The manufacturing and characterization of GaAs/AlGaAs multiple quantumwell ridge waveguide lasers
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Manufacturing and Characterization of GaAs/AlGaAs Multiple Quantumwell Ridge Waveguide Lasers

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Abstract

In this study, the manufacturing process for GaAs/AlGaAs ridge waveguide lasers has been investigated. They are made with quantumwell structures produced by the Solid State Physics group of the Physics Department. Broad area and narrow ridge lasers have been produced and characterized. Also laser arrays and flared waveguide lasers have been manufactured and their performance has been measured.

A good technique for the inspection of layer structures has been found to be the oxidation of cleaved facets. The manufacturing process produces well functioning devices. However, some improvements of the etching of small ridges is desirable for deeper structures. Also the metallization of the back contact needs to be improved for better bonding. This way, laser chips can also be mounted on heatsinks. Further problems arise mainly with the breaking procedure resulting in poor mirror quality of quite a number of lasers.

With broad area lasers, the quantumwell structures give good results. Measurements show low internal absorption and transparency current densities. Also narrow ridge lasers perform very well with continuous operation. Threshold currents as low as 10.8 mA have been measured. Laser arrays show promising results. Problems due to geometrical inaccuracy can probably be solved by using a special light field mask and better cleaving of the laser chips. Of the flared waveguide lasers, especially the tapered versions seem to function well. With improvement of the cavity shape, better results are probably obtainable.

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1 Introduction

During the course of the year 1991/1992, the new laboratory of the Electronic Devices Group has become more and more completed and activities have been started. In the cleanroom several facilities are available for the processing of GaAs devices or will be in the near future. The GaAs research of the group embraces investigation of both electronic and optical devices.

Current developments in fibre optics offer new opportunities for telecommunication and data processing systems. An important part of the research to these systems is the development of high quality optical transmitters in the form of light emitting diodes and, more important, semiconductor lasers. Main points are properties such as stability, light output and lifetime which are ultimately determined by the physical and geometrical composition of the devices. Sufficient control of the technological aspects is therefore required.

In this study the manufacturing of GaAs/AlGaAs ridge waveguide lasers has been investigated. This type of laser allows flexible geometrical design and yields good performing devices. At first, a MOVPE grown double heterostructure was used as starting material. Later on however, the investigations have been concentrated on MBE grown multiple quantumwell structures provided by the Solid State Physics Group of the Physics Department. With these structures, lasers have been manufactured for measurement of the electrical and optical performance of the material. Furthermore, several kinds of lasers with different geometrical shapes have been produced and characterized including single ridge lasers and structures for higher light output such as laser arrays and flared waveguide lasers.

This report starts with an introduction on the principles of ridge waveguide lasers, followed by a discussion of several structure identification techniques. An inventory of the different steps of the manufacturing process is drawn up next, and finally the results of the characterization of the lasers are discussed.
2 Ridge waveguide lasers

Index guided laser structures are characterized by optical confinement in both lateral and transversal direction. The transversal confinement is a result of the electrical and optical properties of double heterostructures as shown in figure 2.1.

![Double heterostructure](image)

These structures consist of an active layer formed by a GaAs-layer between two AlGaAs-layers with a larger energy gap than GaAs. This configuration forms potential barriers on both sides of the active region causing confinement of carriers which in turn results in high carrier densities, allowing a low current to satisfy lasing conditions. In addition to this effect, light is also confined to the active layer as the refractive index of the AlGaAs cladding layers is smaller than the active GaAs layer. The interaction between carriers and photons in the active layer, the stimulated emission, is thus improved and again lasing conditions are satisfied more easily.

Both mechanisms, optical and carrier confinement, can be similarly applied in the lateral direction. In buried structures this is also done by using various materials and their specific physical properties but this requires a rather complicated growing process. Ridge waveguides can be made by etching any geometrical shape using already grown material.
Such a structure is shown in figure 2.2a. Starting from an arbitrary heterostructure, a ridge is formed by etching until just above the active layer, creating a stripe area where the thickness of the top cladding layer is greater than in the area outside the ridge (figure 2.2b). The light in the active layer is partially propagating through the cladding layers and is affected by this small change. Optically this results in an effective index distribution as illustrated in figure 2.3a.
As in the transversal case, the light is confined to the region with a higher refractive index. By oxidizing the region outside the ridge and then metallizing the whole surface, a current distribution similar to that of oxide stripe structures can be obtained (figure 2.3b). The current confinement causes gain guiding, the intensity distribution (fig. 2.3c) however, is mainly a result of the index profile. Therefore ridge waveguide lasers are in general of the index guiding type.

After polishing and metallizing the back, the wafer is cleaved along a crystal plane perpendicular to the ridges, at intervals separated by a certain distance whereafter sawing or breaking between ridges result in separate lasers (figure 2.4). The cleaved facet-planes at the ends of the ridge act as semi-reflecting mirrors and, together with the ridge waveguide, they form a Fabry-Perot optical cavity.

Figure 2.4 Single laser
The main issue of manufacturing ridge waveguide lasers is the etching step. This etching should be performed in a way that the thickness of the cladding layer above the active layer is as small as possible, but etching through the active layer must be avoided. This namely would introduce traps in the energy gap of the active region, due to the bindings at the interface with the amorphous oxide. These traps cause non-radiative recombinations at the sides of the ridge giving rise to high leakage currents. On the other hand, to achieve sufficient lateral optical confinement, the difference in thickness between ridge and the areas next to it must be large enough to cause reflection of light in this ridge. Though the index difference between the active and cladding regions can be relatively high, the thickness of the active layer is in practice much smaller than the wavelength of the propagating light. The low transversal confinement factor resulting from this implies that still a great part of the light is propagating in the cladding layers and is easily affected by changes in these layers. Therefore a practical value for the distance to the active layer can be found in the order of 0.1 µm.

