Implantation isolation in AlGaAs/GaAs structures

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Abstract
In this work the effect of implantation isolation in vertical cavity surface emitting laser (VCSEL) samples have been investigated using cross sectional measurements. The samples consist of two AlGaAs/GaAs Distributed Bragg Reflectors (DBR) structures with a GaAs quantum well region sandwiched in between them. The samples were implanted with 330 and 660 keV helium ions using doses from $7 \cdot 10^{13}$ cm$^{-2}$ to $1 \cdot 10^{16}$ cm$^{-2}$.

Due to variations and uncertainties in the SSRM output quantitative values of resistivity in the highly resistive regions created by ion implantations were not attained. Relative differences, however, were notable for the different doses.

It was found that the resistive regions were not located as deep inside the samples for the 660 keV implantations as for the 330 keV. This does not agree with the simulations performed.

A correlation between implantation dose and the depth of the resistive region created was also found - higher doses caused resistive regions deeper inside the samples.

Furthermore, as the implantation dose is increased the resistive region is confined to only about one AlGaAs/GaAs period of width at the same depth as the wide resistive region for lower doses, i.e. the structure is somehow regaining its conductive properties in the shallow areas only leaving a thin stripe of the resistive region at the deepest end for higher implantation doses.

Samples implanted with low He doses were heated in a vacuum furnace at 300, 350 and 380 °C. The heated samples showed a tendency to regain the conductivity in the resistive region, similar to the samples implanted with high doses. This suggests that there may be some kind of annealing effect for higher doses, possibly due to the increased flux for higher doses.
Acknowledgements

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1 Introduction

Sometimes the intrinsic resistivity of compound semiconductors is not sufficiently high for proper isolation between components. A common method in handling this issue is to selectively bombard the compound semiconductor with energetic ions in order to physically damage the lattice [1], [2]. As the ions penetrate the substrate they cause deep-level traps to form (due to the lattice damage), in which carriers (holes and electrons) recombine and thereby lowers the carrier concentration and hence also increases the resistivity of the selected area [1]. This process is relatively easy and has been applied for light emitting diodes (LEDs) for several years.

1.1 Motivation

The main motivation of this project is not only to investigate how the energy and dose of the ion bombardment correlates to the final resistivity, but rather to investigate in detail how the resistivity spatially differs with the purpose of achieving a greater understanding in how implant isolation affects the material. This will be done by examination of the samples using the technique “Scanning Spreading Resistance Microscopy” (SSRM) which is based on the more known “Atomic Force Microscopy” (AFM). The SSRM produces a two-dimensional chart graphically demonstrating the sample’s resistivity by measuring the current between the microscope’s conductive tip and a biased electrode connected on the backside of the sample. Since the variance of resistivity as a function of depth is of high interest, cross sections of the samples will be examined.
2 Background

2.1 Material

2.1.1 Compound semiconductors

Many compound semiconductors, for instance the III-V material gallium arsenide (GaAs), have a lattice structure called “zincblende” which is basically a mixture of two face-centered cubic structures which overlap by a quarter of the lattice constant, \( a \), in all three dimensions, as seen in Figure 2.1 below. This way, again using GaAs as an example, every gallium atom is surrounded by four equidistant arsenic atoms in a tetrahedral structure, where the gallium is located in the center and the arsenic atoms are located in the corners [3]. Further on every arsenic atom is surrounded by four equidistant gallium atoms in the same way and this pattern continues all through the whole crystal.

![Figure 2.1 Conventional unit cell of the zincblende crystal structure [3].](image)

A difference between compound semiconductors and an elemental semiconductor such as silicon is that in compound semiconductors highly resistive regions can be created fairly simple by bombarding the substrate with ions to form carrier compensating defects [4](deep-level traps), see section 2.1.3 and 2.4. In Si, the damage formed by the incoming ions anneals by itself to a large extent.

2.1.1.1 Doping

In silicon based semiconductor devices, when an n- or p-doped region is desired, one simply substitutes either a donor (group V) material for n-type or an acceptor (group III) material for p-type. This is because the group III atoms will “absorb” an electron from the surrounding Si (group IV) atoms when bound due to the fact that group III material has only three valence electrons while Si has four. Every group V atom will submit an electron, since group V material has five valence electrons and Si has four, when bound to the surrounding Si lattice.

In III-V compound semiconductor devices, however, the procedure is not the same. This is because here the same doping atom, Si for instance, could be used either as a donor or as an acceptor. This property of Si in GaAs is referred to as amphoteric dopant. The decisive fact is whether the doping atoms occupy group III or group V lattice sites. If the group IV doping atoms occupy lattice sites previously occupied by group III atoms the atoms will function as donors, and in the same way the atoms will work as acceptors if they occupy lattice sites previously occupied by group V atoms. Both crystal orientation and growth conditions are factors that influence which lattice sites will be occupied by the doping atoms [5]. The crystal orientation is of importance since the doping atoms are often introduced during epitaxial growth. Depending on the crystal orientation, the surface where the dopant atoms will be incorporated will be different, i.e. certain orientations encourage the
doping atoms to occupy certain lattice sites. In the case of (100) oriented GaAs surfaces, for instance, the Si atoms will occupy Ga lattice sites due to the As excess at the surface, and in the case of (111) oriented GaAs, Si will substitute As atoms due to the fact that the As atoms are more weakly bonded at the surface than the Ga atoms. Figure 2.2 below shows a (n11) oriented GaAs surface which is a combination of both (100) and (111) surfaces.

This method of doping is referred to as “amphoteric doping”.

![Atomic arrangement of the (n11)-oriented surface](image)

Figure 2.2 Atomic arrangement of the (n11)-oriented surface [5].

### 2.1.1.2 Band-Gap engineering

Depending on which application the compound semiconductor is intended for and which properties are needed, custom band-gap energies are desired. For instance, the wavelength of light emitting semiconductors (LEDs, VCSELs etc.) proportionally relates to the actual band-gap of the material [6]. Custom band-gap energies can be realized by carefully choosing the elements of which the lattice will be composed of (see Figure 2.3 below). This method of modifying the compound semiconductor’s band-gap to the desired energy is referred to as “band-gap engineering”. Even though it sounds simple, the whole process is rather complicated and much research is conducted in this matter. When choosing the elements to be included in the lattice of the active region of the device one has to make sure that this lattice is compatible with the bulk material, i.e., their lattice constants should be equal, or very similar. This is to minimize the number of dislocations and other crystalline defects which could negatively affect the performance of the device.

![Band-gap energies of common III-V semiconductor materials and their lattice constants](image)

Figure 2.3 Band-gap energies of common III-V semiconductor materials and their lattice constants [7]. AlAs and GaAs are marked in the picture.
A common choice of material in the active region of a LED or semiconductor laser is Al$_x$Ga$_{1-x}$As grown on GaAs, which is possible because the lattice constants of GaAs and AlAs are almost identical, as can be seen in figure 2.3 above. Also by varying the concentration (x) of Al in the Al$_x$Ga$_{1-x}$As compound one can carefully modify the bang-gap, since there is a relation between the two. This relation is defined as follows:

$$E_g(x) = (1.42 + 1.087x + 0.438x^2)eV \quad (2.1) [6]$$

where $E_g$ is the band-gap energy and $x$ is a variable composition coefficient.

What is not visible in Equation 2.1, however, is that for $x>0.43$ the band-gap becomes indirect [6], which is undesired for optical applications. The band-gap – composition relation is also shown graphically in Figure 2.4 below which shows $E_g$ versus composition for three compound semiconductor materials. The ability to modify the band-gap of III-V semiconductors makes it possible for instance to achieve almost continuously tuneable laser emission in the range of 600 nm - 1.6 µm [8].

