MASTER

Polarisation control in VCSELs by means of asymmetric current injection

Augustin, L.M.

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Polarisation control in VCSELs by means of asymmetric current injection

Luc Augustin

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Polarisation control in VCSELs by means of asymmetric current injection
In this thesis research on controlling the polarisation of Vertical-Cavity Surface-Emitting Lasers (VCSEL) is described. Controlled polarisation switching adds an additional degree of freedom in the modulation of the laser light and can be used for routing purposes, for example in a reconfigurable optical interconnect.

Intra-cavity VCSELs are processed on both a standard wafer for oxide-confined air-post VCSELs and a real intra-cavity structure (both grown on (001) GaAs substrates) to investigate the possibility to actively switch the polarisation of the light emitted by these devices.

Asymmetric current injection in intra-cavity contacted VCSELs has been demonstrated to stabilise the polarisation perpendicular to the current. In this scheme a lateral current component parallel to the epitaxial layer and an anisotropy in the electric field inside the device is introduced. To achieve this, the p- and n-contacts are no longer circumventing the mesa, but are restricted to opposite sides of the top and bottom mesa, respectively.

Besides stabilising the polarisation, this concept can in principle also be used to switch the polarisation actively between two orthogonal directions by implementing a second set of p- and n-contacts, perpendicular to the first.

Asymmetric (two- and four-contact devices) as well as standard symmetric intra-cavity VCSELs are processed by reactive-ion-etching of two mesas and depositing contacts on the bottom of these mesas. The etching is monitored by in-situ reflectometry to be able to determine what layer is being etched. In this way an accurate etch depth control is possible.

The standard structure has no contact layers in between the mirrors and the cavity. Therefore the doped bottom layers of the top-DBR and the top layers of the bottom-DBR are used for contacting.

Selective wet oxidation is applied to achieve lateral current confinement in the device. For the intra-cavity structure, the AlAs/GaAs top-mirror has to be sealed prior to the oxidation process to prevent it from oxidising.

The air-post wafer has been processed and tested. All tested symmetric devices showed a polarisation along the [110] axis, stable with increasing current. It can be concluded that this is the preferred polarisation for this wafer. For our four-contact VCSELs, the polarisation when using the contacts in the [110] direction is found to be along the [110] axis. When using the contacts in the [110] direction, the light was polarised at an angle instead of fully perpendicular to the current. This angle varies slightly from device to device, but it is independent of the pump current.

The polarisation being not completely perpendicular to the current direction is probably due to the absence of intra-cavity layers in this structure, resulting in a smaller lateral current component in the active area of the device. Simulations are done on both structures and they show a large influence of the wafer structure on the lateral component of the current and carrier momentum in the active area of the device.

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According to the simulation, the air-post structure showed only a little anisotropy in the gain. The lateral component is no longer large enough to fully compensate for other polarisation effects, such as crystal orientation and mechanical strain. The intra-cavity structure has been processed, but did not show laser-action due to a mismatch between the gain-maximum, mirror reflectivity and the cavity resonance frequency. Therefore no polarisation measurements could be done on this structure.
Chapter 1

Introduction

Vertical-Cavity Surface-Emitting Lasers (VCSELs) are becoming the device of choice for short-distance telecommunications, due to their many advantages as compared to normal edge-emitting lasers.

These advantages include on-wafer testing yielding lower production costs, a low divergence circular output beam for easy alignment, packaging and coupling to fiber, the possibility of creating 2D arrays of devices, and a smaller surface area.

Furthermore an intra-cavity contacted VCSEL as shown in Fig. 1.1 has some more advantages: the DBRs can be undoped, yielding lower optical losses, dielectric DBRs are possible, because no current has to flow through, and integration with MMICs is possible, because both contacts are on top of the structure.

While in edge emitting lasers the polarisation is always pinned in one direction due to its flat structure, one major disadvantage in VCSELs is that the polarisation of the emitted light is not defined, because of its symmetrical nature [1, 2]. And the polarisation can even switch with increasing current.

The polarisation has to be fixed for polarisation sensitive systems. Asymmetric current injection has been shown to be very effective for doing this [3, 4, 5, 6]. An asymmetric VCSEL is depicted in Fig. 1.2. A net x-component for both the k-vector and the electrical field are introduced. In this way an anisotropy in the gain is present and it will be possible to stabilise the polarisation of the emitted light perpendicular to the current.

Further more all current paths are equal, yielding a more uniform injection, from this a favoured ex-
citation of the fundamental mode as well as a lower threshold current are expected. Apart from this, asymmetric current injection has some more advantages, such as less overlap of the contact layers leading to an improved modulation frequency.

In this thesis the possibility to actively control the polarisation using this mechanism by implementing a second set of contacts perpendicular to the first is treated. Research includes simulations, fabrication and testing of these VCSELs.

First some theory about the polarisation dependency will be treated, then in Chapter 3 the simulations are covered. In Chapter 4 the processing of the devices is shown and the next chapter treats the characterisation of the devices and the comparison to simulations. Finally in Chapter 6 some conclusions drawn from the results are stated.
Chapter 2

Theory

2.1 Polarisation

In standard symmetric VCSELs (Fig. 2.2(a)) the polarisation is not in an a-priori known state, because of its quasi-symmetric shape. To be able to control the polarisation to be in a certain state, an anisotropy in the device is needed. Different measures to do so have been published, for example: applying anisotropic mechanical strain, growth on misoriented substrates, etching an extra line next to the cavity, using feedback, and using an external cavity.

Another possibility to introduce an anisotropy in the gain is to use asymmetric current injection. As it is shown before [3, 4, 5, 6] it is possible to control the polarisation by using this asymmetric current injection.

The influence of the asymmetric injection is explained below. Fig. 2.1 is a plot of the transition strength for recombination from electrons in the conduction band and heavy holes as a function of the angle between the \( \mathbf{k} \) (the electron \( k \)-vector) and \( \mathbf{e} \) (the optical electrical field). This transition strength is proportional to \( 1 - |\mathbf{k} \cdot \mathbf{e}|^2 \) [7].

In this figure, the \( \mathbf{k} \) is pointing in the vertical direction. The direction of \( \mathbf{e} \) can be rotated around \( \mathbf{k} \). As can be seen from the plot, the strength is equally large for \( \mathbf{e} \) pointing in any direction in the xy-plane.

![Figure 2.1: Transition strength between conduction band and heavy hole band](image)

This is the case in the symmetric VCSEL as the momentum of the carriers can be in all directions, the net \( \mathbf{k} \) will still be in the longitudinal direction. This can be seen in Fig. 2.2(a), the transition strength is equal for every direction of the optical field vector \( \mathbf{e} \) in the plane of the quantum well. So no polarisation preference will be present as far as the current is concerned.

Normally the light is polarised along one of the crystal directions and switches from one perpendicular
direction to the other with increasing current. In this case the crystal structure has the main influence on the polarisation.

In the asymmetric devices, the current has a large lateral component in the plane of the quantum well, this causes a net carrier momentum \( k_x \) in the lateral direction. This can be visualised by tilting the torus as shown in Fig. 2.2(b). The image of the torus on the xy-plane, so the plane of the quantum well, is no longer a circle, but it is pushed together. It can be seen that the transition strength is now maximal if the \( e \) is pointing in the y-direction, so perpendicular to the current. So the gain will be largest when the polarisation is perpendicular to the current.

![Symmetric VCSEL vs. Asymmetric VCSEL](image)

**Figure 2.2: Symmetric vs. asymmetric VCSEL**

This can be used not only to pin the polarisation in one direction, but also to switch the polarisation actively by using a layout as depicted in Fig. 2.3. In this case the polarisation of the emitted light can be selected by choosing one set of contacts. According to the previous, when choosing contact-pair 1, the polarisation will be in direction 1 and for contact-pair 2 perpendicular to this, in direction 2.

![4 contact asymmetric VCSEL for polarisation switching](image)

**Figure 2.3: 4 contact asymmetric VCSEL for polarisation switching**

### 2.2 Absorption

Apart from the gain, anisotropy in the absorption will influence the polarisation. Some absorption mechanisms of influence will be treated here.
The asymmetric injection causes an electric field component in the x-direction. This will influence the optical loss and will therefore influence the polarisation as well.

2.2.1 Electro-absorption

One mechanism is electro-absorption or Franz-Keldysh absorption in the contact layers. Although the quantum well emits at a lower energy than the bandgap of the GaAs contact-layers, transitions from the valence band to the conduction band in these layers can take place because of the large lateral component of the electric field.

In literature [6] measurements are described, using an MSM structure, where an electric field was applied in one direction. These measurements show that the absorption parallel to the electric field is the largest. Translated to the VCSELs, this means that the absorption perpendicular to the electric field (ergo perpendicular to the current) is the smallest. The gain is larger in this direction, so this electro-absorption effect as well as the gain will lead to a polarisation perpendicular to the current.

2.2.2 Free carrier absorption

Another absorption mechanism that can influence the polarisation is the free carrier absorption. This is absorption due to transitions between the heavy-hole and the split-off band. This absorption takes place in areas where high hole-concentrations are, so mainly in the P-contact layers. The transition strength for the heavy hole to split-off band is similar to the strength between the heavy hole and conduction band. In this case it is proportional to $|k|^2|k \cdot e|^2$. This means a larger absorption perpendicular to the electric field, so this will counteract the effects of gain and electro-absorption.

2.3 Application

The controlled active switching of the polarisation opens new possibilities for optical communications. One application can be in a reconfigurable optical interconnect. The polarisation gives an additional degree of freedom in the modulation of the light.