As suggested, the method of ridge waveguides can be applied for many geometrical shapes using double heterostructures of any kind, independently of the growing technique used. More complex structures like multiple quantumwells (MQW) can be processed in the same way. Important is still the position of the transition from cladding to active layer.
3 Structure characterization

As stated in the previous chapter, the important part of making ridge waveguides is the determination of the depth to which etching should take place. Though today growing techniques allow good control of configuring layer structures, slight deviations are inevitable among wafers and between the centre part and edges of a single wafer. For the accuracy needed, an inspection of the structures is necessary. Several inspection methods have been used on two structure types: a double heterostructure grown with metal organic vapour phase epitaxy (MOVPE) by Philips Nijmegen, and multiple quantumwell structures grown with molecular beam epitaxy (MBE) by the Solid State group of the physics department of the TU Eindhoven. The aluminium concentration and doping level profiles are shown in figures 3.1 and 3.2.

Figure 3.1
3.1 C/V profiles

The first inspection method consists of measuring the doping profile quantitatively. This has been done with a Polaron Profiler which etches a small circular part of a wafer surface step by step and determines the carrier density by measuring the capacity of an inflicted depletion layer [Polar]. Although this method gives good results with normal silicon and gallium arsenide structures, problems arise when samples are measured with high (∼10¹⁹) doping levels or aluminium concentrations. In this case, the surface of the spot, as it has been etched for a certain depth, will become rough and the calculation of this depth by integrating the etch current will become more invalid. A Polaron-plot of the MOVPE DHS can be seen in figure 3.3 and the concerning etch surface profile is shown in figure 3.4.
Figure 3.3 Polaron plot of the DHS
It shows that the etch depth calculated by the Polaron differs from the actual depth measured in figure 3.4, the dope levels are however reproducible. With the electrolyte used: Tiron, similar results have not been achieved with the quantumwell samples due to the mentioned problems. Another problem arises from fact that doping levels may drop before the aluminium concentration does (fig. 3.2), making this method less useful for locating the active layer.

3.2 Etched facets

Another method affected with that same problem consists of etching a cleaved bar in a solution of K$_3$Fe(CN)$_6$ and KOH in water for a few seconds. As a result
of different etching rates in the different material layers of the sample a surface profile is created as illustrated in figure 3.5a. Illumination of the cleaved facet by polarized light will show the different edges of the profile through a light microscope as bars of various intensities (figure 3.5b). Because space charge carriers affect the etch rate, this method is mainly used to locate p-n junctions.

Figure 3.6 Etched cleaved facets
Top: DHS-sample, bottom: MQW-sample
Figure 3.6 shows the result of this method found with the two structures. These examples show more information than useful: it is hard to see what line represents the transition from cladding to active layer. There are two problems that make this method unfit for use: first the fact that a ramps are created between layers with different etch rates, as illustrated in figure 3.5. This makes it hard to locate the exact transition point. Furthermore, the indication of space charges is again not that useful since the doping levels don't always indicate the precise location of the active layer.

3.3 Scanning electron microscope

The best results examining layer structures are found by using a scanning electron microscope. Figure 3.7 shows the DHS as discussed earlier.

![SEM image from the DHS, back scattering mode](image)
This picture shows clearly the different layers. Back scattering has been used to obtain maximum contrast. Between two dark aluminium layers the active layer is visible with a thickness of approximately 200 nm. By means of energy dispersive spectroscopy (EDS) it is possible to establish the aluminium concentration of the AlGaAs layers which has been found to be about 30%. Together with the Polaron results it is possible to get a good picture of the structure, figure 3.1 has in fact been rendered from these results, but using a SEM is time-consuming and therefore less useful for checking between process steps. Some other techniques have been tried to provide for this kind of use.

3.4 Visualization by electroluminescence

To locate the active layer in a laser structure, the obvious thing to do is to activate this layer and see where light is generated. By placing a probe near the edge of a cleaved facet placed on a conducting holder, and running a current through this probe, spontaneous emission in the active layer is visible at the facet surface by using a microscope with an infrared camera. Though at a low current (< 100 mA) the position of the active layer can be located by the central axes of the light spot, it is difficult to establish the distance between this location and the top of the sample since the beam waist doesn't lay in the same plane as the facet. At a magnification of 1000, the refocussing needed to measure this distance introduces an error that makes this method inaccurate.

3.5 Facet oxidation

The method used to create an oxide layer (see §4.3) can be used to visualize different materials in a layer structure. Anodic oxidation of a cleaved sample will result in a thin oxide layer across the facet, its thickness depending on the applied voltage. The nature of this oxide depends on the underlying material as it has been found to determine the colour of the light reflected by this oxide. The way this occurs has been illustrated in figure 3.8.
Light reflected at the oxide surface, and light reflected at the oxide/AlGaAs interface, interfere as their mutual phase-shift equals approximately twice the optical distance of the oxide layer: $2n_{ox}d$. This way, only light with a wavelength of $n_{ox}d/\pi$ (or $n$-times this length) is reflected causing the colouring. The refractive index and thickness of the oxide layer is determined by its composition which in turn appears to consist of gallium, arsenic and probably aluminium oxides, depending on the aluminium concentration of the layer beneath. The type of doping has little influence on the composition of the oxide, the thickness however depends on the presence of holes during the oxidation process, resulting in thinner oxide on top of n-type GaAs or AlGaAs layers and thus reflecting a colour, different from p-type layers [Schwartz][Hart].