![Figure 2.4 Band-gap energies of (Al$_x$Ga$_{1-x}$)$_{0.5}$In$_{0.5}$P and Al$_x$Ga$_{1-x}$As compounds [9].](image)

It is not only the band-gap energy that can be modified, but also the structure of the valence and conduction bands. This is important since for instance in III-V semiconductors there is a significant asymmetry between the heavy valence band mass and the light conduction band mass [10], which has a negative influence on laser applications. By using quantum confinement and deliberately inducing strain in the lattice this asymmetry can be strongly reduced as can be seen figure 2.5 below.
Figure 2.5 Yablonovitch and Kane [10] numerically calculated what the dispersion for heavy holes without band-structure engineering (dashed line) and what the heavy hole dispersion at the top of the engineered valence band (solid line, “HH1”) would look like. One can see that the engineered band structure is close to the ideal case (absolute symmetry with the conduction band).

2.1.2 Resistivity

Generally when discussing the ability to oppose the flow of electrical current, resistance and ohm’s law comes to mind.

\[
R = \frac{V}{I} \quad (2.2)
\]

R is resistance, V is voltage and I is the current. However, when a measure of how strongly a material opposes the flow of electric current, rather than a whole device, resistance is not an optimal measure. This is because resistance is not strictly material dependent – it also depends on the dimensions of the region measured. A better measure is resistivity, \( \rho \), which is dimension-independent.

The relation between resistance and resistivity is shown in Equation (2.3) below.

\[
R = \rho \frac{L}{W \cdot t} \quad (2.3)
\]

where R is resistance, \( \rho \) is resistivity, L is the length of the region, W is the width and t is the thickness. As seen in equation (2.2), \( \rho \) is strictly material dependent and is therefore a good parameter to compare different materials regarding their ability to oppose electrical current. The
unit for resistivity is Ωcm. This unit can easily be explained by the relation (2.2) above if one solves for ρ and makes a unit analysis. Since R is expressed in Ω and L,W and t are all expressed in cm, the unit for ρ will be $\frac{2 \text{cm}^2}{\text{cm}} = \Omega \text{cm}$.

The resistivity in semiconductor materials varies within a vast range depending on doping and material. The resistivity in semiconductors can actually vary from $\sim 10^{-4}$ Ωcm (for highly doped materials), which is similar to the resistivity of metals, to $\sim 10^6$ Ωcm (for undoped and implant isolated materials) which is considered semi-insulating. Accordingly, the resistivity in semiconductor material has a variance of around 10 orders of magnitude. This high a variance cannot be matched by many other parameters.

Another commonly used parameter is the sheet resistance, $R_s$, which is defined as the resistivity divided by the thickness, or

$$ R = R_s \cdot \frac{L}{W} \quad (2.4) $$

where R is resistance, $R_s$ is sheet resistance L is length of the material and W is the width of the material. The unit of $R_s$ is Ω (since $\frac{L}{W}$ is unitless), but $R_s$ is generally expressed as Ω/□ (“ohm per square”) to emphasize that it gives a measure of the resistance of a square (W=L) [11], rather than just resistance.

A fourth parameter used for current restriction is spreading resistance, $R_{sp}$, which is defined as

$$ R_{sp} = \frac{\rho}{4\pi r} \quad (2.5) $$

where $\rho$ is the local resistivity of the measured region when the current is confined to a very small area and r is the radius of the contact tip. This type of measurement is typically performed when very small regions are to be examined, or when high resolution of resistivity fluctuations is desired. For this measurement a Scanning Spreading Resistance Microscopy (SSRM) can be used which carefully scans the sample and records the spreading resistance.

### 2.1.3 Deep-level traps

Deep-level traps are additional energy states between the valence and the conduction band in which charge carriers are trapped [1]. The reason it is called “deep” is because it is referring to the high amount of energy that is needed for a trapped charge carrier to escape to either the valence or the conduction band. Deep-levels should not be confused with “shallow levels”, which are energy levels situated close to the conduction or the valance band edges. These shallow levels are formed as doping impurities ionize and are utilized to control the concentration of change carriers [3].

Generally in semiconductor processing deep-level traps are considered an undesirable electronic defect because the traps compensate the charge carriers by allowing a location where holes and electrons can recombine, which results in lower conductivity. But in implantation isolation the traps’ compensating ability is, on the contrary, much appreciated since high resistivity is desired. Traps situated mid-gap are preferred because the probability of finding a hole and the probability of finding an electron are both high.
2.2 Implantation isolation and stopping theory

The technique “implantation isolation” utilizes the physical interactions between incoming energetic ions and bound atoms in the lattice of a compound semiconductor. The random collisions lead to displacements of the bound lattice atoms and, for sufficiently high doses, the lattice becomes so damaged that compensation occurs, i.e. electrically isolating. For very high doses the material can even turn amorphous.

2.2.1 Electronic stopping

During ion implantation isolation ions of certain energy penetrate the surface of the material. Initially the ions are mostly slowed down by inelastic collisions with bound electrons in the material. The energy loss of the penetrating ions is due to excitation when electrons enter higher energy states and ionization when electrons receive enough energy to leave their orbits of the lattice atoms [12]. This phenomenon is referred to as “electronic stopping”. Apart from ionization and excitation events the electronic stopping reduces the speed of incoming ions by the creation of a drag force on the ions. This drag is due to the realignments of the valence electrons in order to create a dipole around the ion to minimize the overall electric field [13]. This phenomenon can be compared to a moving particle inside a viscous liquid. An important fact here is that electronic stopping does not cause any displacement of atoms in the lattice and the deviation of the penetrating ion from its original direction is small.

2.2.2 Nuclear stopping

As the ions slow down, mostly due to electronic stopping, elastic collisions between screened nuclei become more frequent. During this type of collisions, a large part of the kinetic energy of the penetrating ion is transferred to the nucleus, or lattice atom, leading to displacement of lattice atoms and the creation of deep-level, carrier compensating defects (“deep-level traps”) [12]. These interactions are referred to as “nuclear stopping”.

The lattice atom recently involved in elastic collisions with incoming ions move with a velocity due to the absorbed kinetic energy and may therefore be able to cause additional collisions with other lattice atoms producing a chain reaction. This is schematically shown in Figure 2.6 below. As the amount of kinetic energy transferred in the collisions of moving target atoms decrease the cascade will eventually end.

![Figure 2.6 Schematic illustration of a collision cascade caused by an incoming ion](14).
2.2.3 Ion energy dependence

When comparing the two stopping mechanisms by the stopping power, or energy loss per unit path length, as a function of ion energy (see Figure 2.7 below) one clearly sees a different trend for the two. For high energies, \( E \gtrsim 10^5 \) eV, the electronic stopping significantly dominates while for lower energies, \( E \lesssim 10^4 \) eV, the nuclear stopping is more powerful than the electronic. Overall, the electronic stopping dominates the loss and only a few percent of the kinetic energy is transferred to the target nuclei, for ions with energies higher than MeV.

![Figure 2.7](image)

Figure 2.7 Relative energy loss, due to electronic (red) and nuclear (green) stopping processes, as a function of ion energy for oxygen ions implanted in a GaAs substrate. The data used for this graph was generated by SRIM calculations [15].

Graphs of stopping powers versus ion energy, as the figure above, can also be used to visualize which stopping power dominates at which depth, since the incoming ions have high energies as they penetrate the surface of the substrate and then lose energy as they penetrate deeper. Hence electronic stopping dominates at shallow depths and nuclear stopping is more important at deeper depths, for incoming ion energies above some 100 keV.

