Gap plasmon mode
distributed feedback lasers

PROEFSCHRIFT

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Aan mijn ouders
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List of symbols and abbreviations

\( \alpha_i \) Internal loss
\( \alpha_m \) Mirror loss
\( \Delta \varepsilon \) Lorentz oscillator strength
\( \varepsilon \) Dielectric constant
\( \varepsilon_\infty \) Residual polarization
\( \gamma(n) \) Overall spontaneous emission enhancement factor
\( \gamma_m(n) \) Spontaneous emission enhancement factor directed to a mode
\( \gamma_n \) Lorentz oscillator damping
\( \Gamma_{yz} \) Confinement factor in the yz-plane
\( \kappa \) Grating coupling constant
\( \lambda \) Wavelength
\( \omega \) Angular frequency, \( \omega = 2\pi f \)
\( \omega_n \) Lorentz oscillator frequency
\( \tau_{p,m} \) Photon lifetime of mode m
\( d_{\text{etch}} \) Total etch depth
\( E_{\text{gap}} \) Band-gap energy
\( h_{\text{core}} \) Height of the InGaAs core region
\( n_d \) Refractive index of the dielectric insulation layer
\( n_{\text{InGaAs}} \) Refractive index of InGaAs
\( n_{\text{InP}} \) Refractive index of InP
List of symbols and abbrevations

\( t_d \)  Thickness/Width of the dielectric layer
\( t_m \)  Thickness/Width of the metal cladding
\( w_b \)  The amount of bulge in the waveguide core due to selective wet etching
\( w_c \)  Width of the semiconductor core
\( w_g \)  Total width of the grating (incl. \( w_c \))

A  Complex amplitude of an electromagnetic wave

k  Angular wave-number

A  Surface recombination velocity

a  Unit of length in FDTD simulations

ALD  Atomic layer deposition

ASE  Amplified spontaneous emission

AWG  Arrayed waveguide grating

B  Bimolecular recombination coefficient

C  Auger recombination coefficient

c  Speed of light in vacuum, \( 2.998 \cdot 10^8 \) [m/s]

C.W.  Continuous wave

DFB  Distributed feedback

EBL  Electron beam lithography

\( F_m \)  Purcell factor of mode m

F.W.H.M.  Full width at half maximum

FDTD  Finite Difference Time Domain

FIB  Focussed ion beam

HSQ  Hydroxy silsesquioxane

I  Current

ICP  Inductively coupled plasma

\( \text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y} \)  Indium Gallium Arsenide Phosphide

InP  Indium Phosphide

L  Length

x
List of symbols and abbreviations

L-I curve  Light-current curve
L-L curve  Light-light curve
M-I-M  Metal-insulator-metal
M-I-S-I-M Metal-insulator-semiconductor-insulator-metal
MMI  Multi-mode interference coupler
MOCVD  Metal-organic vapor deposition
N  Carrier density
NIR  Near infrared
PECVD  Plasma enhanced chemical vapor deposition
PIC  Photonic Integrated Circuit
PML  Perfectly matched layer
Q  Quality factor of a cavity, measure for the decay rate of energy, \( Q \sim \tau_p \)
q  Electron charge
QCL  Quantum cascade laser
QW  Quantum well
R  Power reflection coefficient
r  Amplitude reflection coefficient
RIE  Reactive ion etching
RTA  Rapid thermal annealing
S  Photon density
\( S_a \)  Active surface of a device
SI  Semi-insulating
SMSR  Side-mode suppression ratio
SOA  Semiconductor optical amplifier
t  Time
TE  Transverse Electric
TIR  Total internal reflection
TM  Transverse Magnetic
V  Active volume of a device
\( v_g \)  Group velocity
List of symbols and abbreviations
Chapter 1
Introduction

1.1 Photonic integrated circuits

In conventional photonic integrated circuits (PICs) light can be transported by waveguides. These waveguides come in many different forms, however, the light is always confined to a medium with a high refractive index surrounded by media with a lower refractive index. The minimum dimensions of a waveguide are typically in the order of the wavelength of the light inside the material. Depending on the transverse dimensions and shape, one or more (transverse) modes are sustained by the structure. These modes propagate along the waveguide, possibly with very low loss.

Figure 1.1: Schematic representation of a typical waveguide as seen in InP technology.

A cross-section of a typical waveguide fabricated in InP (Indium Phosphide) technology is shown in figure [1.1]. In this structure the light is confined to the waveguide core, consisting of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$. Many other optical components (such as: MMIs, AWGs and SOAs) are a variation of this basic waveguide structure or consist of a collection of multiple waveguides. Active components, for the amplification or detection of light, can be created by adding
electrical contacts to the waveguide structure.

Photonic integrated circuits are often a collection of several integrated optical components (both active and passive). The InP platform has the advantage that both active and passive optical components can be integrated monolithically. This is possible due to the fact that by changing the composition of the In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ compound, the band gap energy of the material can be tuned from 0.75 eV to 1.35 eV (920 nm - 1650 nm). Light with $E_{\text{photon}} < E_{\text{gap}}$ experiences the material as transparent, whereas light with $E_{\text{photon}} \geq E_{\text{gap}}$ can be amplified or absorbed [1].

Opto-electronic devices are useful for the fast transport and processing of large amounts of data. Their field of application is continuously being extended. Nowadays, they are also being considered for sensing and computing applications etc. Most PICs have still analog functionality, but there is a growing interest in digital integrated optics. Examples of digital PICs are optical logic gates and optical flip-flops. Such PICs would allow us to process data without first converting it from the optical to the electrical domain (for processing) and then back again, leading to very low power and high speed operation.

Compared to integrated electrical circuits, photonic integrated circuits currently suffer from the disadvantage that their size is much larger than that of their electrical equivalent. This is because electrical signals can be transported by small wires down to nanometer dimensions, without being hampered by cut-off conditions. Photonic integrated circuits are limited by the diffraction limit of light. The index contrast of the materials determines minimum dimensions and the minimum allowed bend radius of waveguides. People have come up with elegant ways to reduce the size of PICs, such as photonic crystals, but sub-wavelength confinement of light can not be achieved using ordinary dielectric structures.

1.2 Metals in integrated optics

1.2.1 Optical properties of metals

Metals owe their characteristic properties to the presence of free electrons inside the material. These electrons are loosely bound valence electrons, which become free in the crystal and form a kind of electron gas. It is this electron gas that holds the metal ions together in the crystal structure and constitutes the metallic bond [2].

The free electrons inside the metal can be displaced under the presence of an externally applied electric field. This displacement of carriers causes the material to become polarized. At low frequencies, the unbound electrons are able to follow changes of an external electromagnetic field and prevent penetration of the field into the metal. The perfect electric conductor approximation is valid for most applications. For frequencies approaching the optical domain, penetration into the metal increases. At even higher frequencies, some metals become transparent.

Propagation of any form of electromagnetic radiation can be described by Maxwell’s equations. In Maxwell’s equations, the polarizability of a material is accounted for by the term $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$ with $\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$. This approach is also valid for waves propagating through metals. The highly dispersive nature of a metal can be described with a complex dielectric function.

The complex dielectric function of a metal can be explained over a wide frequency range by a plasma model, in which a gas of free electrons of a particular density moves against a fixed background of positive ion cores [3]. This approach is limited for noble metals, where
inter-band transitions can occur at visible frequencies.

\[ \varepsilon(\omega) = \varepsilon_\infty + \sum_n \frac{\omega_n^2 \Delta \varepsilon}{\omega_n^2 - \omega^2 - i\omega \gamma_n} \quad (1.1) \]

Properties of noble metals, as used in this thesis, can be modeled a Lorentz model (equation 1.1), with one or more oscillator terms \((n \geq 1)\). In this equation, \(\omega\) is the wavelength at which the dielectric constant is defined. \(\varepsilon_\infty, \Delta \varepsilon, \omega_n, \text{and } \gamma_n\) define the residual polarization, the oscillator strength, frequency and damping respectively. The complex dielectric function describing the metal of interest can be experimentally obtained using ellipsometry and fitting the parameters of the model to the data.

1.2.2 Plasmons

Combining Maxwell’s equations, we obtain the wave equation (equation 1.2). A wave can only propagate through a medium, if its fields satisfy the wave equation. If we investigate the solutions for a metal (in the absence of external stimuli), using the complex dielectric function obtained in the previous section, we find that two solutions are possible. One solution involving longitudinal waves and the other involving transverse waves.

\[ \nabla \times \nabla \times E = -\mu_0 \frac{\partial^2 D}{\partial t^2} \quad (1.2) \]

The longitudinal waves exist for situations where \(\varepsilon(\omega, k) = 0\). This occurs for frequencies \(\omega > \omega_p\), where \(\omega_p\) is the plasma frequency. The plasma frequency of silver lies at 9.01 eV \[4\]. The propagating waves corresponding to this solution of the wave equation, are collective longitudinal oscillation of the electron gas. The quanta of these oscillations are called plasmons (from plasma oscillation) or, more specific, volume plasmons. They do not couple to transverse electromagnetic waves and can only be excited by particle impact \[5\].

The second solution is found if we solve the wave equation at the interface between a metal and a dielectric. These waves are coherent oscillations of the unbound electrons present at the interface. The oscillations give rise to a surface wave, which can propagate along the surface of a metal\(^1\) \[5\]. They are therefore referred to as surface plasmon polaritons or surface plasmons. The waves corresponding to this solution are accompanied by a mixed transversal and longitudinal electromagnetic field. It can couple to transverse electromagnetic waves. The dispersion curve \(\omega(k)\) of a surface plasmon mode, propagating along a single interface, lies right of the light line. This implies that surface plasmons have a longer wave-vector than light waves of the same wavelength in vacuum; therefore they are called "non-radiative" surface plasmons. A schematical representation of such a wave is shown in figure 1.2.

1.3 Progress in plasmonics

Since their discovery in 1957 (by R.H. Ritchie \[6\]), surface plasmons (and metallic photonic integrated circuits) have received considerable interest. Mostly because of their ability to confine light on a deep sub-wavelength scale. Currently most device-related research on plasmonics, focuses on passive structures, such as waveguides, tapers and couplers. Although also

\(^1\)Besides metals, also heavily doped semiconductors support propagation of surface plasmons.
applications of surface plasmons in active devices can be found, currently these are mostly limited to quantum cascade lasers (QCL). Examples of both passive and active plasmonic structures are given in this section.

1.3.1 Passive structures

Passive plasmonic structures can be subdivided in two categories. The first category involves devices that guide light at a single metal-dielectric interface (shown in figures 1.3(a) and 1.3(b)). The second category involves structures where two metal-dielectric interfaces are brought in close proximity (within decay length of the electric field), so that the surface plasmons on both interfaces start interacting and form a mode. Most common forms of these structures are M-I-M waveguides and I-M-I waveguides (shown in figures 1.3(c) and 1.3(d)).

Single and double interface plasmonic waveguide structures have extensively been studied by Pradé, Dionne, Kaminow in references [7, 8, 9, 10] as well as V-groove waveguides by Pile in reference [11]. Most other devices are a variation on these structures. Theoretical and experimental studies of couplers have been published [12, 13]. Another area of interest is devoted to the nano-focussing of light by means of plasmonic tapers [14, 15]. Theoretical and experimental studies of wavelength selective components can be found in references [16, 17, 18, 19].

1.3.2 Active structures

As mentioned before, plasmon assisted confinement of light has been used extensively in quantum cascade lasers, operating in the wavelength range of 5 µm up to 25 µm [20]. For wavelengths approaching the near-infrared (NIR), the optical loss in plasmonic waveguides increases due to increased electron scattering. As shown by Maier in [21], common semiconductor materials can provide sufficient gain to overcome this loss. Even so, it was believed for a long time that lasing in plasmonic light confining structures, with dimensions well below the diffraction limit of light, was impossible.

In the mean time, several people have proved that metallic cavities with moderate Q-values can reproducibly be fabricated and that laser operation can be sustained in these structures [22, 23, 24]. Where the structures presented in [24] come closest to application in real PICs, since they are electrically pumped and fabricated from materials widely used for PICs. These devices open a whole new range of possibilities for photonic integrated circuits, allowing operation at very low currents and possibly with very high switching speeds.
1.4 Outline of this thesis

In this thesis we will look at the possibility of creating Distributed Feedback (DFB) lasers based on gap plasmon waveguides. The goal of the distributed feedback is to provide control
over the operation wavelength and emissive properties of the device. The plasmonic DFB lasers could have an application in integrated optical logic gates [25].

In the second chapter of this thesis the behavior of the active gap plasmon waveguide structure is introduced and discussed. The effective mode index, confinement and propagation loss are studied. Also the influence of the sidewall angle, open end-facets and material dispersion are investigated.

The third chapter goes on to describe how distributed feedback can be incorporated in these waveguides. The key structural parameters of the distributed feedback are defined and their influence is studied. Later in the chapter, cavities with distributed feedback are analyzed for their threshold requirements and spontaneous emission enhancement capabilities.

Chapter four gives the design considerations that were taken into account for the fabrication of the plasmonic lasers. It also describes the layout of a chip containing a large number of plasmonic devices. Of these devices, several structural parameters are varied systematically, so that their influence can be studied.

The fifth chapter discusses the fabrication process of the plasmonic DFB and Fabry-Pérot lasers, according to the chip layout presented in chapter four. There will be an emphasis on the lithography and dry etching of the structures. At the end of the chapter the required preparations for characterization of the devices is given.

The sixth chapter contains a description of the measurement setup and its operation are described. Measurement results, gathered from various processing runs, are presented and discussed. The measurement data is fitted to a model in order to extract characteristic parameters and in order to explain the behavior of the devices.

The final chapter discusses the work presented in this thesis. Besides the discussion, also recommendations are given for the continuation of the research.

1.5 Methods

In most literature on plasmonic structures with an application in PICs, structures of interest are analyzed using an effective index approach. However, due to the complex shape of the structures, the presence of abrupt transitions and the high index contrast [26], the most accurate results are obtained with Finite-Difference Time-Domain (FDTD) techniques [27, 28]. Where possible, the simulations discussed in this thesis are performed using the FDTD method.

FDTD simulations can be carried out in 1, 2 and 3 dimensions. The structure is mapped onto a grid, a so-called Yee lattice [29]. The size of this grid is the computational space. The Yee lattice consists of an interlinked array of Faraday’s law and Ampere’s law contours. Time-dependent Maxwell’s equations are discretized using the central difference approximations to the space and time partial derivatives. Due to the nature of the lattice, the Yee algorithm can solve both the electric and magnetic field in time and space, with second-order accuracy [27].

The computational space can be terminated by various types of boundary conditions. Most important boundary conditions are the perfectly matched layers (PMLs) and Bloch periodic boundary conditions. PMLs comprise of an artificial medium which absorbs electromagnetic waves incident from all angles and at all frequencies, without any reflection. The Bloch periodic boundary condition is helpful for analyzing periodic structures of infinite length by calculating the response of just a single period.

FDTD has the advantage that no assumptions are made, the algorithm is omni-directional and allows incorporation of material dispersion and gain in the simulations. Structures can be excited by a continuous source or a Gaussian pulse. This way the frequency response of a
structure can be determined over a large bandwidth by exciting the structure with a short pulse and waiting for a sufficiently long time for the fields to settle down. Even though FDTD is a very powerful tool, it also has disadvantages. The major drawbacks of this technique are that it can be very memory consuming and that the computation time can be very long.

Two FDTD software packages were used. MEEP a free, open-source FDTD tool developed at MIT and Lumerical, a commercial FDTD tool. Lumerical has the advantage of a large material database, non-uniform gridding and a graphical user-interface.
Chapter 1. Introduction
Chapter 2
Waveguiding

2.1 Introduction

In the first section of this chapter the basic structure of the metallic waveguide lasers is introduced and the relevant parameters of the structure are highlighted.

In the second section we look at the modes that are sustained by the metallic waveguides and we study their cut-off condition. It is important to ensure that only the fundamental plasmon mode is supported by the waveguides, since the fundamental TE mode has better overlap with the gain medium and experiences lower optical loss.

After we have determined the maximum width to guarantee pure plasmonic operation, we will discuss the influence of the width and other relevant parameters on the fundamental plasmon mode.

Finally, the influence of dispersion, waveguide termination and etch depth on the waveguide performance are discussed.


2.2 Active plasmonic waveguides

2.2.1 Waveguide structure

The waveguides used for the fabrication of the metallic waveguide lasers are a specific form of the M-I-M waveguide. The core is replaced with a semiconductor core and two thin dielectric layers have been added on both sides of the core. The semiconductor core consists of a standard double hetero-junction and provides vertical confinement and gain \[30, 31, 21\]. The thin dielectric layers electrically shield the semiconductor material from the metal cladding and force the electric current to flow through the semiconductor core, rather than the metal. The dielectric layers also fulfill an important role in the passivation of surface states created during the fabrication of the structures. The metal cladding of the waveguide is made of silver, since it exhibits the lowest optical loss in the wavelength range of interest. However, also other metals could be used, such as gold and aluminium \[10\].

![Waveguide structure diagram](image)

**Figure 2.1:** Schematic cross-section of a metallic waveguide. The definition of the axes, as shown in this figure, will be used throughout the thesis. Propagation is in the x direction.

A schematic overview of a cross-section of such a waveguide is shown in figure 2.1. In the remaining part of this thesis, this type of metal coated waveguide will be referred to as an M-I-S-I-M (metal-insulator-semiconductor-insulator-metal) waveguide. The legend of the figure lists the various materials inside the structure. Besides the materials, the legend also lists some of the key parameters related to the different part of structure. They are listed again below for clarity.

The refractive indices of the various materials in simulations can be found in appendix \[A\]. The presence of the dielectric layers close to the waveguide core has a significant influence on the optical behavior of the waveguide. This will be discussed in the next section.

2.2.2 Waveguide modes

Like dielectric waveguides, metallic waveguides can support TM and TE polarized modes, as shown in figures 2.2(a) and 2.2(a). Depending on \(w_c\), \(t_d\) and the refractive indices of the materials one or more modes are sustained inside the waveguide core. The TM polarized
2.2. Active plasmonic waveguides

\( \varepsilon_m(\omega) \)  \hspace{1cm} \text{Wavelength dependent, dielectric constant of the metal cladding.}
\( d_{\text{etch}} \)  \hspace{1cm} \text{Total etch depth.}
\( h_{\text{core}} \)  \hspace{1cm} \text{Height of the InGaAs core region.}
\( n_{\text{InP}} \)  \hspace{1cm} \text{Refractive index of InP}
\( n_{\text{InGaAs}} \)  \hspace{1cm} \text{Refractive index of InGaAs}
\( n_d \)  \hspace{1cm} \text{Refractive index of the dielectric insulation layer}
\( w_b \)  \hspace{1cm} \text{The amount of bulge in the waveguide core due to selective wet etching.}
\( w_c \)  \hspace{1cm} \text{Width of the semiconductor core} \quad (w_c = w_{\text{InP}} = w_{\text{InGaAs}} - w_b).
\( t_d \)  \hspace{1cm} \text{Thickness/Width of the dielectric layer.}
\( t_m \)  \hspace{1cm} \text{Thickness/Width of the metal cladding.}

modes are either plasmon modes (evanescent) or oscillating modes (sinusoidal shaped) [14]. The TE polarized modes only have an oscillating nature.

![Figure 2.2: Convention for the polarization states. Propagation is in the x direction. The amplitude of the individual components may vary, depending on the structure through which the wave is propagating.](image)

The electric field intensity of the fundamental TE and a TM mode are shown in figures 2.3(a) and 2.3(b). These field-profiles have been calculated using a finite-difference complex mode-solver, included in the Lumerical FDTD software package. For the TE mode, the dominant component is \( E_z \), whereas for the TM polarization \( E_y \) has the largest contribution to the electric field intensity (|E|^2).

Light in the TM polarized mode is concentrated at the transition with the silver cladding, a characteristic property for a surface wave. These waveguides modes are hybrid forms of surface waves and ordinary dielectric modes, similar to the ones predicted by Oulton [32].

We are most interested in the fundamental plasmon mode, since this mode exhibits no cut-off for a decreasing width of the waveguide core [9]. It allows for the sub-wavelength confinement of light. In order to guarantee that the devices discussed in this thesis only sustain the fundamental plasmon gap mode, we have studied the cut-off condition of the various waveguide modes by calculating the band-diagram of a 3 dimensional cross-section of the waveguide. These band-diagrams have been created using the MEEP FDTD package [28].

Band-diagrams are constructed from so-called unit-cells. A unit-cell is the smallest 1-,2- or 3 dimensional element in a periodic structure, from which the total structure can be reconstructed by infinitely repeating these elements in 1-,2- or 3 directions (translational sym-
Chapter 2. Waveguiding

![Electric field intensity (|E|^2) for the fundamental TE (a) and a TM (b) polarized mode. The width of the semiconductor core is 200 nm, the thickness of the dielectric layer 20 nm. The wavelength of both modes is 1550 nm. For TE, the E_z component provides the largest contribution to the electric field intensity distribution. For the TM polarization, the largest contribution is provided by E_y.](image1)

![Cross-section of the electric field intensity (|E|^2) for the fundamental TE (a) and a TM (b) polarized mode. Taken at the point of maximum intensity.](image2)

**Figure 2.3**: Electric field intensity (|E|^2) for the fundamental TE (a) and a TM (b) polarized mode. The width of the semiconductor core is 200 nm, the thickness of the dielectric layer 20 nm. The wavelength of both modes is 1550 nm. For TE, the E_z component provides the largest contribution to the electric field intensity distribution. For the TM polarization, the largest contribution is provided by E_y.

**Figure 2.4**: Cross-section of the electric field intensity (|E|^2) for the fundamental TE (a) and a TM (b) polarized mode. Taken at the point of maximum intensity.

By applying periodic boundary conditions on a single unit-cell, perpendicular to the direction(s) of repetition, the optical response of a seemingly infinite structure can be calculated.

Band-diagrams show the dispersion relation ω(k) of modes inside a unit-cell. They consist of fixed combinations of frequencies and propagation vectors. Collections of these points form bands. Every band corresponds to a mode that is allowed to propagate inside the unit-cell or an infinite repetition thereof. The effective index of a mode at a specific frequency can be found through relation 2.1. The group velocity is given through relation 2.2.

The simulations performed in MEEP require the use of scale-invariant units. This means that parameters such as frequency, wavelength and distance are normalized to a characteristic lengthscale a. The lengthscale used for all calculations in this thesis is a = 100 nm. Frequencies are expressed as a/λ, a wavelength of 1550 nm therefore corresponds to a frequency of 100 nm / 1550 nm = 0.0645. A size of 20 nm, becomes 20 nm / 100 nm = 0.2 in MEEP units.
and a wavelength of 1550 nm becomes 1550 nm / 100 nm = 15.5 in MEEP units. For the band-diagrams, however, the propagation constant \( k \) is normalized to the size of the unit-cell.

\[
\varepsilon(\omega) = \left( \frac{ck}{\omega} \right)^2
\]

(2.1)

\[
v_g = \frac{\partial \omega}{\partial k}
\]

(2.2)

Part of the band-diagrams, will be colored gray. The border between the shaded and unshaded area is referred to as the light line. In the metallic waveguides, we have defined the light line by the material with the lowest refractive index in the system (SiN\(_x\), \( n_d = 1.95 \)). Modes lying in the gray area have an effective mode index which is lower than that of medium (or structure) defining the light line, which is only possible if their wave vector has a significant component not directed along the axis of the waveguide. The light line thus marks the lower boundary for radiation modes that are not confined to the waveguide core. Any mode in the gray area can freely couple to one of these radiation modes and tends to be lossy [27].

The use of band-diagrams is not limited to periodic structures. They can also be used to characterize the behavior of waveguides. Waveguides can be regarded as a repetition of infinitely thin slices, where every slice is a cross-section (with zero thickness), taken perpendicular to the direction of propagation. The unit-cell used to obtain the band-diagrams of the M-I-S-I-M waveguide is the 2D cross-section shown in figure 2.5. The material parameters used for this calculation can be found in appendix A.

![Figure 2.5: 2D Cross-section of a metallic waveguide, used for the calculation of band-diagrams. Propagation is along the axis of repetition.](image)

Figures 2.6(a) and 2.6(b) show band-diagrams for M-I-S-I-M waveguides, with a 10 nm thick dielectric layer and with a 20 nm thick dielectric layer respectively. The band corresponding to the fundamental waveguide mode (TM\(_0\)), never crosses the light-line, indicating that it has no cut-off. The two bands that do cross the light-line belong to the 1\(^{st}\) order TM \( (o) \) and 0\(^{th}\) order TE \( (x) \) modes. The width of the waveguide core was chosen such that the
waveguide is cut-off for these modes, at a wavelength of 1550 nm (indicated by the dashed line).