Anodic oxidation of cleaved facets is simply done by using a platinum cathode in a mixture of glycol and citric acid with an anode formed by the sample held by a pair of steel tweezers making good contact with the top layer. The tweezers should be prevented from touching the electrolyte as the voltage must drop over the sample surface. A voltage of 50 Volts has been applied to obtain a clear colour differentiation among several layers. The whole operation takes no more than a few minutes, the time needed to settle the oxidation current. Some examples of this method are shown in figures 3.9 to 3.11.
In figure 3.10 of the DHS, the layers containing aluminium are visible. In real, the gallium arsenide has a light blue colour, the p-AlGaAs a dark blue and the n-AlGaAs a purple colour. Through the microscope, at a magnification of 1000 the active layer is visible as a thin, light blue line.

Figure 3.11 of a MQW-structure shows a similar pattern. Because of higher aluminium concentrations than the DHS, the colours of the p- and n-AlGaAs are red and yellow. Exposed to an illumination source during oxidation, the n-AlGaAs layer becomes the same colour as the p-type layer (Fig. 3.9, below). At structures with 4 quantum wells, like this one, the active area can then also be distinguished. Structures with smaller areas need to be oxidized in the dark allowing localization by the difference in colour of the p and n-type AlGaAs layers.
To obtain more details, a DHS sample has been etched in a 4% Bromine/Methanol solution descending at a rate of \( \approx 1 \) mm/min to create a ramp. Figure 3.12 shows this sample oxidized in the dark as well as illuminated. Although the DHS is visible, it is not possible to get quantitative dimensional information. As the etch rate differs for the different layers, and because the solution does not descend uniformly, the ramp is not entirely smooth and bends at the edges of the sample. The active layer and the difference between p- and n-type material are quite well visible though. The difference in the thickness of the active layer between the illuminated and the dark side is probably due to diffusion of holes from the highly doped p-AlGaAs to the active layer and even into the n-AlGaAs layer.

With a better way of creating a uniform ramp through the layer structure, for instance by polishing, it shows that the oxidation method can be used to examine these structures in a way that can compete with scanning electron microscopes. It also should be possible then to measure the aluminium percentages by ellipsometry or other means. So far, the oxidation of facets has proven to be the most useful way to investigate structures during processing. An example is shown in figure 3.13: this is the oxidized facet of a ridge waveguide showing the successful etching towards the active layer. Different layers can be distinguished by their colour revealing the aluminium concentration. By dark and illuminated during oxidation, also the type of doping can be determined.
Figure 3.10  DHS, dark oxidation

Figure 3.11  DHS etched ramp,
left: ill., right: dark oxidation
Figure 3.12 MQW-structure L8, dark oxidation

Figure 3.13 DHS 8 \( \mu \)m ridge, oxidized facet
4 Manufacturing process

The various process steps as they have been performed to manufacture ridge waveguide lasers, are discussed in this chapter.

4.1 Photolithography

To prepare samples for the application of photo resist, the native oxide layer is removed by rinsing in an ammonium solution for one minute. Further cleaning is done by rinsing in acetone, isopropanol and chloroform, in that order, for 2 minutes each. To insure total evaporation of these liquids, samples are baked at 100°C for several minutes.

A few positive photo resists have been tried but ultimately AZ1350 has been found suitable for details in the order of one micrometer and for its resistance in environments of the used etch solutions. A resist layer with a thickness of approximately 1 μm is obtained by spinning at 5000 rpm for 30 seconds. After a bake step of 5 minutes at 95°C to harden the resist layer, the sample is ready to be exposed.

A light-field mask containing stripe patterns, ranging from 1 to 50 micrometer wide, is positioned on top of the sample in the proper crystal direction with a Karl Ziß mask-aligner. This is done by using a cleaved edge of the sample as a reference. The sample is exposed for 6 seconds, depending on the quality of the source of light.

After developing in a 1:1 solution of positive photo resist developer (DE 014) and water for about 50 seconds, and rinsing in deionized water for several minutes, the sample is spinned dry. Afterwards, a 2 minute bake step at 95°C prepares the sample for etching. Etching in methanol affects the resist layer and requires longer baking at a higher temperature. Baking at 115°C for 10 minutes is sufficient but makes removal of the resist afterwards more difficult.

Another problem arising with these proceedings is the elevation of the resist layer surface at the edges of the sample after spinning, specially with small samples. As a result of this, good contact between the middle part of the sample and the mask during exposure is prevented. To avoid this, the sample edges should be removed before aligning.
4.2 Wet etching

After the establishment of the depth of the active layer as discussed in the previous chapter, the actual ridge has to be created by etching. Not only the etched distance but also the shape of this ridge depends strongly on the used etching solution, as well as the temperature at which it takes place. Moreover, the direction with respect to the crystal is also determining the ultimate ridge shape (figure 4.1a). This direction is first tested by etching a cleaved part of the sample. When the ridge shape has a wrong profile, the photo resist layer must be removed in hot acetone and replaced by stripes in the other direction. The etch test also provides for the etch rate and, in practice, has to be made only once when processing a series of samples consisting of the same structure.

At first an etching solution consisting of phosphoric acid, hydrogen peroxide and acetic acid (\( \text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{CH}_3\text{COOH} = 1:1:1 \)) has been used at a temperature of 0°Celsius, resulting in an etch rate of approximately 1.5 \( \mu\text{m}/\text{min} \). The sample is thoroughly rinsed in deionized water after etching, removing the rather sticky etchant. The problem confronted with at this temperature is that the quartz basket, containing the sample, warms up the relative small amount of etchant, more than the cooling device can compensate for quickly enough. Apart from this, the etch profile appears to change at the transition from GaAs to AlGaAs (Figure 4.1b). Together with a slight under etching, probably caused by the
rinsing water mixed with the etchant, this makes this method less useful for etching ridges.