The reason why electronic stopping is more common initially as the ions enter the substrate is that the probability that the incoming ions will collide with the nucleus of an lattice atom is very small due to the fact that only a fraction of the atom’s “hit area”, or cross section, consist of the nucleus – the significantly larger part of its cross section consists of electron gas. And also the overall cross section of an incoming ion is very small due to its lack of electrons. But as the ions penetrate deeper into the substrate and lose kinetic energy along the way, allowing for longer interaction times between the ions and substrate particles, electrons start to accumulate on the incoming highly charged ions, eventually neutralizing them into atoms. The incoming atoms or lowly charged ions now have significantly bigger cross section than during their earlier highly charged form, causing the probability of incoming atom - bound atom collisions (nuclear stopping) to drastically increase.
2.2.4 Range

When discussing the range of the implanted ions a common term is the projected range, $R_p$, which is defined as the projection of the range in the direction of the incoming energetic ions [12]. Since the stopping process is stochastic and not all ions experience the exact same stopping forces, nor deflect at the same angle in collisions, all ions will not end up in the same place. This leads to a certain spread in $R_p$. This spread is defined as longitudinal straggle of the projected range, $\Delta R_p$, and a lateral straggle of the projected range, $\Delta R_{pl}$. Figure 2.8 below shows a plot of projected range, longitudinal and lateral straggle as a function of ion energy for oxygen ions implanted in GaAs.

![Projected range, longitudinal straggle and lateral straggle as a function of ion energy for oxygen ions implanted in GaAs](image)

From Figure 2.9 below it can also be seen that the damage profile is shallower than the implanted ion profile itself. This needs to be kept in mind when determining the implantation energy in order to achieve the desired depth of the isolating region. Also, when a thicker isolating region is desired the use of several ion energies should be considered, since the damage profile of a single energy may be too narrow and not homogeneous with depth [16]. Figure 2.10 below gives an example of a multi-energy implantation isolation scheme and the difference in ion (a) and damage (b) distributions.

![Ion and damage profiles for 100 keV protons in GaAs](image)
Figure 2.10 (a) Ion distribution for a multi-energy oxygen implant scheme in GaAs: $5 \times 10^{12} \text{cm}^{-2}$ at 40 keV, $6 \times 10^{12} \text{cm}^{-2}$ at 100 keV, $7 \times 10^{12} \text{cm}^{-2}$ at 200 keV and $8 \times 10^{12} \text{cm}^{-2}$ at 400 keV. (b) Damage distributions for the same implantation scheme [12].
3 Experimental

3.1 Sample preparation

3.1.1 Samples

For this work two different kinds of GaAs based wafers were used. One version is a Vertical Cavity Surface Emitting Laser (VCSEL) wafer which consists of two Distributed Bragg Reflector structures (DBRs), with an intermediate GaAs region containing three InGaAs quantum wells, on top of the GaAs bulk. Throughout this thesis this structure will be referred to as the “VCSEL structure”. Figure 3.1 below shows an SSRM scan of the VCSEL structure where one can clearly distinguish the DBRs. The implantation isolation of the VCSEL structure is of most interest since a detailed knowledge of how ion bombardment affects the actual DBR structures is desired.

The other version of wafer, which from now will be referred to as the “QW structure”, consists of a similar structure as the GaAs quantum well region in the VCSEL structure, but is a bit thicker (400 nm instead of ~ 300 nm) and lacks both DBR structures. Hence, this wafer only consists of a 400 nm quantum well region on the top of the GaAs bulk. This makes it ideal to use as a marker for how a sharp edge is achieved when the wafer has been cleaved, which is one of the major problems with cross sectional SSRM. This is controlled by viewing the cross section in the SSRM to confirm that the 400 nm region at the very edge is seen, i.e., the edge of the cut is sharp enough and no severe chipping has occurred. The QW structure also serves a second purpose as a comparison on how the effect of the ion implantation differs in the DBR regions and in the GaAs bulk. This is because the ions cannot reach high enough energy in the implanter to penetrate deep enough in the VCSEL (for further information see Section 3.1.4). Figure 3.2 below shows an SSRM scan of the QW structure where one can clearly see the strict line at the interface between the QW region and the GaAs bulk.

Figure 3.1 15 µm SSRM cross-section scan of the unimplanted VCSEL structure.

Figure 3.2 4 µm SSRM cross-section scan of the unimplanted quantum well structure.
3.1.2 Ion implantation
Ion implantation is a very common method for doping semiconductor materials since the doping profile is easily controlled compared to dopant diffusion methods. The very same technique can be used to bombard material with ions to electrically isolate them [2]. An important distinction between using ion implantation for doping and for isolation is the choice of ion. This is because the ions have different tasks once they are implanted inside the material depending on if the ions are implanted to isolate or to dope the substrate. Ions intended to dope the substrate should occupy substitutional sites in the lattice [11],[3], and depending on whether n- or p-type doping is desired, to contribute with an electron or a hole. This can be achieved by implanting donor atoms which donate an electron while bonding to the surrounding lattice atoms, or by implanting acceptor atoms which absorb an electron from the surrounding bonds causing a hole to form. Whereas in implantation isolation the ions are chosen to physically damage the lattice in order to cause deep levels to form. The ions used for this should not be electrically active by themselves.

3.1.2.1 Principle
An ion source, where a selected material is ionized in order to achieve ions of the desired element, is used. The ionization is typically realized by vaporizing a solid or using a gaseous source which then is ionized using energetic electrons from a hot filament or plasma discharge [13]. Once the ions are extracted they are led into a magnetic separator. This device is needed since the ion source will not only produce ions of one specific type but ions of several types and isotopes. The magnetic separator is utilizing the relation

\[
\frac{m \cdot v^2}{r} = q \cdot \vec{v} \times \vec{B}
\]

(3.1)

where \( m \) is the mass of the ion (kg), \( v \) is the velocity of the ion (m/s), \( r \) is the radius of the ion’s path (m), \( q \) is the electric charge of the ion (C) and \( \vec{B} \) is the magnetic field perpendicular to the ion’s path (T).

The circular path inside the magnetic separator ends with a narrow slit in order to only let the particles of the desired mass/charge ratio to proceed. This is possible due to the fact that particles which do not possess the desired values for these attributes will simply obtain a different radius of the circular path than the particles that do, causing them to hit the wall instead of passing through the slit, see Figure 3.3 below.

![Figure 3.3 Schematic overview of an ion implanter [17]](image-url)
Since the whole ion source mechanism and the magnetic separator are located on a high positive voltage platform the positive ions are then accelerated toward the substrate due to the voltage difference. By adjusting the voltage of the platform one can control the energy of the ions to be implanted. The machine used for this particular research was able reach a maximum of 330 kV, i.e. the maximum energy for a “+1” ion was 330 keV (660 keV for a “+2” ion).

The accelerated ion beam is then focused before entering a “neutral trap” which traps particles which are not electrically charged. This is necessary due to the fact that some particle neutralization may occur during the acceleration process [13]. To trap the uncharged particles the ion beam is slightly bent using electrostatic force, which does not affect the neutralized particles causing them to continue a linear path and hit the trap, while the charged particles continue further on to the scan plates and finally to the substrate, penetrating into its lattice.

In order to be able to control the amount of ions (the dose) “Faraday’s cups” are used to measure the current due to the flow of charged particles. The information from the faradays cups is then used to calculate the actual dose of ions hitting the substrate material. This is done by utilizing the relation

\[
Dose = \frac{1}{A \cdot q} \int I \cdot dt \quad (3.2)
\]

were A is the implanted area, I is the current due to the ion beam, q is the charge of each ion and t is the integration time.

In order to achieve a desired shape (laterally) of the doping profile the substrate is selectively covered with photoresist (using photolithography) which cannot be penetrated by the ion beam. This is needed since the scan plates only make sure the ion beam scans the whole surface homogenously.

### 3.1.3 Simulation

Before doing any implantations several simulations were performed in order to decide which implantation energy and dose to use. Using a simulation tool called SRIM [15], a table showing the relation between the energy of the incoming ions and their depth of penetration (projected range, \(R_p\)) was generated. Below is a Figure 3.4 showing the relation using the SRIM table.