As can be seen in Fig. 2.4 the data can be intensity-modulated as usual and routing information can be modulated using the polarisation. In this way the routing-data can be split from the payload easily and decoded independently. This will cause an improvement in speed. The polarisation switching will be much slower than the intensity-modulation, but the actual payload will have a much higher rate than the routing-data and this will not be a problem.
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Chapter 3

Simulation

In this chapter the simulation of the VCSELs is described. The simulation consists of 2 parts. The first simulation is done with a simplified electrical model to calculate the electrical field, the current and carrier densities on the basis of the Poisson equation and the carrier continuity equations. Secondly the gain is calculated from the current and carrier densities from the previous simulation.

3.1 Current Simulation

3.1.1 Theory

The electrical simulation is based on two types of semiconductor equations [8, 9, 10]. The first is the Poisson equation:

\[ \nabla^2 V = \frac{q}{\epsilon} (n - p - C) \]  

(3.1)

In this equation \( V \) is the potential, \( q \) is the absolute value of the charge of the particles, \( \epsilon = \epsilon_0 \epsilon_r \) is the permittivity of the material, \( n \) is the electron density, \( p \) the hole density, and \( C \) the doping concentration (all three in \( \text{cm}^{-3} \)). This equation states that the divergence of the gradient of the potential \( V \), so the divergence of the electric field, must be equal to the sum of charges.

For the second set of equations we used the continuity equations for the electrons and holes:

\[ \nabla \cdot \mathbf{J}_n = qR \]  

(3.2)

\[ \nabla \cdot \mathbf{J}_p = -qR \]  

(3.3)

In these equations \( R \) is the recombination-rate in \( \text{cm}^3/\text{s} \). These state that the divergence of the current density must be equal to the charge multiplied by the recombination, so that there will be no current out, except due to generation or recombination of carriers.

The current densities \( \mathbf{J}_n \) and \( \mathbf{J}_p \) are given by:

\[ \mathbf{J}_n = qn \mu_n \mathbf{E} + qD_n \nabla n \]  

(3.4)

\[ \mathbf{J}_p = qp \mu_p \mathbf{E} - qD_p \nabla p \]  

(3.5)

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Here the $\mu_n$ and $\mu_p$ are the electron and hole mobilities in cm$^2$/Vs. The $D_n$ and $D_p$ are the diffusion coefficients for electrons and holes in cm$^2$/s. The mobility model used is taken from [11], the mobility is dependent on temperature, Aluminium fraction, doping concentration and carrier energy.

These coupled equations are solved using SGFramework [10] to simulate the VCSEL structure in a similar way as was done before [8]. Now the recombination model is adjusted to implement current-self-distribution (CSD)[9,12]. The influence of the optical field is taken into account by assuming a Gaussian distribution for the radiative recombination in the active area of the device. This results in a current more concentrated in the middle of the device.

The radiative recombination is calculated using:

$$ R = B(np - n_i^2) \quad (3.6) $$

In this $n$ and $p$ are the electron and hole densities, and $n_i$ is the intrinsic carrier concentration ($1.7 \times 10^6$ cm$^{-3}$). $B$ is the radiative recombination coefficient:

$$ B = B_0 + B_I \exp \left( -\frac{x^2}{w^2} \right) \quad (3.7) $$

Where $B_0$ is the spontaneous emission coefficient ($2 \times 10^{-10}$ cm$^3$/s), $B_I$ the stimulated emission coefficient ($1 \times 10^{-8}$ cm$^3$/s), and $w$ is the beam radius of the optical mode (3$\mu$m according to [13][Fig. 9] for an aperture-radius of 5.0$\mu$m).

The model for the simulation of both symmetric and asymmetric devices is depicted in Fig. 3.1. This is an intra-cavity structure with contact layers surrounding the cavity and a lowly doped spreading layer at the P-side. For the simulation of the asymmetric current injection, only contacts PMETAL1 and NMETAL1 are used.

This structure is identical to the previously used structure. In the processed intra-cavity structure, the P-contact and spreading layer consist of a moderately doped layer with thin highly doped regions, but this is not implemented in the simulation.

Figure 3.1: Model for the intra-cavity structure
CHAPTER 3. SIMULATION

3.2 Gain simulation

To simulate the influence of the direction of the current on the polarisation, the influence on the anisotropy of the gain is considered. To do this, a simplified optical model is used, without feedback to the continuity equations.

3.2.1 Theory

The optical E-vector is assumed to be in the x-direction and the difference in gain is calculated for the current in the x and y-direction. In this case the gain is proportional to:

\[ g_k \propto 1 - \left( \frac{k_x}{k} \right)^2 = \frac{k_x^2 + k_y^2}{k^2} \]  \hspace{1cm} (3.8)

In this \( g_k \) is the local gain at every meshpoint, \( k \) is the wavenumber:

\[ k = \frac{n2\pi}{\lambda} \]  \hspace{1cm} (3.9)

\( k_z \) is fixed, dependent on the thickness \( d_{QW} \) of the quantum well:

\[ k_z = \frac{2\pi}{d_{QW}} \]  \hspace{1cm} (3.10)

and \( k_x \) and \( k_y \) have a thermal distribution, approximated by a Boltzmann distribution. The current introduces a drift velocity in the same direction. This yields a \( k_0 \) which will lead to a shift in the Boltzmann distribution.

Assume a current-component in the x-direction, then

\[ k_0 = \frac{m J_x}{\hbar n q} \]  \hspace{1cm} (3.11)

so the distribution is:

\[ C \exp \left( -\frac{\hbar^2 (k_x - k_0)^2 + k_y^2}{2mk_B T} \right) \]  \hspace{1cm} (3.12)

With \( m \) the electron mass, \( k_B \) Boltzmann's constant and \( T \) the temperature (300 K). The local gain \( g_k \) has to be averaged over \( k_x \) and \( k_y \), for current in x-direction:

\[ < g_{k_x} > = \int_0^\infty \exp \left( -\frac{\hbar^2 (k_x - k_0)^2}{2mk_B T} \right) dk_x \int_0^\infty \frac{k_x^2}{k^2} \exp \left( -\frac{\hbar^2 (k_y)^2}{2mk_B T} \right) dk_y + \]

\[ \int_0^\infty \exp \left( -\frac{\hbar^2 (k_x - k_0)^2}{2mk_B T} \right) dk_x \int_0^\infty \frac{k_y^2}{k^2} \exp \left( -\frac{\hbar^2 (k_y)^2}{2mk_B T} \right) dk_y \]  \hspace{1cm} (3.13)

And the same for \( k_0 \) in the y-direction, while the optical field vector is still in the x-direction:

\[ < g_{k_y} > = \int_0^\infty \exp \left( -\frac{\hbar^2 (k_y)^2}{2mk_B T} \right) dk_y \int_0^\infty \frac{k_x^2}{k^2} \exp \left( -\frac{\hbar^2 (k_x - k_0)^2}{2mk_B T} \right) dk_x + \]

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Equations (3.13) and (3.14) can be rewritten as error functions, respectively:

\[
<g_kz> = \frac{\pi}{2} \frac{m k_B T}{\hbar^2} \left( 1 + \text{erf} \left( \frac{\hbar k_0}{\sqrt{2m k_B T}} \right) \right) \left( \frac{m k_B T}{\hbar^2} \frac{1}{k^3} + \frac{k_x^2}{k^2} \right) \tag{3.15}
\]

\[
<g_{ky}> = \sqrt{2} \left( \frac{m k_B T}{\hbar^2} k_0 \hbar \exp \left( -\frac{\hbar^2 k_0^2}{\sqrt{2m k_B T}} \right) \right)
+ \sqrt{\frac{\pi}{2}} \frac{m k_B T}{\hbar^2} \left( 1 + \text{erf} \left( \frac{k_0 \hbar}{\sqrt{2m k_B T}} \right) \right)
+ \frac{k_x^2}{k^2} \sqrt{\frac{\pi}{2}} \frac{m k_B T}{\hbar^2} \left( 1 + \text{erf} \left( \frac{k_0 \hbar}{\sqrt{2m k_B T}} \right) \right) \tag{3.16}
\]

This solution has to be normalised to match the normal gain when \( k_0 = 0 \):

\[
g_k = B_g (n - N_{th}) \tag{3.17}
\]

In this formula, \( B_g = 5 \cdot 10^{-16} \text{ cm}^2 \), the threshold density \( N_{th} = 1.3 \cdot 10^{18} \text{ cm}^{-3} \) (both values are taken from [14]), and \( n \) the electron density.

The carrier density in the simulation is based on bulk material. Because of the presence of Quantum Wells (QW) in the used structure, the density will be higher. This can be approximated using a correction factor based on the energy level in the Quantum Well (Fig. 3.2).

\[
n_{QW} = n_c \exp \left( \frac{E_{F} - E_1}{k_B T} \right) \tag{3.18}
\]

According to Fig. 3.2 the density in the first energy level will be:

\[
n_{QW} = N_c \exp \left( \frac{E_F - E_1}{k_B T} \right) \tag{3.19}
\]

This results in a ratio:

\[
\frac{n_{QW}}{n_{bulk}} = \exp \left( \frac{E_c - E_1}{k_B T} \right) \tag{3.20}
\]
substituting
\[ E_c - E_1 = \frac{\pi^2 \hbar^2}{2m_1 d^2} \] (3.21)
and using \( m_1 = 0.067 m_0 \), yields a ratio
\[ \frac{n_{QW}}{n_{bulk}} = 29.7 \] (3.22)
This correction is taken into account when calculating the normal gain, so (3.17) becomes:
\[ g_k = B_k \left( \frac{n_{QW}}{n_{bulk}} n - N_{th} \right) \] (3.23)
For the intra-cavity structure, the QWs consist of In_{0.17}Ga_{0.83}As instead of GaAs which will influence the electron density, but this is not taken into account in the simulations.