To cope with these problems, an etchant of phosphoric acid, hydrogen peroxide and methanol \((H_3PO_4:H_2O_2:CH_3OH = 1:1:3)\) has been tried at 20° C. To avoid solving of the resist layer in the methanol, the sample is precedingly baked at 115° C. for 10 minutes. An etch rate of about 1.45 \(\mu m/min\) has been found resulting in a ridge shape according to the one shown in figure 4.1c. Under etching still takes place as rinsing in water is still necessary. Rinsing in pure methanol instead of water should diminish this, but it has been found to solve the resist layer completely, making oxidation afterwards impossible. This is quite remarkable since the methanol in the etch solution does not appear to affect the resist a great deal. As the rinsing afterwards seems to be of great influence on the etch profile and specially on the under etching, it is worth while to investigate if methanol can be treated as to prevent the photo resist from solving.

![Figure 4.2 Etched DHS 8\(\mu m\) ridge, oxidized facet](image)

Figure 4.2 Etched DHS 8\(\mu m\) ridge, oxidized facet
Figures 4.2 and C4 show an example of an 8 μm wide DHS ridge etched with methanol. The sample was cleaved and oxidized showing clearly the etch transition from GaAs to AlGaAs. Although at the active layer the ramp compensates for the under etching, is the DHS with its deep (±3.25 μm) active layer less useful for narrow ridge structures.

![Figure 4.3 SEM picture of a 4μm DHS ridge, 2.7 μm deep, tilted.](image)

This is illustrated by figure 4.3. This SEM-picture gives a good indication of under etching with methanol. Although a mask stripe of 4μm was used, the ultimate top width of the ridge is no more than about 1 μm. Among some dust particles, a remainder of resist can be observed on the top of the ridge. Obvious is that the wet etching of narrow ridges in deep structures as the DHS result in ridge shapes, differing considerably from the ideal shape. For this reason, plasma etching may be very useful when this becomes available.
4.3 Anodic oxidation

To create a window for the metallization of the stripe contact, anodic oxidation is used to obtain the oxide layer. This method is relatively simple and causes enough ohmic resistance in the area outside the ridge. Figure 4.4 shows an outline of the setup to perform this oxidation.

![Figure 4.4 Setup for anodic oxidation](image)

A sample is attached upside down to a steel tube by vacuum. This forms an anode, connected with a clamp to a variable voltage supply via a current meter. The cathode is formed by a platinum wire placed in an electrolyte consisting of a mixture of citric acid and glycol (C₆H₈O₇:CH₂OHCH₂OH = 1:2, pH = 6). The top of the sample, containing the ridges with the photo resist, is lowered until it touches the electrolyte, and then pulled back a little in order to make contact only with the top surface of the sample. When the proper voltage is adjusted, the circuit is shortened and a current will start to flow decreasing exponentially to a stable value. During the current flow, hydrogen gas is formed at the platinum cathode and oxide is formed at the surface of the sample. The water acts in this reaction as the oxidant of the sample and the acid provides for the conduction of the electrolyte.

As the oxide layer grows during the process, the growing rate decreases proportionally to the current until it equals the dissolution of oxide in the solution. At this point the ultimate layer thickness is linearly determined by the
applied voltage [Haseg]. With a ratio of approximately 16 Å/V, a voltage of 60 V. is used to create a 100 nm oxide layer with sufficient ohmic resistance.

The advantage of this method is that it allows to compensate for too lightly etched ridges. By choosing the proper oxidation voltage, oxide can be grown until just above the active layer. After rinsing the sample in deionized water and drying it, the oxide contains a large amount of water that needs to be removed before metallization can take place.

![Figure 4.5 Surface of an oxidized sample](image)

After oxidizing at 60 Volts, the surface has a deep blue colour with traces of purple to pink colours, indicating the presence of AlGaAs at the surface after etching (Figure 4.5). The lighter oval areas, in real light blue, indicate GaAs: the active layer. Though not all of this sample is etched through the active layer, is it clear that due to nonuniform etching this can happen at some places. The solution is not stirred during etching because it affects the etch rate and therefore introduces inaccuracy.
4.4 Baking of the oxide

After oxidizing, the photo resist has to be removed for metallization. As mentioned before this removal is hampered by the high baking temperature of the resist. Because boiling in hot acetone for several minutes doesn't always do the job, rinsing in methanol has been tried, giving better results.

To get rid of the water in the oxide, the samples are baked in an AST rapid thermal annealer (RTA). As the ridges lay unprotected at the surface, oxidation must be prevented. With the thermal annealer, the baking environment can be conditioned in a way that the water in the oxide evaporates without oxygen reaching the ridge surface. This is done by evacuating the chamber of the RTA after loading the sample, purging it with nitrogen and letting a gas mixture of hydrogen and nitrogen (N$_2$:H$_2$ = 2:1 l/min.) flow through the chamber during heating. First warming up to 100°C takes place whereafter heating to a temperature of 400°C in 10 seconds is programmed. In practice, keeping this level for 10 minutes seems sufficient to remove the water from the oxide, enough to prevent bubbles appearing under the metallization after alloying at high temperatures.

After these 10 minutes, the chamber is evacuated and purged again, cooling the sample until below 100°C. The baking is based upon a process used by the Semiconductor Technology group of the University of Duisburg, Germany. The figure below shows a plot of the baking process as it has been programmed on the RTA [AST].

