membrane structures.

Author contribution: sample fabrication (design, e-beam, CAIBE etching), part of data analysis, major part of writing.

PAPER E: Development of damage and its impact on surface recombination velocities in dry-etched InP-based photonic crystals

The material damage introduced by Ar/Cl₂ CAIBE of photonic crystal fields is investigated by time resolved photoluminescence measurements. The surface recombination velocities (SRV) at the exposed hole sidewalls were determined in PhC holes etched for different durations. The SRV increases with etching time, evidencing the presence of accumulated sidewall damage. However this increase is non-linear and
varies more slowly at long etching times. A physical model based on sputtering theory and the evolution of hole shape during etching is developed to explain the experimental data.

**Author contribution:** sample fabrication (design, e-beam, CAIBE etching), part of data analysis, modeling, major part of writing.

**PAPER F: Carrier transport through a dry-etched InP-based two dimensional photonic crystal**

In this paper the electrical properties of InP-based photonic crystal fields are measured experimentally and simulated by a finite element method. The current-voltage characteristics are linear at low applied voltages and show current saturation at higher voltages. For a given period, the resistance of the PhC fields increases with air-fill factor and for a given air fill factor it decreases with lattice period. The current saturation at high applied voltages is attributed to the saturation of the electron drift velocity. From the measured and simulated conductance for the different PhC fields we show that it is possible to determine the sidewall depletion region width and hence the surface potential. We find that at the hole sidewalls the etching induces a Fermi level pinning at about 0.12 eV below the conduction band edge, a value much lower than the bare InP surface potential.

**Author contribution:** sample fabrication (design, e-beam, CAIBE etching, metalization), electrical measurements, part of data analysis, major part of writing.

**PAPER G: Negative refraction at infra-red wavelengths in a two-dimensional photonic crystal**

This paper experimentally demonstrates negative refraction effects at telecommunication wavelengths. A photonic crystal flat lens is fabricated in the InP/InGaAsP/InP material system. Focusing of light is demonstrated and explained using wavevector diagrams from the calculated band structure. The application of lensing for light collection is addressed. Consistent with the band structure, the position of the focal point as well as coupling efficiency for a given placement of the collecting ridge is wavelength dependent.

**Author contribution:** part of fabrication, end-fire measurements, data analysis, major part of writing.

**PAPER H: Experimental observation of excited Bloch modes by Fourier Optics**

Bloch mode coupling into a two-dimensional photonic crystal field is investigated theoretically and experimentally. Fourier optics is used to characterize the out-of-plane radiative modes allowing the experimental assessment of Bloch mode coupling.
in an end-fire configuration to obtain the curvature of the bands at different wavelengths. Equi-frequency contours calculated by Plane Wave Expansion (PWE) and the Fourier Transforms of field maps obtained from Finite-difference Time-domain (FDTD) simulations allow the identification of energy carrying Bloch modes with their respective photonic bands. PhC fields working in the auto-collimation regime are characterized. The shape of the imaged EFS and its variation with excitation wavelength is shown to be consistent with the theoretical simulations.

**Author contribution:** sample fabrication (design, e-beam, CAIBE, preparation for optical measurements) and simulations, parts of optical characterization, major part of data analysis, major part of writing.

**PAPER I: Highly dispersive photonic crystal-based coupled-cavity structures**

In this paper, using a phase shift technique, two photonic crystal based slow light structures are compared with respect to the group indices and group velocity dispersion. The first device is a W1 based coupled cavity waveguide (CCW) with one-hole mirror and the second waveguide is a W3 waveguide regularly constricted to a W1. It is shown that a large value for the group velocity dispersion is obtained for the CCW with the lowest intra-cavity coupling. A group index up to 180 is experimentally obtained for the same design.

**Author contribution:** sample fabrication (CAIBE etching), part of data analysis, part of writing.
General references


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<th>Author(s)</th>
<th>Title</th>
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<tbody>
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