To get the gain for the active area, the next step is to average the local gain for every meshpoint over the electron density and the area of the active region.
\[ \text{gain}_x = \langle \langle g_k(x, y) \rangle N(x, y) A(x, y) \rangle \] (3.24)
In this equation \( N(x, y) \) is the electron density in every meshpoint and \( A(x, y) \) is the area of the mesh-element. This is done for the gain in both cases. The ratio \( \text{gain}_y/\text{gain}_x \) is a measure of the gain anisotropy introduced by the current, and correlated to the polarisation-dependency on the current.

### 3.3 Absorption

From the previous it is shown that the current can be of important influence to the direction of the gain. Another mechanism to introduce anisotropy are the losses. It is therefore useful to look at the absorption, but due to time constraints this is not simulated.

### 3.4 Results

#### 3.4.1 Current

Results for the current in these simulations are shown in Fig. 3.3 for the asymmetric case and Fig. 3.4 for the symmetric case.
CHAPTER 3. SIMULATION

Figure 3.3: Current streamlines in the asymmetric intra-cavity VCSEL structure

Figure 3.4: Current streamlines in the symmetric intra-cavity VCSEL structure

From these results it is clear that there is more crowding at the edges of the current constrictions in the case of the symmetric contacts. In the asymmetric case, crowding is still present, mainly at the P-contact side, but it is much smaller than in the symmetric case.
Furthermore the current in the symmetric case is flowing only in the y-direction, no x-component is present. In the asymmetric intra-cavity structure, the current is flowing more in the lateral direction. The y-axis is about 10 times magnified with respect to the x-axis, so the actual angle of the current is much larger than visible from this figure. This can be of great influence for the polarisation properties of the VCSELs.

3.4.2 Gain

In Fig. 3.5 the $k_x$ is plotted in the active area of the asymmetric device. The $k_x$ is quite uniform, with the peak near the edge of the current constriction.

![Figure 3.5: $k_x$ in the active area of Intra-cavity VCSEL](image)

After averaging the gain, the following result is found for the ratio $\frac{\text{gain}_y}{\text{gain}_x}$:

$$\frac{\text{gain}_y}{\text{gain}_x} = 3.7$$

From this it can be concluded that the intra-cavity VCSEL has a polarisation selectivity as the gain is considered, but the polarisation is also dependent on other mechanisms such as crystal orientation, mechanical stress and losses.

The influence of the current will be smaller in the real device than in the simulated case. In the processed device no lowly doped layer is present, so the lateral component will be smaller. But due to the lower resistance of the whole contact-layer, the resistance will be similar to the N-contact layer. Therefore the current will cross the device in a more straight way from P to N, yielding a more uniform current in the middle and a large lateral component.
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Chapter 4

Processing

In this chapter the processing of the VCSELs will be treated. The processing is based on a previously used recipe [15] with some improvements [16]. Two different wafers have been processed; the first is a standard wafer, meant for processing oxide-confined air-post VCSELs. So this wafer is not designed for intra-cavity contacting. Special measures have to be taken to be able to process good devices from this material. The second is a real intra-cavity structure. The differences in structure and therefore processing are elaborated hereafter.

4.1 Wafers

4.1.1 Air-post VCSEL wafer

The first wafer processed is a standard GaAs VCSEL wafer, designed for emitting a wavelength of 850 nm. The band-structure is as shown in Fig. 4.1 (a).

The structure is MOVPE grown on a doped (100) GaAs substrate. The N-mirror consists of 35 pairs of $\text{Al}_{0.16}\text{Ga}_{0.84}\text{As}/\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ layers with graded transitions in between. The layers have a doping concentration of $1.5 \cdot 10^{18}$ cm$^{-3}$. The cavity consists of an active area with 5 80 Å GaAs quantum wells, emitting at a wavelength of 850 nm, and N- and P-confinement layers consisting of a graded Aluminium content from 0.2 to 0.54.

Furthermore there are $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layers at both sides from which current constrictions can be formed by lateral wet selective oxidation.

On top there is a P-doped DBR, consisting of 20 pairs alternating $\text{Al}_{0.16}\text{Ga}_{0.84}\text{As}/\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ with graded transitions. The doping concentration of this top DBR is $3 \cdot 10^{18}$ cm$^{-3}$ for the topmost 15 layer-pairs and $1 \cdot 10^{18}$ cm$^{-3}$ for the lowest 5 pairs.

4.1.2 Intra-cavity wafer

The band structure for the intra-cavity wafer is shown in fig. 4.1(b). This structure is grown on a semi-insulating (100) GaAs substrate. The bottom DBR consists of 28.5 pairs undoped GaAs/AlAs. Here the cavity consists of 2 strained 80 Å $\text{In}_{0.17}\text{Ga}_{0.83}\text{As}$ quantum wells, designed for emission at 980 nm, separated by 80 Å GaAs barriers. The active area is surrounded by confinement layers: $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ for hole confinement at the N-side and $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ for electron confinement at the P-side.

Because of the lower mobility of the holes, the barrier at the N-side can be lower than 30%, cancelling
CHAPTER 4. PROCESSING

Figure 4.1: Band structure for used wafers

(a) Air-post VCSEL wafer

(b) Intra-cavity VCSEL wafer

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negative effects as described in [17].
For the formation of current constrictions AlAs layers are present outside the confinement layers. The intra-cavity contacts are going to be made on the contact layers. The N-contact layer is a single GaAs layer with a doping of $2 \cdot 10^{18}$ cm$^3$.
For the P-contact layer, alternating layers with high doping (350 Å, $1 \cdot 10^{19}$ cm$^3$) and low doping (1050 Å, $2 \cdot 10^{18}$ cm$^3$) are used. This is a trade-off between high doping for good ohmic contacts and low doping for low optical losses, caused by free carrier absorption. The highly doped layers are placed in the nodes of the standing wave pattern of the optical field inside the structure, see fig. 4.2. In this way the absorption is the highest where the intensity is low, influencing the field the least.

![Doping profile and optical intensity](image)

Figure 4.2: Doping profile and optical field in the intra-cavity structure

Both contact layers are quite thick because of the etching being not uniformly enough to stop exactly at the right depth.
On top of the P-contact layer is the top mirror; a 18 pair GaAs/AlAs DBR. This mirror, as the bottom DBR is undoped.

### 4.1.3 Differences between wafers

The difference in structure yields different processing steps as discussed below:

- For the standard structure at least 6 DBR-pairs have to remain after etching the top-mesa. The lowest layers have a lower doping concentration, so no good ohmic contact will be possible on these. Furthermore it is important that the layer at the surface is the low Aluminium containing mirror layer, again because of contact resistance, which increases with increasing Aluminium
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content. This has been made possible with the reflectometry set-up as discussed in section 4.2.3, but because of the non-uniformity of the dry etch, an extra selective wet etch step (see section 4.2.2) is needed.

- The same goes for the N-contacts, here again 4 mirror layers are etched and the low Aluminium-layer is used as contact layer. Because this layer still contains 16% Aluminium and this layer is at the surface during the wet oxidation, the area where N-contacts are to be formed have to be protected, see 4.2.6.

- The intra-cavity structure has rather thick (560 nm) contact layers, the non-uniform etch will not be any problem. Because of the mirror layers being the same as the current constriction layer (AlAs) a sealing is needed to protect the upper mirror from oxidising during the oxidation of the current constriction layers, this is explained in section 4.2.4.

- The lateral wet selective oxidation has to be calibrated for both structures, as both have different thicknesses and materials (Al_{0.96}Ga_{0.02}As as compared to AlAs).

- There are evidently differences in performance, this aspect will treated in chapter 5.

4.2 Processing recipe

In this section the processing of the VCSELs is discussed step by step. The detailed processing recipe is in appendix B. In Fig. 4.3 and 4.4 the processing recipes for both structures are schematised.

![Processing Diagram](image_url)

Figure 4.3: Processing of the air-post wafer

Polarisation control in VCSELs by means of asymmetric current injection
### 4.2.1 Cleaning and cleaving

First the 2" wafer is cleaved into samples of about 1 cm². After cleaving small particles are removed by blowing N₂. The native oxides have to be removed, this is done by a NH₄OH solution. If the sample is not clean enough, this can eventually be followed by spraying acetone and isopropanol.

### 4.2.2 Etching top mesa

The first step is to deposit Silicon-Nitride as masking material. On this a thin positive resist is spinned and the lithography is done for the top-mesa. The Silicon-Nitride is dry etched using Ar and SF₆. With this etch mask, the semiconductor can be etched using Reactive Ion Etching (RIE) with Ar and SiCl₄ as etchants. The etch depth is controlled using in-situ reflectometry [18, 19, 6, 16] which is explained in the next section.

In-situ reflectometry allows us to stop etching at the right layer, which is critical for both structures; in the real intra-cavity structure the etching has to stop at the P-contact layer, the surrounding layers are undoped and therefore not suitable contacting.

In the air-post structure, six or seven Al₀.₁₆Ga₀.₈₄As layer-pairs of the top mirror have to remain after etching, because the lowest five layer-pairs have a lower doping. The RIE is not uniform over the whole sample and the layers are only 360 Å; at some places the high Aluminium containing layers are at the surface. To overcome this, after the dry etch, Al₀.₉₂Ga₀.₀₈As is wet etched selectively using a K₂Cr₂O₇ solution. This etches high Aluminium containing layers and stops at an Aluminium fraction of 0.2. The result is a more uniform, low Al-content P-contact layer at the surface, at which the metal contact is to be deposited.