![Diagram of RTA baking process](image)

Figure 4.6 RTA baking process
4.5 Metallization

The top layer of the used structures consists of highly doped (\(\pm 10^{19} \text{ cm}^{-3}\) or more) p-GaAs. Ohmic contacts are obtained by deposition of platinum and gold. This has been done by sputtering and, later on, by using a Leybold evaporator. Because the metallization peels off from the oxide during bonding, a thin titanium layer has been deposited before the platinum layer for better adhesion. It also prevents gold from diffusing through the platinum into the GaAs causing high resistance [Howes]. But with the RTA, improvements have also been gained baking the oxide layer more efficiently. To improve contact between bondings and the top gold layer, a titanium layer has also been applied beneath this layer as it is supposed to improve the gold structure on top of it after annealing. A structure of Ti/Pt/Ti/Au = 10/20/40/200 nm. has thus been evaporated with the Leybold, giving good results.

After polishing, ohmic contacts on the back of the n-type substrate are created with a 12% germanium alloy with gold and nickel, followed by a gold layer. The Ge is used as a dopant for the relatively low doped n-substrate. It swaps places with the gallium in the substrate which in turn diffuses into the gold layer [Will]. The nickel is used as a wetting agent, assuring a uniform contact after annealing. At first the contact has been deposited again by sputtering, later on with the Leybold. With a structure of Ge/Ni/Au = 20/15/200 nm, good results have been obtained. Bonding on the back, necessary with mounting of the ridge-side on top of a heatsink, doesn't work very well as the germanium seems to diffuse to the surface of the gold layer. To prevent this, titanium as been tried again to act as a buffer between the germanium and the surface. This structure of Ge/Ni/Au/Ti/Au = 20/15/50/50/150 nm. however, appears to have serious attachment problems as it peels of the backside of the sample during cleaving. Annealing longer does not seem to have any influence on this. Better attachment is achieved using a 10 nm. titanium buffer layer, but no true ohmic contact is obtained this way. V/I-measurements through the back contact show a diode characteristic, indicating a poor Au/Ge/Ni alloy. Annealing longer and at higher temperatures has little effect, only a change of colour at the surface from gold to a more pale silver-like colour was observed. An improvement may be expected from annealing the AuGeNi before the evaporation of the titanium and top gold layer, assuring the proper alloying of the n-contact.
4.6 Annealing

Top and back contacts are annealed with the RTA similar to the way the oxide is baked (§4.4). Contact layers containing titanium tend to react with hydrogen, creating a whitish smear on the gold surface. To prevent this, only a nitrogen flow is used. Annealing for ten seconds at 400°C for p-type, and 380°C for n-type contacts, as used at the Duisburg University, resulted in good ohmic contacts. Less successful has been the addition of titanium to the back metallization grown with the Leybold as mentioned before. For optimalization, research has been performed by Jan van Hassel to find the proper annealing temperature and duration. This is specially important for both p- and n-contacts containing titanium, as this strongly affects the ultimate eutectic temperature.

4.7 Polishing

Before metallization of the n-type contact, the backside of the substrate is polished down to ±120 μm to minimize the series resistance of the lasers, but also to make cleaving of small lasers (L < 250 μm) easier.

Samples are glued ridge side down on a glass disc that is heated to approximately 100°C and greased with wax. At least three samples must be equally distributed along the edge of the disc to insure stable rotation. Covered by filtration paper, the samples are fixed in a vacuum press and disposed of the surplus of wax. After cooling down, the disc with the samples is placed in a polishing machine, pressed down by an adjustable weight. Rough polishing is done using 3 μm aluminium oxide powder in water in combination with a glass polishing disk. By checking the thickness of the samples regularly, this is stopped at approximately 10 to 20 μm before the ultimate value. After removal of the polishing powder from the edges of the samples is the sample holder replaced on a velvet polishing disk. Using 1 μm powder, polishing is maintained until the right thickness is reached and a smooth surface is obtained. Finally, after cleaning the samples again, they are chemically polished on a blank velvet disk with bleach (NaOCl in water) until the back of the samples is shiny. The holder is then rinsed in water and dried with nitrogen.

To remove the oxide, hydrochloric acid (HCl) is dropped on top of the polished surface. After rinsing in water and drying, the samples are removed from the holder in hot trichloro ethylene, solving the wax. Rinsing in that same
liquid followed by isopropanol must assure the cleaning of the top layer. After drying, the back contact can be applied.

The total procedure does not give any problems. Dust particles need to be avoided from getting trapped in the wax between the samples and glass holding disc. As their thickness diminishes, the samples become more vulnerable to tensions and break easily. In this respect, the purity of the wax is quite essential. Care should furthermore be taken when removing the samples from the holder. Although the wax may be solved completely, the samples can still be sucked to the glass disc, causing scratching of the metallization and damaging of the etched ridges as they are moved. To avoid this, only the glass discs with holes pierced through them should be used for they enable solvent to flow under the samples and thus keep them from getting stuck.

4.8 Cleaving and breaking

Separate lasers are cleaved and broken using a Loomis scriber. To do this, the sample is stuck with the ridge side up on a plastic foil by putting a weight, preheated to approximately 120°C, on top of it for about 30 seconds. The sample together with the foil is than placed on the chuck of the scriber. First, a series of scratches at adjusted intervals is made at the top edge of the sample parallel to the ridges, using the dragged notch method [Loom]. The foil and sample is then removed and covered with a piece of aluminium foil and another plastic foil. After removal of the air between by evacuation, separate laser bars are cleaved. This is done by gently rolling a steel rod over the backside of the sample which is placed on a flexible steel band, braced over a rubber mat. The plastic foil to which the sample is stuck prevents the bars from shifting. This way the sample can be placed back on the scriber's chuck entirely and then be scribed for the full length of the sample, between the ridges of the bars. Breaking the separate laser chips is done the same way as the cleaving.