![Band-diagram](image)

**Figure 2.6:** Band-diagrams for a 160 nm wide waveguide (a) and a 160 nm wide waveguide (b) for which the 1st order plasmonic and 0th order TE are close to cut-off. The thickness of the SiNx layer is 10 nm in figure (a) and 20 nm in figure (b). The dashed line indicates the cut-off wavelength of interest, 1550 nm ($a = 100 \text{ nm}$).

Modes left of the light-line show a strong negative z-component of the Poynting vector (directed downward) in the center of the cavity (see figure 2.7(a)), indicating that power is leaking away from the waveguide core. For modes lying right of the light-line the positive and negative part of the Poynting vector cancel each other out, as can be seen from figure 2.7(b).

![Poynting vector plots](image)

**Figure 2.7:** These plots show the z-component (normalized intensity and direction) of the Poynting vector of the $TM_1$ mode above the light line (a) and below the light line (b). Above the light line the Poynting vector is directed toward the substrate, below the light line the z-component is directed toward the center of the guiding layer. Modes below the light line are considered to be propagating modes; modes above the light line are cut-off, as far as cut-off is defined in lossy structures.

A reduction of the thickness of the dielectric layer, from 20 nm to 10 nm, causes an average increase in refractive index. As a result the effective mode index increase and the bands shift to the right ($n_{\text{eff}} = k/\omega$).
2.3 Mode properties

In this section the influence of various waveguide properties on the propagating mode are discussed. The impact of the etch depth, side wall angle and waveguide termination on the performance of the waveguide are investigated using FDTD techniques [28]. Also the influence of the dielectric insulation layer on the effective index, confinement and propagation loss of the waveguide mode is discussed; this information was obtained using the Olympios complex mode solver. In all calculations, only the fundamental TM mode is considered.

The first parameter of interest is the etch depth into the semiconductor layer-stack. The etch depth has to be large enough to prevent coupling of the propagating mode to the substrate and minimize propagation loss. Figure 2.8 shows the propagation loss of the fundamental waveguide mode as a function of the etch depth. Beyond an etch depth of 1.6 µm the fundamental mode does not suffer from radiation to the substrate anymore. The loss does remain dependent on other waveguide parameters, such as the width.

![Figure 2.8: Propagation loss as a function of etch depth in a \( w_c = 120 \) nm wide waveguide. The dashed line marks a total etch depth of 1.6 µm. Etching further than 0.8 µm below the film layer does not improve the propagation loss any further.]

In the previous section we have seen that most of the field of the propagating mode is confined to the dielectric insulation layer between the waveguide core and the metal cladding. The layer thickness and refractive index, will have a significant influence on the properties of the modes.

In figure 2.9 we see that the strong increase in mode index, as seen in M-I-M waveguides, is reduced as a consequence of introducing the insulation layer. The behavior of the M-I-S-I-M waveguide approaches the behavior of a typical M-I-M waveguide as the thickness of the insulation layer is reduced, or if the refractive index of the layer is increased.

The presence of the dielectric layers leads to a reduced confinement, as defined by equation 2.3, inside the semiconductor core and a reduced dependence of the effective index on its width. Figure 2.10(a) \((n_d = 1.9)\) shows, that if the thickness of the dielectric layer increases, the confinement in the active layer decreases. This is caused by the fact that, due to the interaction with the free electron gas in the metal, the maximum field intensity is located at the interface with the metal. As the layer thickness increases, most of the light will thus be in
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Figure 2.9: Effective mode index as a function of the waveguide width for various thicknesses of the dielectric layer \(n_d = 1.95\) (a) and for various refractive indices of the dielectric layer \(t_d = 20\) nm (b). The total etch depth is 1.6 µm.

![Effective mode index graph](a)

![Effective mode index graph](b)

From figure 2.10(b) we can also see that for \(t_d > 0\) nm, an increasing width of the total structure results in a higher confinement in the active region of the structure. This is because the interaction between the free electrons in both metal slabs becomes less as the distance between the slabs grows. Light can still travel along the independent metal interfaces, but the total structure starts behaving more and more like an ordinary, dielectric waveguide.

Finally, the loss of the structure has been investigated. Loss in plasmonic waveguides limits the propagation distance to several hundreds of micrometers [34, 32]. In these waveguides the
biggest part of the optical field is located near the junction with the metal. Good overlap with a gain medium, required for amplification or lasing, is therefore not trivial.

Figure 2.11 shows that for higher refractive indices of the dielectric layer the loss increases. For an increasing refractive index of the layer, the effective mode index will increase as well, causing the light to travel slower and allowing more interaction with the metal. The same effect is found when decreasing the thickness of the dielectric layer.

To obtain a good confinement in the waveguide core, either the refractive index of the insulation layer has to be increased, or the thickness of the layer has to be decreased. However, both options also result in higher propagation loss. The amount of gain required to overcome this loss is determined in chapter 3.

2.3.1 Sidewall straightness

A difficult aspect in the fabrication process of photonic structures with feature sizes < 100 nm, is the preservation of shape. The final shape of a structure is very much dependent on the dry-etch equipment and process parameters, as we will see in section 5.5. Typical problems encountered are: critical dimension loss, side-wall non-verticality, roughness etc.. In this section, the influence of the side-wall non-verticality on the energy decay rate in a Fabry-Pérot cavity is discussed.

To study the effect of a non vertical side-wall on the cavity’s quality factor, 3D FDTD simulation have been performed, in which the angle of the side-wall was varied from 0° to 1°. As an example, for a waveguide width of 100 nm at the top of the device, a side-wall angle of 1° results in a width of 156 nm at the bottom of the device (1.6 µm etch-depth).

In figure 2.12 we see the energy distribution in three waveguide cross-sections with angles varying from perfectly straight (left) to an angle of 1 degree (right). Where the energy of the mode is neatly confined to the waveguide core for the case of zero side-wall angle, the energy leaks away to the substrate for angles greater than 0 degrees.

Energy decay in a cavity is often expressed by the so-called quality factor. The decay rate is inversely proportional to this quality factor. For a side-wall angle of zero degrees, the quality factor of the cavity is 221. For a side-wall angle of 1 degree the quality factor is reduced
to 173, indicating a higher decay rate of energy and thus a higher loss. Based on this, we have set the criterion for the side-wall angle to be less than 1 degree from vertical. All other optimizations of the waveguide structure are canceled out, if the sidewall angle does satisfy this condition.

### 2.3.2 Waveguide termination

Previously fabricated lasers, based on the M-I-S-I-M waveguide structure, were all fully enclosed by the metal cladding [30]. The devices therefore had to be characterized by collecting light through the substrate. This is the limiting factor for their applicability in photonic integrated circuits. It is expected that termination of the metallic waveguide other then by the metal cladding will still result in enough reflectivity to sustain laser operation in these devices [14].

Figure 2.13 shows the reflectivity of an open end-facet as a function of the waveguide width. The overall power reflection is > 30%, which is very high compared to dielectric facets. The high reflection coefficient is most likely due to the large mismatch in mode-overlap between the waveguide modes and free space. For longer wavelengths the reflection coefficient even increases to values close to 60%, even for the widest waveguides.

If required, the reflectivity of the end-facet can be reduced by modifying the shape. A wedge-shaped end-facet, that can be created with focused ion beam milling, can reduce the reflectivity by at least a factor of 2; provided the angle is small enough.

### 2.4 Dispersion in the gain medium

In the last section of this chapter we will look at effect of material dispersion in the core layer of the waveguide. The active region inside the metallic nano-lasers has a considerably smaller cross-section than regular photonic devices. This reduction in size can lead to high carrier
2.4. Dispersion in the gain medium

Figure 2.13: Power reflectivity of an open facet of a metallic waveguide. The reflection is plotted versus the wavelength and for various waveguide widths; for TM polarized light.

Figure 2.14: Schematic representation of an angled waveguide facet created by focused ion beam milling.

Figure 2.15: Reflectivity for various angles of the modified end-facet; for TM polarized light.

densities, during operation of the device. The real and imaginary part of the refractive index of semiconductor material are related through the Kramers-Kronig relation [35]. An increase in carrier density will therefore not only result in an increase in gain, but also in a change in
refractive index and dispersion. The material dispersion influences the behavior of the optical mode \cite{36,37}.

The carrier-induced change in refractive index in bulk semiconductor material can be calculated according to \cite{38,39}. Parabolic bands are assumed to describe the optical absorption as a function of energy near the band-gap ($\alpha_0$). Equation (2.4) is split in two parts to include contributions from both the heavy-hole and light-hole band. $C_{hh}$ and $C_{lh}$ are material dependent parameters.

\begin{equation}
\alpha_0(E) = \frac{C_{hh}}{E} \sqrt{E-E_g} + \frac{C_{lh}}{E} \sqrt{E-E_g} \quad E \geq E_g
\end{equation}

\begin{equation}
\alpha_0(E) = 0 \quad E < E_g
\end{equation}

Equation (2.4) gives the density of states at a specific energy level in the material. The probability of occupation of a particular energy level in one of the bands follows Fermi-Dirac statistics \cite{2} and is given by equations (2.5) and (2.6). The quasi-Fermi levels $E_{F_c}$ and $E_{F_v}$ inside the bands can be calculated through the Nilsson approximation \cite{40}. The parameters $E_{bh, bl}$ and $E_{ah, al}$ are the energy levels inside the conduction and valence band, between which a transition takes place to yield a photon of a specific energy.

\begin{equation}
f_c(E_{bh, bl}) = \left[1 + \exp\left(E_{bh, bl} - E_{F_c}\right)/k_B T\right]^{-1}
\end{equation}

\begin{equation}
f_v(E_{ah, al}) = \left[1 + \exp\left(E_{ah, al} - E_{F_v}\right)/k_B T\right]^{-1}
\end{equation}

By combining the density of states with the appropriate probability functions, the change in absorption at a specific energy level can be calculated as a function of carrier density, N (with respect to N = 0). By applying the Kramers-Kronig integral to this equation, the change in refractive index is obtained. Finally, the change in refractive index for a specific carrier density can be used to calculate the actual refractive index.

\begin{equation}
\Delta \alpha(N, P, E) = \frac{C_{hh}}{E} \sqrt{E-E_g} \left[f_v(E_{ah}) - f_c(E_{bh}) - 1\right] + \ldots
\end{equation}

\begin{equation}
\Delta \alpha(N, P, E) = \frac{C_{lh}}{E} \sqrt{E-E_g} \left[f_v(E_{al}) - f_c(E_{bl}) - 1\right]
\end{equation}

\begin{equation}
\Delta n(N, P, E) = \frac{2c_h}{e^2 P} \int_0^\infty \frac{\Delta \alpha(N, P, E')}{E'^2 - E^2} dE'
\end{equation}

Using the parameters found on \cite{41} (and listed in Appendix A), we obtain the wavelength dependent refractive index for various carrier densities. The dispersion can be as high as $\sim 5 \cdot 10^{-14} s \cdot rad^{-1}$. This point of maximum dispersion occurs for carrier densities of $\sim 1 \cdot 10^{18}$ cm$^{-3}$. Furthermore, an overall decrease in refractive index is found for an increasing carrier density.
2.4. Dispersion in the gain medium

The high material dispersion leads to interesting effects. According to equation 2.9, it allows the group index to become much larger than the index of the material (usually the group index is 30%-40% higher [42]), however increases by a factor of $\sim 300\%$ have been observed in plasmonic devices [30]. An other effect related to dispersion is the increase in confinement of energy in the dispersive medium. This will be discussed briefly in chapter 3.

$$n_g = n + \omega \cdot \frac{dn}{d\omega}$$  \hspace{1cm} (2.9)

The dispersion of the material can be included in the FDTD simulations by fitting a Lorentz-model to the profile in the desired wavelength range and limiting the bandwidth of the simulation to the range in which the Lorentz-model is valid (see appendix A).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{permittivity.png}
\caption{Permittivity of bulk-InGaAs as a function of wavelength for 80K (a) and 300K (b).}
\end{figure}

Let us first have a look at how dispersion influences the single-mode condition of a plain metallic waveguide. For these calculations we have assumed maximum dispersion ($N = 1 \cdot 10^{18} \text{ cm}^{-3}$). Figure 2.17(a) and figure 2.17(b) again show the dispersion of the waveguide described in section 2.2.2. Due to carrier injection the overal dielectric constant decreases. Essentially forcing the waveguide to stay single mode for a longer time.
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Figure 2.17: Band-diagrams for a 170 nm wide waveguide (a) and a 160 nm wide waveguide (b) for which the 1st order plasmonic and 0th order TE are close to cut-off. The thickness of the SiN$_x$ layer is 10 nm in figure (a) and 20 nm in figure (b). The dashed line indicates the cut-off wavelength of interest, 1550 nm ($a = 100$ nm)
2.5 Conclusions

In this chapter the structure (M-I-S-I-M) of the metallic waveguides has been introduced and the key parameters have been pointed out. The metallic waveguides support both TE and TM polarized modes. The fundamental TM mode experiences no cut-off for decreasing width of the semiconductor core.

The M-I-S-I-M waveguides are single mode at 1550 nm if the width of the semiconductor core is smaller than 160 nm. If material dispersion is taken into account the width for which the metallic waveguides are single mode does not change significantly.

For the TM polarized mode, a significant proportion of the modal energy is confined to the dielectric insulation layer between the semiconductor core and the metal cladding. This layer will therefore have a large influence on the optical properties of the waveguides.

Thinner dielectric layers, or dielectric layers with a higher dielectric constant lead to improved confinement in the semiconductor core of the metallic waveguides. High quality, thin dielectric layers could be realized using atomic layer deposition (ALD). However, there will always be a compromise between the thickness and the breakdown voltage of the layer.

Propagation loss is in the order of 2-3 dB per 10 µm and increases for a decreasing waveguide width. The total etch depth of the waveguide core should be > 1.6 µm to minimize propagation loss. The sidewall angle has a significant impact on the performance of the waveguides. All optimizations of the waveguide structure can be undone if the sidewall angle is not within 1° from vertical.

Waveguides terminated by an open end-facet experience a reflection coefficient which is ≥ 10% higher than the reflection coefficient of an all dielectric waveguide facet. If necessary, the reflection coefficient can be reduced by a factor of 2, by creating a wedge-shaped end-facet using focused ion beam techniques.
Chapter 3
Distributed Feedback

3.1 Introduction

In this chapter we will describe distributed feedback included (DFB) in metallic waveguide lasers. The goal of including distributed feedback in the lasers is to make the emission wavelength tunable, independent of the size of the cavity and independent of an open end-facet for side-emission.

First the principle of distributed feedback is introduced and we show how distributed feedback can be incorporated in metallic waveguides. In the next section we study the dependence of the Bragg wavelength on the period of the grating and the feedback strength. We will also discuss the influence of the shape of the grating and the influence of material dispersion.

In the third section we will look at the formation of cavities with the form of distributed feedback discussed in the first part of the chapter. The cavities can be characterized by the modes they support and the decay rate of the energy in these modes. The fourth section discusses the determination of the threshold condition of the DFB cavities and the amount of spontaneous emission enhancement that can be obtained in these cavities.
3.2 Principle of distributed feedback

Abrupt transitions in the dielectric constant, for example at the interface between two materials, cause reflections for electromagnetic waves traveling through these materials. These reflections can be used to provide feedback. Distributed feedback refers to the situation where electromagnetic waves are gradually and repeatedly coupled back into the laser cavity. If the period of the feedback is approximately equal to half the wavelength of the radiation inside the cavity, constructive interference of the reflected waves occurs. This way, wavelength selectivity and high reflection coefficients can be obtained.

Structures with periodic index variations exist in many different forms. They have been realized in 1, 2 and 3 dimensions, with various shapes and in many different materials. Two types of distributed feedback often used in integrated optic devices are gratings (1D) and photonic crystals (2D & 3D). In the remainder of this thesis we will focus on distributed feedback realized by gratings.

There are two ways in which grating couplers can be incorporated in a laser cavity. They differ only in the presence of gain inside the grating. Laser cavities where the gratings do not contain gain material are generally referred to as Distributed Bragg Reflectors (DBR). They are generally placed in a waveguide outside the active region. Laser cavities where the gratings do contain gain material are referred to as Distributed Feedback (DFB), here the grating is part of the active region [43].

Analysis of DBRs is relatively simple, but the fabrication requires active/passive transitions. These active/passive transitions are often hard to realize in integrated optical devices/networks. The DFB implementation is easier to fabricate, but more complex to analyze. In the remainder of this thesis we will focus on the DFB type lasers.

Laser cavities in which distributed feedback is incorporated have interesting properties. Their operation wavelength can be tuned, there can be very effective suppression of other wavelengths apart from the lasing wavelength and they can have low threshold currents.

Distributed feedback in semiconductor lasers is often realized by a slight corrugation of the active region or a neighboring layer, to reduce the strength of the feedback. Distributed feedback as discussed in this thesis, is realized by a similar periodic corrugation of the sidewall of the device. Such a grating is also known as a vertical groove grating [44,45]. A schematic representation is given in figure 6.15.

![Figure 3.1: Schematic representation of feedback by vertical groove gratings incorporated in the sidewall of a semiconductor waveguide. The semiconductor core will later be covered by silicon nitride and silver.](image)
3.3 Metallic gratings

Gratings in passive metallic waveguides have been studied by Han and others \[18, 17, 19\]. A general approach taken for the design of passive metallic structures, is to derive the dispersion relations for the modes involved \[9, 7\]. These equations are then used to determine the effective mode index and derive the structure’s behavior (e.g. reflection coefficients, Bragg wavelengths) using a plane wave approximations. This approach is not suitable for the sections of the grating, since it does not account for the reflections caused by large differences in mode profile \[26\]. Instead we will rely on FDTD simulations for the analysis of the behavior of the device.

![Figure 3.2: Schematic overview of a unit-cell of the metallic grating.](image)

3.3.1 Wavelength tuning

FDTD Simulations can be used to create a band-diagram of a unit-cell of the grating (shown in figure 3.2). Such a band-diagram is similar to that of the waveguide in the previous chapter and shows which modes are allowed to propagate inside the grating, assuming it were infinitely long. Figure 3.3 shows a typical band-diagram of a metallic grating with a period of 220 nm, for which \(w_c\) and \(w_g\) are 100 nm and 200 nm respectively. For this grating period, the wavelength of maximum reflection of the grating is expected to lie somewhere in the range of 1400 - 1600 nm. The width \(w_c\) was chosen such that the waveguide core is definitely single mode, the value of \(w_g\) is an initial guess.

The band-diagram shows two bands entering the area between the dashed lines, which define the wavelength range of interest\(^1\) (1000 nm - 2000 nm). These bands are TM polarized modes. The gap in the middle, defined at \(k = \pi/\Lambda_g\), is the stop-band. The group velocity of the modes approaches zero \((d\omega/dk = 0)\); in this frequency range no modes can propagate and are reflected by the grating. The wavelength of maximum reflectivity, also known as the Bragg wavelength, can be extracted from the band-diagram. The corresponding wavelength is located symmetrically between the two wavelengths that define the stop-band \[46, 47\].

From the band-diagram it can be seen that the Bragg wavelength lies around 1500 nm, which is in the expected range. Figures 3.4(a) and 3.4(b) show the mode profiles of the two modes with \(k_x\) equal to \(\pi/\Lambda_g\). The group velocity of these modes, defined by equation 2.2, approaches zero \((d\omega/dk = 0)\). As can be seen, their period exactly matches the period of grating.

\(^1\)See the remarks about normalized units in section 2.2.2
Figure 3.3: Band-structure of a rectangular grating with: $\Lambda_g = 220 \text{ nm}$, $w_c = 100 \text{ nm}$, $w_g = 200 \text{ nm}$ and $t_d = 20 \text{ nm}$. The TM and TE polarization are indicated by $O$ and $X$ respectively. The area between the dashed lines is the wavelength range between 1000 - 2000 nm. The TE polarized mode ($X$) is well outside the wavelength range of interest.

Figure 3.4: $|E|^2$ Intensity distribution of the TM modes at the band edge. Figure 3.4(a) is the profile of the mode at the lower frequency boundary of the band-gap. Figure 3.4(b) is the profile of the mode at the upper frequency boundary of the band-gap. The parameters of the grating are: $\Lambda_g = 230 \text{ nm}$, $w_c = 140 \text{ nm}$, $w_g = 190 \text{ nm}$ and $t_d = 20 \text{ nm}$.

This technique can also be used to determine the polarization dependence of the grating. Figure 3.3 also shows the dispersion curve of the TE mode. As can be seen from the band-structure, no TE polarized mode is allowed in the wavelength range of interest (1000 nm - 2000 nm), even though locally the grating is wider than the cut-off width for the TE polarization.

The resonant wavelength of the grating is dependent on the period of the structure. The period of the structure should be equal to half the wavelength of the light for maximum reflection. Figure 3.5 shows the Bragg wavelength as a function of grating period for various widths of the core waveguide. The period of the grating is increased in steps of 5 nm. The width of the grating, $w_g$, has been reduced to $w_c + 50 \text{ nm}$, to ensure plasmonic behavior in all sections of the grating even for larger values of $w_c$.

The wavelength dependence of the grating, for wavelengths other than the Bragg wave-
3.3. metallic gratings

The effect of material dispersion on the Bragg wavelength can be seen from figure 3.6, which, compared to figure 3.5, has a much smaller slope. Injection of carriers causes the overall effective mode index to decrease, shifting the Bragg wavelength to shorter wavelengths. Also, the refractive index of the material in the waveguide core is higher at shorter wavelengths (~1300 nm) than it is at longer wavelengths (~1600 nm). This leads to a reduced dependency of the wavelength on the period of the grating.

Figure 3.6: Bragg wavelength vs. grating period for various widths of the waveguide core. Material dispersion included \( (N = 1 \times 10^{18} \text{ cm}^{-3}) \). Other parameters are: \( w_g = w_c + 50 \text{ nm}, t_d = 20 \text{ nm} \).

Figure 3.5: Bragg wavelength vs. grating period for various widths of the waveguide core. Other parameters are: \( w_g = w_c + 50 \text{ nm}, t_d = 20 \text{ nm} \).

The presence of dispersion also reduces the size of the band-gap of the grating, for the same
reasons just mentioned. At shorter wavelengths the dielectric constant increases, pushing the upper band-edge mode to longer wavelengths, while at longer wavelengths the dielectric constant is decreased, pushing the lower band-edge mode to shorter wavelengths.

### 3.3.3 Feedback strength and reflection bandwidth

In this section we will take a closer look at the wavelength dependence of the grating and at the strength of the feedback introduced by the structure. Figure 3.7 shows the reflection spectra of a 3 period grating in a waveguide with a core width of $w_c = 100$ nm. The total width of the grating is varied from $w_g = w_c + 20$ nm to $w_g = w_c + 80$ nm.

![Figure 3.7: Reflection spectra of a 3-period metallic waveguide grating. $w_c = 100$ nm and $\Lambda_g = 220$ nm. The thickness of the SiN$_x$ dielectric layer is 20 nm. The wavelength of maximum reflection slowly shifts to longer wavelengths, due to the increase in mode index related to the increase in grating width.](image)

The feedback strength of a grating is expressed by the coupling constant of the grating. At the Bragg wavelength, the coupling constant can be determined via equation 3.1 [46]. In this equation $R$ is the power reflection coefficient, $\kappa$ and $L$ are the coupling constant and grating length, respectively.

$$R = |r|^2 = \tanh^2(\kappa L)$$

From figure 3.8(a) we learn that even for very short gratings, the total reflectivity can be very high. The figure shows the reflection coefficient at the Bragg wavelength for an increasing depth of the vertical groove grating. Figure 3.8(b) shows the corresponding coupling coefficients. The coupling coefficients typical for the vertical groove gratings in the plasmonic waveguides are somewhere between 10 and 100 times bigger than the coupling coefficients for similar gratings in ordinary dielectric waveguides [42].