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Polarisation control in VCSELs by means of asymmetric current injection

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CHAPTER 4. PROCESSING

Figure 4.4: Processing of the intra-cavity wafer
CHAPTER 4. PROCESSING

4.2.3 Reflectometry

To be able to stop at the right layer an accurate depth control is required. This is done by making use of in-situ reflectometry at 650 nm, and is based on the difference in reflection for the layers with low- and high Aluminium content. The wavelength well below the designed wavelength for the structure will be strongly absorbed by the DBR layers and only a small number of DBR layers play a role for the reflection.

Simulation

Using the following refractive index model, the reflection coefficient can be simulated [6]:

\[
\begin{align*}
    n_{\text{GaAs}} &= 3.87 - 0.3i \\
    n_{\text{AlAs}} &= 3.13 - 0.001i
\end{align*}
\]

In the plot of the simulation of the reflection coefficient during etching (Fig. 4.5(a)), every individual mirror layer can be identified. This is not dependent on the exact wavelength (and refractive index model) and therefore the dimensions of the system are not critical. Using this method it is easy to determine what layer is being etched and hence a good depth-control becomes possible.

Set-up

To do this reflectometry measurement, a set-up is made as is shown in Fig. 4.6. The semiconductor laser emits at a wavelength of 650 nm, the beamsplitter splits the light, one part directly to detector 1. This one monitors the emitted power (PD1). The other half of the emitted light goes through a window in the Oxford 100 RIE and reflects at the etched sample surface, back to detector 2 (PD2). The ratio \( PD1/PD2 \) is then recorded using LabView and a DAQ-card. This way the reflectance of the present layers during etching is determined. An example of a measured signal is shown in Fig. 4.5(b). The measurement and the simulation are similar, and in both the different layers can be identified. The measurement data show a long-term oscillation of which the nature is not known. This does not influence the measurement itself, so the measured data can still be used.

![Figure 4.5: Reflectance as function of etch depth](image)

(a) Simulation

(b) Measurement

Figure 4.5: Reflectance as function of etch depth

Polarisation control in VCSELs by means of asymmetric current injection
We have etched separately and completely test samples of both structures and use the reflectometry measurement as a reference when etching the real samples meant for device processing. By this calibration an easier identification of the layers is possible and there is no need to simulate first.

4.2.4 Sealing top mirror

For the intra-cavity structure, an extra sealing step is needed because the mirror layers and the current constriction layers are the same (846 Å thick AlAs). When oxidising the current constrictions, the AlAs mirror layers will oxidise as well. Due to the fact that the top-mesa diameter is about 10 μm, and the current constrictions have to be about 15 μm, the mirrors will be fully oxidised even before the current constriction is completely formed.

Although the use of intra-cavity contacts enables the use of dielectric mirrors, this wafer is not designed for this. Above that, Aluminium Oxide has a volume shrinkage of 12 to 13% as compared to AlAs, this will lead to strain and possible delamination of the top mirror layers.

The problem in the sealing is the plasma introduced excess damage of the preceding dry-etching step. When the mesa is sealed using a short oxidation step as is published by Huffaker et al. [20], the sealing does not work. Because of the damages, channels remain through which the reagents can reach the non-oxidised parts, yielding a further oxidation into the structure.

To overcome this problem, the plasma-damage has to be removed by a wet etch dip. This is done by a diluted etch solution (NH₄OH:H₂O₂:H₂O = 1:2:100) [15, 21]. This is a non-selective GaAs/AlAs etch with an etch rate of 40 Å/s.

After a short dip of 10 seconds, only the outer 40 nm will be removed, this is enough to remove the damaged area and the size of the top-mirror is not influenced very much. The sealing is done in the RTA for 30 seconds at 550 °C under a gas mixture of Nitrogen and Oxygen (N₂:O₂ = 9:1) [20].

Fig. 4.7 shows a SEM image of the top mirror after the wet lateral oxidation, as can be seen the sealing was successful. The mirror is not oxidised while the current constriction layer is.
4.2.5 Etching second mesa

The processing of the second mesa is similar to the described process for the top-mesa. Because of the large height-differences (~1.5 μm), a thicker resist is needed (AZ4533). In the first runs Silicon-Nitride was used as an etch mask, in the same way as for mesa 1. Because of this resist being so thick, resist can be used as an etch mask. An extra advantage is that the sloped sidewalls of the resist profile can be transferred to the sample, if the etch-rates for resist and the semiconductor are in the same order of magnitude. The slope of the resist can be controlled by changing the temperature or duration of the hardbake step.

The normal recipe is a hardbake of 10 minutes at 105 °C. The following tests were done: 10 minutes at 125 °C and 30 minutes at 105 °C. By inspection with the optical microscope, the slope is visible. Both samples were dry etched for 20 minutes and the resulting mesas are examined in the SEM after removal of the photoresist. It can be seen in Fig. 4.8 the sidewalls are not sloped for both samples. This is because the etch rate for the AlGaAs is much faster than for resist. Resist can be used as an etch mask, but no sloped sidewalls will be present. To reach this, the etch-rates of the semiconductor and the resist have to be tuned. This can probably be done by mixing SF6, but this is not investigated any further.

Replacing the Nitride by photoresist in this step can cause problems in the etching of the alignment marks, this is explained in Fig. 4.9. The problem is due to the fact that for certain alignment marks, the area of mesa 1 is larger than mesa 2. That is why the Silicon-Nitride covering the mesa is etched first, and if this layer is too thick, the semiconductor is not etched. When Silicon-Nitride is used as an etch mask for this mesa, it is already etched away when the Nitride mask for mesa 2 is etched, and then it is no problem.

A solution for this problem could be to remove the Nitride on mesa 1 before applying resist for mesa 2. In that case, the top mesa is not covered when oxidising, but this should not be a problem as the top layer is GaAs and therefore does not oxidise fast.

This whole process goes only for the intra-cavity structure, as the P-contact layer is GaAs, so it will not oxidise. In the air-post structure this layer is Al0.16Ga0.84As so this has to stay covered with Silicon-
(a) 30 min at 105 °C

(b) 10 min at 125 °C

Figure 4.8: Etch tests with resist as etch mask for different hardbake steps

Mesa 1 + SiNx  Resist mask mesa 2  Etch mesa 2  Strip resist + SiNx

Devices

Mesa 1 + SiNx  Resist mask mesa 2  Etch mesa 2  Strip resist + SiNx

Alignment marks

Figure 4.9: Etching mesa 2 with AZ4533 as an etch mask

Polarisation control in VCSELs by means of asymmetric current injection
Nitride when the oxidation is done.

4.2.6 Protection against oxidation

On the air-post VCSEL wafer, the layer at the bottom of the second mesa where the N-contacts are going to be formed is a Al$_{0.16}$Ga$_{0.84}$As. This layer still contains Aluminium and, when oxidised, this will influence the contact-resistance. To protect this layer against oxidation, the area where the N-contact is to be evaporated, is covered by Silicon-Nitride.

A 300 nm thick Silicon-Nitride layer is deposited on the sample. For masking, AZ5214 is used with an image reversal process. In this way, the same dark-field mask can be used for the lithography of the oxidation-protection and the lift-off for the N-contacts.

In the intra-cavity structure, the N-contact layer is a GaAs layer and this will not be a problem.

4.2.7 Wet lateral oxidation

The oxidation of the current constriction layers to from the constrictions is an important and critical step in the processing of the VCSELS. If the constrictions are not oxidised far enough, the current will not flow through the middle of the device, underneath the top-mirror, but will be concentrated at the edges, yielding a very low efficiency. If it is too far, the aperture will be too small and with the risk that there is no aperture at all.

An extra problem is that the oxidation is a one-shot process: once oxidised, the constrictions will not oxidise further. Thus the oxidation has to be controlled accurately.

The lateral oxidation is done by making use of the set-up shown in Fig. 4.10.

![Figure 4.10: Set-up for the lateral wet oxidation](image)

The bubbler is put in a bath with a temperature of 95 °C. Nitrogen passes through this deionised water at a flow of 2 l/min and into the furnace. The sample is placed on a preheated quartz platen and put in the middle of the furnace. On the other end, the exhaust gasses are extracted to the scrubber where poisonous gasses are removed. Before the oxidation, the furnace is allowed to equilibrate with the wet nitrogen flowing.

For the air-post structure, the top mirror consists of Al$_{0.92}$Ga$_{0.08}$As, the constriction layers are Al$_{0.98}$Ga$_{0.02}$As. The ratio of the oxidation rates of Al$_{0.98}$/Al$_{0.92}$ depend strongly on temperature [22, 23]. The data from...
Choquette is used as a starting point for the calibration of the oxidation process. At 420 °C, Al$_{0.98}$ is expected to oxidise approximately 8 times faster than Al$_{0.92}$. This is the first experiment done. After oxidation, the oxidation front is not very clearly visible by optical inspection, so it has to be cleaved and examined in the SEM. Some more experiments are done at different temperatures (and corresponding oxidation times to agree with [22]). This results in the oxidation extends as seen in Fig. 4.11 and in table 4.1.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Duration (min.)</th>
<th>Ratio 0.98/0.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>31 min.</td>
<td>6.2</td>
</tr>
<tr>
<td>420</td>
<td>15 min.</td>
<td>3.8</td>
</tr>
<tr>
<td>440</td>
<td>5 min. 55 sec.</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 4.1: Ratio in oxidation extent for Al$_{0.98}$Ga$_{0.02}$As/Al$_{0.92}$Ga$_{0.08}$As

From these results, in the real process the oxidation will be at 400 °C for 30 min.