This method has the advantage of breaking the lasers of the different bars in one time. The drawback is the friction between the faces of adjacent bars after cleaving and during breaking of the separate lasers, leading to damage of the mirrors. This can be prevented by making notches as well as pecks (short scribe lines along the break line and between cleave lines) at the same time as to enable cleaving directly followed by breaking. But in practice this takes long for the scriber to perform (1 cm² sample can contain more than 150 lasers), and with cleaving, bars may stop half-way into the sample by a peck. The best way
seems to be breaking each bar separately although this is time consuming. A special chuck for this purpose can be of some assistance.

Cleaving as described yields bars with a minimal width of about 200 \( \mu \text{m} \), depending on the thickness of the sample. To achieve lasers with smaller lengths (down to 50 \( \mu \text{m} \)), cleaving bars in two by hand is possible with a little luck and a lot of patience.

4.9 Mounting and bonding

As mentioned earlier the bonding on both top and back contact has given rise to several problems. At first the top metallization stripped from the oxide layer, probably as a result of water in that layer, and later on the attachment of the bondings to the top gold layer gave rise to some problems. All this has been solved but bonding of the back is yet still a problem, making mounting on heatsinks as yet impossible.

On top of a 16-pin DIL package that is sawed in half, mounting of 4 laser chips is done using Epo-tek to establish conduction between the lasers and the bottom of the package (Figure 4.7).

![Figure 4.7 Laser mounting and bonding on a DIL-16 package](image-url)
A Riber bonder is used because its method has been found to work better on the lasers. Ultrasonic bonding has been tried, but this damages the top surface and the oxide layer beneath. The thermal bonding of the Riber makes it possible to bond even on the ridges themselves. In spite of the lack of cooling this kind of mounting is suitable for pulsed operation of the lasers and, when consisting of narrow ridges, also continuous operation.

A very convenient way of placing separate lasers on the package is by using a chiptester. With this device, lasers are picked up by capillary vacuum tweezers, and tested for laser operation. When functioning, the chips can be precisely placed on top of the Epo-tek and the mirror face can be adjusted. Damage to the lasers or covering up by Epo-tek is excluded this way.
5 Characterization of the lasers

At the Electronic Devices group, several facilities are on hand for the characterization of lasers or will be in the near future. These are formed mainly by an integrated optical and electrical testing setup as illustrated in figure 5.1.

The heart of this setup is a probe board on top of an adjustable stand, on which laser packages can be mounted and to which control and measuring signals are connected, together with a light microscope creating an image of the laser's optical field for the two CCD-cameras and the monochromator [Vrol]. All optical equipment is mounted on a vibrationproof table. The revolver of the microscope contains moreover a sensor for measurement of the light output of the laser. A control unit determines the continuous or pulsed excitation of the laser, and the analysis device to send its signal to the output device: an x/y-recorder. The analysis devices consist of video analyzers for both near and far
field, the already mentioned intensity sensor and of course, samplers for V/I-
measurements. Furthermore, a device for measuring the series-resistance of the
laser is installed [Bar], as will be a monochromator for spectral analysis. For
better measurement of the far field, alterations to the chip tester are intended.

Satisfactory results have been gained measuring lasers of different kinds,
both pulsed and continuous. With the measurement of field patterns at large
magnifications, some problems caused by vibrations have occurred. As they
appear to originate from the floor, the problem may be solved by a minor
adjustment of the table-legs.

For the pulsed measurement of unmounted lasers, the chiptester is very
useful. Because it is equipped with accurate samplers, a fast and good
characterization of separate laser chips is possible. Addition of an indicator for
current, voltage and light output signals would be helpful though for adjustment
and gauging.
5.1 Broad area lasers

The MBE structures produced by the physics department consist of 1 (structure L7), 2 (L5), 3 (L6) and 4 (L8) quantumwells. Their layer structures are all similar to the latter one of which an outline was shown earlier in figure 3.2, except for the quantumwell part of it. A detail of the L8-structure as it was designed is shown below.

![Aluminium Profile MQW structure](image.png)

Figure 5.2 Detail of the L8-structure

The quantumwells are formed by variations in the aluminium profile as illustrated. The wells are 70Å wide and separated by 150Å of Al_{0.2}Ga_{0.8}As. Optimal confinement of light and coupling is created by the so-called graded index separate confinement heterostructure (GRINSCH) between the Al_{0.7}Ga_{0.3}As-layers.

To measure the electrical and optical performance of these structures, 30 and 50μm wide ridge waveguide lasers have been manufactured. These relatively broad ridges are used in order to make the edge-effects, in the range of a few micrometers, in both light and current distribution negligible when calculating the current density. For the same reason is the accuracy concerning the etched distance towards the active layer less important. Figure 5.3 shows the result for a 1.7μm deep etching of an L8-structure as described in §4.2, using an etchant based on methanol.
Although the facet was oxidized under relatively dark conditions, the n-AlGaAs layer has the same colour as the p-layer. This indicates that the n-layer is able to generate holes at low exposure by laying near the surface. Although this doesn't automatically mean that etching through the active layer has occurred, appears this layer to lay a little less than 2 μm from the top surface (see also figure 3.10). This difference from the structure design in figure 5.2 may be caused by a constant error in the measurement. To avoid etching through however, 1.7 μm together with oxidation at 60 Volts is used resulting in a depth of ±1.8μm.

5.1.1 Near field patterns

After processing the different samples, lasers of various lengths ranging from 200 to 1500 μm are cleaved and mounted. The lasers are operated with a pulsed current source (100 ns. at 100 kHz) to prevent heat from being generated, influencing the threshold behaviour.
Examples of the near field patterns of the produced lasers is given in figures A1, A2 and A3 in the appendix. Figure A1 shows the near field of a single quantumwell laser, perpendicular to the active layer below and above threshold ($I_{th} = 32\text{mA}$). The shift between the curves is a result of movement of the laser between measurements and the pikes are mainly the result of the sensitivity to vibrations at this magnification. Different attenuations have been used making these curves not to scale. Due to fundamental restrictions at this magnification the plot is only an indication of the actual distribution with no real quantitative significance. The confinement of light by the graded index structure is clearly visible though and shows improvement above threshold.