![Figure 3.4 Simulation data showing the relationship between projected range and energy of incoming ions.](image)

Figure 3.4 Simulation data showing the relationship between projected range and energy of incoming ions.
However, the depth of penetration for the ions is not of as much importance as the depth of the actual damage and the two distributions differ in depth, as mentioned in Section 2.3.4. Therefore, simulations showing both the ion – and vacancy distributions were performed. In Figure 3.5 below, showing ion distribution (red), vacancies due to ion collisions (blue) and vacancies due to recoils (green) versus depth, one can see that there is a difference in depth of penetration for the implanted ions and the actual lattice damage (vacancies) distributions.

3.1.4 Ion implantation of the wafers
For the implantation of the different wafer types each wafer was cleaved into small square pieces with an area of roughly 1 cm$^2$. Each of these squares was then marked on the backside and put in small plastic boxed marked in the same manner.

All ion implantations were performed at “Ångströmlaboratoriet”, located at Uppsala University in Sweden. A drawback of the equipment used for the ion implantation is that the maximum voltage is 330 kV, meaning a maximum of 660 keV for He$^{2+}$ and only 330 keV for He$^+$ is achievable. This means that it is only possible to implant ions in the upper half of the top DBR in the VCSEL wafer.

For the first implantation the samples were placed two by two in the target chamber in order to get two samples for each dose and energy.

Table 3.1 on the next page is showing the implantation parameters used for the first implantation.
Table 3.1 Implantation parameters for the first implantation.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wafer type</th>
<th>Ion energy(keV)</th>
<th>Ion dose(cm$^2$)</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>VCSEL</td>
<td>660</td>
<td>1\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>1.2</td>
<td>VCSEL</td>
<td>660</td>
<td>1\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
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<td>VCSEL</td>
<td>660</td>
<td>8\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
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<td>8\cdot10^{14}</td>
<td>He$^{2+}$</td>
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<td>VCSEL</td>
<td>330</td>
<td>7\cdot10^{15}</td>
<td>He$^+$</td>
</tr>
</tbody>
</table>

For the second implantation the samples were placed in groups if three, one QW structure and two VCSEL structures for each dose and energy. The QW structures were used to investigate if there were any differences regarding, for instance, projected range or spreading resistance between the QW and VCSEL structures.

Table 3.2 below is showing the implantation parameters used for the second implantation.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wafer type</th>
<th>Ion energy(keV)</th>
<th>Ion dose(cm$^2$)</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>VCSEL</td>
<td>660</td>
<td>7\cdot10^{13}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>T1</td>
<td>QW</td>
<td>660</td>
<td>7\cdot10^{13}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>V1</td>
<td>VCSEL</td>
<td>660</td>
<td>7\cdot10^{13}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>2.2</td>
<td>VCSEL</td>
<td>660</td>
<td>2\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>T2</td>
<td>QW</td>
<td>660</td>
<td>2\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>V2</td>
<td>VCSEL</td>
<td>660</td>
<td>2\cdot10^{14}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>2.3</td>
<td>VCSEL</td>
<td>660</td>
<td>1\cdot10^{15}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>T3</td>
<td>QW</td>
<td>660</td>
<td>1\cdot10^{15}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>V3</td>
<td>VCSEL</td>
<td>660</td>
<td>1\cdot10^{15}</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>2.4</td>
<td>VCSEL</td>
<td>330</td>
<td>5\cdot10^{15}</td>
<td>He$^+$</td>
</tr>
<tr>
<td>T4</td>
<td>QW</td>
<td>330</td>
<td>5\cdot10^{15}</td>
<td>He$^+$</td>
</tr>
<tr>
<td>V4</td>
<td>VCSEL</td>
<td>330</td>
<td>5\cdot10^{15}</td>
<td>He$^+$</td>
</tr>
<tr>
<td>2.5</td>
<td>VCSEL</td>
<td>330</td>
<td>1\cdot10^{16}</td>
<td>He$^+$</td>
</tr>
<tr>
<td>T5</td>
<td>QW</td>
<td>330</td>
<td>1\cdot10^{16}</td>
<td>He$^+$</td>
</tr>
<tr>
<td>V5</td>
<td>VCSEL</td>
<td>330</td>
<td>1\cdot10^{16}</td>
<td>He$^+$</td>
</tr>
</tbody>
</table>

Table 3.2 Implantation parameters for the second implantation.

For the third implantation hydrogen ions were used instead if helium ions in order to compare possible differences.

Table 3.3 below is showing the implantation parameters used for the third implantation.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wafer type</th>
<th>Ion energy(keV)</th>
<th>Ion dose(cm$^2$)</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>VCSEL</td>
<td>330</td>
<td>8\cdot10^{15}</td>
<td>H$^+$</td>
</tr>
<tr>
<td>T6</td>
<td>QW</td>
<td>330</td>
<td>8\cdot10^{15}</td>
<td>H$^+$</td>
</tr>
<tr>
<td>V6</td>
<td>VCSEL</td>
<td>330</td>
<td>8\cdot10^{15}</td>
<td>H$^+$</td>
</tr>
</tbody>
</table>

Table 3.3 Implantation parameters for the third implantation.
3.2 Scanning Spreading Resistance Microscopy (SSRM)

For monitoring the damage in the material caused by the implanted ions a scanning spreading resistance microscope (Digital Instruments Dimension 3100) was used (see Figure 3.6 below). The method is based on the more known Atomic Force Microscopy (AFM) which scans the surface of the substrate and registers the height and typography by the use of piezoelectric crystals.

![Digital Instruments Dimension 3100 SSRM machine used for this work.](image)

3.2.1 Principle

The principle of AFM is to acquire a view of the topography of the sample’s surface. This is realized by letting a probe with a very sharp tip raster the surface with a constant pressure (contact mode), by oscillating the probe and only allowing it to “tap” the sample’s surface for a short time for each oscillation (tapping mode) or by placing the tip close enough to the sample to register van der Waals and electrostatic forces between the sample and the tip (non-contact mode). In order to manoeuvre the probe with the required accuracy piezoelectric crystals are used both for scanning along the x- and y-axes and also for adjustments along the z-axis. To register the z-position of the probe a laser is pointed at the probe’s backside. The laser is then reflected onto a photodetector, which can be seen in Figure 3.7 on the next page.
Figure 3.7 Schematic overview of the principle behind AFM/SSRM. The blue arrows represent spreading current due to the biasing during SSRM.

The difference between AFM and SSRM is that during SSRM the sample is biased and an electrode is attached to the conductive scanning probe. By measuring and registering the current through the probe the *spreading resistance* (see Section 2.1.2) for each measurement point can be measured.
3.2.2 Calculations

Typically, SSRM is a qualitative technique, requiring calibration of the output with samples of known resistivity. Nevertheless, the theory is that the output from the SSRM states the voltage applied by the SSRM to keep the current constant. The change of one volt here corresponds to a change of one order of magnitude of the total resistance (spreading resistance, contact resistance and bulk resistance altogether).