For the intra-cavity structure, the constriction layers consist of AlAs. In previously used recipes for a similar structure [15], an oxidation of 5 min. at 400 °C is used. This is therefore used in the first processing run. Because only a small amount of material is available, no extensive calibration is done for this structure. An oxidation of 5 min. yields an oxide extent of ~ 2.5 µm, instead of the wanted 15 µm as can be seen in Fig. 4.12(a). Next, oxidation is done for 20 minutes, now the N-current constriction is too far (Fig. 4.12(b)).

In this test it seems that the N-AlAs oxidises faster than the P-AlAs. A difference in oxidation rate is reported earlier [15], but a more extensive testing is needed to investigate this. This is not seen in the oxidation of the air-post sample where Al$_{0.99}$Ga$_{0.02}$As is oxidised. Ultimately an oxidation time of 15 min. is chosen. In this case the oxide extension is about 8 µm for the P-constriction and 10 µm for the N-side (Fig. 4.12(c)). Again the N-AlAs is oxidised further. The optimum would be to oxidise a little further, but due to the non-uniformity on the sample, this is not recommended.

After the oxidation all Silicon-Nitride is removed, so the mesas and the N-contacts are cleared.
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4.2.8 PN Isolation

The P-contacts are partly on the same level as the N-contacts and therefore an isolation layer is needed in between. For this, Silicon-Nitride is deposited, annealed to vaporise the water and then dry etched. The thickness of this layer (1000 Å) is chosen that there is a good side-wall coverage and the step for the metal is not too high. If this layer is too thick, the P-metal evaporated on top of this has to bridge a too large step and will not be connected, see Fig. 4.13.

4.2.9 P-metallisation

The P-contact is made on a highly doped P layer. For the air-post case, this layer is a Al$_{0.16}$Ga$_{0.84}$As layer with a doping concentration of $4 \times 10^{18}$ cm$^{-3}$. For the intra-cavity structure, the layer consists of GaAs with a doping concentration of $2 \times 10^{18}$ cm$^{-3}$ with thin (350 Å) highly doped layers with a concentration of $1 \times 10^{19}$ cm$^{-3}$. The initially used metal scheme for the contact is Ti/Au. Titanium is used for adhesion, but it has a low work function. This could be the cause that the P-contact is not ohmic. An alternative is to use Ni/Au. A test is done with Ni, but the adhesion was very bad, the metal bubbled after annealing at 400 °C, and the gold was dissolved into the Silicon-Nitride isolation layer as can be seen in Fig. 4.14. Because of this, no further tests are done, and Ti/Au is used for the other processing. The P-contact is made on top of the second mesa, therefore it has to bridge a step of ~700 nm for the intra-cavity structure and even ~1.5μm for the air-post structure. The metal has to be evaporated in stead of sputtered because of the lift-off process, which will be difficult when the metal fully covers the resist.
The evaporation can cause problems because of the before mentioned step. The solution to this is to put the sample at an angle in such a way that the sidewalls are evaporated on, see Fig. 4.15(a). This results in a coverage of the sidewalls, but two problems arise: at first, after annealing the metal flows in the gaps of the sidewalls and forms drops of metal. This results in a higher resistance. This can also cause a problem when current is put through, these small drops will then easily melt and the contact will be disrupted. Second, high walls of metal are formed at the sides of the contacts, because the metal is evaporated against the resist that is removed afterwards. These walls could cause short circuits, but this is accounted for in the mask design as far as possible. Both are visible in Fig. 4.15(b).

A solution could be to evaporate the N-contact first, then anneal this and after that deposit the P-contact.

4.2.10 N-metallisation

The N-metal is evaporated on the bottom of the second mesa and defined by a lift-off process. The used metal is Ge/Ni/Au. The Ge diffuses into the semiconductor and is used as a doping, Ni is used for adhesion.

4.2.11 Annealing

After deposition and lift-off, the P- and N-contacts need to be annealed, this is done in the RTA for 1 minute at a temperature of 400 °C under a N₂ flow.

4.3 Testing

When the contacts are annealed, the devices are finished. They can be tested immediately using a probe station. The devices are excited using a curve tracer, the voltage is increased and the current is measured. The VCSELs are observed with an IR-viewer through the binocular. With this simple test it is possible...
to see whether the devices lase or emit only spontaneously, or do nothing at all. The working devices are marked on a schematic drawing of the sample and they can be used for further characterisation as described in the next chapter.
Chapter 5

Characterisation and discussion

In this chapter the performed measurements are described and compared to the simulations. On the intra-cavity structure it has not been possible to fabricate working lasers, but these devices do show a spontaneous emission. Devices processed on the standard air-post VCSEL structure do lase. From devices processed on the intra-cavity structure, the optical spectrum is measured at different temperatures.

The characterisation of the air-post VCSELs includes L-I curve, optical spectrum and polarisation behaviour. The simulations include current-path and gain simulations for both structures.

5.1 Spectrum of the intra-cavity structure

Unfortunately none of the devices processed on the intra-cavity structure showed laser-action. Devices are made on different locations on both the real wafer and on a test wafer. Most of them emit light, but no stimulated emission takes place. The spectrum of these LEDs is measured using the set-up in Fig. 5.1.

The devices are excited using a DC voltage source. The outcoming light collimates in the lens and via the mirror and a second lens an image is made on the end of a multi-mode fibre, this end is put on an xyz-controller to be able to align the fibre carefully. The coupling is controlled by a watching the other end of the fibre with a CCD camera. In this way an easy and fast aligning is acquired.

When aligned well, the fibre is connected to the ANDO optical spectrum analyser and the spectrum is recorded with a wavelength resolution of 2 nm. A typical spectrum for the spontaneous emission is

![Measurement set-up to measure spectrum of VCSELs](image)

Figure 5.1: Measurement set-up to measure spectrum of VCSELs
shown in Fig. 5.2.

Figure 5.2: Optical spectrum of spontaneous emission for intra-cavity devices

From this figure it is clear that the mirror-reflectance is highest for 950 nm. Here is a dip in the spontaneous emission spectrum, the light is not amplified and is reflected instead of being transmitted. The gain-maximum, mirror reflectivity and cavity resonance frequency are shifted with respect to each other. Previously done Photo-Reflectivity and Photo-Luminescence measurements on this wafer showed that the cavity resonance lies at the edge of the stop band of the mirrors and a very high optical gain will be needed for laser action to take place. The spontaneously emitted light experiences too little gain to overcome this. One possible solution is to measure the devices at low temperatures and hence causing a shift in the resonance frequency and also reduce the optical losses which can possibly allow laser operation. This is shown in the next sections.
5.1.1 Cooling with liquid nitrogen

To investigate this, a first simple experiment is done: Fig. 5.3. The sample is put in a small copper tray, which will function as a heat-sink, this whole is put in a larger Teflon tray. The probes are put on the sample and the voltage is applied to it. When emitting liquid Nitrogen is poured carefully into the Teflon tray, trying to avoid that the Nitrogen flows over the sample. The spectrum measurement is started while continuously pouring Nitrogen in the tray.

![Figure 5.3: Set-up to cool sample using liquid N2](image)

Some of the problems encountered during these measurements are: the refractive index of the air will change dramatically with decreasing temperature, so the reflectivity of the top mirror will be different; moreover the Nitrogen flows over the sample, which results in an even more different refractive index on top of the top mirror. Although this method has some disadvantages, it is still a quick and easy method to cool the sample and measure roughly the influence of the temperature on the spectrum. Results from this measurement are in Fig. 5.4.

The spectrum is similar to the previous devices, again there is a dip in the intensity around 950 nm. A larger peak is present at 970 nm, but this is too far from the optimum mirror reflectivity, so no lasing takes place. When cooled the expected blue-shift is visible and the spectrum narrows, but again no lasing.

5.1.2 Measurements in cryostat

A more sophisticated measurement is done using a cryostat. For these measurements the sample has to be cleaved and packaged first. The sample is mounted on a TO-5 package and 1 N-contact and 2 P-contacts of the device are bonded. The device is measured in a vacuum and cooled down to -200 °C. It is excited using a DC current source. The outcoming light is examined using a microscope lens and a CCD camera, and is coupled into a multimode polymer fibre to measure the spectrum using the optical spectrum analyser.

Measurements are done at different temperatures and currents. Results are in Fig. 5.5. Again this device does not lase under any condition. With decreasing temperature there is a blue-shift in the spectrum, and the spectrum narrows. But when increasing the current at -200 °C, the spectrum broadens again.
Chapter 5. Characterisation and Discussion

Spectrum Gent2

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Figure 5.5: Optical spectrum for intra-cavity device cooled in the cryostat
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5.2 Spectrum of the air-post structure

5.2.1 Fabry-Perot interferometer

The optical spectrum for the VCSELs, processed on the air-post wafer, is measured at the VU Brussels using a Fabry-Perot interferometer. The set-up of Fig. 5.6 is used for the measurement of both the spectral and polarisation behaviour. For the spectrum measurement power meter 1 is replaced by the fibre coupler. The VCSEL is excited using a DC current source and a probe station, the light is converged in the lens and via a polarisation filter the light is coupled into the fibre.

![Figure 5.6: Measurement set-up to measure polarisation and spectral behaviour of VCSELs](image)

Results for these measurements are shown in Figs. 5.7 and 5.8, and Appendix D. The free spectral range for this analyser is 75 GHz.

![Figure 5.7: Optical spectrum for symmetric intra-cavity contacted air-post VCSEL USA3_D1](image)
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As can be seen, the devices are single mode above threshold, some devices emit higher order modes far above threshold (> 1.5 $I_{th}$), but they are all polarised in 1 direction. Furthermore, the asymmetric devices have a lower threshold current than the symmetric devices.