The lateral field distributions in figures A2 and A3 of respectively 30 and 50 $\mu$m ridge lasers, also show good confinement above threshold. The curves indicate higher lateral modes as can be expected with lasers of these widths. Figure A3 clearly shows a fourth order mode at $I = 75\text{mA}$. It can be concluded from these distributions that these ridge waveguides function satisfactorily. In some cases, dark spots in the near field have been noticed that could indicate irregularities in the mirror surface, but these lasers mostly seem to work just as well. Contamination of the mirrors by crystal particles, originating from the cleaving and breaking of the chips, is therefore more probably the cause of this.

5.1.2 Threshold current

From the lasers of the various structures, the P/I characteristics have been measured in order to establish the threshold current. Per package, lasers of a certain structure and with a certain length have been mounted, two with 30 and two with 50$\mu$m wide ridges. Figures A4 and A5 represent the measurements of two of these packages. Poor back contacts have been obtained as a result of bad alloying with a titanium buffer layer (see §4.5), but although this resulted in high threshold voltages, still good measurement of the currents could be made with pulsed operation. Because some of these packages contained bad lasers, in spite of the use of the chiptester, additional lasers have been mounted for measurement resulting in the data as shown in table I. The threshold current in the table is the result of lasers with the lowest value found for a given geometry. The calculated threshold current densities are also given in the table. With structures L5 and L7, lasers shorter than 200$\mu$m have been cleaved and measured using the chiptester in order to see the behaviour at these lengths.
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<th>J_n [kA/cm²]</th>
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<td>0.33</td>
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Table I Results P/I measurements
A plot of the data from table I is shown in figures A6 up to A9. A linear dependence to the cavity length is noticeable in each of them as well as the influence of the cavity width, the rate increases with the number of quantumwells. The difference between L7 and L5 is however much larger than between the structures consisting of more quantumwells. This is partly due to the higher overall confinement factor of the 3 and 4 QW laser types although they seem to have almost the same current densities for the same gain values which is not expected.

A good impression of the effect of short cavities is given in figure A10 for 30μm wide single and double quantumwell ridge lasers. For small cavity lengths an increase of threshold current density with reduction of laser length can be observed. This is explained by the nonlinear behaviour of the quantumwell optical gain as a function of injected current density. For low injected carrier densities, the gain has an almost linear dependence. This carrier density causes spontaneous emission which gives rise to a current density proportional to the injected carrier density and thus proportional to the obtained optical gain. For high injection densities two effects become important: the optical gain saturates due to band filling and the step-like QW density of states distribution and furthermore, by thermal emission more and more carriers escape from the quantumwell subbands which are becoming more filled, causing leakage currents. Obviously, for shorter cavities, higher QW gain values are required which, due to the low confinement factor (Γ≈3%), are highest for the SQW lasers. This explains the observed saturation and current leakage effects of short cavity SQW lasers. In these lasers the internal absorption are relatively low compared to mirror losses. Therefore the required gain for lasing is almost inversely proportional to the laser length of short lasers. The DQW lasers should show the same behaviour at short lengths as the SQW lasers. Due to the fact that the confinement factor of the DQW lasers (Γ≈6%) is about twice that of SQW structures, the gain factors that can be reached without saturation are also twice as high. Therefore the onset of the effect occurs for DQW lasers at a cavity length that is approximately half that of SQW lasers.

The calculated current densities are also plotted out in figures A11 to A14. Except for the L6 structure the width of the ridges has little effect on the current density at a given length, proving the edge-effects to be negligible at these widths. Cause of the behaviour of the L6 structure might be an undeep etched ridge: figure A2 does show more spontaneous emission next to the ridge area then the field pattern in figure A3 (SQW).
The importance of the density curves can be made visible by the expression for the threshold current density which can be found as [Cas][Cheo]:

\[
J_{th} = \frac{d}{\eta_i} \frac{1}{\beta \Gamma} \frac{1}{L} \left( \frac{1}{R} + \alpha_i \right)
\]

With \(\eta_i\): the internal quantum efficiency which is assumed to be little less than 1, \(J_n\): the nominal volume-current needed to achieve transparency in the active region, \(\Gamma\): the transversal confinement factor which can be estimated to be \(\pm 3\%\) per quantumwell, \(\beta \approx 0.044 \text{ cm} \mu \text{m} / \text{A}\): the gain factor determining the (linear) dependence of the gain to the current density above transparency. This factor can be extracted from the current density curves and proves to be about the same for all these curves except, again, for L6 which has a gain factor of 0.036 cm\(\mu\)m/A. R is the mirror reflectivity assumed to be approximately 0.3 for both mirrors and \(\alpha_i\): the total internal absorption is related to the absorption in active layer and cladding layers according to:

\[
\alpha_i = \Gamma \alpha_a + (1-\Gamma) \alpha_c
\]

Because of relative low confinement (3-12%), the absorption could be formed mainly by the cladding absorption \(\alpha_c\). The cladding absorption is however expected to be much lower than that of the quantumwells which is high as a result of scattering of the light due to high carrier concentration. Dependence of the absorption to the number of quantumwells therefore probable.

The transparency current and the absorption are mainly important as they give an indication of the quality of the grown structures independent of the mirror quality. The intersection of the curves in figures A11 to A14 with the y-axis indicates the threshold current density at infinite cavity length or ideal mirror reflectance: \(J_{th}\). For the isolation of these parameters, more information is needed.
5.1.3 Differential efficiency

Another parameter can be obtained from the curves in figures A6 to A9 by establishing the derivatives of the light output $P$ (for one side of the laser cavity) above threshold:

$$V_g \frac{dP}{dI} = \eta_i \frac{1}{L} \frac{1}{R} \ln \frac{1}{R}$$

$V_g$ is the bandgap energy in eV and $\eta_i$ can again be assumed to be 1. The derivatives found from the light output curves are listed in table II, together with the calculated differential efficiency for a bandgap of 1.46 eV ($\lambda = 840$ nm).