The high reflection coefficient, and related coupling coefficient, can be explained on the basis of the intensity distribution of the fundamental plasmon mode. Since most light is confined to the dielectric cladding between the waveguide’s core and the metal, even a small change in waveguide width will lead to a large difference in mode-overlap and thus to a large reflection coefficient. The high coupling coefficient is the reason for the high reflection bandwidth. Due to the high reflection per grating period, light in the grating only experiences feedback from a few periods (< 5) resulting in the large reflection bandwidth. Roughness in the sidewall of the metallic waveguide will also cause considerable feedback and should therefore be minimized.
3.4. DFB Cavities

\[ \text{Figure 3.8: Power reflection (a) and coupling coefficient (b) of a 3-period rectangular grating.} \]
\[ w_c = 100 \text{ nm and } \Lambda_g = 220 \text{ nm. Data acquired from a 2D FDTD simulation.} \]

3.3.4 Grating shape

During the fabrication of the devices the shape of the grating, as defined by the electron beam lithography system, is affected by mask erosion. The resulting shape will therefore lie somewhere between a sinusoidal (as shown in figure 3.9) and a rectangular grating. In practice the shape resembles more closely a rectangular grating.

\[ \text{Figure 3.9: Schematic overview of a unit-cell of the metallic grating.} \]

The calculations of the reflection/transmission spectra from the previous section have been repeated a grating with a sinusoidal shape. The change in shape barely affects the reflection/transmission characteristics of the grating. Figure 3.10 shows a 10% - 15% decrease in reflection, as compared to the rectangular grating.

3.4 DFB Cavities

From the telecom perspective, single mode operation is a much desired property of a laser. Distributed feedback lasers are known to excel in this area. However, cavities with distributed feedback are not single mode by nature. In cavities with an uninterrupted grating along the cavity, also referred to as pure DFB cavities, the lasing condition is not satisfied at the Bragg wavelength.
A pure DFB structure permits propagation of waves through the grating in two frequency bands, one on each side of the Bragg wavelength (see figure 3.3). The finite length of the cavity gives rise to a set of longitudinal modes that fit inside the cavity, as well as in the grating\(^1\). These modes are similar to the band-edge modes found in photonic crystals.

In a dielectric DFB cavity, these modes are symmetrically distributed around the Bragg wavelength. Every mode on one side of the Bragg wavelength has a degenerate partner on the other side of the Bragg wavelength, with the same threshold gain. Because there is no reliable technique to determine which of the modes will reach threshold first, the pure DFB lasers are of little interest from a communications point of view\,[48].

The issue of the degenerate modes can be overcome in several ways. The easiest solution is to introduce a \(\lambda/4\)-phase-shift in the center of the grating. A schematic representation of such a cavity, implemented in the M-I-S-I-M waveguide structure, is given in figure 3.12.

Due to the quarter wavelength phase-shift, waves propagating at the Bragg wavelength experience a total phase-shift of \(2\pi\) during one round-trip through the cavity. The lasing condition is therefore satisfied at the Bragg wavelength. In a dielectric DFB cavity, this mode has the lowest threshold gain and the degeneracy issue is solved. In the remainder of this thesis
we will focus on DFB structures with a $\lambda/4$-phase-shift in the center of the cavity.

![Figure 3.12: Schematic overview of a DFB cavity with a $\lambda/4$-phase-shift in the center of the cavity, as seen from the top (a) and as seen from the side (b).]

### 3.4.1 Cavity modes

The fact that the lasing condition can be satisfied at the Bragg wavelength, does not imply that the other longitudinal modes cease to exist. To demonstrate this we have calculated the spectral response of DFB cavity, by exciting the cavity with Gaussian dipole sources and monitoring the fields inside the cavity. The dipole sources were randomly positioned throughout the cavity to ensure excitation of all modes. After the calculation, the evolution of the fields over time was Fourier transformed to obtain the spectral response of the cavity. The results of this calculation are shown in figure 3.13.

The spectrum shows a peak around 1490 nm, which is the Bragg wavelength. Also visible in the spectrum are two neighboring peaks, at a distance of $> 100$ nm from the Bragg wavelength. These peaks correspond to the band-edge modes mentioned earlier. The field distribution of the mode at the Bragg wavelength and of one of the side modes are shown in figures 3.14(a) and 3.14(b) show typical field distributions of modes inside a DFB cavity. The mode located at the Bragg wavelength is strongly confined around the $\lambda/4$-phase-shift, and covers only

---

1. If the strength of the distributed feedback is reduced to zero, the cavity is basically a Fabry-Pérot cavity. The modes referred to would then be the Fabry-Pérot modes of this cavity.
Chapter 3. Distributed Feedback

Figure 3.13: Spectral response of a DFB cavity with a $\lambda/4$-phase-shift in the center. The parameters of the grating are: $w_c = 120$ nm, $w_g = 170$ nm, $\Lambda_g = 220$ nm, $t_d = 20$ nm and $n_{\text{periods}} = 28$.

3.4.2 Quality factors

Resonant cavities are often characterized by their quality factor, or Q-factor. The quality factor is a measure of the decay rate of the electromagnetic field at a particular frequency and is given by equation (3.3). In this equation, $\omega$ is the complex valued (angular) frequency and $\tau_p$ the photon lifetime. The complex nature of $\omega$ is illustrated by equation (3.2) where it includes information about both the frequency and the decay in the time dependence of a propagating wave ($A$ is the complex amplitude of the wave). The decay rate, $-2\text{Im}[\omega]$, is inversely proportional to the photon lifetime. The quality factor is also a measure for the linewidth of the cavity’s resonance.

\[
A \exp(j\omega t) = A \exp(j(\omega_r + j\omega_i)t) = A \exp(j\omega_r t) \cdot \exp(-\omega_i t) \tag{3.2}
\]

\[
Q = \frac{\text{Re}[\omega]}{-2 \cdot \text{Im}[\omega]} = \omega \cdot \tau_p \tag{3.3}
\]

We will first look at the quality factor of DFB cavities embedded in silver. Later we will use the quality factor to study the influence of one or more open end-facets on the feasibility of laser operation. The Q-factor will also to investigate the influence of the phase of the reflections from the end-facets.

It has been shown that a quality factor of $\approx 140$ is sufficient to obtain laser operation inside a metallic nano-cavity at a temperature of 77K [24]. Figure 3.13 shows the spectrum of a closed DFB cavity. The quality factor of the modes can be extracted by dividing the center frequency of the peak by its FWHM. However, all quality factors presented in this thesis were extracted from the time evolution of the fields by a method called harmonic inversion [49]. Using the Johnson & Christy data [50] for silver at room temperature, we find that the Q-factor of the main peak is $\sim 330$. The Q-factor of the side modes is $\sim 240$. The quality factor of metallic
3.4. DFB Cavities

Figure 3.14: $|E|^2$ Distribution of the mode at the Bragg wavelength of the grating ($\lambda = 1492\text{nm}, Q=335$) (a) and of the first side mode ($\lambda = 1395\text{nm}, Q=280$) (b). The parameters of the grating are: $w_c = 120\text{nm}$, $w_g = 170\text{nm}$, $\Lambda_g = 220\text{nm}$, $t_d = 20\text{nm}$.

Figure 3.15: $|E|^2$ Distribution of the mode at the Bragg wavelength of the grating, as seen from the side. The parameters of the grating are: $w_c = 120\text{nm}$, $w_g = 170\text{nm}$, $\Lambda_g = 220\text{nm}$, $t_d = 20\text{nm}$. The black lines show the outline of the structure.

cavities is mainly determined by the optical loss due to phonon scattering of the electrons in the metal.
Chapter 3. Distributed Feedback

It is expected that the quality factor can be increased by reducing the ambient temperature, similar as for the gold clad metallic cavities [24], where a lower temperature results in lower phonon scattering of the free electrons inside the metal cladding. Following the same approach, for silver this would imply that at cryogenic temperatures, the absorption loss is reduced by a factor of 5 [51] and the Q factor increases to $\sim 1500$.

3.4.3 End-facet dependence

All metallic structures discussed so far, were completely encapsulated by the silver cladding. If the end-facet of a metallic cavity with distributed feedback is not covered by silver, the grating can still provide enough feedback to create a resonant cavity, on the condition that it has enough periods on each side.

The quality factor of the mode at the Bragg wavelength in an open cavity is shown in figure 3.16. The plot shows the quality factor of a one and two sided open cavity, as a function of the number of grating periods on each side of the $\lambda/4$-phase-shift.

![Figure 3.16: Quality factor of a single and double sided open cavity with distributed feedback. The x-axis shows the number of grating periods on one side of the $\lambda/4$-phase-shift. The parameters of the grating are: $w_c = 100$ nm, $w_g = 150$ nm, $\Lambda_g = 230$ nm, $t_d = 20$ nm.](image)

The quality factor of the cavity stabilizes at a value of $\sim 310$, for 18 grating periods on each side. However, even for less grating periods, still a reasonable quality factor can be obtained. The overall spectral response of a DFB cavity, open on both sides, is shown in figure 3.17. Comparing this figure with figure 3.13 we see that the wavelengths of the cavity modes remains almost unaffected.

3.4.4 End-facet phase

Open end-facets introduce a deviation in phase in the reflection, depending on the position where the device (and grating) are terminated. This random phase can interfere constructively or destructively with the light propagating inside the grating, causing the Q-factor and resonant frequency of the cavity to vary with the distance removed from the end of the structure. In devices with $\kappa L < 3$, random facet reflections can also affect the single-mode operation [48].

Figures 3.18(a) and 3.18(b) show this dependency for a DFB cavity with $2 \times 10$ and $2 \times 20$ periods.

The Q-factor of the cavity consisting of $2 \times 10$ grating periods is strongly affected by even the slightest imbalance (asymmetry) between the two gratings in the device. The wavelength
3.5. Gain and threshold

Figure 3.17: Spectral response of an open DFB cavity with a λ/4-phase-shift in the center. The parameters of the grating are: \( w_c = 120 \text{ nm}, w_g = 170 \text{ nm}, \Lambda_g = 220 \text{ nm}, t_d = 20 \text{ nm} \) and \( n_{\text{periods}} = 28 \).

Figure 3.18: Q Factor (a) and resonant wavelength (b) as a function of the length of the section removed from one end of the cavity. The parameters of the grating are: \( w_c = 120 \text{ nm}, w_g = 170 \text{ nm}, \Lambda_g = 230 \text{ nm}, t_d = 20 \text{ nm} \).

varies about 10 nm with the removal of the first 250 nm of structure. This change in wavelength increases, as larger parts of the structure are removed to open an end-facet.

The changes in wavelength and Q-factor are much less pronounced for the 2 \( \times \) 20 period structure. It is therefore recommended that the DFB structure is at least 2 \( \times \) 20 grating periods long, if the end-facet is to be opened by, for example, focussed ion beam milling. This in order to reduce the effect of the random position of the newly created end-facet.

3.5 Gain and threshold

3.5.1 Material gain

In this section the gain and threshold relations of the metallic DFB lasers are investigated. In section 2.3 we have seen that the propagation loss in a metallic waveguide with a core width of 100 nm is approximately 0.3 dB/µm. This corresponds to \( \alpha_i = 690 \text{ cm}^{-1} \). For dielectric Fabry-Pérot lasers equations 3.4 to 3.5 can be used to approximate the material gain required
Chapter 3. Distributed Feedback

for laser operation [42].

Equation 3.4 gives the mirror loss for a cavity of length $L$, with two open end facets, with reflectivities $R_1$ and $R_2$. Equation 3.5 states that, in order to achieve laser operation, the average internal loss ($\alpha_i$) and the mirror loss ($\alpha_m$) have to be compensated. The required material gain ($g_{th}$) can be found by dividing the modal gain by the confinement factor $\Gamma_{act}$. The confinement factor can be found via equation 2.3.

$$\alpha_m = \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) \quad (3.4)$$

$$\Gamma_{act} v_g g_{th} = \frac{1}{\tau_p} = v_g (\alpha_m + \langle \alpha_i \rangle) = \frac{\omega}{Q} \quad (3.5)$$

For dielectric DFB cavities, the threshold gain can be calculated by numerically solving the coupled mode equations [43], which depend on similar parameters as the equations just mentioned. However, these equations do not hold for metallic devices, since they assume the feedback to be caused by small perturbations of the effective mode index.

The method used to calculate the threshold gain, used in the previous paragraph is applicable to cavities which are invariant over a large distance compared to the wavelength of the mode of interest. For smaller and complex shaped cavities determination of the threshold gain is more complicated. In this situation the approach taken in [52] is very useful.

The method described in this paper relates the decay time of the mode, which is proportional to the Q-factor, to the energy distribution of the mode in the various absorbing materials of which the cavity consists. The method requires the materials to be described by a Lorentz model and properly takes into account the additional energy storage due to dispersion [36].

$$\varepsilon(\omega) = \varepsilon_{\infty} + \sum_n \frac{\Delta \varepsilon_n \omega_n^2}{\omega_n^2 - \omega^2 - i\gamma \omega} \quad (3.6)$$

From chapter 1 we recall that the dispersive and absorptive nature of the materials composing the cavity can be described by equation 3.6. A more accurate fit can be obtained by adding more terms to the equation [44]. Given the dielectric constant of a material, the refractive index can be obtained via:

$$n + i\kappa = \sqrt{\varepsilon(\omega)} \quad (3.7)$$

The average energy contained by such a material is given by equation 3.8 and is directly proportional to $|E|^2$. The values for $\omega, n, k$ and $\gamma$ can be obtained via or directly from equation 3.6. For lossless, non-dispersive media the equation reduces to $W = \varepsilon_0 \varepsilon_r |E|^2$.

$$W = \frac{\varepsilon_0}{2} \left( n^2 + \frac{2\omega nk}{\gamma} \right) |E|^2 \quad (3.8)$$
The decay rate of the energy in the material is given by equation 3.9 [37].

\[
\frac{1}{T} = \frac{4\omega^2 \Lambda^2 \gamma}{\left[ \sqrt{(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2} + \sqrt{(\omega_0^2 - \omega^2 + \Lambda^2)^2 + \omega^2 \gamma^2} \right]^2 + 4\omega^2 \Lambda^2 - \Lambda^4} \tag{3.9}
\]

With:

\[
\Lambda^2 = \frac{\Delta \varepsilon \omega_0^2}{\varepsilon_\infty} \tag{3.10}
\]

In equations 3.9 and 3.10 \(\omega\) is the wavelength of interest and \(\omega_0\), \(\gamma\), \(\Delta \varepsilon\) and \(\varepsilon_\infty\) are the parameters defining the material. For silver at 300K, this decay time is equal to 32.1 fs (using the parameters given in table A.5).

The cavity of the metallic waveguide lasers consists of 4 different materials: InP, InGaAs, SiN\(_x\) and Ag. If we assume that the only loss the electromagnetic field experiences is caused by the presence of the silver, we can relate the decay time of the mode to the decay time of the energy contained by the silver. This relation is given by equation 3.11.

\[
T_{\text{mode}} = T_{\text{metal}} \cdot \frac{W_{\text{InP}} + W_{\text{InGaAs}} + W_{\text{SiN}} + W_{\text{metal}}}{W_{\text{metal}}} \tag{3.11}
\]

Assuming the other materials are lossless, we can derive a similar expression for the time constant of the active material. This expression can be used to calculate the material gain required to exactly overcome the loss introduced by the metal and thus the threshold gain.

If the device operates at the peak of the gain spectrum, the final expression for the threshold gain becomes:

\[
g_{\text{th}} = \frac{1}{cn_s} \cdot \left( n_m^2 + \frac{2\omega_n k_m}{\gamma_m} \right) \frac{1}{T_m} \cdot \frac{|E_m|^2}{|E_s|^2} \tag{3.12}
\]

In this expression \(c\) is the speed of light and \(n_s\) is the refractive index of the semiconductor core. The ratio \(|E_m|^2/|E_s|^2\) can be calculated by any complex mode solver. For a 140 nm wide waveguide, with a 20 nm bulge and covered by a 15 nm SiN\(_x\), this ratio is \(|E_m|^2/|E_s|^2 = 0.0374\) at a wavelength of 1450 nm. Using the parameters from table A.5 we find that \(g_{\text{th}}\) is in the order of 1240 cm\(^{-1}\) at a wavelength of 1450 nm.

### 3.5.2 Spontaneous emission enhancement

Spontaneous emission is not an intrinsic property of a material, but results from the coupling of atoms to the vacuum modes of the electromagnetic field [47]. The rate with which these atoms emit energy can be altered by changing the electromagnetic environment they can radiate into.

The presence of a cavity can either enhance or reduce the radiative emission rate. Enhancement, for example, occurs when an atom at rest inside a cavity is resonant with one of the cavity modes [47, 53]. Increased coupling of spontaneous emission to the main mode of a semiconductor laser reduces the change in slope of the L-I or the L-L curve of a laser around
threshold. If all spontaneous emission would be coupled to the laser mode, the laser would exhibit threshold-less operation [47].

The enhancement of the radiative emission by a complex-shaped photonic cavity can be estimated using FDTD techniques [54]. Hereto, a single Gaussian dipole source is placed inside the cavity. The radiation rate of the dipole source is determined by integrating the normal component of the Poynting vector over the closed surface containing the dipole (see equation 3.13). By comparing the radiation rate inside the cavity to the radiation rate of the same dipole in vacuum, an enhancement factor can be determined.

\[
P(\omega) = \int \int n \cdot (E' \times H) dS
\] (3.13)

In the next section we will look at the enhancement and suppression of spontaneous emission inside plasmonic Fabry-Pérot and DFB cavities, by performing FDTD simulations as discussed in the previous paragraph. These simulations have been carried out in 2D and 3D.

3.5.2.1 Emission in bulk semiconductor material

Let us first study the emission of a dipole emitter in bulk semiconductor material in 2D (in the absence of a cavity). The semiconductor material is defined as an infinite medium with a dielectric constant of \(\varepsilon = 12.88\), similar to InGaAs. A Gaussian dipole source is placed at the center and during the simulation, the flux emitted by the source is accumulated over a surface surrounding the source. For the TE polarization an electric dipole is used, the TM polarization is excited by a magnetic dipole source.

![Figure 3.19: Emission rate spectrum of Gaussian dipole placed in an infinite medium with a dielectric constant of \(\varepsilon = 12.88\) (to represent InGaAs). The simulation was carried out for both the TE and the TM polarization.](image)

The computed flux of a TE and TM polarized dipole sources inside a medium with \(\varepsilon=12.88\), are shown in figure 3.19. The Gaussian frequency distribution of the sources remains unaffected in a medium of infinite size. These flux spectra will be our reference for the calculation of the spontaneous emission enhancement factor in the following paragraphs.

3.5.2.2 Emission inside a cavity

The dipole emission rate spectra of a Fabry-Pérot cavity and a distributed feedback cavity are shown in figures 3.20(a) and 3.20(b). The DFB cavity has a core waveguide (\(w_c\)) width of 120
3.5. Gain and threshold

nm and a total grating width ($w_g$) of 170 nm. The period of the grating $\Lambda_g = 230$ nm, making the cavity resonant for a wavelength of 1558 nm. The emission rates are now changed by the presence of the cavity, because the number of modes the source can transfer its energy to has been reduced drastically, with respect to the infinite medium.

The spontaneous emission enhancement factor of both types of cavities can be obtained by dividing their emission rate spectra by the emission spectra calculated in the previous section (see 3.19). The enhancement and suppression of radiation are higher in the case of the DFB cavity, because of the number of available modes is less than that in the Fabry-Pérot cavity.

![Emission rate spectra of a magnetic dipole in a Fabry-Pérot cavity (a) and a distributed feedback cavity (b). The distributed feedback cavity is tuned to a normalized frequency of 0.0642 (= 1558 nm).](image)

The calculated enhancement and suppression factors are shown in figures 3.21(a) and 3.21(b). For the Fabry-Pérot cavity, a spontaneous emission enhancement between 3.5 - 4.5 times can be obtained over multiple longitudinal modes in the TM polarization. In between the modes, the enhancement factor is < 1, indicating a suppression of spontaneous emission at the intermediate frequencies. The enhancement factor (~ 47), for the TM polarized mode at wavelength 1558 nm, obtained by the distributed feedback cavity is much larger.

The figures also show that for a Fabry-Pérot cavity the TE polarization is suppressed for wavelengths larger than ~ 1440 nm. In the DFB cavity, the spontaneous emission enhancement spectrum shows peaks. These peaks are most likely caused by the presence of the grating. The peaks disappear as the wavelength increases.

As a comparison we have also calculated the spontaneous emission enhancement factor for a DFB type cavity with the same period as the cavity discussed earlier ($\Lambda_g = 230$ nm). However, the core waveguide width and the total grating width are reduced to $w_c = 80$ nm and $w_g = 130$ nm. The results are shown in the figure below. As can be seen the spontaneous emission enhancement for the TE polarization is reduced to values $\ll 1$ over most part of the bandwidth, corresponding to our expectations regarding the cut-off of the M-I-S-I-M waveguides. The enhancement factor for the TM polarized mode at the Bragg wavelength increases, due to tighter confinement of the mode.
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3.5.2.3 Comparison to 3D cavities

The results presented in the previous paragraphs were obtained from 2D FDTD simulations, assuming the structures are of infinite length in the 3rd dimension. In this section we compare the results of the 2D simulations with 3D simulations. Figure 3.23(a) and 3.23(b) show the emitted flux spectrum of TE and TM polarized sources in free space ($\varepsilon = 12.88$) and inside a DFB cavity.

From figure 3.24 it can be seen that the spontaneous emission enhancement factor is about 3 times smaller than expected from the 2D simulation. This is may be due to loss of radiation in the third dimension (z direction). The position of the peak, however, remains the same. An important difference is the suppression of the TE polarization, which appears to significantly stronger when calculated in 3D.

3.5.2.4 Interpretation of the spontaneous emission enhancement factor

The enhancement factors calculated in the previous sections were calculated under the assumption of a single, perfectly polarized emitter located at the center of the cavity. This situation does not apply to the fabricated devices, discussed in the following chapters. Bulk
3.6 Conclusions

In this chapter we have investigated the possibility of incorporating distributed feedback in gap plasmon waveguides based on the M-I-S-I-M structure. More specifically this feedback is realized via vertical groove gratings in the side wall of the waveguide.
Chapter 3. Distributed Feedback

We found that due to the surface-wave-like nature of the mode, the reflection per grating period can be high. Because of this high reflection, light only experiences feedback from a few periods. The reflection bandwidth will therefore be large. The order of magnitude of the reflection bandwidth is several hundreds of nanometers. The coupling coefficient, derived from the maximum reflection coefficient, is at least a factor 10 higher than found in the dielectric equivalent of this structure.

The large bandwidth and the high reflection coefficients are caused by the large difference in mode-overlap between the small and the wide sections of the grating. In dielectric vertical groove structures, often only the tail of the mode experiences the presence of the grating; in the metallic gratings, a significant part of the light sees a step in the waveguide width.

Deviations in shape of the grating profile do not affect the performance of the grating much. A purely sinusoidal shaped grating results a 10% reduction in reflection.

The wavelength dependence of the gratings was investigated by constructing the band-diagrams of gratings with different dimensions. This band-diagram shows the modes that are allowed to propagate inside the grating. At the point \( k_x = \frac{\pi}{\Lambda_g} \) the group velocity of these modes is zero and the modes do not longer propagate inside the grating. The distance (expressed in terms of wavelength) between the two bands at this point is called the stop-band. The Bragg wavelength is in the middle of the stop band.

With material dispersion, the Bragg wavelength can be varied from 1300 nm to 1450 nm, by varying the grating period from 180 nm to 240 nm. If the materials were dispersion free, the tuning range could even be larger and range from 1250 nm to 1650 nm for the same grating periods.

Cavities based on distributed feedback can be created either by modulating the width of the cavity over the whole length without interruption, or by modulating it over the length of the cavity and introducing a \( \lambda/4 \)-phase-shift in the center of the cavity. The \( \lambda/4 \)-phase-shift allows the round-trip phase-condition, required for resonance, to be satisfied at the Bragg wavelength.

The Q-factor for the mode at the Bragg wavelength is typically > 300 at a temperature of 300K, which is sufficient to sustain laser operation inside the cavity, provided enough gain is available. The threshold condition of a metallic DFB cavity can be determined by relating the cavity loss to the loss induced by the silver via the field distribution inside the cavity. The required material gain found with this technique lies between 1200 - 1300 cm\(^{-1}\) and can be obtained from standard bulk InGaAs material.

From previous experiments with gold clad cavities, it is expected that the Q factor can be increased five-fold by operating the cavity at a temperature of 77K.

If a DFB cavity is not fully enclosed by a silver cladding, but has one or two open end-facets, the Q-factor becomes increasingly dependent on the amount of periods in the grating. It is expected that for 20 or more grating periods, on each side of the \( \lambda/4 \)-phase-shift, the Q-factor of an open cavity is equal to that of a closed cavity. The Q-factor of the cavity is dependent on the phase of the light reflected from the open end-facet. If either the coupling constant or the length of the grating is long enough to satisfy \( \kappa L > 3 \), the influence of the phase can be neglected.