The relation between output voltage and input current is:

\[ V_{out} = \log \left( \frac{10^6}{V_{bias}} \right), \quad V_{bias} > 0 \] (3.3a)

\[ V_{out} = -\log \left( \frac{10^6}{V_{bias}} \right), \quad V_{bias} < 0 \] (3.3b)

Where \( V_{out} \) is the output voltage, \( I \) is the input current and \( V_{bias} \) is the bias voltage of the substrate. Now there are two ways to convert this into the total resistance (\( R_{SSRM} \)); either by using the transfer curve shown in Figure 3.8 on the next page or by rearranging (3.3) into:

\[ R_{SSRM} = \frac{V_{bias}}{I} = \frac{10^6}{10^{V_{out}}}, \quad V_{bias} > 0 \] (3.4a)

\[ R_{SSRM} = \frac{V_{bias}}{I} = \frac{10^6}{10^{-V_{out}}}, \quad V_{bias} < 0 \] (3.4b)

![Figure 3.8 Transfer curve to convert the output voltage into resistance.](image)

This relation can be utilized to directly convert the output of the SSRM machine into the total resistance, \( R_{SSRM} \). Since the spreading resistance is of more interest some calculations are needed to convert the total resistance into spreading resistance. The total resistance is defined as

\[ R_{SSRM} = R_{contact} + R_{spread} + R_{bulk} \] (3.5)

Both the \( R_{bulk} \) and \( R_{contact} \) can be approximated as constant, since the measured area is very small and homogenous. This gives a new relation:
\[ R_{SSRM} = R_{\text{spread}} + R_{\text{constant}} \quad (3.6) \]

where \( R_{\text{constant}} = R_{\text{bulk}} + R_{\text{contact}} \quad (3.7) \)

Typically \( R_{\text{spread}} \gg R_{\text{constant}} \) which means one can do the approximation:

\[ R_{SSRM} \approx R_{\text{spread}} \quad (3.8) \]

By combining Equation (3.8) and (3.4a) an equation to convert the output voltage, \( V_{\text{out}} \), into spreading resistance, \( R_{\text{spread}} \), is achieved:

\[ R_{\text{spread}} \approx \frac{10^6}{10^6 V_{\text{out}}} \cdot V_{\text{bias}} > 0 \quad (3.9) \]

To convert the spreading resistance, \( R_{\text{spread}} \), into resistivity the relation:

\[ R_{\text{spread}} = \frac{\rho}{4a} \quad (3.10) \]

can be utilized, where \( \rho \) is the resistivity of the material in the measured region and \( a \) is the radius of the SSRM probe (here \( a \approx 30 \text{ nm} \)). By rearranging Equation (3.10) the relation:

\[ \rho = R_{\text{spread}} \cdot 4a \quad (3.11) \]

is achieved. Also, when the resistivity has been calculated one can use a chart of resistivity versus doping, like the one in Figure 3.9 on the next page, in order to get an approximate value of the local doping.

![Figure 3.9 Resistivity versus doping concentration for GaAs, Ge and GaP [18].](image)
3.3 Thermal annealing

For normal implantation doping the purpose of annealing is to remove the lattice damage caused by implantation of ions and also to activate them to function as dopants. By activation of dopants one is referring to the fact that doping atoms need to be ionized by occupying substitutional sites rather than interstitial ones to be electrically active. The annealing also contributes in restoring the damaged lattice’s carrier mobility [13].

In implant isolation, annealing is mainly used to assure that the isolating region will endure high operating temperatures and not be degraded by long term operation at elevated temperatures.

Usually annealing is done in a furnace which can hold several wafers at a time. A downside with furnace annealing is that it takes some time (several minutes) to successfully anneal the wafers, which leaves time for the implanted dopants to diffuse causing the dopant profile to change. A solution to this issue is to use rapid thermal annealing (RTA) instead. By heating a wafer very rapidly to the desired anneal temperature and then cooling it one shortens the time for diffusing significantly.

For this thesis a vacuum furnace was used to see when/if material anneals, See Figure 3.10 below. The samples are placed on a carrier inside the vacuum chamber. Then a glass disc is placed over the opening of the vacuum chamber and a mechanical pump together with a turbo is creating a vacuum. When a low enough pressure is achieved the cart is loaded, through a metal pipe, inside the furnace.

![Figure 3.10 The vacuum furnace used for the anneals in this thesis. The furnace itself is located to the left in the picture and the vacuum chamber is located to the right.](image-url)
4 Results

4.1 SRIM simulations

The measured SSRM output was compared to the calculated vacancy distribution data from SRIM multiplied with the used He$^{2+}$/He$^+$ doses. In this way the expected vacancy distribution for each ion dose could be plotted. In Figure 4.1 below this is shown for two He energies, 330 keV (4.1 a) and 660 keV (4.1 b).

![Vacancy distribution for different He doses, 330 keV](image)

Figure 4.1a Vacancy distributions for different 330 keV helium doses versus depth. The data was produced using SRIM simulations.

![Vacancy distribution for different He doses, 660 keV](image)

Figure 4.1b Vacancy distributions for different 660 keV helium doses versus depth. The data was produced using SRIM simulations.
4.2 Measurements before annealing

Once the implantations of all samples were done each squared sample was cleaved in the middle in order to get a fresh surface for cross sectional SSRM measurements.

In this section graphical presentations and data plots of the output of the SSRM machine for some of the implantation settings are presented. Even though the graphs do not present an absolute value of resistivity one can still clearly see the effect the implantations have had on the structures’ resistivity.

4.2.1 SSRM cross sectional 2D area scans

In order to get an overview of the effect of the different implantation doses a compilation consisting of a stripe of each SSRM output aligned next to each other was done, see Figure 4.2 and table 4.1 below. The different pictures are placed so that the easily visible quantum well GaAs region in-between the upper and lower DBRs of each picture align vertically. The reason why the middle GaAs region was used for alignment, rather than just using the edge of the structures, is that there are some artefacts in the SSRM output close to the edge, which is further discussed in Section 5.1. These artefacts can be seen the figure as lines and blurry dots occurring to the left of the edge – where the tip is scanning outside of the sample. One can also see that the bottom GaAs regions align well, i.e. no scaling seem to have occurred.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dose [cm⁻²]</th>
<th>Energy [keV]</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>7·10¹³</td>
<td>660</td>
<td>He²⁺</td>
</tr>
<tr>
<td>b</td>
<td>2·10¹⁴</td>
<td>660</td>
<td>He²⁺</td>
</tr>
<tr>
<td>c</td>
<td>8·10¹⁴</td>
<td>660</td>
<td>He²⁺</td>
</tr>
<tr>
<td>d</td>
<td>1·10¹⁵</td>
<td>660</td>
<td>He²⁺</td>
</tr>
<tr>
<td>e</td>
<td>5·10¹⁵</td>
<td>330</td>
<td>He⁺</td>
</tr>
<tr>
<td>f</td>
<td>7·10¹⁵</td>
<td>330</td>
<td>He⁺</td>
</tr>
<tr>
<td>g</td>
<td>1·10¹⁶</td>
<td>330</td>
<td>He⁺</td>
</tr>
<tr>
<td>h</td>
<td>8·10¹⁵</td>
<td>330</td>
<td>H⁺</td>
</tr>
</tbody>
</table>

Table 4.1 Parameters for the different samples measured

Figure 4.2 Compilation of 15 µm SSRM output for the different implantation doses. The edge of the sample located to the left and the depth increases to the right in the picture. Simulated depths by SRIM are marked with red (330 keV) and orange (660keV). Darker regions represent higher resistivity.
4.2.2 SSRM 1D line data
To get a more detailed view of the magnitude of the resistivity change due to the implanted ions 1D line data from the SSRM was also used. This Section contains plots of these 1D line data for selected implant doses. The plots are basically cross sections of the images in Figure 4.2 above, where only one data line is used. A typical graph of the 1D line data from the SSRM scan can be seen in Figure 4.3a below.

![SSRM output](image)

**Figure 4.3** Example of (a) unmodified 1D line data from an SSRM scan and (b) the modified version of the same data. Output voltage versus depth. Higher voltage indicates lower resistivity (ref. Section 3.3.1 “Calculations”)

Naturally, the artefacts mentioned in Section 4.2.1 are also present in the 1D line data. Therefore, data to the left of the edge of the DBR structure (~5.2 µm from the GaAs quantum well region according to the growth recipe for the samples) were excluded. Also data to the right of the GaAs quantum well region were excluded since the interesting region for this work is only in the top DBR. Figure 4.3b above shows the graph of the modified version of the data used in Figure 4.3a.

In order to make sure no “true data” were accidentally removed due to the fact that there is an error margin for the SSRM machine in distance measurements, the periods of the DBR structure in the graph of modified data were counted and compared to the given specification for the samples.