5.2.2 Optical Spectrum Analyser

At the University of Eindhoven some spectrum measurements are also done, using the ANDO optical spectrum analyser in the set-up in Fig. 5.1. The sample is excited using probes and a DC voltage source, for these measurements a wavelength resolution of 0.1 nm is used.

Some typical results are in Figs. 5.9 and 5.10

Figure 5.8: Optical spectrum for asymmetric intra-cavity contacted air-post VCSEL USA5_D3

Figure 5.9: Optical spectrum for asymmetric intra-cavity contacted air-post VCSEL USA5_D6 $I=5$ mA

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Figure 5.10: Optical spectrum for asymmetric intra-cavity contacted air-post VCSEL USA5.D8
I=4.8 mA

The top-mesa dimensions are 10 x 10 \( \mu m \) for both devices. They all emit around 870 nm.

5.3 Polarisation and optical power of the air-post structure

The devices processed on the air-post wafer do show stimulated emission so their polarisation behaviour can be investigated.

The asymmetric injection should cause the polarisation to be perpendicular to the current, as can be concluded from theory (Chapter 2), simulations (Chapter 3) and previously performed measurements [3, 5, 6]. To verify this and to see whether it is possible to switch the polarisation, polarisation measurements are also done at the VU Brussels using the set-up in Fig. 5.6.

The VCSEL again is excited using a DC current source and a probe station, after the light is split by the beam splitter, each beam is transmitted through a polarisation filter, set to pass perpendicular polarisations. The transmitted power is measured by the power meters.

The current is swept to beyond threshold and the L-I curve is measured for both polarisations. The results for these measurements are shown in Fig. 5.11 and appendix C.

The VCSELs are processed on a (100) substrate, the orientation with respect to the crystal axes is shown in Fig. 5.12.

All tested symmetric devices show a polarisation along the [110] axis, stable with increasing current. It can be concluded that this is the preferred polarisation for this wafer, as in these symmetric devices the current does not introduce any anisotropy.

For the four-contact VCSELs, the polarisation when using the contacts in the [1 1 0] direction is found to be along the [1 1 0] axis. When using the contacts in the [1 1 0] direction, the light was polarised at an angle instead of fully perpendicular to the current. This angle varies slightly from VCSEL to VCSEL, but it is independent of the injection current.

Fig. 5.11(a) shows the saturation at higher currents. In Fig. 5.11(b) it can be seen that there is some power in the polarisation parallel to the current, this is spontaneous emission, which of course has no
Figure 5.11: Polarisation resolved P-I for standard VCSEL wafer
fixed polarisation. This can also be seen in Fig. 5.13 where the power is measured below threshold. Here, no preference for one or another polarisation is present.

![Figure 5.12: Orientation of VCSELs with respect to wafer](image)

The presence of a preferred polarisation comes clear from the measurements done at the symmetric VCSELs. In these devices the direction of the current can not influence the polarisation. So the choice of a certain polarisation will be due to the crystal structure, mechanical strain and other structure-related issues. In the tested devices, the polarisation does not switch with increasing current as often happens in other VCSELs. From this it can be concluded that in this structure it can be very hard to switch the polarisation.

In the polarisation-switchable devices a lot of effort is needed to deviate from this preferred polarisation. In summary, the devices processed from the standard air-post wafer do lase. It is shown that polarisation switching is possible, though not fully over 90°. This could be due to the x-component of the k-vector being not large enough to overcome the other mechanisms that pin the polarisation.

The devices processed using the intra-cavity wafer do not lase, this is due to a mismatch between the gain-maximum, mirror reflectivity and cavity resonance.
5.4 Simulation results

Simulations are done to verify the difference in polarisation dependent gain between the intra-cavity structure and the standard air-post structure.

The model used for the device on the standard air-post wafer is shown in Fig. 5.14, here 7 top DBR layers, with alternating Aluminium content, are used as P-contact layers. The second bottom DBR layer and the layers below, again with alternating Aluminium content, are used for the N-contact.

Results for the current path simulation are shown in Fig. 5.15 together with the previously shown results for the intra-cavity structure.
The x-component of the electrical field in the middle of the active area is plotted in Fig. 5.16. The x-component of the current density as well as the angle of the current are plotted in Figs. 5.17 and 5.18.
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Figure 5.16: Electrical field $E_x$

Figure 5.17: Current density $J_x$

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From these figures, the difference in performance between the two wafers comes clear. In the air-post structure, there is more crowding at the edge of the current constrictions at the side of the P-contact. The angle of the current is little larger in the intra-cavity case. The next step is to look at the influence of the current- and electron-density on the gain.

In Fig. 5.19 the $k_x$ is plotted in the active area of both devices. It is clear that this is much larger in the case of the intra-cavity structure, so the influence on the gain will be larger. Furthermore, in the intra-cavity case, the $k_x$ is more uniform, in the other case, there are two peaks visible at the edges of the current constrictions. This could lead to an easier excitation of higher order modes.

In Fig. 5.20, the normal gain in the active area is plotted. Again this is larger and little more uniform in the situation of the intra-cavity structure.

After averaging the gain, the following results are found for the ratio $\text{gain}_y/\text{gain}_x$:

\[
\begin{align*}
\text{intra-cavity wafer} & \quad \frac{\text{gain}_y}{\text{gain}_x} = 3.7 \\
\text{air-post wafer} & \quad \frac{\text{gain}_y}{\text{gain}_x} = 1.5
\end{align*}
\]

From this it can be concluded that the intra-cavity VCSEL has a more pronounced polarisation selectivity as compared to the air-post wafer. This is probably due to the absence of intra-cavity layers in this structure, resulting in a smaller $x$-component of the k-vector in the active area of the device.

This can be an answer to the question why the devices processed on the air-post wafer do not switch fully for 90 degrees, but their polarisation is dependent on other mechanisms such as crystal orientation, mechanical stress and losses.

Another thing to look at is to vary the height of the contacts in the air-post wafer, trying to force the current more in the lateral direction. Some simulations are done, but the influence is too little to be of importance to the anisotropy of the gain.
CHAPTER 5. CHARACTERISATION AND DISCUSSION

Polarisation control in VCSELs by means of asymmetric current injection

Figure 5.19: $k_x$ in the active area of VCSELs

(a) Intra-cavity wafer

(b) Air-post wafer
CHAPTER 5. CHARACTERISATION AND DISCUSSION

Figure 5.20: Gain in the active area of VCSELs

(a) Intra-cavity wafer

(b) Air-post wafer

Gain in active area of asymmetric contacted VCSEL (intra-cavity structure)

Gain in active area of asymmetric contacted VCSEL (air-post wafer)

Polarisation control in VCSELs by means of asymmetric current injection
Chapter 6

Conclusions

Intra-cavity VCSELs with 4 contacts are processed on a standard wafer meant for oxide confined air-post VCSELs and an intra-cavity wafer to investigate the possibility to actively switch the polarisation of the emitted light.

The devices processed on the standard wafer emit around 850 nm. Two types of devices are measured: symmetric VCSELs, where the current does not introduce an anisotropy in the gain, and asymmetric VCSELs with 4 contacts where the current should introduce an anisotropy in the gain, forcing the polarisation in one direction, dependent of the choice of contacts. The symmetric devices on this wafer all have the same polarisation, stable with increasing current. Because the current flow in the xy-plane is equally spread in every direction, the direction of the current can not influence the polarisation. So it can be concluded that this measured polarisation (along the [110] axis) is the preferred polarisation for this wafer, fixed by more dominant mechanisms such as the crystal structure and mechanical strain.

All measured asymmetric devices emit light polarised along this preferred direction when contacted in the [110] direction. In this case the polarisation is perpendicular to the current, as expected. When the contacts along the [110] axis are used, the polarisation is not always perpendicular to the current, but at an angle with respect to the [110] axis. Polarisation switching takes place with the changing of contacts, but it seems that the influence of the current-direction is not large enough to fully overcome the other mechanisms that fix the polarisation. The polarisation does not switch with increasing current as is seen in other VCSELs.

The same devices are processed on a real intra-cavity structure. These devices do not lase, because of a mismatch between the gain-maximum, the reflectivity optimum, and the cavity resonance frequency. The devices are measured at very low temperatures (-200 °C) but no stimulated emission takes place. Because of this, no polarisation selectivity is present.

From simulations it is expected that the used intra-cavity structure should perform better than the standard air-post structure. In this structure, the lateral component of the k is larger and more uniform than in the air-post case. Because of the better uniformity, this could lead to a more preferred single-mode behaviour.

Though the two observed polarisations with the 4-contact VCSELs are not perpendicular we have demonstrated experimentally the possibility of polarisation switching in VCSELs. This extra parameter can be
CHAPTER 6. CONCLUSIONS

used for routing purposes in reconfigurable optical interconnects.
Chapter 7

Acknowledgements

To conclude I would like to thank everybody who helped me with my work during my graduation. Especially Barry Smalbrugge for teaching me the skills and fun of processing and for the support during my work in the cleanroom. Erik-Jan Geluk for all the beautiful SEM-pictures and help with processing. Ben van Roy for the support in the cleanroom. Theo van de Roer and Remco Strijbos for the discussions, the valuable feedback and help with the simulations. Guy Verschaffelt from the Vrije Universiteit Brussels for help with the polarisation measurements, for the discussions and useful tips. Fouad Karouta for his general support and fruitful discussions and Prof. Meint Smit for giving me the opportunity to graduate in his group.