Due to the scale of confinement of light in the metallic DFB cavities described in this thesis, an enhancement of the radiative emission rate is expected at the Bragg wavelength. At the same time, emission away from the main mode is expected to be suppressed. The maximum enhancement factor can be calculated by comparing the flux emitted by a single source inside
a cavity to the flux emitted by the same source in free space. The expected enhancement factor of the spontaneous emission coupling to the mode at the Bragg wavelength is in the order of $10^{-100}$.

2D And 3D simulations predict similar wavelengths and orders of magnitude of enhancement for the modes located at the Bragg wavelength. Away from the Bragg wavelength 3D simulations predict a higher suppression, due to the extra dimension to which the light is confined.

The simulations only apply to the case where a single emitter is positioned at the center of the cavity. In reality effects such as random polarization, carrier diffusion and interference with other emitters will result in the observed alteration of the radiative emission rate being much less pronounced (than calculated in this chapter).
4.1 Introduction

*In this chapter we will discuss the layout of a chip with metal coated lasers. This design was fabricated and later characterized. The fabrication process and the results of the characterization will be discussed in subsequent chapters. This chapter starts with the design considerations. Next, the layout of the chip is presented and finally, the structure of a single block of devices is discussed.*
4.2 Design considerations

In chapter 2 we studied the modes that are sustained by a metal coated waveguide of various widths. We found that, in order to guarantee pure plasmonic behavior, the width of the waveguide core should be less than 160 nm (excl. SiNx layers). In the chip design, the core waveguide width of the distributed feedback lasers will therefore be varied from 80 nm to 180 nm.

In chapter 3 we studied the strength of the feedback as a function of total grating width. We saw that for grating widths of \( w_g = w_c + 50 \) nm considerable coupling coefficients could be obtained. Taking into account that the size and shape of the grating are affected by other steps in the fabrication process and that the minimum feature size that can reasonably be obtained is \( \sim 25 \) nm, the choice was made to fabricated gratings with a total width of \( w_g = w_c + 50 \) nm. A second set of devices was fabricated with a total grating width of \( w_g = w_c + 100 \) nm, in case the grating width of the first set of devices would prove to be insufficient.

In chapter 3 also the dependence of the Bragg wavelength on the grating period was investigated. The Bragg wavelength ranges from \( \geq 1600 \) nm for a grating period of \( \Lambda_g = 240 \) nm, to a value of 1250 nm for a grating period of \( \Lambda_g = 180 \) nm. If dispersion is taken into account, the lower and upper boundary of this range become \( \sim 1300 \) nm and \( \sim 1450 \) nm. It is expected that the bulk-InGaAs material can provide sufficient gain to sustain laser operation in the wavelength range between 1300 nm to 1600 nm. The grating period will therefore be varied between 180 nm and 240 nm in steps of 10 nm.

4.3 Chip layout

The chip layout consists of 7 rows with each 4 blocks of devices. Inside a block we find 8 devices. Depending on the row, a block contains either 7 DFB lasers and 1 Fabry-Pérot laser, or 8 Fabry-Pérot lasers. In a block with DFB lasers, the period of the grating is varied from 180 nm to 240 nm in steps of 10 nm. The DFB lasers each consist of 400 periods with a \( \lambda/4 \)-phase-shift in the center. The large number of grating periods, and related length of the device, ensure that proper device operation (lasing) is not limited by the amount of available gain. The Fabry-Pérot laser was added to compare the spectra of devices inside a block to a similar device without grating.

Every block containing DFB lasers, corresponds to a particular core waveguide width and is identified by their row number and a letter. The core waveguide width is varied from 80 nm to 180 nm in steps of 20 nm. For every value of \( w_c \) there is a block with \( w_g = w_c + 50 \) nm and a block with \( w_g = w_c + 100 \) nm, resulting in 12 blocks. This series of 12 blocks is repeated twice on the chip, in order to spread fabrication risks. In the center of the chip 4 blocks of Fabry-Pérot lasers are included, to serve as a reference for the DFB lasers and to study properties as the group index etc..

An overview of all the blocks on the chip is given in table 4.1. The overview of the whole chip layout is shown in figure 4.1. The comb-like structures define the shape of common the p-contact, the pads in between are the individual n-contacts. On top of the n-contacts, rectangles are visible. These are adhesion pads, surrounding the individual devices, their function will be described in the Processing chapter. In the corners of the mask there are 6 alignment structures, to align the optical masks with respect to the devices. Between the blocks of devices, there is sufficient space for cleaving. In this space also incorporates measurement structures (two lines of 2 \( \mu \)m and 5 \( \mu \)m wide). The use of these structures is also explained in...
4.3. Chip layout

the processing chapter.

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Table 4.1: An overview of the different blocks of devices on the chip and their corresponding dimensions.
Figure 4.1: Overview of the complete chip. The dimensions of the design are 14 mm by 16.5 mm. The design contains 224 lasers, of which 60 Fabry-Pérot lasers and 164 DFB lasers.
4.4 Device block

Figure 4.2 shows a close-up of a single block of devices. The dimensions are typically 3 mm × 2 mm. In the bottom left corner of the block, we find the identification number (7A). The devices (indicated by black lines) are placed inside the small rectangles at the top of the block. If the block contains DFB devices, then the grating period increases from left to right. The Fabry-Pérot device is always in the top right corner. For a block with Fabry-Pérot devices only (row 4), the width of the devices increases from left to right, from 80 nm to 220 nm.

As discussed in the previous section: the dark pads are the individual n-contacts of each device, the light-gray comb-like structure is the shared p-contact. The n- and p-contact are not connected. They are separated by a polyimide layer on which the n-contacts are placed. The polyimide is removed locally (indicated by the dotted line) to access the devices and the p-contact.

![Figure 4.2: A single block of devices.](image)

4.5 Conclusions

A design for the fabrication of a chip was made. This design contains both Fabry-Pérot and DFB lasers. A large variety of waveguide widths is included in the design, as well as two grating widths. Also the period of the grating is chosen such that the Bragg wavelength will lie in the wavelength range where the gain medium can provide sufficient gain. For every laser, a duplicate is present in the upper part of the chip, so that failure due to fabrication issues are reduced.
5.1 Introduction

In this chapter the fabrication process of the metallic lasers is discussed. The processing is different from the one typically used for the fabrication of photonic integrated circuits [55], but it relies on the same techniques. We will start with the structure of the base material. Then, the general outline of the processing scheme is given and the most relevant stages are described. In the other sections, special attention is devoted to the lithographic process required for the definition of the lasers and to the dry etch process. These are the most critical steps for the fabrication of the nanometer sized gratings incorporated in the lasers. A step-by-step overview of the processing can be found in appendix C. Detailed information about the process parameters, is listed in appendix B.
5.2 Base material

A schematic overview of a typical metallic waveguide is given in figure 5.1. For characterization purposes, the metallic waveguide lasers are fabricated on double-polished, semi-insulating InP wafers. This implies that both n- and p-contact will be located on top of the sample, which allows characterization of the devices through the substrate. The layer-stack of the wafer is given in table 5.1.

![Figure 5.1: A schematic overview of the device structure.](image)

All structures are deeply etched, to a depth of 800 nm below the core layer (total etch depth $d_{etch} = 1.6 \mu m$). At this etch depth, the propagation loss of the waveguide stabilizes (see chapter 2). The core active region consists of bulk-InGaAs material. The InGaAs material has a band-gap of $\sim 0.75$ eV (1650 nm), so that under common operating conditions the gain peak will lie in the desired wavelength range.

The layers of the wafer are grown by metal-organic vapor deposition (MOCVD). They are grown in reverse order of what is common for integrated optic devices. The n-contact is placed on top, to prevent heating of the device due to the higher Ohmic loss in the p-contact [56, 57]. The p-contact is formed by a heavily doped Q125 layer. The material and band-gap of this layer were chosen such that absorption and emission of light in the intended operational part of the spectrum of the devices is prevented. The Q125 layer also serves as an etch-stop layer for the wet chemical etch required to access the p-contact.

5.3 Process outline

The fabrication process of metallic waveguide devices consists of 5 stages, of which the first three are the most critical. These stages are:

1. Definition of the structures
2. Etching and cleaning
3. Metallization
4. Fabrication of the contacts
5. Mounting and bonding

Each of these stages relies on three process steps: deposition of materials, removal of materials and lithography.

Various deposition techniques can be used during a process step. Polymers (e.g. photo-resist and polyimide) are applied using spin coating techniques, where the layer thickness and uniformity depend on spin speed, acceleration and time. Metals are deposited using evaporation
5.3. Process outline

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material:</th>
<th>Thickness [nm]:</th>
<th>Doping [$cm^{-3}$]:</th>
</tr>
</thead>
<tbody>
<tr>
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<td>n-InP</td>
<td>50</td>
<td>&gt; 5.0 · 10^{18}</td>
</tr>
<tr>
<td>10</td>
<td>n-In_{0.53}Ga_{0.47}As</td>
<td>100</td>
<td>&gt; 1.1 · 10^{19}</td>
</tr>
<tr>
<td>9</td>
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<td>50</td>
<td>&gt; 5.0 · 10^{18}</td>
</tr>
<tr>
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<td>150</td>
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<tr>
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<td>n.i.d.</td>
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<td>1.0 · 10^{18}</td>
</tr>
<tr>
<td>4</td>
<td>p-InP</td>
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<td>5.0 · 10^{18}</td>
</tr>
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<td>3</td>
<td>p-InP</td>
<td>1000</td>
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<tr>
<td>0</td>
<td>InP</td>
<td>-</td>
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</table>

Table 5.1: A detailed overview of the layer-stack of the wafers used for the fabrication of the metallic waveguide lasers. Q1.25 indicates the quarternary alloy In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$, with the values for x and y chosen to yield a band-gap of 1.25 µm. All layers are grown lattice matched to InP.

and sputtering. Metal evaporation can be performed by heating the metal source thermally or with an electron beam. The quality of the metal layer depends on the evaporation speed, distance to the source and temperature of the target surface [58]. For the deposition of dielectrics plasma-enhanced chemical vapor deposition (PECVD) is used. This technique is used for the deposition of SiN$_x$ and SiO$_2$.

Removal of materials, usually referred to as etching, can be done dry, by means of a plasma, or wet-chemically. Dry etching techniques generally have the advantage of being anisotropic. They use a mix of physical and chemical etching to remove material. In a wet-chemical etch, the material is subjected to a liquid etchant, which reacts with the material. High selectivity can be obtained with respect to other materials, if the appropriate etchant is chosen. Wet-chemical etches are isotropic and their etch rate depends on the morphology of the material.

With lithography, patterns are transferred from a mask or design to a photo-resist layer. The photo-resist layer can then be used to shield certain areas of the wafer from a process; if the process step involves deposition, the resist can be used for lifting off the material deposited on top of the resist, only leaving material where the resist was opened by the lithography. If the process step following the lithography concerns the removal of material, the resist shields the areas that are covered from the influence of chemicals or the plasma to which it is exposed. Stage 1 is represented by figures 5.2(a) to 5.2(f). The sample is prepared for processing. The layout of the devices is transferred to the chip and etched into a hard-mask. This hard-mask layer is the basis for stage 2.

Stage 2 The patterned hard-mask is used to etch the wafer. After the etching, the mask layer is removed, the structures are cleaned and a thin electrical insulation layer is deposited. This is shown in figures 5.2(g) to 5.2(j).

Stage 3 This stage involves preparing the sample for and performing the actual deposition of the metal cladding. Figures 5.2(k) and 5.2(n) refer to this stage.
Chapter 5. Processing

**Stage 4** Work on the individual devices is finished. In stage 4, the contact layers are exposed, and the electrical contacts are created (figures 5.2(o) and 5.2(p)).

**Stage 5** The devices are finished. The chip is divided in sections. The sections are bonded and mounted on sub-mounts for characterization.

The different stages of the processing will be discussed in further detail in the next sections.
5.3. Process outline

(a) epitaxial wafer

(b) hardmask deposition

(c) resist deposition

(d) pattern resist

(e) etch hardmask

(f) remove resist

(g) etch structures

(h) remove hardmask
(i) clean

(j) deposit SiN

(k) deposit adhesion layers

(l) open SiN

(m) deposit contact metal

(n) deposit silver & gold

(o) create side contact

(p) create top contact

Figure 5.2: Schematic overview of the processing scheme
5.4 Structure definition

The minimum feature size of the metallic lasers and the gratings incorporated in their sidewalls is on the order of 50 nm. The structure of the metallic nano-lasers is therefore defined by means of electron beam lithography (EBL). Electron beam lithography uses electrons, instead of light, and is therefore not bound by the diffraction limit of light. This makes it suitable for the fabrication of nanometer-sized structures.

In order to pattern the semiconductor stack, a charge-sensitive resist layer is deposited on top of the stack. An EBL system scans the surface of the sample with a narrow beam of electrons, bombarding it with charge. By varying the beam current and the time a specific position is exposed to electrons, structures are defined.

The position of the electron beam is controlled by a pattern generator. The pattern generator maps a design, or part of a design, onto a discrete exposure grid. This grid is referred to as a write-field; it is the maximum area that can be exposed without moving the sample. The actual size of a single write-field is determined by the magnification of the system. The smaller the size of write-field, the more accurate the exposure.

After the exposure the charge-sensitive resist is subjected to a development step. Depending on the tone of the resist (positive or negative), either the exposed area or the unexposed area is dissolved by the developer, respectively.

A technique commonly used in combination with positive tone electron beam resists, is lift-off (such as ZEP and PMMA) [59]. Lift-off is used to invert the resist pattern after development. However, for features with sizes below 100 nm the performance of this technique quickly deteriorates [60]. It is limited by the roughness introduced by the boundary of the metal and by the thickness of the underlying hard-mask layer.

5.4.1 HSQ/HPR504 Bilayer resist

Due to the limitations of positive tone electron beam resists in combination with lift-off, a different approach was chosen for the fabrication of the nanometer-scale metallic structures. This approach comes in the form of a so-called bilayer electron beam resist [61].

The bilayer resist consists of a 450 nm thick, hard-baked HPR504 photoresist layer, on which an 80 nm thick layer of hydroxy silsesquioxane (HSQ) is applied (process parameters are listed in appendix B). HSQ is a negative tone electron beam resist with a high lateral contrast and a low sensitivity to exposure, suitable for applications in which a high resolution is required. Due to the low sensitivity to exposure, patterns in HSQ require a considerably higher dose as compared to ordinary electron beam resists (10 - 50 times higher).

Figures 5.3(a) and 5.3(b) illustrate the high resolution and contrast of HSQ (type XR1541-6%) in a straight line and a grating pattern. The dose for both structures is close to 2000 µC/cm^2.

The second resist layer, consisting of the hard-baked HPR504, is required because the HSQ layer itself is not sufficiently strong to withstand the etching of the underlying SiO2 hardmask layer. The selectivity of this dry-etch process, towards the HSQ is low (≈1:1).

5.4.2 Electron beam lithography

The electron beam lithography is performed on a Raith 150 system. A writefield size of 100µm × 100µm was chosen; using a 16-bit pattern generator, this results in a grid resolution of ∼1.6 nm. The length of the devices was kept smaller than 100 µm, so that the whole device fits in a single writefield and stitching errors are avoided. The acceleration voltage was set to 30 kV to
reduce backscattering effects and obtain the maximum resolution. Before the sample is loaded into the system a small stripe of gold is deposited on the sample, away from the structures, to facilitate focusing of the electron beam.

After the electron beam exposure, HSQ is developed in a tetramethyl-amoniumhydroxide (TMAH) based developer \[62\] and used as an etch mask for the hard-baked HPR504 layer. The HSQ pattern is transferred to the HPR504 by means of an O\(_2\) based RIE process. Figures 5.4(a) and 5.4(b) show a patterned HPR504 layer with the original HSQ pattern still on top.

The 450 nm thick HPR504 layer is sufficiently thick to dry-etch the SiO\(_2\) hardmask (see figure 5.5(a)). After the hardmask has been etched, the remaining HPR504 and HSQ are removed (see figure 5.5(b)) by means of stripping, rinsing in acetone and a wet etch to remove oxides.

### 5.5 Etching and cleaning

After opening the hard-mask, the semiconductor stack is etched in a CH\(_4\)/H\(_2\) based ICP-RIE process \[63\]. ICP etching was chosen over plain RIE etching because a better anisotropy can be obtained. During the process, a number of CH\(_4\)/H\(_2\)-based etch steps, followed by an O\(_2\) descum step, are executed, until the appropriate etch depth is reached. CH\(_4\)/H\(_2\) Based
5.5. Etching and cleaning

chemistries have a lower etch speed than chlorine based processes, but produce smoother surfaces and less surface damage [64].

The shape of the structure after etching is dependent on the process parameters (power, pressure, temperature, gas ratios etc.) and on the material used. For structures smaller than 300 nm, the quality of the etch is very sensitive to changes in the parameters and to the condition of the process chamber. In chapter 2 we have seen that the sidewall angle should differ less than 1° from vertical, over the active area, to minimize substrate leakage of the propagating mode. Therefore, before etching real samples, several tests are performed to optimize the ICP process. Typical results are shown in figures 5.7 to 5.9.

It is clear that the shape of the etched ridges changes if power and/or pressure are adjusted. The shape also changes if an n-doped InP (n-InP) substrate is used, rather than a semi-insulating InP (SI-InP) substrate. For ridges fabricated on SI-InP, the width of the ridge is reduced by approximately 20 nm after etching (with respect to the width in the design), compared to ridges fabricated on an n-InP substrates. Most likely this is caused by the different electrical and thermal properties of the material.

The power of the etch plasma also affects the damage caused to the etched surface. After the dry etch process, the sample is put through a series of cleaning steps to remove this damage [65]. The effect of these cleaning steps has been verified by performing them on test structures and comparing the photoluminescence of these structure before and after the treatment [66].

The cleaning involves repeated stripping of the sample in an O₂ plasma and consequently removing the oxidized material with a phosphoric acid based wet etch and BHF. The repeated exposure of the structures to the cleaning steps affects the shape of the structure. The InP is etched faster than the ternary material, resulting in a slight bulging (∼20 nm) of the active region. This bulge is beneficial to the confinement of light in the vertical direction (see chapter 2).

After the surface damage has been removed, the sidewalls of each structure are passivated with a thin SiNx layer. The layer also isolates the core from the metal cladding and therefore has to be sufficiently thick to withstand the applied electric field of ∼2 MV/cm (∼5 MV/cm would be desirable). The SiNx is deposited by means of PECVD, in two consecutive steps. First 5 nm of SiNx is deposited at a temperature of 30°C [67]. The remaining 15 nm are deposited at a temperature of 200°C. The first 5 nm passivate surface states, the other 15 nm
**Figure 5.6:** Typical breakdown of a 20 nm SiN layer

provide the electrical insulation.
5.5. Etching and cleaning

**Figure 5.7:** Ridges on n-InP. Etched for 10 cycles with: \( \text{CH}_4 - \text{H}_2, 30 - 10 \text{ sccm}, 200\text{W ICP} - 106\text{W RF}, 6 \text{ mTorr}, 60^\circ\text{C}, 1 \text{ minute} \). Descum step: \( \text{O}_2, 40 \text{ sccm}, 200\text{W ICP} - 110\text{W RF}, 18 \text{ mTorr}, 60^\circ\text{C}, 14 \text{ seconds} \). Sidewall angle: 0.85°

**Figure 5.8:** Ridges on n-InP. Etched for 15 cycles with: \( \text{CH}_4 - \text{H}_2, 30 - 10 \text{ sccm}, 200\text{W ICP} - 112\text{W RF}, 6 \text{ mTorr}, 60^\circ\text{C}, 1 \text{ minute} \). Descum step: \( \text{O}_2, 40 \text{ sccm}, 200\text{W ICP} - 110\text{W RF}, 18 \text{ mTorr}, 60^\circ\text{C}, 14 \text{ seconds} \). Sidewall angle: 0.31°

**Figure 5.9:** Ridges on SI-InP. Etched for 21 cycles with: \( \text{CH}_4 - \text{H}_2, 30 - 10 \text{ sccm}, 200\text{W ICP} - 112\text{W RF}, 6 \text{ mTorr}, 60^\circ\text{C}, 1 \text{ minute} \). Descum step: \( \text{O}_2, 40 \text{ sccm}, 200\text{W ICP} - 110\text{W RF}, 18 \text{ mTorr}, 60^\circ\text{C}, 14 \text{ seconds} \). Sidewall angle: 0.90°
5.6 Metallization

After etching the structures and removal of surface damage, the silver cladding is applied. Silver itself does not adhere well on III-V material, nor on SiNx. Therefore adhesion pads are created around the individual devices (figure 5.2(k)). The adhesion pads consist of Ti/Au and are defined using a lift-off process. During the lift-off, the devices are covered in photoresist, to prevent any metal being deposited on the sidewall of the device.

The second step in the metallization process is the fabrication of the top contact. The top of the device is covered by SiNx, as described in the previous section. To open the nitride at the top of the device, the sample is covered with photoresist and soft baked. The photoresist is then etched back, using developer, until 300 nm below the top of the devices. The SiNx is etched using a CHF3-based RIE process. Due to the anisotropy of the etch process and the protection of the resist, the SiNx on the sidewalls remains unaffected (figure 5.2(l)). The photoresist is removed by rinsing the sample in solvent and stripping in a barrel etcher with an O2-plasma.

The InGaAs contact layer at the top of the device is now exposed. The same photoresist etch-back technique is applied, as was used for the opening of the SiNx layer, to encapsulate the whole structure except for the contact layer. The top-contact metallization consists of Ti/Pt/Au and created by means of lift-off (figure 5.2(m)). Before the contact metals are deposited, the InGaAs layer is cleaned with a wet etch process. After the deposition of the metals, the resist and redundant metal are removed by soaking the sample in solvent and by O2 stripping.

The structure is now ready for the deposition of the silver cladding (figure 5.2(n)). The silver is deposited in two steps. During the first step, the angle between the top of the sample and the evaporation source is deliberately made high (80° and 45°) to ensure proper sidewall coverage. After the first deposition, the metal is annealed. The sample is quickly heated to a temperature of 400°C and kept at this temperature for 1 minute, in order to increase the grain size. This reduces the number of lattice boundaries, increases the free propagation range of the electrons inside the metal and thus reduces the damping experienced by these same electrons. Besides the structural improvement of the silver, the rapid thermal annealing (RTA) also allows the silver to form a solid bond with the gold layer of the adhesion pad and serves to remove crystal defects in the semiconductor material, by promoting recombination of the defects and restructuring of the broken bonds [65].
5.7. Contacting

It is important that the silver is properly attached to the side wall of the devices and that the number of holes in the silver is minimal. Also, the indentations of the grating have to be fully infiltrated by the metal. To verify that this has happened the structures are cut open using a focused ion beam (FIB). Cross-sections of a typical device are shown in figures 5.13(a) and 5.13(b). The first figure shows a cross-section in the transverse direction, the second a cross-section in the longitudinal direction. Figure 5.13(b) shows that the grating indentations are completely filled with silver.

A second deposition of silver is carried out at lower angles (45°, 30° and 10°) to cover the top and base. After the second deposition a protective gold layer is sputtered on the sample to prevent the silver from oxidizing. The devices are now all electrically connected through the metal cladding. A protective mask is created on top of the devices, using photoresist and an optical lithography step. The excess metal is then removed by a wet chemical etch.

5.7 Contacting

The final stage in the processing of the metallic nano-lasers involves the creation of p-contact and the contact pads. The p-contact is shared between 8 devices (see figure 5.14). Optical lithography is performed to define the area of the contact. First the SiN$_x$ layer is opened, after
Figure 5.13: Lateral (a) and longitudinal (b) cross-section of a metallic waveguide

which the contact layer is exposed by means of a wet chemical etch. Consequently, the contact metals (Ti/Pt/Au) are deposited (figure 5.2(o)).

Figure 5.14: A section of the total chip, showing eight devices with their n- and p-contacts.

The n-contact was fabricated during the metallization stage of the processing. To create a contact pad, suitable for bonding, the sample is covered with polyimide. The polyimide is photosensitive and a lithography step is performed to make the top of the devices accessible. The contact pad for the n-contact is then defined by a final lithography step, sputtering and lift-off (figure 5.2(p)).

5.8 Mounting and bonding

The samples are characterized either by collecting light through the substrate or by looking at an end-facet of an in-plane emitting device. The samples are mounted such, that characterization via either method is possible. A schematic representation of a mounted sample is shown in figure 5.15.