4.2.2.1 660 keV He$^{2+}$ implantation
Figures 4.4-4.6 below show how the VCSEL structures are affected by the lower implanting doses, 7 · 10$^{13}$ and 1 · 10$^{15}$ cm$^{-2}$. For these doses He$^{2+}$ ions and 330 kV accelerating voltage were used, i.e. the incoming ions had a total kinetic energy of 660 keV. In Figure 4.4 and 4.5 one can clearly see how a highly resistive region of about 1.5 µm depth is created. In Figure 4.6, however, the resistive region is not as low as in the previous figure, and one can also see a different shape at the deepest part – the resistivity is decreased and at the deepest end of the region there is a “spike” of higher resistivity. Also, one notices that the damaged resistive region seems to be located slightly deeper inside the DBR structure as the dose increase.
Figure 4.4 1D line data of sample V1 (dose $7 \cdot 10^{13} \text{cm}^{-3}$, He$^{2+}$ ions, 660 keV). Output voltage versus depth. Higher voltage indicates lower resistivity (ref. Section 3.3.1 “Calculations”)

Figure 4.5 1D line data of sample V2 (dose $2 \cdot 10^{14} \text{cm}^{-3}$, He$^{2+}$ ions, 660 keV). Output voltage versus depth. Higher voltage indicates lower resistivity (ref. Section 3.3.1 “Calculations”)
Figure 4.6 1D line data of sample 2.3 (dose $1 \cdot 10^{15} \text{cm}^{-2}$, He$^{2+}$ ions, 660 keV). Output voltage versus depth. Higher voltage indicates lower resistivity (ref. Section 3.3.1 “Calculations”)

4.2.2.2 330 keV He$^+$ implantation

Looking at Figure 4.7 and 4.8 below one can see how the VCSEL structure is affected by one of the higher implanting doses, $7 \cdot 10^{15}$ and $1 \cdot 10^{16}$ cm$^{-2}$. For these high doses He$^+$ ions and 330 keV were used, i.e. the incoming ions had a total kinetic energy of 330 keV this time, compared to 660 keV for lower doses. This is because it is very time consuming to achieve enough He$^{2+}$ ions to perform implantations of these high doses.

A similar profile of the resistive region as in Figure 4.6 above is found in Figure 4.7 and 4.8 on the next page, only the resistivity is decreased more this time and the resistive region deeper inside the sample. Here the resistive region is much fainter at the shallower part and ends with a strong, narrow resistive part.
Figure 4.7 1D line data of sample #8 (dose $7 \times 10^{15} \text{cm}^{-3}$ He$^+$ ions, 330 keV). Output voltage versus depth. Higher voltage meaning lower resistivity (ref. Section 3.3.1 “Calculations”)

Figure 4.8 1D line data of sample 2.5 (dose $1 \times 10^{16} \text{cm}^{-3}$ He$^+$ ions, 330 keV). Output voltage versus depth. Higher voltage meaning lower resistivity (ref. Section 3.3.1 “Calculations”)

(modified SSRM output)

(modified SSRM output)
### 4.2.2.3 330 keV H⁺ implantation

One implantation with H⁺ ions was also done for comparison with the other He⁺/He²⁺ implantations. In Figure 4.8 below showing the output voltage of the SSRM as a function of distance (depth) one clearly sees how the output voltage drops significantly about 3.2 µm from the edge. One can also see that the voltage is decreased at the edge of the surface (to the left in the figure) and then slowly climbs towards the original value (~2.7 V) as the depth increases, until the big drop comes – i.e. same phenomena as in figure 4.6 and 4.7 above. The fact that the very narrow resistive region, seen for high helium doses, is also created by the H⁺ implantation rules out that it was created only because of some local defect in that particular AlGaAs/GaAs period, since it is now found at a different depth. It also rules out the possibility that this phenomenon is somehow linked to the choice of He⁺/He²⁺ implanting ion.

![Figure 4.8 1D line data of sample V6 (dose 8 \( \cdot 10^{15} \) cm\(^{-2}\), H⁺ ions, 330 keV). Output voltage versus depth. Higher voltage meaning lower resistivity (ref. Section 3.3.1 “Calculations”)](image-url)
4.2.3 Sweep Electron Microscope (SEM) images

A sweep electron microscope was also used as a comparison to the SSRM measurements. Figure 4.9 below shows four measurements of different samples with the depth of the damaged highly resistive areas marked in the images. The parameters for the measured samples are found in Table 4.2 below. The depths agree with the ones measured by SSRM and it was also observed for these images that the damaged resistive regions seem to be located deeper inside the DBR structure as the dose increase.

![SEM images of VCSEL structures](image)

Figure 4.9 Sweep electron microscope images of VCSEL structures implanted with doses shown in Table 4.2 below. The microscope’s depth measurements are included in the figure.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dose [cm$^{-2}$]</th>
<th>Energy [keV]</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>7\cdot10^{13}</td>
<td>660</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>b</td>
<td>1\cdot10^{15}</td>
<td>660</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>c</td>
<td>1\cdot10^{16}</td>
<td>330</td>
<td>He$^+$</td>
</tr>
<tr>
<td>d</td>
<td>8\cdot10^{15}</td>
<td>330</td>
<td>H$^+$</td>
</tr>
</tbody>
</table>

Table 4.2 Parameters for the different samples measured

4.2.4 Depth comparison with simulations

As can be seen in Table 4.3 below which shows the measured depth of the highly resistive regions and the depth calculated in SRIM for different doses and energies, the measured depths of the resistive regions do not agree well with the simulated values.

<table>
<thead>
<tr>
<th>Ion dose [cm$^{-2}$]</th>
<th>Energy [keV], Ion</th>
<th>Calculated depth (SRIM) [µm]</th>
<th>Measured depth (SSRM) [µm]</th>
<th>Measured depth (SEM) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 \cdot 10^{13}</td>
<td>660, He$^{2+}$</td>
<td>2.10</td>
<td>1.28</td>
<td>1.35</td>
</tr>
<tr>
<td>2 \cdot 10^{14}</td>
<td>660, He$^{2+}$</td>
<td>2.10</td>
<td>1.46</td>
<td>-</td>
</tr>
<tr>
<td>8 \cdot 10^{14}</td>
<td>660, He$^{2+}$</td>
<td>2.10</td>
<td>1.52</td>
<td>-</td>
</tr>
<tr>
<td>1 \cdot 10^{15}</td>
<td>660, He$^{2+}$</td>
<td>2.10</td>
<td>1.58</td>
<td>1.60</td>
</tr>
<tr>
<td>5 \cdot 10^{15}</td>
<td>330, He$^+$</td>
<td>1.24</td>
<td>1.93</td>
<td>-</td>
</tr>
<tr>
<td>7 \cdot 10^{15}</td>
<td>330, He$^+$</td>
<td>1.24</td>
<td>2.11</td>
<td>-</td>
</tr>
<tr>
<td>1 \cdot 10^{16}</td>
<td>330, He$^+$</td>
<td>1.24</td>
<td>2.05</td>
<td>2.00</td>
</tr>
<tr>
<td>8 \cdot 10^{15}</td>
<td>330, H$^+$</td>
<td>2.75</td>
<td>3.25</td>
<td>3.16</td>
</tr>
</tbody>
</table>

Table 4.3 calculated depth and actual depth for different ion doses and energies.
4.2.5. QW structures

SSRM measurements were also performed for the QW structures so see possible differences between the alternating AlGaAs/GaAs layers of the VCSEL structure and the pure GaAs of the QW structure regarding the created resistive region and its depth.

4.2.5.1 SSRM cross sectional 2D area scans

Looking at Figure 4.10 and table 4.4 below one notices that the resistive regions are deeper for the 330 keV implantations than for the 660 keV ones. One also notices that for doses from $1\times10^{15}$ to $1\times10^{16}$ cm$^{-2}$ (c-e in the Figure) the region created by the ion implantations seem brighter than the ones for lower doses, i.e. the regions have lower resistivity.