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And last but certainly not least I want to thank my parents for all their support during my studies.
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Polarisation control in VCSELS by means of asymmetric current injection
Appendix A

Program files

A.1 Polarisation dependent gain

Matlab file to calculate polarisation dependent gain from SG-framework output.

close all;
clear all;

hP = 6.6260755e-34; % [Js] Planck's constant
hbar = hP./(2.*pi); % [Js] Reduced Planck's constant
kB = 1.38066e-23; % [J/K] Boltzmann's constant
g = 1.60218e-19; % [C] Electron charge
mO = 9.11e-28; % [g] Electron rest mass
T = 300; % [K] Temperature
e0 = 8.854e-14; % [F/cm] Permittivity of vacuum
aQW = 8e-9; % [m] Thickness QW for bandstructure
dqw = 80e-7; % [cm] Thickness Quantum Well
lambda = 980e-7; % [cm] Wavelength
Energy= 1.24/(lambda*le7); % [eV] Photon Energy
m1 = 0.067 *9.11e-31; % [kg] Effective electron mass in 1st energy level

% scaling constants
T0 = 300; % [K] temperature scaling
V0 = kB*T0/q; % [V] potential scaling
C0 = 2.0e18; % [cm^-3] concentration scaling
u0 = 0.5e3; % [cm^-2/V s] mob. coef. scaling
X0 = 1.0e-4; % [cm] distance scaling
D0 = u0*V0; % [cm^2/s] diff. coef. scaling
tm0 = (X0^2)/D0; % [s] time scaling
E0 = V0*X0; % [V/cm] E-field scaling
J0 = q*D0*C0/X0; % [A/cm^2] current scaling
L0 = (V0*q0)/(X0^2*C0); % [cm^-3/s] recombination coefficient scaling

kr = sqrt(m0*kB*T0)/hbar; % [1/cm] k-scaling

% number of gridpoints
nx=100;
ny=50;

% directory and input filenames for dataseries
DataDir = 'c:\simulators\sgfw\polarization\0107vc\'; % airpost
DataDir = 'c:\simulators\sgfw\polarization\020306cc\'; % intracavity
xFilename = 'x.002';
yFilename = 'y.002';
Filename = 'n.002';

Polarisation control in VCSELs by means of asymmetric current injection 55
APPENDIX A. PROGRAM FILES

pFilename = 'p.002';
JnxFilename = 'Jnx.002';
JnxFilename = 'Jny.002';
AFilename = 'A.002';

% labels for all axis
xLabelText = 'x (cm)';
yLabelText = 'y (cm)';
zLabelText = 'z';

% method of interpolation:
% 'linear' - Triangle-based linear interpolation (default).
% 'cubic' - Triangle-based cubic interpolation.
% 'nearest' - Nearest neighbor interpolation.
% 'v4' - MATLAB 4 griddata method.
method = 'linear';

% load files
xO = load (strcat(DataDir, xFilename));
yO = load (strcat(DataDir, yFilename));
nO = load (strcat(DataDir, nFilename));
pO = load (strcat(DataDir, pFilename));
JnxO = load (strcat(DataDir, JnxFilename));
JnzO = load (strcat(DataDir, JnyFilename));
AO = load (strcat(DataDir, AFilename));

% select variables only in active area:
% 1ge-4 < x < 2ge-4
% 0.8022 < y < 0.9382 for 020306 (intra-cavity)
% 0.2905 < y < 0.3545 for 020107 (air-post)

xmax=29e-4;
xmin=19e-4;
ymin=0.8022e-4;
ymax=0.9382e-4;

for m = 1:length(yO),
    if (yO(m) <= ymax) & (yO(m) >= ymin),
        if (xO(m) <= xmax) & (xO(m) >= xmin),
            n(1,1) = xO(m);
            n(1,2) = yO(m);
            n(1,3) = nO(m);
            n(1,4) = pO(m);
            n(1,5) = JnxO(m);
            n(1,6) = JnzO(m);
            n(1,7) = AO(m);
            l=l+1;
        end
    end
end

% sort rows of the matrix to the first column (x-coordinate)
% Calculate band difference between QW and bulk
dE=((pi^2)*(hbar^2))/(2*m1*(aQW)^2);
ratio=exp((dE)/(kB*T));

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX A. PROGRAM FILES

Polarisation control in VCSELs by means of asymmetric current injection

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APPENDIX A. PROGRAM FILES

for i = 1:length(n(:,3)),
gkx = gkx + n(i,3)*local_gkx(i)*n(i,7);
gky = gky + n(i,3)*local_gky(i)*n(i,7);
ntot = ntot + n(i,3);
Atot = Atot + n(i,7);
end

gkx = gkx / (ntot*Atot)
gky = gky / (ntot*Atot)

%-------------------------------------------------------------------------
% define dimensions and step for mesh
xstep = (xmax-xmin) ./ nx;
ystep = (ymax-ymin) ./ ny;

% make mesh
[XX,YY] = meshgrid(xmin:xstep:xmax, ymin:ystep:ymax);

% fit surface z on mesh
z = griddata(n(:,1), n(:,2), gain, XX, YY, method);

% define structure (data outside structure are undefined)
for i = 1:size(XX,1),
    for j = 1:size(XX,2),
        if YY(i,j) < 0.8022e-4 || YY(i,j) > 0.9382e-4
            z(i,j) = NaN;
        end
        if XX(i,j) > 48e-4
            z(i,j) = NaN;
        end
    end
end

figure(1);
surf(XX, YY, z); % plot the actual figure
shading flat; % use flat shading
colorbar; % plot color bar for reference colors

Title ('Gain in active area of asymmetric contacted VCSEL');
xlabel(xLabelText);
ylabel(yLabelText);
zlabel(zLabelText);

figure
z = griddata(n(:,1), n(:,2), k0x, XX, YY, method);
surf(XX, YY, z); % plot the actual figure
shading flat; % use flat shading
colorbar; % plot color bar for reference colors

Title ('k_x in active area of asymmetric contacted VCSEL');
xlabel(xLabelText);
ylabel(yLabelText);
zlabel(zLabelText);

%-------------------------------------------------------------------------

% write data to file
fid = fopen((strcat(DataDir, 'polarisation.dat')), 'w');
fprintf(fid, 'Gain in active area of VCSEL\n\n');
fprintf(fid, 'File: %s\n', DataDir);
fprintf(fid, 'ratio gainy/gainx = %3.5f\n', gky/gkx);
fclose(fid);
Appendix B

Processing intra-cavity VCSELs

B.1 Etch small mesa

Cleaving

- cleave sample + N₂-blow (removal of particles)
- sample size:
- mark sample orientation on wafer topography

Cleaning

1 min NH₄OH:DI H₂O = 1:10
water rinse
N₂ blow dry

SiNx deposition

Cluster tool, chamber 3
Batch SiNx-dep-300
T=300 °C  N₂  100 sccm
P=150 W  NH₃  50 sccm
p=100 mTorr SiH₄  2 sccm
t=25 min  N₂  50 sccm
layer thickness 300 nm

Lithography

S1805  30 sec  3000 RPM
Soft bake  95 °C  5 min
Mask Exposure  15 sec  UV 300
Post Exposure Bake  105 °C  5 min
Development  1 min  MP2401:H₂O = 10:100
water rinse and N₂ blow dry

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

Visual check

smallest mesas, crosses
resistheight

Dry etch SiNx

Cluster tool, chamber 1
Batch SiNx-etch
\[ T=12 \, ^\circ C \quad SF_6 \quad 10 \, \text{sccm} \]
\[ MW=400 \, \text{W} \quad Ar \quad 2 \, \text{sccm} \]
\[ RF=20 \, \text{W} \quad t=5 \, \text{min} \]
\[ DC_{bias}=-50 \, \text{V} \]
etch rate 70 nm/min (check!)
SiNx open? Compare colors in non-polarized light

Resist stripping

(a)
Spray bottle Acetone above waste container (10x)
Spray bottle Isopropanol above waste container (10x)
\[ N_2 \text{ blow dry} \]

(b)
Cluster tool, chamber 1
Batch BS-precl-SiN (weak O2 plasma)
\[ T=12 \, ^\circ C \quad O_2 \quad 30 \, \text{sccm} \]
\[ MW=400 \, \text{W} \quad Ar \quad 2 \, \text{sccm} \]
\[ RF=20 \, \text{W} \]
\[ DC_{bias}=-53 \, \text{V} \]
Minor resist traces? t=2 min.
Major resist traces? t=4 min.
Visual check!

Dry etch small mesa

OPT system 100
Dummy run before real etch (same conditions), without sample and sacrificial wafer, t=15 min.

Process conditions:
VCSEL non-sel. GaAs/AlAs
\[ T=20 \, ^\circ C \quad SiCl_4 \quad 10 \, \text{sccm} \]
\[ P=60 \, \text{W} \quad Ar \quad 10 \, \text{sccm} \]
\[ p=11 \, \text{mTorr} \]
\[ DC_{bias}=-315 \, \text{V} \pm 10 \, \text{V} \]
Use laser-reflectometry to determine etch-depth.

- etchrate depends on:

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

- mask material and thickness,
- sample size if no sacrificial wafer is used.

• Argon is used for easier ignition and a more stable plasma.
• Plasma damage up to 200 Å

• lower pressure results in more anisotropic etch

• \( \text{SiCl}_4 + 2 \text{H}_2\text{O} \rightarrow \text{SiO}_2 + 4 \text{HCl} \)
SiO\(_2\) dust and poisonous HCl gas.

• place sample in middle of sacrificial wafer. Reposition big wafer until spot on glass of loadlock is in the middle of the sample.
• observe reflected laserbeam.
• try to avoid reflections back in the laser, because of noise generation.
• study graph on computer (and x-t recorder) to determine which layer is being etched.