The samples are mounted using a silver epoxy, referred to as Epotec. After every step in which Epotec is applied, the sample is baked for 20 minutes at a 120 °C to harden the applied epoxy. First 20 µm Ø gold wires are glued to the contact pads. Thereupon, the sample is glued to a copper cube, which is then glued to an Al₂O₃ IC package. After the copper cube supporting the sample has been attached to the IC package, the wires are glued to the pins of
5.9 Conclusions

The epitaxial semiconductor material for the fabrication of the metallic lasers has been introduced, along with the outline of the fabrication process. The process can be divided into five stages, of which the definition of the structures by electron beam lithography and the dry etching of the structures in the wafer are the most critical.

For the electron beam lithography a new bilayer resist scheme, with high resolution and low sensitivity, was developed. The bilayer resist consists of a 80 nm thick HSQ layer on top of 450 nm hardbaked HPR504 resist. The HSQ is used for the definition of the structures, the HPR504 layer only serves as an intermediate for the etching of the SiO$_2$ hardmask. This approach is suitable for the definition of structures with dimensions well below 100 nm and results in very low surface roughness.

The patterns are transferred to the wafer using a CH$_4$/H$_2$ based ICP-RIE process. ICP Etching results in high anisotropy, which is required to obtain a side-wall non-verticality of less than 1°. The CH$_4$/H$_2$ based process produces less surface damage and smoother sidewalls than chlorine based processes. The little damage that is caused to the etched surface, is removed via oxidizing and wet etching the surface a number of times.

After the dry etching of the structure a 20 nm thick SiN$_x$ layer is applied to provide electrical insulation. The nitride layer is deposited by means of PECVD and is able to withstand voltages in excess of 10 Volt. This is sufficient for operation of the devices.

The metal cladding of the structures is deposited using thermal evaporation. During the deposition process the sample is positioned under various angles and is continuously rotated, to ensure good sidewall coverage. Correct filling of the grating periods was verified by looking at the lateral and longitudinal cross-section of the structures. These were created using a Ga$^{2+}$ focussed ion beam. The grain size of the metal is improved by exposing the sample to a
rapid thermal anneal cycle. This anneal process also improves (decreases) the amount surface recombination occurring at the etched surface.

After fabrication the samples are cleaved. The individual pieces are manually fitted with bonding wires. The bond wires have a diameter of 20 µm and are glued to the contact pads using silver epoxy. The samples are then mounted upside-down on a Al₂O₃ substrate for measuring.
Chapter 6
Device characterization

6.1 Introduction

In this chapter an overview of the measurement setup and measurement techniques is given. Furthermore the measurement results, obtained from the various fabricated samples, are presented. The properties of interest of the device are: the emitted polarization, the wavelength of operation, the threshold current and the linewidth. The performance of the devices on all of these points is discussed.

Three types of lasers were investigated. The first section of this chapter discusses metallic Fabry-Pérot lasers, fabricated to test the concept of side-emission. In the second section the measurements results, obtained from plasmonic Fabry-Pérot lasers, are presented. These results will be the reference for the devices discussed in the third section. The third section discusses the measurement results obtained from plasmonic DFB lasers. The performance of the DFB will be compared to the performance of their Fabry-Pérot counterparts.

For the metallic waveguide lasers to be a real alternative to pure dielectric lasers, room-temperature operation is required. In the final section of this chapter, we will look at the performance of the metal coated DFB lasers at temperatures higher than 80K. The issues with room temperature operation are discussed.

All measurement presented in this chapter will be fitted to a rate equation model in order to extract characteristic parameters of the devices and explain their behavior. In the final section of the chapter, the results are summarized and conclusions are drawn.
6.2 Measurement setup

The measurement setup is built around a continuous flow cryostat, suitable for cooling with LN₂ or LHe. In this cryostat devices are placed on a pedestal, located directly under a quartz window. In this cryostat up to 8 devices can be connected at the same time and operated in a temperature range from 10K to 330K. Some of the electrical connections of the cryostat are fitted with coaxial wires leading to the devices, so high frequency signals can be transferred to the devices. The cryostat is placed on a X/Y-translation stage controlled by micrometers.

The light emitted from the devices is collected by a microscope objective lens with a long working distance (≈ 17 mm) and a high numerical aperture (0.42). Via a set of mirrors the light is lead through a linear film polarizer and guided to a beam-splitting cube. The beamsplitting cube distributes the light equally over an InGaAs camera and a single mode optical fiber, leading to a spectrometer.

Additionally the single-mode fiber can be connected to an optical power meter or a red laser-source. The camera is used for alignment and imaging of the devices in the setup. It supports integration times ranging from 1 µs to 1s. The sensor can be cooled to a temperature of 260K, in order to reduce background noise.

The grating spectrometer contains three gratings (150 l/mm, 300 l/mm and 600 l/mm), offering either a high bandwidth (500 nm) or high resolution (100 nm bandwidth with 0.4 nm resolution). The spectrometer requires a maximum entrance slit opening of 50 µm in order to obtain the maximum resolution. The detector array can be cooled with LN₂ to a temperature of 170K, also to reduce background noise.

A schematic overview of the measurement setup is given in figure 6.1. In the setup the devices are powered by a microampère current source, the voltage over the device is monitored using a voltmeter. The total optical loss, from the collection lens at the cryostat, to spectrometer/powermeter is ≈ 9 dB (including coupling loss, fiber loss and loss from the beam-splitter).

Figure 6.1: Schematic overview of the measurement setup

All measurements discussed in this chapter are performed using continuous-wave current
injection (CW current injection), unless specified otherwise. Pulsed current injection is particularly suited for measurements at higher temperatures. It minimizes the amount of stress on the device during operation, as well as heating related effects.

The incorporation of a polarizer in the optical path of the measurement setup enables us to distinguish between both polarization states, as described in B, even although the devices are characterized through the substrate. This has been verified by 3D FDTD simulations of which the results are shown below.

Figures 6.3(a) to 6.3(c) show the characteristics of a TM polarized mode in a 6 µm long, 250 nm wide Fabry-Pérot cavity, as observed through the substrate (100 nm below the structure). Figure 6.3(a) shows the vertical component of the Poynting vector, which is directed towards the observer. From this plot it can be seen that most light is directed downward at the end of the cavity. If we now compare at the $E_x$ and $E_y$ components of the electric field, we find that $|E_y|^2$ is $> 20 \times$ larger than $|E_x|^2$. The component $|E_z|^2$ is left outside the discussion, because it does not propagate in the direction of the observer. It therefore has no influence on the measurement.

Figures 6.4(a) to 6.4(c) show the same characteristics for a TE polarized mode (100 nm below the structure). Figure 6.4(a) again shows the vertical component of the Poynting vector. We now see that most light is directed downward somewhat away from the end of the cavity. For the TE polarized mode we find that $|E_x|^2$ is $> 20 \times$ larger than $|E_y|^2$, which is the opposite of the TM polarized case. Since the polarizer passes either $E_x$ or $E_y$ we can distinguish the TE and TM polarized modes from each other.

An important, final note on the characterization of the DFB lasers through the substrate is that the characterization is complicated by the emission angle of the light from the cavity. From figure 6.2 it can be seen that the light radiates from the center of the cavity under an angle of $\sim 60$ degrees from the normal. The critical angle of the InP/Air transition is defined by $\theta_c = \arcsin(n_2/n_1) = \arcsin(1.0/3.16) = 18.45^\circ$. Most light is therefore trapped inside the substrate, due to total internal reflection (TIR).

![Figure 6.2: Simulated substrate emission for a DFB cavity operating at the Bragg wavelength.](image)

Better measurement results may be obtained if the devices are characterized in plane.
Figure 6.3: A TM polarized mode, 100 nm below the device, as observed through the substrate. (a) Shows the vertical component, $P_z$, of the Poynting vector. Indicating that most light is directed downward at the end of the cavity. (b) And (c) show the $|E_x|^2$ and the $|E_y|^2$ components of the electric field, respectively. $|E_y|^2$ is $> 20 \times$ larger than the $|E_x|^2$ component. $|E_z|^2$ does not propagate and is therefore not collected.
6.2. Measurement setup

Figure 6.4: A TE polarized mode, 100 nm below the device, as observed through the substrate. (a) Shows the vertical component, $P_z$, of the Poynting vector. Indicating that most light is directed downward close to the end of the cavity. (b) And (c) show the $|E_x|^2$ and the $|E_y|^2$ components of the electric field, respectively. $|E_x|^2$ is $> 20 \times$ larger than the $|E_y|^2$ component. $|E_z|^2$ does not propagate and is therefore not collected.
6.3 Side-emitting metallic waveguide lasers

In this section we will look at the characterization of metal coated Fabry-Pérot lasers. These lasers have been fabricated to study the feasibility of side-emission of metal coated devices. The lasers discussed in this section were fabricated on different material and have undergone a somewhat different processing than the other devices discussed in this thesis. These differences will be clarified in the following paragraphs.

![Diagram of Fabry-Pérot structure with open end-facets.](image)

**Figure 6.5:** A schematic overview of the Fabry-Pérot structure with open end-facets.

The base material used for the side-emitting lasers consists of an n-doped InP substrate on which a InP/InGaAsP/InP hetero-junction is grown. In the 510 nm thick InGaAsP film layer, 8 InGaAs quantum wells (QW) are grown. The layerstack of material is shown in table 6.1.

The n-doped InP substrate has the advantage that it allows contacting via the back of the wafer, which reduces the number of processing steps considerably. Another advantage is that the QWs provide more gain near the band edge [42]. A disadvantage of this particular layerstack is that the top p-InP buffer, between the contact and the gain region is very thick, requiring deeper etching and making it harder to obtain straight sidewalls.

The fabrication process of the side-emitting devices differs on the following points. Firstly, the wafer was patterned using a positive electron beam resist in combination with a lift-off process. Secondly, due to the different layerstack the required etch depth is larger (∼3 µm). Thirdly, since the substrate is n-doped, the backside can be used as an electrical contact.

After the deposition of the metal cladding only two relatively simple contact metallizations are required to finish the device. After fabrication, the devices are cleaved in two and the end-facets were cleaned using an Ar⁺-beam cross-section polisher.

Figures 6.6(a) and 6.6(b) show a schematic cross-section of the device and a SEM photo of the cross-section of an actual device. The width of the waveguide core is typically 200 nm, the length is 65 µm. In the following paragraphs the performance of the side-emitting structures is investigated. Here to the devices were placed inside the cryostat and cooled to an ambient temperature of 77K, using LN₂.

Due to the presence of the metal cladding, correct operation of the device can first be verified after the fabrication process has finished. The electrical insulation by the SiNx layer and diode operation are checked by performing I-V measurements. In case of a short circuit, due to a bad SiNx layer, zero voltage will be measured if current is injected. Figure 6.7 shows the I-V curve typical for a diode, confirming correct electrical operation of the device. As can be seen, the voltage increases over 3 Volts at an injection current of 500 µA. Ideally, at this
6.3. Side-emitting metallic waveguide lasers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material:</th>
<th>Thickness [nm]:</th>
<th>Doping [$cm^{-3}$]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>p-InGaAs</td>
<td>200</td>
<td>$&gt; 1.0 \cdot 10^{19}$</td>
</tr>
<tr>
<td>24</td>
<td>p-InP</td>
<td>1000</td>
<td>$1.0 \cdot 10^{18}$</td>
</tr>
<tr>
<td>23</td>
<td>p-InP</td>
<td>200</td>
<td>$5.0 \cdot 10^{17}$</td>
</tr>
<tr>
<td>22</td>
<td>Q1.25</td>
<td>20</td>
<td>$3.0 \cdot 10^{17}$</td>
</tr>
<tr>
<td>21</td>
<td>p-InP</td>
<td>300</td>
<td>$3.0 \cdot 10^{17}$</td>
</tr>
<tr>
<td>20</td>
<td>Q1.25</td>
<td>205</td>
<td>n.i.d.</td>
</tr>
<tr>
<td>19</td>
<td>InGaAs barrier (9)</td>
<td>6.3</td>
<td>n.i.d.</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>4</td>
<td>InGaAs QW (1)</td>
<td>4.1</td>
<td>n.i.d.</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs barrier (1)</td>
<td>6.3</td>
<td>n.i.d.</td>
</tr>
<tr>
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<td>205</td>
<td>n.i.d.</td>
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<tr>
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<td>n-InP</td>
<td>500</td>
<td>$3.5 \cdot 10^{17}$</td>
</tr>
<tr>
<td>0</td>
<td>n-InP</td>
<td>-</td>
<td>$2.0 \cdot 10^{18}$</td>
</tr>
</tbody>
</table>

Table 6.1: Layer-stack of the wafer used for the fabrication of the side-emitting metallic waveguide lasers. There are 8 InGaAs quantum wells, each surrounded by 2 barrier layers. Layer 0 is the substrate. Q1.25 indicates the quaternary alloy $In_{1-x}Ga_xAs_yP_{1-y}$, with the values for $x$ and $y$ chosen to yield a band-gap of 1.25 µm.

![Figure 6.6](image)

Figure 6.6: Schematic cross-section of a side-emitting metallic waveguide laser (a) and a SEM photo of a side-emitting metallic waveguide laser after polishing of the end-face (b). $d_{etch}$ is approximately 3 µm and $h_c = 500$ nm. The SEM photo shows the silver cladding, covered by the gold protection layer.

injection current the voltage is well below 2 Volts (as we will see for the other devices). The high voltage is caused by a high resistance of the p-contact.

For the optical characterization of the device the output power as a function of current is measured, together with the spectral output of device. The spectral output of the device was collected by the ANDO AQ6315A optical spectrum analyzer\(^1\), which is connected to the output fiber of the measurement setup. The L-I curve (light-current-curve) was obtained by replacing the spectrometer by an Agilent optical power meter. For laser operation, a super-linear L-I curve is expected. The spectrum of a Fabry-Pérot laser below threshold is characterized by

1.75
amplified spontaneous emission (ASE) and the absence of spectral peaks. Above threshold, the spectrum is expected to contain a number of peaks on top of the pedestal of ASE. These peaks are (almost equally) spaced, according to equation (6.1). In this equation $\lambda_0$ is the center wavelength, $n_g$ is the group index and $L$ is the length of the cavity.

$$\Delta \lambda \simeq \frac{\lambda_0^2}{2n_g L}$$ (6.1)

Besides the I-V curve of the device, figure 6.7 also shows the L-I curve. The L-I curve shows the expected super-linear behavior, indicative for Fabry-Pérot lasers. The threshold current of the laser is estimated at 150 µA, based on the L-I curve and on the spectra. In figure 6.8 spectra, obtained with the spectrometer at different injection currents, are shown. For currents below 100 µA the ASE spectrum is relatively smooth, around 100 µA the first signs of modes become visible on top of the ASE. At an injection current of 500 µA a clear Fabry-Pérot spectrum is visible. The Fabry-Pérot cavity modes are spaced 3 nm apart, which corresponds to a FSR = 444 GHz. Although the width of the waveguide allows the existence of both TE and TM polarized modes, the devices operate in the TM polarization (as defined for metallic waveguides), due to a better overlap of the electric field with the quantum wells.

The wavelength of the main laser peak is located close to 1450 nm, despite the fact that the gain material was optimized for operation at 1550 nm at room temperature. The blue shift is due to the high current density inside the device, the high gain required for lasing and the low operating temperature. The output power level at the wavelength peak 0.14 µW (in-fiber), at $I_{pump} = 500$ µA. At this current, the power level in the main laser peak is 30 dB above the background ASE level.

Another important indicator for laser operation is the reduction of the width of the spectral peaks (linewidth) as a function of power, which should follow a $\Delta \lambda \simeq 1/P$ trend. Figure 6.9(a) shows high resolution scans of the highest spectral peak for three values of the injection current. The wavelength of the peaks is 1447.1 nm, 1446.3 nm and 1445.8 nm respectively.

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1The ANDO AQ6351A optical spectrum analyzer has only been used to characterize the devices discussed in this section. The other experiments were carried out using a Horiba Jobin Yvon grating spectrometer.
6.3. Side-emitting metallic waveguide lasers

Figure 6.8: Emission spectra collected from the side-emitting metallic waveguide lasers for various injection currents.

The FWHM decreases from 0.719 nm at $I_{pump} = 150 \, \mu A$ to 0.102 nm at $I_{pump} = 500 \, \mu A$. In figure 6.9(b) the linewidth is plotted as function of injection current. It can be seen that the linewidth does indeed follow the expected $1/P$ trend. The smallest linewidth measured for these devices is 68 pm, but is possibly smaller due to the limited resolution of the ANDO spectrum analyzer.

Figure 6.9: (a) Comparison of the main laser peaks for various injection currents. (b) Linewidth of the main laser peak as a function of current, the fit with $1/P$ is also plotted.

The devices discussed in this section prove that the reflectivity of open end-facets and gain provided by the waveguide core are sufficient to sustain laser operation in side-emitting metal coated waveguide lasers. The devices have an extremely low threshold current of 150 $\mu A$ and show the expected Fabry-Pérot behavior. As mentioned in the introduction of this chapter, the side-emitting devices have been subjected to a slightly different processing scheme. In the next sections we will look at Fabry-Pérot devices and DFB device fabricated on a semi-insulating InP substrate.
Chapter 6. Device characterization

6.4 Plasmonic Fabry-Pérot lasers

As a reference for the DFB lasers, discussed later in this chapter, Fabry-Pérot lasers have been fabricated following the same processing scheme as the DFB lasers. This is the processing as described in chapter 5. These devices have electrically and optically been characterized. To study the performance of the Fabry-Pérot and DFB lasers, we will focus on several properties.

First of all, we will look at the L-I curves and threshold current of both types of devices. Both types of devices are expected to have a super-linear L-I curve. For the Fabry-Pérot lasers, a considerably higher threshold current is anticipated, than for the DFB devices. Also the L-I curve of the DFB lasers are expected to have a less sharp transition around the threshold, due to the higher spontaneous emission enhancement in these devices (see chapter 3).

The second point of interest is the spectrum of the devices. The Fabry-Pérot devices are expected to have spectra containing multiple spectral peaks, like the side-emitting devices from the previous section. The DFB devices were designed to operate at a single wavelength.

The last point we will look at is the clamping of the amplified spontaneous emission levels, emitted by the device. Clamping of the spontaneous emission levels, emitted by the device, indicates that if additional power is fed to the device, this power is directed to the laser mode.

In this section we present the results of these measurements for the Fabry-Pérot lasers. We will start with the electrical properties of the devices. The I-V characteristics of a Fabry-Pérot laser, with a width of 200 nm and a length of 100 µm, are shown in figure 6.11. The I-V curve shows the expected diode characteristic, indicating the device is operating as a proper diode. The voltage measured across the device is considerably smaller than the voltage measured across the devices from the previous section. The lower voltage is due to the higher doping levels and n-doped top contact on this wafer.

While being operated, the devices are continuously monitored using the InGaAs camera. Two images of the device, taken at an injection current of 2000 µA are shown in figure 6.12. The images were collected with the polarizer set to TE (figure 6.12(a)) and to the TM polarization (figure 6.12(b)). The colorbars next to the images show that the amount of power in the TM polarization is > 10 times larger than the power in the TE polarization, which is typical for plasmonic operation (see chapter 2). Based on the width of the waveguide ($w_c = 200$ nm), however, a TE polarized mode would be expected. The image taken in the TM polarization shows intensity peaks near the end of the devices, indicative for a propagating mode scattering at the end-facet.
6.4. Plasmonic Fabry-Pérot lasers

Figure 6.11: The I-V characteristic of a metal coated Fabry-Pérot laser at a temperature of 77K. The devices show a significantly lower voltage across the junction compared to the devices from the previous section. This due to the n-doped top contact for these devices.

Figure 6.12: Images of a $w_c = 200$ nm wide Fabry-Pérot laser, taken at a current of 2000 µA. The polarization filter is set to transmit TE polarized light (a) and TM polarized light (b), respectively. The intensity is normalized with respect to the highest intensity measured in the TM polarization. The fraction of power emitted in the TE polarization is less than 10% of the power emitted in the TM polarization. The power distribution in the TE polarization is more or less uniform along the cavity, typical for spontaneous emission. The TM polarization shows strong intensity peaks near the end-facet of the cavity, indicating a propagating mode.

Now that we have confirmed the devices is emitting TM polarized light, let us have a look at the L-I behavior of the device and the spontaneous emission levels. These are shown in figures 6.13(a) and 6.13(b) respectively. The L-I curve shows the integrated emission of the laser modes versus the injection current, which has the expected super-linear behavior. The threshold current of the device is approximately 1 mA ($\sim 5$ kA/cm$^2$). Figure 6.13(b) shows the integrated spontaneous emission level which increases at first and then stabilizes above threshold, as predicted. Both the L-I and spontaneous emission curves were extracted from emission spectra collected from the device. The separation of the laser modes from the spontaneous emission has an influence on the value of the threshold current. This results in a somewhat (10-20%) higher estimate of this value, in comparison to what measurements with
a power meter may give.

Figure 6.13: (a) The L-I curve of a $w_c = 200$ nm wide metal coated Fabry-Pérot laser at a temperature of 77K. The curve has been extracted from device spectra taken at different values of the injection current. The curve represents the power in the laser modes. (b) The integrated emission levels away from the laser modes (spontaneous emission). The threshold current of the device is approximately 1 mA, as can be seen from the L-I curve. The spontaneous emission is clamped, indicating laser operation.

In the last part of this section we will study the spectrum of the Fabry-Pérot lasers. Figure 6.14(a) shows the spectrum of the device at an injection current of 2 mA. The spectrum contains multiple peaks on a pedestal of spontaneous emission. The mode spacing is 1.4 nm. Using equation 6.1 we find a group index $n_g = 8.4$. The high group index can be explained by the material dispersion discussed in chapter 2 and has been observed before in [30].

Figure 6.14: High resolution spectrum taken at $I = 2000 \mu$A (a), figure (b) shows the evolution of the spectrum for different injection currents on a logarithmic scale. Notice the high base of spontaneous emission below the modes.
6.5 Metal coated DFB lasers

In this section the performance of the Fabry-Pérot laser will be compared to that of a similar DFB device. As mentioned before, we expect the performance of the DFB laser to differ on several points. These are: a lower threshold current and operation in a single longitudinal mode. The DFB laser discussed in this section has a waveguide core width $w_c = 140$ nm and a total grating width $w_g = 190$ nm. The thickness of the SiN$_x$ layer on the sidewalls is 15 nm and the length of the period $\Lambda_g = 230$ nm.

**Figure 6.15:** A schematic overview of the DFB structure.

Figure 6.16 shows the I-V of a metal coated DFB laser. The electrical characteristics are similar to that of the Fabry-Pérot laser from the previous section.

**Figure 6.16:** The I-V characteristic of a metal coated DFB laser at a temperature of 77K. The characteristic dimensions of the DFB laser are: $w_c = 140$ nm, $w_g = 10$ nm, $t_d = 15$ nm and $\Lambda_g = 230$ nm. The electrical properties of the structure are similar to those of the Fabry-Pérot device in the previous section.

The most interesting properties are expected to be found during the optical characterization of the device. Based on the size of the structure, the device is expected only to sustain the fundamental TM mode (plasmon mode). Before continuing with the optical characterization, this is verified by comparing the emission in both polarizations using the camera.

Camera images of the device, taken at an injection current of 2000 $\mu$A, are given in figures 6.17(a) and 6.17(b). The polarizer is set to transmit TE polarized light (figure 6.17(a)) and TM
polarized light (figure 6.17(b)) respectively. The scales have been normalized with respect to the maximum intensity, measured in the TM polarization. Also for this device, the amount of light emitted in the TE polarization is less than a tenth of the power in the TM polarization.

![Camera images of the device taken at a current of 2000 µA with the polarizer set to TE (a) and to TM (b). The temperature of the device was 77K.](image)

Figure 6.17: Camera images of the device taken at a current of 2000 µA with the polarizer set to TE (a) and to TM (b). The temperature of the device was 77K.

Let us now have a look at the L-I curve and spontaneous emission levels of the device. These are shown in figures 6.18(a) and 6.18(b). The first important difference we make up from the L-I curve is that the DFB structure has a considerably lower threshold current of $\sim 500 \, \mu\text{A}$ ($\sim 3.16 \, \text{kA/cm}^2$), which is about half the threshold current of the Fabry-Pérot laser. Also the transition from sub-threshold operation to laser operation is much smoother than the transition found for the Fabry-Pérot device. For the device discussed in this section, the spontaneous emission was indiscernible from the spectrometer noise. Therefore no conclusions can be drawn from the integrated spontaneous emission levels. However, figure 6.18(b) is shown for completeness.