![SSRM measurements for the QW structure implanted with doses 7\times10^{13} - 1\times10^{16} cm^{-2}. The samples are aligned at the surface edge.](image)

<table>
<thead>
<tr>
<th>Picture #</th>
<th>Dose [cm$^{-2}$]</th>
<th>Energy [keV]</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$7\times10^{13}$</td>
<td>660</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>b</td>
<td>$2\times10^{14}$</td>
<td>660</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>c</td>
<td>$1\times10^{15}$</td>
<td>660</td>
<td>He$^{2+}$</td>
</tr>
<tr>
<td>d</td>
<td>$5\times10^{15}$</td>
<td>330</td>
<td>He$^+$</td>
</tr>
<tr>
<td>e</td>
<td>$1\times10^{16}$</td>
<td>330</td>
<td>He$^+$</td>
</tr>
</tbody>
</table>

Table 4.4 Parameters for the quantum well structure samples in Figure 4.9

4.2.5.2 SSRM 1D line data

Figure 4.11 below is showing the 1D line data of the SSRM scans of the QW structure implanted with doses $7\times10^{13}$ - $1\times10^{16}$. Since there is no distinct “depth marker” in the QW structures such as the DBR in the VCSEL structures, it is harder to identify where the actual edge is. For this reason the data is aligned at the steep voltage drop at around 1 µm depth in the figure. Not knowing exactly what data is true and what is artefact at the edge makes it hard to make good depth measurements. The approximate depths, however, seem to agree with the ones measured for the VCSEL structures (≈2.3 µm for the $7\times10^{13}$ - $1\times10^{15}$ cm$^{-2}$ 330 keV implantations and ≈1.7 µm for the $5\times10^{15}$ - $1\times10^{16}$ cm$^{-2}$ 660 keV ones).
Figure 4.11 SSRM 1D line data for the QW structure implanted with doses $7 \cdot 10^{13}$ - $1 \cdot 10^{16}$ cm$^{-2}$. The data is shifted in the y-axis to align the data by the signal from the GaAs bulk (4-10 µm on the x-axis).

### 4.3 Annealed samples

When all samples had been measured in the SSRM setup some samples were picked out for annealing. This was done to investigate how the highly resistive regions created by the ion implantations are affected by heat treatment. Three isochronal anneals with a time of 30 minutes and the temperatures; 330 °C, 350 °C and 380 °C respectively were performed, see Table 4.5 below.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Temperature (°C)</th>
<th>Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>330</td>
<td>30</td>
</tr>
<tr>
<td>V2</td>
<td>350</td>
<td>30</td>
</tr>
<tr>
<td>V2</td>
<td>380</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4.5 Parameters for the thermal treatment.

Since each sample had been cleaved into two pieces for the SSRM measurements it was possible to use each sample in two anneals. Samples V1 and V2 were chosen because they both had similar implantation dose ($7 \cdot 10^{13}$ and $2 \cdot 10^{14}$ cm$^{-2}$ respectively).
4.3.1 SSRM cross sectional 2D area scans

After the annealing the samples were again measured in the SSRM machine to investigate possible changes caused by the heat treatment. Figure 4.12 and 4.13 below show the pre and post anneal image outputs from the SSRM of the V1 and V2 samples. The parameters of the samples can be seen in Table 4.6 below.

![Graphical comparison between the unannealed and the annealed V1 sample (660 keV, 7·10^{13} \text{cm}^{-2}\text{He}^{2+})](image1)

![Graphical comparison between the unannealed and the annealed V2 sample (660 keV, 2·10^{14} \text{cm}^{-2}\text{He}^{2+})](image2)

<table>
<thead>
<tr>
<th>Picture #</th>
<th>Sample #</th>
<th>Temperature [°C]</th>
<th>Dose [cm^{-2}]</th>
<th>Energy [keV]</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>V1</td>
<td>Non-annealed</td>
<td>7·10^{13}</td>
<td>660</td>
<td>He^{2+}</td>
</tr>
<tr>
<td>1b</td>
<td>V1</td>
<td>330</td>
<td>7·10^{13}</td>
<td>660</td>
<td>He^{2+}</td>
</tr>
<tr>
<td>2a</td>
<td>V2</td>
<td>Non-annealed</td>
<td>2·10^{14}</td>
<td>660</td>
<td>He^{2+}</td>
</tr>
<tr>
<td>2b</td>
<td>V2</td>
<td>350</td>
<td>2·10^{14}</td>
<td>660</td>
<td>He^{2+}</td>
</tr>
<tr>
<td>2c</td>
<td>V2</td>
<td>380</td>
<td>2·10^{14}</td>
<td>660</td>
<td>He^{2+}</td>
</tr>
</tbody>
</table>

Table 4.6 Parameters for the samples in Figure 4.1 and 4.2

As seen in Figure 4.12 and 4.13 above the highly resistive regions seems to become less resistive as the samples are heated. Also the trend for the samples with low implantation dose indicate that for higher temperatures the width of the resistive regions may be reduced to a very narrow region of the same type as seen for the samples of higher implantation doses \(\gtrsim 1\cdot10^{15} \text{cm}^{-2}\), for instance sample #8 (Figure 4.7 in section 4.2.2.3).
4.3.2 SSRM 1D line data

When the data is plotted as a 1D line, the trend that the resistive regions become less resistive for higher annealing temperatures is even more evident. In Figures 4.14 and 4.15 below it can clearly be seen that the characteristic alternating high and low resistivity regions of the DBR structure is reappearing as the samples undergo heat treatment.

![SSRM output graph](image)

Figure 4.14 1D line data of sample V1 (dose $7\cdot10^{13}\text{ cm}^{-3}$, H$^+$ ions, 660 keV) untreated (green line) and after thermal treatment of 330˚C for 30 min (blue line). Output voltage versus depth. Some scaling of the data in the y-axis was performed in order to enhance visibility.

![SSRM output graph](image)

Figure 4.15 1D line data of sample V2 (dose $7\cdot10^{13}\text{ cm}^{-3}$, H$^+$ ions, 660 keV) untreated (blue line), after thermal treatment of 350˚C for 30 min (green line) and after thermal treatment of 380˚C for 30 min (red line). Output voltage versus depth. Some scaling of the data in the y-axis was performed in order to enhance visibility.

A difference between Figure 4.13 and 4.14 above is that the periods line up well in figure 4.13 while they do not in Figure 4.14. Possible reasons for this is further discussed in Section 5.2.1.1
4.4 Altering of the sample due to SSRM
Since the tip needs to be pressed with a high force against the sample, in order to establish a sufficiently good electrical contact, both the sample and the tip get damaged. The pressure of the tip can actually be several billion Pascal [19]. However, the strong force has some positive effects such as the high pressure allows the tip to penetrate native oxide layers which can be formed on the sample. Figure 4.16 below shows the cross-section of the VCSEL wafer after it has been scanned by the SSRM probe. One can clearly see how the oxide has been removed in the regions where the tip has rastered the sample.

![Image of VCSEL wafer with oxide removed](image)

Figure 4.16 Snap shot from an optical microscope showing the oxide removing effect from the rastering of the SSRM tip on the sample’s surface.

4.5 Limitations and sources of error
In this section a list of possible sources of error and other limitations which may have affected the results is presented.

- The VCSEL wafers could have “unknown” epitaxial layers on top of the VCSEL structure described in the text. This is due to the fact that the wafers provided were old and there was a risk that they may have been used for some testing involving growth of additional epitaxial layers on top of the original VCSEL structures.

- As the SSRM probe passes the edge of the sample it is difficult to distinguish “true data” from artefacts. This in combination with the possible additional epitaxial layers made it hard to interpret the data correctly at the edge.

- SSRM is a qualitative method which needs calibration measurements. It is recommended that SSRM should be used in combination with for instance SIMS in order to get a proper calibration and accuracy of the measurements [20],[21].

- Due to the fact that the tip of the SSRM probe is not spike shaped, but is rather cone shaped, the “side walls” of the tip will in fact touch the edge of the wafer when the actual tip has passed the edge and therefore cause artefacts. This is illustrated in Figure 4.17 on the next page.
The SSRM probe is approaching the edge.