Selective \( \text{Al}_{0.92}\text{Ga}_{0.08}\text{As} \) etching (USA-wafer only)

• 0.5077 g K\(_2\)Cr\(_2\)O\(_7\)
• 250 ml H\(_2\)O
• 5 ml H\(_3\)PO\(_4\) (conc.)
• 5 ml H\(_2\)SO\(_4\) (conc.)

mix well
cool down to 20 °C
etch rate: 40 nm/min
t=30 sec.
epi-up, with slow sample movement.
H\(_2\)O rinse and N\(_2\) blow dry.
Etches \( \text{Al}_{0.92}\text{Ga}_{0.08}\text{As} \) and stops at \( \text{Al}_{0.2}\text{Ga}_{0.8}\text{As} \)

B.2 Sealing top-DBR (Gent-wafer only)

Room ambient hydrolysis
Mesa height measurements
In total about 10 minutes
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

Dip in diluted wet-etch solution

- NH$_4$OH:H$_2$O$_2$:H$_2$O = 1:2:100
  Room temperature
  etch rate: 40 Å/s
  10-12 seconds.
- N$_2$ blow dry

Rapid Thermal Anneal

- 30 seconds at 550 °C in 10% O$_2$ or H$_2$ and 90% N$_2$
  RTA recipe: 550nos30.1

B.3 Etch large mesa

SiN$_x$ deposition

Same as B.1.
Note: SiN$_x$ mask mesa 1 still present!

Lithography

| AZ4533 | 30 sec | 5000 RPM |
| Soft bake | 95 °C | 20 min |
| Mask Exposure | 15 sec | UV 400 |
| Development | 2.5 min | AZ dev. : H$_2$O = 60:60 |
| water rinse and N$_2$ blow dry |
| Hard bake | 105 °C | 10 min |

Dry etch SiN$_x$

Same as B.1.

Resist stripping

Same as B.1.

Dry etch small mesa

Same as B.1, except etch time is much shorter → reflectometry.

Selective Al$_{0.92}$Ga$_{0.08}$As etching (USA-wafer only)

Same as B.1, except t=45 sec.
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

B.4 Protection N-contact (USA-wafer only)

SiN$_x$ deposition

Same as B.1, except $t=10$ min. $\rightarrow$ 1000Å.

Lithography: image reversal

<table>
<thead>
<tr>
<th>Process</th>
<th>Time</th>
<th>Temp</th>
<th>Duration</th>
</tr>
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<tr>
<td>AZ5214</td>
<td>30 sec</td>
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<td>5 min</td>
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<tr>
<td>Mask Exposure</td>
<td>45 sec</td>
<td>UV 300</td>
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<tr>
<td>Post exposure bake</td>
<td>1.5 min</td>
<td>115 °C(setpoint 126 °C)</td>
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<tr>
<td>Flood exposure</td>
<td>7.5 sec</td>
<td>UV 400</td>
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<tr>
<td>Development</td>
<td>20 sec</td>
<td>AZ dev. : H$_2$O = 60:60</td>
<td></td>
</tr>
</tbody>
</table>

Development very critical! Watch development process carefully!

Water rinse and N$_2$ blow dry

Dry etch SiN$_x$

Same as B.1.

Resist stripping

Same as B.1.

B.5 Wet oxidation (USA wafer)

In furnace: $400$ °C, 2 l/min N$_2$, $T_{bubbler}=95$ °C, $t=35$ min.

B.6 Wet oxidation (Gent wafer)

In furnace: $400$ °C, 2 l/min N$_2$, $T_{bubbler}=95$ °C, $t=15$ min.

B.7 PN Isolation

Dry etch all SiN$_x$

Same as B.1, now 10 min.

Deposit SiN$_x$

Same as B.1, except $t=10$ min. $\rightarrow$ 1000Å.

Polarisation control in VCSELS by means of asymmetric current injection
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

Annealing SiN$_x$

RTA, recipe 450a_m10.1

Lithography

<table>
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<th>Process</th>
<th>Duration</th>
<th>Temperature</th>
<th>Other Conditions</th>
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<tr>
<td>Soft bake</td>
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<td>Mask Exposure</td>
<td>15 sec</td>
<td>UV 400</td>
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<tr>
<td>Development</td>
<td>2.5 min</td>
<td>AZ dev.: H$_2$O = 60:60</td>
<td>2.5 min</td>
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<tr>
<td></td>
<td></td>
<td>water rinse and N$_2$ blow dry</td>
<td>2.5 min</td>
</tr>
<tr>
<td>Hard bake</td>
<td>105 °C</td>
<td>10 min</td>
<td></td>
</tr>
</tbody>
</table>

Dry etch SiN$_x$

Same as B.1.

Resist stripping

Same as B.1.

B.8 P-metallisation

Lithography

<table>
<thead>
<tr>
<th>Process</th>
<th>Duration</th>
<th>Other Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ4533</td>
<td>30 sec</td>
<td>5000 rpm</td>
</tr>
<tr>
<td>Soft bake</td>
<td>95 °C(Hot plate setpoint 80°C)</td>
<td>15 min(10 min)</td>
</tr>
<tr>
<td>Mask Exposure</td>
<td>15 sec</td>
<td>UV400</td>
</tr>
<tr>
<td>PE-soak</td>
<td>20 min Chlorine-Benzene, N$_2$ blow dry</td>
<td>20 min Chlorine-Benzene, N$_2$ blow dry</td>
</tr>
<tr>
<td>Development</td>
<td>170 sec</td>
<td></td>
</tr>
</tbody>
</table>

- water rinse and N$_2$-blow dry
- After development: HCl dip (10%)
- No Hardbake!

P-metal evaporation

In Leybold

- Ti-Au (500 Å+ 2500 Å)
- evaporation at an angle, see Fig. B.1
- Lift-off

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

![Figure B.1: Evaporation angle for P-metal](image)

B.9 N-metallisation

**Lithography**

<table>
<thead>
<tr>
<th>Step</th>
<th>Time/Temp/Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ4533</td>
<td>30 sec</td>
</tr>
<tr>
<td>Softbake</td>
<td>95°C (Hot plate setpoint 80°C)</td>
</tr>
<tr>
<td>Mask Exposure</td>
<td>15 sec</td>
</tr>
<tr>
<td>PE-soak</td>
<td>20 min Chlorine-Benzene, N₂ blow dry</td>
</tr>
<tr>
<td>Development</td>
<td>170 sec</td>
</tr>
</tbody>
</table>

- water rinse and N₂-blow dry
- After development: HCl dip (10%)
- **No Hardbake!**

**N-metal evaporation**

In Leybold

- Ge-Ni-Au (200 Å + 150 Å + 2000 Å)
- Lift-off

Ge: doping diffuses into semiconductor
Au: lower serial resistance
Ni: adhesion/smoothen surface.

B.10 Annealing contacts

RTA: recipe 400n_m01.1
APPENDIX B. PROCESSING INTRA-CAVITY VCSELS

Polarisation control in VCSELS by means of asymmetric current injection
Appendix C

L-I Curves

C.1 Sample USA3

Device 1

Figure C.1: Symmetric VCSEL USA3_D1

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX C. L-I CURVES

Device 2

Polarization resolved output power USA3_D2

Figure C.2: Symmetric VCSEL USA3_D2

Polarisation || [110]

Device 3

Polarization resolved output power USA3_D3

Figure C.3: Symmetric VCSEL USA3_D3

Polarisation || [110]
C.2 Sample USA5

Device 1

Figure C.4: Symmetric VCSEL USA5.D1

Polarisation $\parallel [110]$

Device 2

No current sweep done.

- Contacts $\parallel [1\overline{1}0] \Rightarrow$ polarisation $\parallel [110]$

- Contacts $\parallel [110] \Rightarrow$ polarisation at $45^\circ$
Device 3

![Graph showing polarisation resolved power vs. current for VCSEL USA5.D3, contacted parallel to minor axis.](image)

Figure C.5: Asymmetric VCSEL USA5.D3

- Contacts $\parallel [110] \Rightarrow$ polarisation $\parallel [\overline{1}0]$

- Contacts $\parallel [\overline{1}0]$ resistance too high.
APPENDIX C. L-I CURVES

Device 4

Figure C.6: Asymmetric cross shaped VCSEL USA5-D4, contacted || [110] ⇒ polarisation at -45°

Figure C.7: Asymmetric cross shaped VCSEL USA5-D4, contacted || [110] ⇒ polarisation at 25°

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX C. L-I CURVES

Polarisation control in VCSELs by means of asymmetric current injection
Appendix D

Spectrum measurements

D.1 Sample USA3

Device 1, symmetric 9 µm

Figure D.1: Symmetric VCSEL USA3.D1

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX D. SPECTRUM MEASUREMENTS

Device 2, symmetric 10 μm

![Graph](image)

Figure D.2: Symmetric VCSEL USA3.D2

D.2 Sample USA5

Device 1, symmetric 9 μm

![Graph](image)

Figure D.3: Symmetric VCSEL USA5.D1

Polarisation control in VCSELs by means of asymmetric current injection
APPENDIX D. SPECTRUM MEASUREMENTS

Device 3, asymmetric 11 μm

![Optical spectrum of VCSEL USA5_D3 (asymmetric 4-contact), contacted NS, I=4.61mA](image)

Figure D.4: Asymmetric VCSEL USA5_D3

Device 4, asymmetric cross shaped 6 μm

![Spectrum of VCSEL USA5_D4 (4-contact, cross-shape), contacted EW, I=1.77mA](image)

Figure D.5: Asymmetric cross shaped VCSEL USA5_D4

Polarisation control in VCSELs by means of asymmetric current injection
Device 7, asymmetric 10 μm

Figure D.6: Asymmetric VCSEL USA5.D7