High resolution spectra of the DFB laser are shown in figures 6.19(a) and 6.19(b). The spectrum shows a single peak at 1477 nm. This peak is $> 21 \, \text{dB}$ above its nearest neighbor, located at 1472 nm. Peaks in the Fabry-Pérot spectra shown earlier in this chapter did not differ more than a factor of 10 in intensity. Other longitudinal modes appear to be efficiently suppressed in the DFB cavity. The four other peaks, visible at higher currents, are side-modes of the laser cavity. The mode spacing is $\Delta \lambda = 4.53 \, \text{nm}$, which would correspond to a group index of $n_g = 2.48$. This is the combined result of: (1) the modes being able to propagate through the grating and (2) the same modes being sustained by the cavity formed by the total length of the device. It is unclear why the modes only appear on one side of the laser peak and why the number of side modes is limited. For other DFB lasers, like the one studied in [44], a large number of regularly spaced side-modes are visible at both sides of the operating wavelength.

Also investigated is the linewidth of the main laser peak as a function of injected power. The results are shown in figure 6.20. As can be seen, the device’s linewidth follows the expected $1/P$ behavior. The linewidth approaches 0.6 nm, which is close to the resolving limit of the spectrometer ($\sim 0.4 \, \text{nm}$).

Perhaps the most important property of the distributed feedback lasers is the possibility to control the wavelength of operation. In figure 6.21 the operating wavelength of various
Figure 6.18: (a) The L-I characteristic of the dominant mode inside a metal coated DFB laser at a temperature of 77K (including side-modes). (b) The integrated emission levels away from the dominant mode (spontaneous emission). The threshold current of the DFB structure is 50% lower than that of the Fabry-Pérot laser. The transition from sub-threshold operation to laser operation proceeds gradually. The spontaneous emission levels collected from the DFB device are indiscernible from the spectrometer noise.

Figure 6.19: (a) A high resolution spectrum taken at I = 3000 µA at T=77K. (b) The evolution of the spectrum for different injection currents (also at T=77K) on a logarithmic scale. The side-mode suppression-ratio (SMSR) is ≥ 21 dB.

devices is plotted as a function of the grating period. Two domains can be distinguished. The devices of which the wavelength lies close to the upper black line, are believed to operate at the Bragg wavelength; the wavelengths close to the lower black line most likely correspond to a band-edge mode. The data were obtained from a large number of devices with varying widths $w_c$ (which also affects the wavelength) from various locations on chip. Choosing more closely related widths $w_c$ results in closer clustering to the Bragg wavelength line.

Besides the dependency on the width of the waveguide core, the wavelength of operation is also dependent on the size of the $\lambda/4$-phase-shift in the center of the cavity. Simulations indicate that a deviation of 1 nm in the length of the phase-shift, results in a $\sim 5$ nm change in resonant wavelength. It is expected that a better trend can be obtained if the grating
Chapter 6. Device characterization

Figure 6.20: The extracted linewidth of the main laser peak as a function of injection current. The measurement is limited by the resolution of the spectrometer.

period range is extended to longer grating periods. FDTD simulations give a somewhat high wavelength estimate if the resolution is limited.

Figure 6.21: Wavelength of the main spectral peak as a function of grating period. Two domains can be distinguished. The devices of which the wavelength lies close to the upper line, are believed to operate at the Bragg wavelength; the wavelengths close to the lower black line most likely correspond to a band-edge mode. The data were obtained from a large number of devices with varying widths $w_c$ (which also affects the wavelength) from various locations on chip. Choosing more closely related widths $w_c$ results in closer clustering to the Bragg wavelength line.

6.6 Rate equation model

The measurement data, presented in the previous sections, was fitted to a multi-mode rate equation model specific to each device. Using the rate equation model, estimates of device properties were obtained and compared to values gathered from simulations in previous chapters. These parameters are: the Q factor, the confinement factor and spontaneous emission enhancement factor. In this section the rate equation model is introduced, together with the results obtained from fitting the model to the measurement data.

The rate equation model uses the following equations to describe the carrier and photon densities (see equations 6.2 and 6.3). For every device a single carrier reservoir is assumed.
The behavior of this reservoir is described by equation 6.2. Carriers enter the carrier reservoir via the term $I/V$, where $I$ is the current and $V$ is the volume. The next three terms account for carrier disappearing from the reservoir: via surface recombination ($S_a/V \cdot AN$), bimolecular recombination (spontaneous emission) ($\gamma(n)BnN$) and via Auger recombination ($Cn^2N$). The remainder of equation 6.2 represents the carriers disappearing from the reservoir due to the total stimulated emission (in all the modes).

$$\frac{dN}{dt} = \frac{I}{V} - (\frac{S_a}{V}A - \gamma(n)Bn - Cn^2)N - \Gamma v \sum m g_m(n)S_m \quad n = N/V \quad (6.2)$$

$$\frac{dS_m}{dt} = \Gamma v g_m(n)S_m + \gamma_m(n)BnN - \frac{S_m}{\tau_{p,m}} \quad m \in 1...#modes \quad (6.3)$$

In the rate equation model every cavity mode (indicated by the mode number $m$) is assigned its own photon density rate equation. In this equation the first term ($\Gamma v g_m(n)S_m$) gives the number photons added to the mode by stimulated emission. The second term, $\gamma_m(n)BnN$, represents the number of photons added to the mode by spontaneous emission. The last term of the equation describes the number of photons disappearing from the mode, due to the various loss mechanisms (internal loss, mirror loss, scattering etc.).

Special attention should be paid to the $\gamma(n)$ and $\gamma_m(n)$ variables in the equations. Based on calculations in chapter 3, it is expected that the radiative emission rate is significantly altered by the presence of the cavity. $\gamma(n)$ is the factor by which the total radiative emission rate is modified. With the total radiative emission, we mean the spontaneous emission directed to the cavity modes, as well as the spontaneous emission not directed to the modes. The term $\gamma_m(n)$ only specifies by what factor the radiative emission rate directed to a specific mode is changed. For clarity: $\gamma(n) = \gamma_m(n) + F_{ext}$, where $F_{ext}$ describes the emission directed to the free-space modes. The calculation of the $\gamma(n)$ parameter is discussed later in this section.

The gain spectrum was approximated using a parabolic band model for the bulk-InGaAs material (equation 6.4). The wavelength range over which the medium exhibits positive gain is determined by the parameter $\Delta E_f(N)$, the change in Fermi level, which is function of the carrier density. This parameter ($\Delta E_f(N)$), including the band-gap shrinkage [39], is calculated using the Nilsson approximation [40]. The gain spectrum is scaled via the $C$ parameter (in equation 6.4) to yield a gain of 3500 cm$^{-1}$ [68] at a wavelength of 1485 nm, at a carrier density of $2.5 \cdot 10^{19}$ cm$^{-3}$ (T=77K).

$$g(E,N) = C \cdot \sqrt{E - E_g} \left( \exp \left( \frac{E - \Delta E_f(N)}{kT} \right) + 1 \right)^{-1} - 0.5 \quad (6.4)$$

As was discussed earlier, it is expected that the radiative emission rate of the bulk-InGaAs material will be affected by the presence of the plasmonic cavity. The spectral behavior of the radiative emission is determined by the normalized carrier energy distribution $\xi(E,N)$, which gives the probability of positive gain (and thus radiative emission) at a specific wavelength for carrier density N. The parameter was calculated by using the parabolic band approximation, similar to the calculation of the gain.
Chapter 6. Device characterization

The overlap of $\xi(E,N)$ with the cavity resonance (a Lorentzian with center-wavelength $\lambda_{\text{cav}}$ and quality factor $Q$) is taken into account via the integral in equation 6.5. During the fitting process, the Purcell factor $F_{\text{cav}}$ is varied to obtain a correct fit to the measurement data. For the Fabry-Pérot lasers an average Purcell factor is assigned to all the cavity modes ($F_{\text{ave}}$), whereas for the DFB laser each mode is assigned its own Purcell factor, $F_m$, where $m$ is the mode number.

The Purcell factors found by the fitting process will be different from the values found in chapter 3. This is due to the fact that the simulations in chapter 3 consider only a single emitter, located at the center of the cavity. The calculations do not account for the presence of other emitters, location, random polarization or carrier diffusion effects.

$$\gamma(N) = \int F_{\text{cav}} \xi(N,\lambda) \frac{1}{1 + 4Q^2(\lambda/\lambda_{m} - 1)^2} d\lambda + F_{\text{ext}}$$  \hspace{1cm} (6.5)

The differential equations (equations 6.2) are solved by a single step Runge-Kutta algorithm over a fixed time span (3 ns), which is long enough for the equations to settle. At the end of the integration, the end state is fed back to the solver as start parameters. If the absolute difference between the first integration and the second is smaller than the specified tolerance ($10^{-2}$), the end state is accepted as the steady-state solution of the problem.

In the next sections we will look at the fitting of the rate equation model to the L-I measurement data of the various plasmonic devices presented earlier. The fits are obtained by scaling the calculated photon numbers by a constant, to match the number of counts collected by the spectrometer. An exact match between the photon number and measured power is not possible, due to the unknown collection efficiency. A similar approach is taken for the integrated spontaneous emission, which is fitted to the calculated carrier number.

The fitting will focus on three parameters: the Q-factor ($Q$) of the mode(s), the confinement factor ($\Gamma$) and the Purcell factor of the cavity ($F_{\text{cav}}$). The values of the other parameters are assumed constant. The value for the bimolecular recombination rate $B$ is taken $9 \cdot 10^{-10} \text{cm}^3\text{s}^{-1}$ \cite{70}. The value for the Auger recombination rate ($C$) is $9.8 \cdot 10^{-30} \text{cm}^6\text{s}^{-1}$ at a temperature of 77K. At room temperature, the Auger recombination rate is a factor 10 higher. The group velocity, $v_g$, is $10^{10}\text{cm} \cdot \text{s}^{-1}$. The parameters $S_a$ and $V$ are device dependent.

6.6.1 Fabry-Pérot cavities

Again we will first look at the Fabry-Pérot laser. For this cavity type 75 modes were included, with a mode spacing of 1 meV or 2 nm, starting at an energy of 770 meV ($\sim 1615$ nm).

Figures 6.22(a) and 6.22(b) show the measurement data, presented earlier this chapter, and the fit obtained with the rate equation model. As discussed before, both fits were obtained by scaling the photon and carrier numbers calculated by the model to match the number of counts. The non-radiative recombination velocity, $A$, was varied slightly to obtain the correct threshold.

Using the rate equation model, the value obtained for the confinement factor is 0.24. The value of $F_{\text{ave}} = 0.01$, is close to the value of $F_{\text{ext}}$, describing the coupling to free-space modes. All modes are given an initial Q-factor of 300, corresponding to a sub-threshold linewidth of about 5.0 nm. An overview of the whole parameter set can be found in table 6.2.

The non-radiative recombination velocity is somewhat higher than the expected value of $6.5 \cdot 10^{-3} \text{cm/s}$, however, this may be due to the way the data were obtained. As discussed
6.6. Rate equation model

![Graph](image.png)

(a) Figure 6.22: L-I Curve and spontaneous emission data obtained from a \(w_c = 200\) nm wide Fabry-Pérot cavity at a temperature of 77K.

![Graph](image.png)

(b) Figure 6.23: The calculated carrier density inside a metallic Fabry-Pérot laser as a function of injection current. The parameters used to obtain this curve are listed in table 6.2.

earlier this chapter, the L-I curve of the power in the laser modes and integrated spontaneous emission were extracted from the spectra collected from the device. Depending on how the laser modes and spontaneous emission are separated from each other, the threshold point can vary slightly (10-20%).

The average Purcell factor assigned to the modes is lower than expected, which we believe is due to the large number of longitudinal modes and the somewhat larger width of the waveguide \(w_c = 200\) nm). The Purcell factor found from the fitting of the measurement data should not be regarded as a well-defined parameter, but merely as a reference for comparison with the DFB cavity measurement data.

### 6.6.2 DFB cavities

A similar fit has been obtained for the DFB structure. For this device only 2 modes were taken into account, one at the peak wavelength of the device (1475 nm) and one at the expected position of the band-edge mode (1405 nm). The confinement factor, obtained from the fit, has a value \(\Gamma = 0.20\). The Q-factors for both modes are 200 and 100 respectively. Figures 6.24(a) and 6.24(b) show the fitted L-I curve and spontaneous emission levels of
Table 6.2: Parameters for the Fabry-Pérot rate equation model at 77K.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FP}$</td>
<td>$11.50 \cdot 10^3$</td>
<td>$\text{cm/s}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$9.00 \cdot 10^{-10}$</td>
<td>$\text{cm}^3/\text{s}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$9.80 \cdot 10^{-30}$</td>
<td>$\text{cm}^6/\text{s}$</td>
</tr>
<tr>
<td>$F_{ave}$</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.24</td>
<td>-</td>
</tr>
<tr>
<td>$Q_{FP}$</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>$S_{FP}$</td>
<td>$6.0 \cdot 10^{-7}$</td>
<td>$\text{cm}^2$</td>
</tr>
<tr>
<td>$V_{FP}$</td>
<td>$6.0 \cdot 10^{-12}$</td>
<td>$\text{cm}^3$</td>
</tr>
</tbody>
</table>

In section 6.5 we noted that the spontaneous emission levels lie within the noise limit of the spectrometer and that therefore no conclusion could be drawn based on this data. The trendline, shown in the plot of the spontaneous emission levels, is a result of fitting the rate equation model to the L-I data of the DFB cavity. The obtained parameter set was then used to calculate the expected behavior of the integrated spontaneous emission levels, which is shown in figure 6.24(b).

The spontaneous emission levels being too low to see a trend are a big contrast to the results obtained from the Fabry-Pérot laser, where the spontaneous emission dominates the spectra.
and the integrated spontaneous emission power exceeds the power in the laser mode.

**Figure 6.25:** Carrier density inside a metallic DFB laser as a function of injection current (calculated by the rate equation model). The carrier density exceeds the $10^{18}\text{cm}^{-3}$ mark, dispersion will have a significant effect on the performance of the device.

The unscaled carrier density, calculated by the rate equation model are shown in figure 6.25. The density predicted by the model is higher than that predicted for the Fabry-Pérot laser, which is partly due to the smaller volume. Based on this calculation we expect the material dispersion, discussed in chapter 2, to be likely to occur.

### Table 6.3: Parameters used for the distributed feedback rate equation model

<table>
<thead>
<tr>
<th>Parameter:</th>
<th>Value:</th>
<th>Unit:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{DFB}$</td>
<td>$4.40 \cdot 10^3$</td>
<td>$\text{cm/s}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$9.00 \cdot 10^{-10}$</td>
<td>$\text{cm}^3/\text{s}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$9.80 \cdot 10^{-30}$</td>
<td>$\text{cm}^6/\text{s}$</td>
</tr>
<tr>
<td>$F_1,F_2$</td>
<td>5, 1</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>$Q_1,Q_2$</td>
<td>200 &amp; 100</td>
<td>-</td>
</tr>
<tr>
<td>$S_{DFB}$</td>
<td>$7.2 \cdot 10^{-7}$</td>
<td>$\text{cm}^2$</td>
</tr>
<tr>
<td>$V_{DFB}$</td>
<td>$4.2 \cdot 10^{-12}$</td>
<td>$\text{cm}^3$</td>
</tr>
</tbody>
</table>

The Q factors found for the modes of the DFB cavity are lower than the Q factors of the modes in the Fabry-Pérot cavity, although it was expected to be the other way around. The cause of this might be related to the shape of the fabricated DFB cavity (sidewall angle and grating shape), which is much more susceptible to deviations in the fabrication process. This would also explain the slightly lower confinement factor ($\Gamma$).

### 6.7 High temperature performance

In this section the performance of the DFB lasers at temperatures higher than 77K is investigated. For these plasmonic devices to be a real alternative to dielectric PICs, operation at room temperature (295K) is required. It is expected that the performance of the device will decrease, for temperatures approaching 295K. This expectation is based on the following grounds. First
of all the non-radiative surface recombination velocity has a square root dependence on the absolute temperature \cite{71}. Secondly the Auger recombination rate, which did not play a significant role at cryogenic temperatures, is increased by a factor of 10 at room temperature \cite{70}. Thirdly, the amount of gain available at the gain peak is approximately 2100 cm$^{-1}$, instead of the 3500 cm$^{-1}$ at 77K. Finally, the optical loss from the silver is expected to be higher at room temperature.

The measurements discussed in this section were performed using pulsed current injection. Pulsed operation prevents heating and degradation of the device. The device under test is connected to the output of a pulsed voltage source. The repetition rate of the source was set to 1 MHz, with a duty-cycle between 1-5%, resulting in pulses with a length of $\sim 50$ ns. The pulse source is externally triggered by the controller of the spectrometer, so that the device is only active during the actual collection of light.

The voltage across the device is monitored by a high-impedance measurement probe, connected to an oscilloscope. The current through the device is estimated by dividing the on-state voltage measured by the probe by the series resistance of the device. The series resistance of the DFB laser discussed in the previous sections of this chapter, is $\sim 490$ $\Omega$, and was extracted from figure 6.16.

In figures 6.26(a) and 6.26(b) the L-I curve and spontaneous emission of a DFB laser operating at a temperature of 294K are plotted. The device has a core waveguide width $w_c = 140$ nm and a total grating width $w_g = 190$ nm. The period of the grating $\Lambda_g = 210$ nm and the thickness of the nitride layer $t_d = 15$ nm. From the L-I curve of the laser we see that the threshold current has increased to a value of $\sim 2.5$ mA. Also at room temperature the spontaneous emission levels are significantly lower than the power in the main spectral peak. The spontaneous emission does not show a very clear trend, except that it appears to stabilize for currents higher than 6 mA.

A reasonably good fit with the rate equation model could be obtained for the high-temperature measurement data. The values used are listed in table 6.4. The L-I curve is slightly off for data points around/below threshold. We expect this to be related to inaccuracies in the determination of the operating current, which is calculated by dividing the voltage over the device
by a constant resistance. This approximation fails if the voltage over the device approaches the built-in voltage of the diode, where the resistance is higher.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value:</th>
<th>Unit:</th>
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<tbody>
<tr>
<td>$A_{DFB}$</td>
<td>$23.8 \cdot 10^3$</td>
<td>[cm/s]</td>
</tr>
<tr>
<td>$B$</td>
<td>$9.00 \cdot 10^{-10}$</td>
<td>[cm$^3$/s]</td>
</tr>
<tr>
<td>$C$</td>
<td>$9.80 \cdot 10^{-29}$</td>
<td>[cm$^6$/s]</td>
</tr>
<tr>
<td>$F_1, F_2$</td>
<td>2, 1</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>$Q_1, Q_2$</td>
<td>150 &amp; 75</td>
<td>-</td>
</tr>
<tr>
<td>$S_{DFB}$</td>
<td>$6.25 \cdot 10^{-7}$</td>
<td>[cm$^2$]</td>
</tr>
<tr>
<td>$V_{DFB}$</td>
<td>$3.65 \cdot 10^{-12}$</td>
<td>[cm$^3$]</td>
</tr>
</tbody>
</table>

**Table 6.4:** Parameters used to model a DFB laser with $w_c = 140$ nm, $w_g = 190$ nm, $\Lambda_g = 210$ nm and $t_d = 15$ nm at a temperature of 294K.

We note that of the three fitting parameters, only the $Q$ factor has undergone a significant decrease. This decrease is assigned to the higher loss exhibited by the metal cladding at room temperature. The Purcell factors of both modes (at room temperature) are still significantly larger than that of the Fabry-Pérot cavity measured at $T=77$K, indicating that the alteration of the radiative emission rate by the cavity is not affected by the higher temperature.

**Figure 6.27:** Spectra obtained from a DFB type cavity with $w_c = 140$ nm, $w_g = 190$ nm, $\Lambda_g = 210$ nm and $t_d = 15$ nm on a linear scale (a) and on a logarithmic scale (b) for clarity. Measurements were taken under pulsed current injection at a temperature of 294K.

Figure 6.27 shows the spectrum of the device. The spectrum contains two peaks, one at a wavelength of approximately 1515 nm and the other at a wavelength of 1380 nm. The peak at 1380 nm has a $\sim 10$ times lower intensity and is much wider. The linewidth of the dominant peak is shown in figure 6.28 and satisfies the $1/P$ dependence, expected for a laser. The linewidth of the device operating at 294K is at least a factor 10 times larger than when operated at cryogenic temperatures. This may be due to cavity heating during the pulsed injection of current. Or, to strong spontaneous emission coupling to the mode and that the true compensation of optical losses by the gain medium has not yet been achieved.
Chapter 6. Device characterization

Figure 6.28: Linewidth of the main spectral peak, shown in figures 6.27, as a function of injection current. The linewidth is a factor \( \sim 10 \) larger than for cryogenic temperatures, possibly due to heating effects occurring in the cavity, but still shows a clear \( 1/P \)-dependence.

Similar linewidths have also been observed in optically pumped plasmon lasers, based on CdS and operating at a wavelength of \( \sim 495 \) nm\(^\text{[72]} \). However, pulsed optical pumping generates little heating of the device. This is the first demonstration of at least the onset of electrically pumped plasmon mode lasing for the near infrared wavelengths at room temperature. Such room temperature lasing with a strongly confined plasmonic optical mode will be of critical importance for most applications.

6.8 Conclusions

In this chapter we have presented a measurement setup suitable to characterize lasers based on metal coated waveguides and with waveguide widths well below the diffraction limit of light. The measurement setup can characterize the devices at temperatures as low as 4K (LHe cooling) and 77K (LN\(_2\) cooling), up to 300K. The setup is capable of visualizing the device (via an InGaAs camera) and characterizing it spectrally at the same time (via the connected spectrometer). The spectral resolution is limited to \( \sim 0.4 \) nm and can be obtained by the grating of 600 lines/mm.

The devices in the measurement setup can be operated by means of CW current injection or pulsed current injection. The latter is particularly suitable for measuring at temperatures higher than 77K, since it prevents heating of the device. Pulsed current injection is performed by using a repetition rate of 1 MHz and a pulse width of approximately 60 ns. The maximum current supplied to the device, for both types of sources, is in the order of 10 mA.

We have shown that it is possible to fabricate side-emitting metallic waveguide Fabry-Pérot lasers. The width of these lasers is such that plasmonic operation can not be guaranteed, however, the emitted light is TM polarized. The devices show that the open end-facets provide sufficient reflection to enable laser operation. The devices operate at very low currents, starting from 150 \( \mu \)A, and show a clear Fabry-Pérot spectrum. The linewidth obeys the predicted \( 1/P \) dependence; the smallest linewidth measured was 68 pm, which is close to the resolution of the ANDO spectrometer.

A second set of Fabry-Pérot lasers was fabricated using the fabrication process and material also used for the plasmonic DFB lasers. These Fabry-Pérot lasers, fabricated as reference for the plasmonic DFB structures, were measured via the substrate and show the spectrum characteristic for these devices. The threshold current is \( \sim 1000 \) \( \mu \)A, which is higher than that
of a DFB laser of similar length. The amount of light emitted by the device, shows strong maxima near the end-facets of the cavity, indicating a propagating mode scattering from the end-facets. The spontaneous emission levels are higher than the power in the laser modes. The spontaneous emission level increases for currents lower than the threshold current and is clamped above threshold.

Two factors may contribute to the fact that the side-emitting laser has such a low threshold current. First of all, the waveguide is somewhat wider than the other devices discussed. Wider waveguides lead to lower loss (see chapter[2]). The other reason could be that the (commercial) quantum well material provides a lot more gain than the bulk material grown at our physics department. Concerning the linewidth, the linewidth of the side emitting device was measured using an ANDO spectrum analyser, with a much higher resolution. This spectrum analyser could only be used with the side-emitting devices, because we could collect more light from these structures.

We have also shown that it is possible to fabricate DFB lasers based on the M-I-S-I-M waveguide structure. These lasers can have widths as small as 120 nm (core waveguide width) and have a grating depth of 50 nm. The lasers emit light through the substrate. This light is predominantly TM polarized, which is a characteristic property of plasmonic operation. The threshold current for a 82 µm long cavity is typically around 500 µA (at 77K). This is about 2 times lower than the threshold current of a Fabry-Pérot cavity of similar length. The DFB laser performs better (in terms of threshold current) than its Fabry-Pérot equivalent because it has a much stronger feedback mechanism, which is directed to one (or a few, at most) mode.

Above threshold the DFB lasers show a side-mode suppression ratio of more than 21 dB over the nearest other peak in the spectrum. The linewidth of the main laser peak follows the expected 1/P-trend and decreases to 0.6 nm, which is close to the limit of the Horiba spectrometer. The extracted spontaneous emission levels are very low and appear to be constant at all injection currents. This gives an indication that spontaneous emission outside the main laser mode is efficiently suppressed. Based on the light current curve of the device, a Purcell enhancement factor of 5 is expected.