The SSRM probe has reached the actual edge. From here on until the probe switches direction again there should be no contact between tip and sample.

As the SSRM probe passes the edge the “side walls” of it start to touch the edge of the wafer. This means that the SSRM receives a signal even though the actual tip is outside the wafer.

Figure 4.17 Schematic illustration of the movement of the SSRM probe at the edge of the sample. A possible source of artefacts of SSRM measurements is that a “faulty” signal is registered when the actual tip is outside the wafer but the side walls are touching (3).
5 Discussion

The results from the SSRM regarding the geometry of the sample can be trusted since the output agrees well with the specifications of the samples regarding sizes (see Section 5.2.1) and the individual layers of the DBRs are clearly visible. The SSRM method naturally has its limitations as well, which is discussed in section 5.3.

5.1 Resistivity – dose dependence

When one is comparing the different graphs for all doses one can see that initially the resistivity increases with dose for doses $7 \cdot 10^{13} \text{cm}^{-2}$ and $2 \cdot 10^{14} \text{cm}^{-2}$. Then, surprisingly, the characteristic alternating high and low resistivity regions of the DBR structure is visible again as the dose is increased further - and finally only a narrow highly resistive region is visible. The highly damaged resistive region between the surface and the narrow peak seems to recover with increasing dose. When this was seen in the first implantation batch suspicions that something went wrong during the implantation process arose, for instance a mix up of samples. However, as the second implantation batch shows the same phenomena the results have to be considered as real.

One explanation could be that the alternating layers of AlGaAs and GaAs in the DBR do not get severely damaged, i.e. the atoms from each layer do not get scattered to other layers, nor does the crystal structure itself get damaged by the incoming ions, even though many deep-level traps are introduced. As the dose increase the density of deep-level traps increase as well, eventually resulting in a high enough density of traps to allow electrons to jump from one trap to another – so called “hopping conductivity”[22]. Since the traps are naturally more distant from each other for lower densities hopping is less likely to occur between the traps for the lower ion doses. The big issue here, though, is why there still is a narrow region with high resistivity, comparable to an AlGaAs/GaAs period size-wise, left.

Another explanation could be that the higher ion doses have an annealing effect on the substrate caused by energy due to electronic stopping, ref. Section 2.3.1. This is also suggested by the results from the heat treatments of the samples. The heated samples showed a tendency to regain their conductive properties in the damaged region, except at the deepest end – similar to the samples implanted with high doses.

A third, highly speculative, explanation could be that there is some kind of gettering effect, or driving force for defect diffusion, for the higher ion doses which makes the material more conductive. This is plausible since the ion-beam induced gettering can be noted at depths of two to three times the projected range of the ions [23]. The motion of point defects could also be driven by the field gradients due to doping differences of the alternating layers in the DBR structure.
5.2 Depth of penetration

Another issue with the results is the fact that the highly resistive regions caused by implantations with lower energy (330 keV) actually seem to reach further into the structures than the regions created by implantations with higher energy (660 keV). Figure 5.1 below shows the SSRM data for some of the samples. One can see from the figure that the depths of the highly resistive regions seem to increase with the ion dose, rather than depending on the ion energy.

![SSRM output voltage versus depth for six implantation doses.](image)

Figure 5.1 SSRM output voltage versus depth for six implantation doses. Note that the graphs are both displaced and scaled in the y-axis (voltage) for better visibility. The focus of this graph should be in the 1-2.5 µm of depth area where the bottom of the highly resistive regions are located.

One should note that the GaAs active region, same as used for alignment in Section 4.2.1, is used in the same way here for alignment. The GaAs region is visible as the slope at about 5.2 µm of depth.

The strange behaviour with deeper damage peak for 330 keV than 660 keV He ions is still very confusing and no good explanation exist. To determine the actual depth of the implanted He secondary ion mass spectrometry (SIMS) measurements will be done.

5.2.1 Scaling

In order to make sure that the difference in depth of the highly resistive regions seen in Figure 5.1 above are not due to scaling or a shift of the x-axis (depth) caused by variance between different SSRM scans, another plot was done. This time, however, the data was not displaced in the y-axis allowing one to investigate whether the periods have the same length or not, i.e. to see if they overlap or not (see Figure 5.2 on the next page).
Figure 5.2 SSRM data for three ion doses plotted on top of each other to see that the periods of the DBR structure are of the same length, i.e. there is no scaling caused by variance between different SSRM scans.

As seen in Figure 5.2 above the periods align very well in the undamaged region (≥ 2.5 µm of depth) and scaling can therefore be ruled out.

5.2.1.1 Annealed samples
In the 1D line data for the annealed samples, however, there clearly is some scaling since the periods do not align well along the whole DBR structure, see Figure 5.3 below and 5.4 on the next page.

Figure 5.3 1D line data of sample V2 (7 \cdot 10^{13}\text{cm}^{-3}, \text{H}^+ \text{ions, 660 keV}) untreated (blue line), after thermal treatment of 350°C for 30 min (green line) and after thermal treatment of 380°C for 30 min (red line). Output voltage versus depth. Some scaling of the data in the y-axis was performed in order to enhance visibility. The data was aligned at the GaAs region as described in Section 4.2.1.
Figure 5.4 1D line data of sample V2 (dose $7 \times 10^{13} \text{cm}^{-2}$, H$^+$ ions, 660 keV) untreated (blue line), after thermal treatment of 350°C for 30 min (green line) and after thermal treatment of 380°C for 30 min (red line). Output voltage versus depth. Some scaling of the data in the y-axis was performed in order to enhance visibility. The data was aligned at the deep end of the resistive regions.

Since no scaling due to the SSRM was encountered for the other samples it is rather unlikely that that is the case here. A more plausible explanation is that the material has reacted to the thermal treatment – in this case by decreasing in size.

5.3 Conclusion

Since SSRM is a qualitative method it is hard to establish a quantitative correlation between measured resistivity data and simulated defects without further calibration measurements, for instance secondary ion mass spectrometry (SIMS). The SSRM measurements in this work only offers relative values of resistivity, i.e. no calculations of actual damage (vacancy distribution) created by the ion implantations could be performed.

Even though the periods in the DBR structures of the VCSEL offers a background pattern which aids depth identification and orientation, by allowing one to count the periods of known size and thereby attain the depth, the advanced doping profiles of each of the periods can also be a source of problem since the effect of the penetrating ions can be altered.

The 330 keV ions create highly resistive regions deeper inside the samples than the 660 keV ions do. The simulations show the opposite.

The damaged highly resistive regions fade as the ion dose is increased. This was also observed for the annealed samples – the damaged resistive regions become less resistive as the samples undergo thermal treatment.
6 Future aspects

To understand the mechanics behind the results attained in this work some additional measurements are needed. Secondary ions mass spectrometry (SIMS) measurements could be used to map out where the actual ions end up. This is needed since even though the methods used in this work (SSRM and SEM) show lattice damage and change in resistivity they give no indication on the ion distribution inside the samples. Furthermore, the SIMS measurements could also be used to calibrate the SSRM measurements which would allow the possibility to analyze quantitative values of resistivity and also to extract hole and electron concentrations. One would then be able to investigate the correlation between ion dose and, for instance damage, resistivity and carrier concentrations.

Also future comparisons of samples implanted with the same dose but different ion energies is suggested in order to conclude how different ion energies affect the eventual resistive region.

Further experiments with annealing are also suggested. The heat treatments in this work were all for 30 minutes and to further investigate the effect of annealing on these damaged regions additional annealing times are appreciated.

To eliminate some of the variations in the SSRM measurements future implantations could be performed with multiple doses in one sample. This would remove process of changing samples in the SSRM holder for each dose. In this way only one calibration would be needed for all doses in that particular sample.
Bibliography