For the DFB lasers, the operation wavelength shows a dependence on the grating period. If the wavelength of the device is plotted versus the grating period, two wavelength ranges can be distinguished. One ranges from 1400 - 1550 nm, this range most likely corresponds to the mode at the Bragg wavelength. The other range starts at 1300 nm and ends at 1400 nm. This range corresponds to the short-wavelength side mode of the grating. The overall operation wavelength of the devices is lower than expected from FDTD simulations. This may be a combined result of: over estimating the wavelength due to a too low resolution in the simulations and the presence of dispersion.

The devices have also been tested at temperatures higher than 77K. Measurements have been done for temperatures up to 296K. For increasing temperature, the intensity of the emitted light is reduced. Also the linewidth increases from 0.6 nm at 77K, to ∼ 5 nm at 220K and a value < 9 nm at 294K. We expect this increase to either be caused by heating of the device or by strong spontaneous emission coupling to the mode. Despite the large linewidth, the L-I curves remain to show a super-linear behavior and the spontaneous emission appears to be clamped. Characterization via an end-facet could provide a definite answer if laser operation is achieved, but at least we see the onset of lasing.

All measurement results have been fitted to a rate equation model. From the fit parameters several conclusions can be drawn. First of all, the Q factors and confinement factor of the
Chapter 6. Device characterization

DFB cavity (\(Q_1=200, Q_2=100 \text{ & } \Gamma = 0.20\)), operating at 77K, appear to be slightly smaller than those of the Fabry-Pérot cavity (\(Q=300 \text{ & } \Gamma = 0.24\)). This may be related to the more complex shape of the DFB cavity.

For the DFB cavity, however, a much higher Purcell enhancement factor (\(F_1=5, F_2=1\)) was required to obtained a good fit of the measurement data. The Fabry-Pérot measurement data required an enhancement factor of \(F_{ave}=0.01\). At high temperatures, the surface recombination rate increased, as expected. The Q factors of the DFB cavity are reduced to 75% of their original values. The Purcell factor was also reduced, but remains in the same order of magnitude.
Chapter 7
Conclusions and discussion

7.1 Introduction

This chapter summarizes the work discussed in the previous chapters. The main conclusions are presented and an outlook and recommendations for further work are given.
Chapter 7. Conclusions and discussion

7.2 Conclusions

In this thesis we have shown that despite the high internal loss, laser operation can definitely be sustained in metallic cavities of sub-wavelength dimensions. Not only is it possible to fabricate Fabry-Pérot type lasers, but, as was shown, also more complicated devices can successfully be fabricated. Eventually such devices may have an application in low-power, high speed photonic integrated circuits.

Distributed feedback was introduced into waveguides based on the M-I-S-I-M structure. The behavior of these gratings was analyzed using FDTD simulations. The wavelength of maximum reflection can be determined by the period of the gratings. Very large reflection coefficients and bandwidths are expected, even for short gratings.

The distributed feedback can be used to create wavelength selective, resonant cavities. These cavities have a high enough quality factor (both at room-temperature and cryogenic temperatures) to sustain lasers operation. Operation at the Bragg wavelength can be enabled by introducing a $\lambda/4$-phase-shift in the center of the cavity.

The threshold material gain required by the devices is in the order of $1200 \text{ cm}^{-1}$, a value easily obtainable by bulk semiconductor material. The effect of the removal of the metal end-facets was investigated, but does not seem to affect the quality factor or threshold conditions as long as the cavity consists of more than $2 \times 20$ periods.

Due to the strong confinement of the light inside the cavity and due to the strong reduction of available modes, a high spontaneous emission enhancement factor is predicted for DFB structures operating at the Bragg wavelength. Outside the mode of the Bragg wavelength and also in the TE polarization, the spontaneous emission is expected to be efficiently suppressed. Possibly by a factor $> 100$.

A new lithography process was developed, suitable for the fabrication of structures with feature sizes down to 25 nm. This process has successfully been used to produce several series of both metal coated Fabry-Pérot and DFB lasers, based on the waveguide structure discussed before, with core waveguide widths down to 80 nm.

224 Devices, of which 60 Fabry-Pérot lasers, are accommodated on a single chip. Sections of 8 devices were mounted on $\text{Al}_2\text{O}_3$ substrates for characterization. For some of these devices one of the metal end-facets was removed for characterization from the side, the other devices were characterized by inspection through the substrate. The devices were characterized at temperatures ranging from 80K to 300K.

Fabry-Pérot structures have been measured as a reference to the DFB structures. These structures typically have a threshold current in the order of 1000 $\mu$A. The measured spectra are as anticipated for these devices. They consist of around 20 modes that reach threshold for laser operation. Above threshold the spontaneous emission levels are clamped. The SE power levels are higher than the power in the lasing modes. The average Purcell enhancement factor of the cavity modes, extracted with the rate equation model, is 0.01. This value is close to the value used to account for the coupling to free space modes.

The distributed feedback lasers show a much lower threshold current than their Fabry-Pérot equivalents. The typical threshold current value lies around 500 $\mu$A. A side-mode suppression ratio of $> 21$ dB was observed. The linewidth of the main spectral peak shows a $\Delta \lambda \approx 1/P$ dependence and the minimum linewidth observed is $\sim 0.4$ nm, which is close to the resolution of the spectrometer. The spontaneous emission levels observed were so low that no real relation with the injection current could be discovered, however, the levels do not appear to
7.3 Discussion of the results

The L-I curve of several of the DFB lasers was matched to a rate equation model. Based on this model, we expect that the Purcell enhancement, exhibited by the cavity at 77K, is approximately 5. At room temperature the enhancement factor is about 2. This is still much larger than the enhancement factors extracted for the Fabry-Pérot cavities.

Looking at the wavelength of the largest peaks in the spectra of the DFB lasers, we see an increase in wavelength of operation for increasing grating periods. Some points in the plot appear to deviate from the expected trend, which might be caused by the different width of the waveguide core. In the wavelength plot, two regions are visible, one ranging from 1400 - 1550 nm, the second ranging from 1300 - 1400 nm. It is believed that these regions correspond to the Bragg wavelength mode and to the band-edge mode.

7.3 Discussion of the results

The design of metallic structures is complicated by the highly dispersive nature of the silver cladding. The wavelength dependencies, other than the ones introduced by the structure itself, can not be neglected. Good wavelength selectivity may be difficult to achieve in metallic DFB cavities. The presence of a λ/4-wavelength shift will enable lasing at the Bragg wavelength of the grating. However, since the propagation loss in the cavity is dependent on the wavelength, the presence of the phase-shift does not necessarily mean that the mode at the Bragg wavelength will be the mode with the lowest overall loss. This effect introduces more uncertainty if the properties of the metal cladding vary a lot over every deposition.

For proper DFB operation the reflection spectrum of the grating and the gain spectrum should be well aligned [43]. Power concentrated in center of laser leads to increased stimulated emission and larger carrier depletion in the center of the cavity. Thus the carrier density at the ends of the cavity increases and cause the effective index and the deviation from the Bragg wavelength to decrease. Reflection of side modes increases near facets and therefore the side modes reach threshold.

Due to the small size of the cavities, field intensities and carrier densities can become very large. This may lead to the occurrence of various undesired effects, such as: dispersion, spectral and spatial hole burning. These effects are enhanced by the non-uniformity of carrier injection and field distributions. Also related to the small modal volumes, and the related Purcell enhancement, a lot of spontaneous emission will be coupled to the lasing mode of the device. The linewidth of the lasing mode is proportional to the spontaneous emission coupling rate [73]. Since the coupling of spontaneous emission appears to be strongly enhanced, it is suspected that the linewidth will not be as small as seen in ordinary DFB lasers. Future versions of these devices need to be studied carefully for the occurrence of these effects.

A recurring question about metallic nano-lasers, related to the high internal loss, is whether they can have a high enough differential efficiency. Recent theoretical studies have shown that despite the high loss, efficiencies (defined as \( \eta_{\text{extr}} = \frac{Q_{\text{rad}}}{Q_{\text{tot}}} \)) as high as 0.32 at room temperature can be obtained [74]. Other studies [75, 76] indicate that the extraction efficiency can be improved at the cost of a slightly higher threshold gain requirement.
Chapter 7. Conclusions and discussion

7.4 Recommendations

Currently, the major challenge of active plasmonic devices is the fabrication process. The performance of the devices is very much dependent on the quality of the ICP dry etch. The main issues are: side-wall angle, surface roughness and surface damage caused by the dry etch process. The performance of the dry etch process, on all these aspects, is strongly dependent on the condition of the process chamber, the position of the sample in the chamber and on minute changes in the process parameters. The largest improvement can be obtained by developing an etch process that is more robust (less dependent on process history of the machine), without compromising its performance.

Another point of attention in the design and fabrication of the metallic lasers are the dielectric insulation layers and deposition thereof. Layers with a high refractive index, high dielectric strength and with nanometer accuracy in the deposited thickness are desirable. Thinner dielectric layers, with a higher refractive index can improve the confinement of the mode in the active medium, thereby reducing the requirements on the gain. Atomic layer deposition could play an important role here.

Finally, a step towards better performing metallic lasers can be made by improving the metal cladding. Current issues with the silver cladding are: the optical loss and the adhesion of the cladding to semiconductor and dielectric materials. The silver is deposited by means of thermal evaporation. Other deposition techniques may result in larger crystals, reducing the amount of scattering from crystal boundaries and thereby reducing the optical loss. Also a carefully chosen alloy could provide the negative dielectric constant required for the support of surface plasmon waves, but with reduced optical loss.

So far only active devices, based on the M-I-S-I-M structure, have been fabricated and characterized. An important extension of the research on these structures would be to fabricate and characterize passive waveguides with the same structure. From these waveguides better estimates of the optical loss, introduced by the metal, can be obtained. Also other properties, such as: the reflection and transmission spectra of the sidewall gratings and effective mode indices could be verified by measurements.

It was shown that in-plane emission of metal coated waveguide lasers is feasible. This allows the active plasmonic devices to be incorporated in PICs. Direct connections, by means of gratings or tapers, are obvious possibilities. Also evanescent coupling to a waveguide passing under the device, similar to what is done in membrane PICs, could prove to be a good way to connect such devices. These possibilities need to be explored.

The behavior of the structures in this thesis was analyzed using FDTD simulations. These simulations demand a lot of computational power and are very time consuming. The accuracy of the results increases with an increase of resolution, making it more difficult to obtain accurate results. The development of robust numerical models capable of describing metallic structures, without neglecting the wavelength dependence and the effects related to the surface-wave-like nature of the modes, could provide a considerable boost to their development.
Appendix A
Calculation parameters

A.1 Introduction
This appendix lists all material parameters and models used for the FDTD simulations. Due to memory and computational constraints, the dispersive characteristics of not all materials can be included in simulations. For the simulations discussed in this thesis, the choice was made to include the dispersive nature of silver and InGaAs. All other materials are represented by their dielectric permittivity.
Appendix A. Calculation parameters

A.2 Polarization conventions

A plane wave incident on the interface between to media $n_1$ and $n_2$ is reflected. Two polarization states can be distinguished: TE (Transverse Electric) and TM (Transverse Magnetic). In the TE polarization the electric field is parallel to the interface, whereas in the TM polarization the magnetic field is parallel to the interface.

In literature on plasmonic structures, it is common practice to determine the polarization state with respect to the interface with the metal. Resulting in the polarization convention shown in figure A.1(c). Note that this is different from the definition of TE and TM in dielectric waveguides discussed in [77].

![Figure A.1: Convention for the polarization states, as used in the FDTD simulations.](image)

A.3 Semiconductor materials & dielectrics

For most calculations, it suffices to model the different dielectric materials by a single, frequency independent dielectric constant. Values for the various materials are given in table A.1.

100
A.3. Semiconductor materials & dielectrics

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP</td>
<td>10.00</td>
</tr>
<tr>
<td>InGaAs</td>
<td>12.88</td>
</tr>
<tr>
<td>SiN_x</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Table A.1

The material parameters used to calculate the dispersion of InGaAs in chapter 2 are listed in table A.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_g )</td>
<td>0.8</td>
<td>[eV]</td>
</tr>
<tr>
<td>( n )</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>( m_e )</td>
<td>0.041 ( m_0 )</td>
<td>[kg]</td>
</tr>
<tr>
<td>( m_{hh} )</td>
<td>0.460 ( m_0 )</td>
<td>[kg]</td>
</tr>
<tr>
<td>( m_{lh} )</td>
<td>0.051 ( m_0 )</td>
<td>[kg]</td>
</tr>
<tr>
<td>( C )</td>
<td>( 3 \cdot 10^{12} )</td>
<td>( \text{cm}^{-1} \cdot \text{s}^{-1/2} )</td>
</tr>
</tbody>
</table>

Table A.2: Material parameters used to calculate the wavelength dependent dielectric constant of In-GaAs for various carrier densities and at various temperatures.

Tables A.3 and A.4 list the parameters obtained from fitting a Lorentz model to the data presented in 2.16(a). The parameter values were obtained performing a non-linear least-squares fit on the measurement data. These parameters are only valid in the wavelength range mentioned in the caption of the tables. The current densities are \( 1 \times 10^{18} \text{ cm}^{-3} \) and \( 1 \times 10^{19} \text{ cm}^{-3} \) respectively. The \( \gamma_n \) parameter can be set to zero, if a situation without gain is required. A \( \gamma_n = -7.5 \times 10^{-4} \) results in a gain of approximately 1200 \( \text{cm}^{-1} \).

Simulation parameters for \( a = 100 \text{ nm} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_\infty )</td>
<td>2.73897</td>
</tr>
<tr>
<td>( \Delta \varepsilon )</td>
<td>3.70229</td>
</tr>
<tr>
<td>( \omega_n )</td>
<td>0.09</td>
</tr>
<tr>
<td>( \gamma_n )</td>
<td>( -7.5 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Table A.3: Model parameters fitted to match the InGaAs dispersion characteristic for \( N = 1 \times 10^{-18} \text{ cm}^{-3} \), in the wavelength range of 1.25 \( \mu \text{m} \) to 1.6 \( \mu \text{m} \), for a temperature of 80K.
Appendix A. Calculation parameters

Simulation parameters for $a = 100$ nm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\infty}$</td>
<td>1.11973</td>
</tr>
<tr>
<td>$\Delta\varepsilon$</td>
<td>3.12735</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>0.089</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>$-7.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table A.4: Model parameters fitted to match the InGaAs dispersion characteristic for $N = 1 \times 10^{-19}$ cm$^{-1}$, in the wavelength range of 1.25 $\mu$m to 1.6 $\mu$m, for a temperature of 80K

A.4 Metals

The model for the dielectric constant of silver is based on the data published by Johnson and Christy in [50]. The material data and fit are shown in figures A.2(a) and A.2(b). If the model is to be extended for wavelengths below 500 nm, more oscillator terms need to be added to the model in order to obtain a good fit.

Simulation parameters for $a = 100$ nm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\infty}$</td>
<td>2.6043207</td>
</tr>
<tr>
<td>$\Delta\varepsilon$</td>
<td>13198</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>0.0063593931</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>0.0016545937</td>
</tr>
</tbody>
</table>

Table A.5: Model parameters fitted to match the Johnson and Christy paper in the wavelength range of 0.5 $\mu$m to 2 $\mu$m

Figure A.2: A comparison of the model with the measurement data. (a) & (b) Show the real and imaginary part of the permittivity of silver at room temperature. The measurement data are taken from reference [50] and were obtained via ellipsometry.

For ideal free-electron metals the permittivity approaches the constant $\varepsilon_0$ for $\omega \to \infty$. For noble metals an extension of this model is needed for $\omega > \omega_p$. These metals have a high residual polarization, which can be described by the term $P_\infty = \varepsilon_0(\varepsilon_\infty - 1)E$, where $1 \leq \varepsilon_\infty \leq 10$ [3]
A.4. Metals

Simulation parameters for a = 100 nm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_\infty$</td>
<td>3.4497</td>
</tr>
<tr>
<td>$\Delta\varepsilon$</td>
<td>13201</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>0.0063569351</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>0.0002962231</td>
</tr>
</tbody>
</table>

Table A.6: Model parameters fitted to match the Johnson and Christy paper, in the wavelength range of 0.5 µm to 2 µm, for a temperature of 80K

Simulation parameters for a = 100 nm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_\infty$</td>
<td>3.4496</td>
</tr>
<tr>
<td>$\Delta\varepsilon$</td>
<td>13200</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>0.0063568585</td>
</tr>
<tr>
<td>$\gamma_n$</td>
<td>0.0000018656</td>
</tr>
</tbody>
</table>

Table A.7: Model parameters fitted to match the Johnson and Christy paper, in the wavelength range of 0.5 µm to 2 µm, for a temperature of 10K

The imaginary part of the complex dielectric constant of silver is responsible for the absorption loss and is directly proportional to the electrical conductivity. At lower temperatures the absorption loss decreases due to reduced free-electron phonon scattering. To obtain an estimate of the loss at temperatures of 80K and 10K, the imaginary part of the complex dielectric index is scaled by a factor of 0.1774 and a factor of 0.0007 respectively [51]. The parameter values were obtained performing a non-linear least-squares fit on the measurement data.
Appendix A. Calculation parameters
Appendix B
Process parameters

In this appendix all process parameters are specified. The process flow can be found in appendix C.
### B.1 III-V Wet etch chemistries

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemistry:</th>
<th>Ratio [ml]:</th>
<th>T [°C]:</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. InP-etch</td>
<td>H$_3$PO$_4$-HCl</td>
<td>4-1</td>
<td>R.T.</td>
<td>60</td>
</tr>
<tr>
<td>2. InGaAs-etch</td>
<td>H$_2$SO$_4$-H$_2$O$_2$-H$_2$O</td>
<td>200-1-1</td>
<td>R.T.</td>
<td>8</td>
</tr>
<tr>
<td>3. Dil. Phosph. acid</td>
<td>H$_3$PO$_4$-H$_2$O</td>
<td>1-10</td>
<td>R.T.</td>
<td>120</td>
</tr>
</tbody>
</table>

Table B.1

### B.2 Silicon wet etch chemistries

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemistry:</th>
<th>Ratio [ml]:</th>
<th>T [°C]:</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. HF 1%</td>
<td>N.A.</td>
<td>N.A.</td>
<td>R.T.</td>
<td>10</td>
</tr>
<tr>
<td>2. BHF</td>
<td>N.A.</td>
<td>N.A.</td>
<td>R.T.</td>
<td>120</td>
</tr>
</tbody>
</table>

Table B.2

### B.3 Metal wet etch chemistries

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemistry:</th>
<th>Ratio [ml]:</th>
<th>T [°C]:</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gold etch</td>
<td>KI-I$_2$</td>
<td>N.A.</td>
<td>R.T.</td>
<td>30</td>
</tr>
<tr>
<td>2. Gold etch</td>
<td>KCN (Degussa)</td>
<td>N.A.</td>
<td>R.T.</td>
<td>120</td>
</tr>
<tr>
<td>3. Silver etch</td>
<td>NH$_3$OH-H$_2$O$_2$-H$_2$O</td>
<td>14-13-73</td>
<td>R.T.</td>
<td></td>
</tr>
</tbody>
</table>

Table B.3

### B.4 Developer

<table>
<thead>
<tr>
<th>Name</th>
<th>Chemistry:</th>
<th>Ratio:</th>
<th>T [°C]:</th>
<th>Time [s]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. HSQ</td>
<td>MaD-531S</td>
<td>N.A.</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>2. MaN-440</td>
<td>MaD-531S</td>
<td>N.A.</td>
<td>R.T.</td>
<td></td>
</tr>
<tr>
<td>3. MaN-415</td>
<td>MaD-531S</td>
<td>N.A.</td>
<td>R.T.</td>
<td></td>
</tr>
<tr>
<td>4. PI2737$^1$</td>
<td>DI9040-R19180</td>
<td>N.A.</td>
<td>R.T.</td>
<td>120-60</td>
</tr>
<tr>
<td>5. AZ4533</td>
<td>MaD-531S</td>
<td>N.A.</td>
<td>R.T.</td>
<td></td>
</tr>
</tbody>
</table>

Table B.4
### B.5 Dry etch chemistries

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gasses [sccm]:</th>
<th>Power [W]:</th>
<th>P [mT]:</th>
<th>T [°C]:</th>
<th>Time:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. InP/InGaAs</td>
<td>CH₄-H₂ 30-10</td>
<td>200 (ICP) - 116 (RF)</td>
<td>10</td>
<td>60</td>
<td>60 sec.²</td>
</tr>
<tr>
<td>1b. Descum</td>
<td>O₂ 40</td>
<td>200 (ICP) - 110 (RF)</td>
<td>18</td>
<td>60</td>
<td>12 sec.</td>
</tr>
<tr>
<td>2. SiO₂</td>
<td>CHF₃ 100</td>
<td>50 (RF)</td>
<td>15</td>
<td>18</td>
<td>28 min.</td>
</tr>
<tr>
<td>3. HPR504</td>
<td>O₂ 20</td>
<td>50 (RF)</td>
<td>15</td>
<td>18</td>
<td>7 min.</td>
</tr>
<tr>
<td>4. SiNx</td>
<td>CHF₃-O₂ 50-5</td>
<td>100 (RF)</td>
<td>56</td>
<td>18</td>
<td>25 sec.</td>
</tr>
</tbody>
</table>

Table B.5

### B.6 PECVD chemistries

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gasses [sccm]:</th>
<th>Power [W]:</th>
<th>P [mT]:</th>
<th>T [°C]:</th>
<th>Time [s]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. SiO₂</td>
<td>SiH₄-N₂-N₂O 8.5-161.5-710</td>
<td>50 (RF)</td>
<td>1000</td>
<td>300</td>
<td>360</td>
</tr>
<tr>
<td>2. SiNx</td>
<td>SiH₄-NH₃-N₂ 16.6-13.4-650</td>
<td>20 (RF)</td>
<td>650</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>3. SiNx</td>
<td>SiH₄-NH₃-N₂ 16.6-13.4-500</td>
<td>50 (RF)</td>
<td>650</td>
<td>200</td>
<td>28</td>
</tr>
</tbody>
</table>

Table B.6

### B.7 Dry clean processes

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gasses [sccm]:</th>
<th>Power [W]:</th>
<th>P [mT]:</th>
<th>T [°C]:</th>
<th>Time [s]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Short clean</td>
<td>O₂</td>
<td>300 (RF)</td>
<td>N.A.</td>
<td>R.T.</td>
<td>300</td>
</tr>
<tr>
<td>2. Long clean</td>
<td>O₂</td>
<td>300 (RF)</td>
<td>N.A.</td>
<td>R.T.</td>
<td>600</td>
</tr>
</tbody>
</table>

Table B.7

¹ After exposing the polyimide to the developer, the development has to be stopped using a stopping agent. This stopping agent is RI9180. It is important that the sample is not exposed to water, after the sample is exposed to the stopping agent, not even for rinsing!

² The InP/InGaAs dry etch process is run in cycles of 1 minute each. Each cycle is followed by an O₂ descum step. The parameters of this descum step are listed as process 1b. Due to the size of the structures successful etching requires: manually cleaning the process chamber every 150 cycles, a 10 cycle preconditioning and several test runs to fine-tune the RF power and descum time, in order to get the sidewall angle within 1° from vertical.
Appendix B. Process parameters

## B.8 Resist spin parameters

<table>
<thead>
<tr>
<th>Name:</th>
<th>Spinner:</th>
<th>Lid:</th>
<th>Speed [rpm]:</th>
<th>Accel. [rpm/s]:</th>
<th>Time [s]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. HPR504</td>
<td>Gyrset</td>
<td>Closed</td>
<td>5000</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>2. HSQ</td>
<td>Convac</td>
<td>N.A.</td>
<td>4000</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>3. MaN-440³</td>
<td>Gyrset</td>
<td>Closed</td>
<td>1000</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>4. MaN-415⁴</td>
<td>Gyrset</td>
<td>Closed</td>
<td>800</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>5. AZ-4533</td>
<td>Gyrset</td>
<td>Closed</td>
<td>1000</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>6. PI-2737 (Polyimide)</td>
<td>Laurell</td>
<td>Closed</td>
<td>1500</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

Table B.8

## B.9 Resist bake parameters

<table>
<thead>
<tr>
<th>Name:</th>
<th>Equipment:</th>
<th>T [°C]:</th>
<th>Time [min]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Softbake S1805</td>
<td>Oven</td>
<td>100</td>
<td>≥ 10:00</td>
</tr>
<tr>
<td>2. Softbake S1805</td>
<td>Oven</td>
<td>75</td>
<td>22:00</td>
</tr>
<tr>
<td>3. Hardbake HPR504, 1</td>
<td>Hotplate</td>
<td>150</td>
<td>02:00</td>
</tr>
<tr>
<td>4. Hardbake HPR504, 2</td>
<td>Hotplate</td>
<td>220</td>
<td>02:00</td>
</tr>
<tr>
<td>5. Hardbake HPR504, 3</td>
<td>Oven</td>
<td>250</td>
<td>02:00</td>
</tr>
<tr>
<td>6. Hardbake XR1541, 1</td>
<td>Hotplate</td>
<td>150</td>
<td>02:00</td>
</tr>
<tr>
<td>7. Hardbake XR1541, 2</td>
<td>Hotplate</td>
<td>220</td>
<td>02:00</td>
</tr>
<tr>
<td>8. Softbake MaN-440³</td>
<td>Hotplate</td>
<td>120</td>
<td>05:00</td>
</tr>
<tr>
<td>9. Softbake MaN-440⁴</td>
<td>Hotplate</td>
<td>95</td>
<td>05:00</td>
</tr>
<tr>
<td>10. Softbake AZ4533</td>
<td>Hotplate</td>
<td>95</td>
<td>05:00</td>
</tr>
<tr>
<td>11. Post-exposure bake AZ4533</td>
<td>Hotplate</td>
<td>120</td>
<td>40:00</td>
</tr>
<tr>
<td>12. Softbake PI2737</td>
<td>Hotplate</td>
<td>40 → 90⁵</td>
<td>05:00</td>
</tr>
<tr>
<td>13. Post-exposure bake PI2737</td>
<td>Oven</td>
<td>90 → 120⁵</td>
<td>45:00</td>
</tr>
</tbody>
</table>

Table B.9
### B.10 MA-6 exposure parameters

<table>
<thead>
<tr>
<th>Name:</th>
<th>Mask:</th>
<th>Contact method:</th>
<th>No. exposures:</th>
<th>Time [s]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Adhesion pads</td>
<td>1</td>
<td>Soft contact</td>
<td>3</td>
<td>111</td>
</tr>
<tr>
<td>2. Device separation</td>
<td>2</td>
<td>Soft contact</td>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>3. P-Contact mask</td>
<td>3</td>
<td>Soft contact</td>
<td>3</td>
<td>111</td>
</tr>
<tr>
<td>4. Polyimide litho</td>
<td>4</td>
<td>Soft contact</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>5. N-Contact mask</td>
<td>5</td>
<td>Soft contact</td>
<td>3</td>
<td>111</td>
</tr>
</tbody>
</table>

Table B.10

### B.11 EBL exposure parameters

This section lists the parameters used for the fabrication of the metallic DFB and Fabry-Pérot lasers. They may be used as a guide for finding the correct parameters for other designs.

The exposure was carried out using a high tension of 30 kV, 100 µm × 100 µm write-fields and an aperture size of 10 µm. The beam step-size is set to 2 nm (1 pixel).

The dose parameters used for the various structures are listed in table [B.11]. No advanced proximity effect correction was required, the dose of the grating extensions is increased slightly with respect to the dose of the grating core. The core waveguides are placed in layer 1, the grating extensions, if any, are placed in layer 2. Both layers have to be exposed at the same time, together with the optical alignment markers, which are located in layer 7.

The markers can also be exposed using the 30 µm aperture. This will drastically decrease the total exposure time. In this case, the following procedure has to be followed: align EBL with 10 µm aperture & save parameters, switch to 30 µm aperture, align EBL with 30 µm aperture & save parameters, expose markers, change aperture to 10 µm & reload alignment parameters, expose the devices and finish with the remaining structures.

<table>
<thead>
<tr>
<th>Structure:</th>
<th>Dose [µC/cm(^{-2})]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguides (&lt; 300 nm)</td>
<td>1750</td>
</tr>
<tr>
<td>DFB Waveguide core</td>
<td>1500</td>
</tr>
<tr>
<td>DFB Grating extensions</td>
<td>1950 (= 1500 × 1.3)</td>
</tr>
<tr>
<td>Optical alignment markers</td>
<td>300</td>
</tr>
<tr>
<td>Text dose</td>
<td>600</td>
</tr>
<tr>
<td>Measurement structure small (2 µm wide)</td>
<td>400</td>
</tr>
<tr>
<td>Measurement structure large (5 µm wide)</td>
<td>600</td>
</tr>
</tbody>
</table>

Table B.11

---

3 For lift-off purposes.
4 For planarization purposes.
5 Place sample on hotplate when first temperature is reached, then set second temperature and wait for the indicated time.
## B.12 Metal deposition parameters

<table>
<thead>
<tr>
<th>Name:</th>
<th>Equipment:</th>
<th>Speed [Å/s]:</th>
<th>Thickness [nm]:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Au</td>
<td>AJA Sputter coater</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2. Ti/Au (top-contact)</td>
<td>AJA Sputter coater</td>
<td>50/50</td>
<td></td>
</tr>
<tr>
<td>3. Au (EBL)</td>
<td>Edwards (new)</td>
<td>2</td>
<td>7.5</td>
</tr>
<tr>
<td>4. Ag</td>
<td>Edwards (old)</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>5. Ti/Au (adhesion)</td>
<td>FC2000</td>
<td>50/40</td>
<td></td>
</tr>
<tr>
<td>6. Ti/Pt/Au (n-contact)</td>
<td>FC2000</td>
<td>20/15/15</td>
<td></td>
</tr>
<tr>
<td>7. Ti/Pt/Au (p-contact)</td>
<td>FC2000</td>
<td>60/75/200</td>
<td></td>
</tr>
</tbody>
</table>

Table B.12
Appendix C
Process flow

In this appendix the complete process flow for the fabrication of metallic lasers is given. The process is divided in stages. The stages are labeled with a description and number, which indicates how often the stage should be repeated. If required, a recipe number is given. The corresponding process parameters can be found in appendix B.
Appendix C. Process flow

<table>
<thead>
<tr>
<th>Sample preparation</th>
<th>Repeat: 1</th>
<th>Action:</th>
<th>Amount:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step: Dry clean</td>
<td>Striper, recipe B.7-1/2</td>
<td>00:05:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Backside protection</td>
<td>Manual, paint S1805</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Soft bake</td>
<td>Recipe B.9-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Wet clean</td>
<td>Manual, recipe B.1-3</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Rinse</td>
<td>Manual, UPW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Etch protection layer</td>
<td>Manual, recipe B.1-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Rinse</td>
<td>Manual, UPW</td>
<td>00:10:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Remove resist</td>
<td>Manual, acetone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: IPA rinse</td>
<td>Manual, isopropanol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Dry clean</td>
<td>Striper, recipe B.7-1</td>
<td>00:05:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Wet clean</td>
<td>Manual, recipe B.1-3</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Rinse</td>
<td>Manual, UPW</td>
<td>00:10:00 (hh:mm:ss)</td>
<td></td>
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<table>
<thead>
<tr>
<th>E-Beam lithography</th>
<th>Repeat: 1</th>
<th>Action:</th>
<th>Amount:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step: Oxide deposition</td>
<td>PECVD, recipe B.6-1</td>
<td>440 nm</td>
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</tr>
<tr>
<td>Step: Spin resist</td>
<td>Recipe B.8-1</td>
<td>450 nm</td>
<td></td>
</tr>
<tr>
<td>Step: Hard bake 1</td>
<td>Recipe B.9-3</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Hard bake 2</td>
<td>Recipe B.9-4</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Hard bake 3</td>
<td>Recipe B.9-5</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Spin resist</td>
<td>Recipe B.8-2</td>
<td>80 nm</td>
<td></td>
</tr>
<tr>
<td>Step: Hard bake 1</td>
<td>Recipe B.9-6</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Hard bake 2</td>
<td>Recipe B.9-7</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Evaporate gold</td>
<td>EDWARDES, recipe B.12-3</td>
<td>7.5 nm</td>
<td></td>
</tr>
<tr>
<td>Step: E-Beam lithography</td>
<td>Recipe B.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Remove gold</td>
<td>Manual, recipe B.3-1</td>
<td>00:00:30 (hh:mm:ss)</td>
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</tr>
<tr>
<td>Step: Rinse</td>
<td>Manual, UPW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step: Develop</td>
<td>Manual, B.4-1</td>
<td>00:02:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>Step: Rinse</td>
<td>Manual, UPW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step</td>
<td>Description</td>
<td>Action</td>
<td>Amount</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>3.1</td>
<td>Etch polymer</td>
<td>Polymer RIE, recipe B.5-3</td>
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<td>3.2</td>
<td>Etch oxide</td>
<td>Nitride RIE, recipe B.5-2</td>
<td></td>
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<tr>
<td>3.3</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
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</tr>
<tr>
<td>3.4</td>
<td>Acetone strip</td>
<td>Manual, acetone</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>Wet clean</td>
<td>Manual, recipe B.1-3</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>HF Dip</td>
<td>Manual, recipe B.2-1</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>3.10</td>
<td>ICP Etch</td>
<td>ICP-RIE, recipe B.5-1 a &amp; b</td>
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<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
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<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Wet etch</td>
<td>Manual, recipe B.2-1</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Wet etch</td>
<td>Manual, recipe B.1-3 1</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Wet etch</td>
<td>Manual, recipe B.2-2 1</td>
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</tr>
<tr>
<td>5.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>Wet clean</td>
<td>Manual, recipe B.1-3 1</td>
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</tr>
<tr>
<td>6.3</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Nitride deposition 1</td>
<td>PECVD, recipe B.6-2</td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Nitride deposition 2</td>
<td>PECVD, recipe B.6-3</td>
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</tr>
</tbody>
</table>
## Appendix C. Process flow

### Create adhesion pads

**Repeat:** 1

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>HDMS Primer</td>
<td>Manual, old primer oven</td>
<td></td>
</tr>
<tr>
<td>8.3</td>
<td>Spin resist</td>
<td>Recipe B.8-3</td>
<td></td>
</tr>
<tr>
<td>8.4</td>
<td>Softbake</td>
<td>Recipe B.9-8</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>Lithography</td>
<td>MA-6, recipe B.10-1</td>
<td></td>
</tr>
<tr>
<td>8.6</td>
<td>Develop</td>
<td>Manual, B.4-2</td>
<td></td>
</tr>
<tr>
<td>8.7</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>8.8</td>
<td>Evaporate Ti/Au</td>
<td>FC2000, recipe B.12-5</td>
<td></td>
</tr>
<tr>
<td>8.9</td>
<td>Acetone vapor</td>
<td>Manual, upside down 01:00:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>8.10</td>
<td>Acetone soak</td>
<td>Manual, upside down 01:00:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>8.11</td>
<td>IPA rinse</td>
<td>Manual, isopropanol</td>
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</tr>
</tbody>
</table>

### Prepare for planarization

**Repeat:** 1

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>9.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>9.3</td>
<td>HMDS</td>
<td>Manual, old primer oven</td>
<td></td>
</tr>
<tr>
<td>9.4</td>
<td>Spin resist</td>
<td>Recipe B.8-4</td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td>Softbake</td>
<td>Recipe B.9-9</td>
<td></td>
</tr>
</tbody>
</table>

### Resist planarization

**Repeat:** Till a 300 nm step height is obtained

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>Planarize resist</td>
<td>Manual, MaD-531S</td>
<td></td>
</tr>
<tr>
<td>10.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>10.3</td>
<td>Measure</td>
<td>Alpha stepper²</td>
<td></td>
</tr>
</tbody>
</table>

### Open nitride

**Repeat:** 1

<table>
<thead>
<tr>
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<th>Description</th>
<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>Etch nitride</td>
<td>Nitride RIE, recipe B.5-4</td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>Acetone strip</td>
<td>Manual, acetone</td>
<td></td>
</tr>
<tr>
<td>11.3</td>
<td>IPA rinse</td>
<td>Manual, isopropanol</td>
<td></td>
</tr>
</tbody>
</table>

---

¹Perform wet etch in dark environment.
²6-8 Locations on chip.
³Rotate 60 degrees every 10 seconds.
Prepare for planarization  
Repeat: 1

<table>
<thead>
<tr>
<th>Step:</th>
<th>Description:</th>
<th>Action:</th>
<th>Amount:</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1</td>
<td>Dry clean</td>
<td>Stripper, recipe B.7-1</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>12.3</td>
<td>HMDS</td>
<td>Manual, old primer oven</td>
<td></td>
</tr>
<tr>
<td>12.4</td>
<td>Spin resist</td>
<td>Recipe B.8-4</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>Softbake</td>
<td>Recipe B.9-9</td>
<td></td>
</tr>
</tbody>
</table>

Resist planarization  
Repeat: Till a 200 nm step height is obtained

<table>
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<th>Action:</th>
<th>Amount:</th>
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</thead>
<tbody>
<tr>
<td>13.1</td>
<td>Planarize resist</td>
<td>Manual, MaD-531S</td>
<td></td>
</tr>
<tr>
<td>13.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>13.3</td>
<td>Measure</td>
<td>Alpha stepper²</td>
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</tr>
</tbody>
</table>

Deposit top-contact  
Repeat: 1

<table>
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<th>Description:</th>
<th>Action:</th>
<th>Amount:</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1</td>
<td>Wet clean</td>
<td>Manual, recipe B.1-3</td>
<td></td>
</tr>
<tr>
<td>14.2</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>14.3</td>
<td>Wet etch contact</td>
<td>Manual, recipe B.1-2</td>
<td></td>
</tr>
<tr>
<td>14.4</td>
<td>Rinse</td>
<td>Manual, UPW</td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td>Evaporate Ti/Pt/Au</td>
<td>FC2000, B.12-6</td>
<td></td>
</tr>
<tr>
<td>14.6</td>
<td>Acetone vapor</td>
<td>Manual, upside down 01:00:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>14.7</td>
<td>Acetone soak</td>
<td>Manual, upside down 01:00:00 (hh:mm:ss)</td>
<td></td>
</tr>
<tr>
<td>14.8</td>
<td>IPA rinse</td>
<td>Manual, isopropanol</td>
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</table>

Deposit silver  
Repeat: 1

<table>
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<th>Description:</th>
<th>Action:</th>
<th>Amount:</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1</td>
<td>Dry clean</td>
<td>Stripper, B.7-2</td>
<td></td>
</tr>
<tr>
<td>15.2</td>
<td>Deposit silver</td>
<td>Recipe B.12-4 angle 75°³</td>
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</tr>
<tr>
<td>15.3</td>
<td>Deposit silver</td>
<td>Recipe B.12-4 angle 50°³</td>
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</tr>
<tr>
<td>15.4</td>
<td>Anneal</td>
<td>Jipilec, 400°C 00:01:00 (hh:mm:ss)</td>
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</tr>
<tr>
<td>15.5</td>
<td>Deposit silver</td>
<td>Recipe B.12-4 angle 50°³</td>
<td></td>
</tr>
<tr>
<td>15.6</td>
<td>Deposit silver</td>
<td>Recipe B.12-4 angle 30°³</td>
<td></td>
</tr>
<tr>
<td>15.7</td>
<td>Deposit silver</td>
<td>Recipe B.12-4 angle 10°³</td>
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</tr>
<tr>
<td>15.8</td>
<td>Sputter gold</td>
<td>AJA Sputtercoater, B.12-1 00:14:31 (hh:mm:ss)</td>
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</tbody>
</table>
### Appendix C. Process flow

#### Separate devices

<table>
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<th>Action</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
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<td>16.1</td>
<td>HMDS primer</td>
<td>Manual, old primer oven</td>
<td></td>
</tr>
<tr>
<td>16.2</td>
<td>Spin resist</td>
<td>Recipe B.8-5</td>
<td></td>
</tr>
<tr>
<td>16.3</td>
<td>Softbake</td>
<td>Recipe B.9-10</td>
<td></td>
</tr>
<tr>
<td>16.4</td>
<td>Lithography</td>
<td>MA-6, recipe B.10-2</td>
<td></td>
</tr>
<tr>
<td>16.5</td>
<td>Develop</td>
<td>Manual, B.4-5</td>
<td></td>
</tr>
<tr>
<td>16.6</td>
<td>Rinse</td>
<td>Manual, UPW</td>
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#### Create p-contact

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#### Apply polyimide

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Appendix C. Process flow
References


References


[58] Internal communication with E.J. Geluk.


References


Summary

Unlike conventional dielectric photonic structures, metal coated or plasmonic structures can confine light on a sub-wavelength scale. It has been shown that despite high internal losses, lasing is possible in plasmonic cavities, with dimensions well below the diffraction limit of light. Due to the small size and high current density, it is possible that future metallic nanolasers will have switching speeds in the terahertz range. Until now, integration of these lasers with other optical components was difficult since they are fully enclosed by a metal layer of several hundreds of nanometers thick. This thesis discusses the possibility of incorporating distributed feedback in plasmonic waveguides to control the wavelength of operation, to control the emissive properties of the devices and to enable coupling to waveguides.

The research which was carried out can be divided in three major parts. The first part involves the analysis and design of plasmonic waveguide lasers. The optical properties of plasmonic waveguides were determined using FDTD and FEM techniques. The FDTD simulations were carried out in 2D and 3D and included the presence of gain, absorption, material dispersion and imperfections in shape. The dependence on structural and material properties was studied. After studying the behavior of basic plasmonic waveguides, the incorporation of distributed feedback through vertical groove gratings was investigated. The wavelength dependence and feedback strength were determined. Also the behavior of resonant cavities, in which this distributed feedback was incorporated, was investigated. Finally, the threshold gain requirements and spontaneous emission enhancement were determined.

The second part of the project consisted of developing a fabrication process for the plasmonic waveguide lasers. Existing processing techniques, used for wafer-scale fabrication of photonic integrated circuits, have been modified to make them suitable for the fabrication of plasmonic devices. A novel, high-resolution electron beam lithography process was developed capable of defining structures with 50 nm feature sizes in the III-V material system. The effect of various processing steps on surface and material quality was studied. A full fabrication run of the devices was carried out and the devices have been mounted afterwards. Some of the devices went through additional processing steps in order to open their end-facets (using focused ion beam milling).

The final part of the project involved the characterization of the fabricated devices. A new measurement setup was built, in which the devices could be imaged and measured at the same time. The measurement setup is suitable for characterization through the substrate and through an open end-facet of the device. Measurements can be carried out at temperatures
ranging from 4K to room temperature, in a continuous flow cryostat.

Electrically pumped, surface plasmonic lasers have been realized, with core waveguide widths well below the diffraction limit of light (min. 100 nm). The lasers have been characterized through the substrate as well as via an open end-facet. Threshold currents as low as 400 µA for 100 µm long devices have been observed. The distributed feedback lasers show line-widths below 0.5 nm (limited by the resolution of the spectrometer) and have a side-mode suppression ratio of over 20 dB. Their emission wavelength could be tuned over a 100 nm range by changing the period of the distributed feedback by 60 nm. The devices have initially been characterized at cryogenic temperatures (80K), using continuous current injection, and in a later stage also at room temperature (> 295K), using pulsed current injection.

Milan Marell
Nog wat laatste wijzigingen doorvoeren en dan is het zo ver, dan kan dit boekje naar de drukker. De hoogste tijd om ook eens over het dankwoord na te denken. Allereerst wil ik natuurlijk Martin bedanken, de stille kracht van OED. Ik heb graag met je samengewerkt en ik heb erg veel van je kunnen leren. Je draait nergens je hand voor om: theorie, processing, zelfgemaakte meetapparatuur … daar heb ik veel bewondering voor. Daarnaast ken je ook nog de mooiste, bochtige wegen in de Belgische Ardennen (om met de motor of een snelle auto te gaan rijden) en ging je graag mee naar concerten van de U2 Tribute Band, ik vond het erg gezellig!

Meint, bedankt dat ik bij OED heb mogen promoveren en voor alle mogelijkheden die ik daarbij heb gekregen. Ik kijk met veel plezier terug op de leerzame, maar gezellige tijd bij OED.

Beste Erwin en Jos, dankzij jullie heb ik na mijn afstuderen een vliegende start kunnen maken bij OED. Jullie deur staat altijd open, voor interessante discussies of gewoon een praatje. Erwin, hopelijk hebben we de studenten iets bij kunnen brengen tijdens het OGO. Maar met de hulp van Johan Cruijff kan het niet verkeerd gaan! Jos, de nabeschouwingen van het vOEDbal ga ik missen.

Xaveer, ik denk met veel plezier terug aan de winterschool in Zwitserland, het skieën, spannende busritjes en aan de LEOS Annual in New Port Beach. Bedankt ook voor alle hulp met LaTeX en Linux, waar ik dankzij jou veel van heb geleerd.

Siang bedankt voor de goede adviezen tijdens het optimaliseren van de fabricage processen. Youcai, thank you for all your help in the cleanroom and with the various measurements.

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Boudewijn, lekker nuchter, altijd relaxed en nooit te beroerd om je meest recente vakantie-/klimavonturen met ons te delen. Succes met het verder opzetten van je bedrijf en veel geluk met As! Jan Hendrik, Genia, Luc, Martijn jullie hebben mij goed op weg geholpen tijdens mijn afstuderen en aan het begin van mijn promotie. Leuk dat we elkaar nog met enige Regelmaat treffen. Ling, Pietro, I have enjoyed the time we spent together at OED. The dinners, conferences and the nights out.

My most recent roommates: Manuela, Dima and Elton. We had to shuffle our desks a bit, but we had fun the last couple of months. Manuela, I’m a great fan of La Solitudine, it was an honor! You’re the eldest in the office now, make sure you keep the guys in line. Antonio, Josselin, Emil, Kasia, Ray, Srivaths, Stanislaw, Tim and Yuqing, thank you too! Good luck with all your projects. I’m keen to hear about your breakthroughs and experiences. Keep me posted when we meet in the Walhalla.

Bauke, het is bijna achter de rug en ik denk dat we trots mogen zijn op het resultaat. Ik heb bewondering voor je, dat je je promotie wist te combineren met een gezin. Ik wens jou, Emmy en Marta heel veel geluk in Zwitserland.

Saeed and Jing I believe the both of you are next in line, I wish you all the best in bringing your research to a good end!

Er kan niet altijd gewerkt worden en ik ben blij dat ik mijn vrije tijd door kan brengen met een groot aantal goede vrienden. Een aantal wil ik hier met name noemen. Alain, Maurice, Ward, op jullie kan ik altijd rekenen. Bedankt voor de voortdurende interesse, discussies, suggesties en het regelmatig helpen verzetten van mijn gedachten. Anabella en Taco, Ana voor het ontwerp van de kaft en beiden voor de grote interesse en de altijd gezellige dagen met zijn vieren. Sean, Stet you make Ireland my second home, where would I have been without you during my internship? Ellen, wie had op het VWO gedacht dat we alle twee zouden promoveren? Het is gezellig om regelmatig af te spreken en (vakantie)verhalen uit te wisselen.

Pap en mam, jullie hebben het allemaal mogelijk gemaakt. Bedankt dat jullie ons altijd hebben gesteund en dat jullie altijd voor ons klaarstaan. Het is altijd weer fijn om thuis te komen. Chantal, je bent mijn lieve zus, bedankt! Beste Wim en Thekie, het is fijn om altijd zo warm onthaald te worden. Dankzij jullie voel ik me ook helemaal thuis in Zeeland.

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Milan Marell was born in Heerlen (The Netherlands) on March 29th, 1982. After finishing secondary school in 2000 (Scholengemeenschap Serviam, Sittard, The Netherlands), he studied Electrical Engineering at the Eindhoven University of Technology (Eindhoven, The Netherlands). With integrated optics as a main subject, he had his practical training at University College Dublin (Dublin, Ireland) where he stayed for four months. His Master’s thesis was on 2R regeneration realized in a polarization based integration scheme (POLIS). The research was carried out in the Opto-Electronic Devices group under supervision of dr. Jos van der Tol and dr. Erwin Bente. In August 2006 Milan obtained his Master of Science degree in Electrical Engineering at the Eindhoven University of Technology.

After his graduation Milan continued working for the Opto-Electronic Devices group, where he helped set-up the JePPIX course. In January 2007 he started his PhD project at the Opto-Electronic Devices group at the Eindhoven University of Technology (The Netherlands) under supervision of prof. dr. Martin Hill and prof. dr. ir. Meint Smit.
List of publications

Journal papers


International conferences

• M.T. Hill and M.J.H. Marell (2011), Plasmonic and metallic nano-cavity lasers, CLEO Pacific

• M.J.H. Marell and M.T. Hill (2011), Lasing and spontaneous emission in gap-plasmon mode Bragg grating waveguides, CLEO Baltimore


List of publications


Local conferences