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<th>$\alpha_i$</th>
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<td>$\mu$m</td>
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<td>cm$^{-1}$</td>
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<td>0.36</td>
<td>28.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L8</td>
<td>4</td>
<td>30</td>
<td>0.42</td>
<td>0.57</td>
<td>42.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.48</td>
<td>0.66</td>
<td>14.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>302</td>
<td>0.48</td>
<td>0.66</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>200</td>
<td>0.42</td>
<td>0.57</td>
<td>42.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>302</td>
<td>0.37</td>
<td>0.51</td>
<td>36.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>408</td>
<td>0.52</td>
<td>0.71</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>702</td>
<td>0.40</td>
<td>0.62</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table II Results of the $dP/dI$-measurements
The values are plotted out in figures A15 up to A18 in the form of $1/8 \eta_D$ from which the total internal absorption can be calculated as:

$$\alpha_i = \frac{1}{L} \ln \left( 1 - \frac{1}{R \eta_D} \right)$$

These values are shown in figures A19 up to A22. The data shows a lot of scattering as can be seen from the plots of the differential efficiency and the calculated absorption. This is mainly due to the quality of the mirrors of the measured lasers. Lasers with almost equal threshold current can display complete different behaviour concerning the derivative of the light output (figures A4 and A5). The dust particles as they have been noticed on top of the mirror faces are probably the cause of this behaviour as they may stop the light coming from the cavity without affecting the reflectivity of the mirrors. Small mirror damages may cause mode instabilities in the laser cavity also causing unreliable P/I curves. The scattering of the data indicates that the results can give no more than an impression of the absorption in the lasers. As the absorption should be independent of the length and because external factors can only enlarge the value, the best estimate of the value is found taking the minimum from figures A19 to A22. This results in figure A23 where the total internal absorption is plotted out as a function of the number of quantumwells. Except again for L6 the values are about 7 cm\(^{-1}\). Because the L6-value is probably much higher due to bad mirror contamination, for further calculations, a value is adopted of $\alpha'_i = 7.7$ cm\(^{-1}\), the cross in figure A23. Although a slight variation is noticeable this may well be the result of the scattering of the absorption data. From the expression for the total internal loss with $\Gamma \approx 3\%$/QW, figure A23 would indicate values of $\alpha_c \approx 5$ cm\(^{-1}\) and $\alpha_a \approx 80$ cm\(^{-1}\).

Together with the current density for ideal mirror reflection: $J_\infty$, the nominal transparency current density can be calculated according to:

$$J'_n = \frac{\eta_i}{d} J' = J_\infty - K \alpha_i$$

with a constant $K$:

$$K \Delta \frac{d}{\eta_0 \Gamma} \frac{1}{\Gamma} = \frac{d}{\ln L} \frac{1}{R}$$

which can be derived from figures A11 to A14. As both $d$ and $\Gamma$ depend on the number of quantumwells, this value like $\beta$ is supposed to be constant for all the
structures. $J'$ is the true current density, $J_n'$ is a volume current that is also independent of the thickness of the active region. This results in the data in the following table.

<table>
<thead>
<tr>
<th>QWs</th>
<th>$J_0$</th>
<th>$\alpha_l$</th>
<th>$J'$</th>
<th>$J_n'$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acm$^{-2}$</td>
<td>cm$^{-1}$</td>
<td>Acm$^{-2}$</td>
<td>kA/µm$^{-1}$cm$^{-2}$</td>
<td>Acm$^{-1}$</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>6.2</td>
<td>73.6</td>
<td>10.5</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>7.0</td>
<td>273.6</td>
<td>19.5</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>320</td>
<td>18.7</td>
<td>295.4</td>
<td>14.1</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>326</td>
<td>8.4</td>
<td>293.3</td>
<td>10.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Table III: Derived parameters

This data has been plotted out in figures A24 and A25. As stated before the threshold current density isn't proportional to the number of quantumwells. In an attempt to draw a line from the origin of the plot through the different markers, the L5-lasers (2 QWs) appear to be too high and the L8-lasers (4QW) too low. Because of the rather low absorption the transparency current is close to the current value for $L=\infty$. The current density of less than 100 A/cm$^2$ for one quantumwell can also be considered quite low. The overall behaviour is visible in figure A25 of the nominal transparency current density. Due to the nonlinearity the scattering in this picture allows no more than an estimation for the nominal current of 10 to 15 kA/µmcm$^2$. This high value is normal for quantumwells of the designed dimensions.

The absence of a clear linear behaviour with respect to the number of quantumwells can partly be ascribed to the worse etching of the L6-ridge and the quality of the laser mirrors as explained earlier. This could also explain the high current densities of the L5 lasers. A better overall confinement factor with structures containing more quantumwells could be of some influence though. Finally one could consider the possibility of nonlinearity imposed by the improved distribution of carriers between a larger number of quantumwells. For this, the investigation of the carrier capture efficiency in QW structures by the Solid State Physics Group maybe results in a satisfactory explanation. Also accurate processing and measurement of the L5 and L6 structure may produce more information.
5.2 Narrow ridge lasers

The lasers discussed in the previous section were only suitable for pulsed operation. The heat caused by the high currents of these lasers is quite large. This results in a high operation temperature at which lasing is impossible. For continuous operation, low currents are obtained by etching narrow ridges. This is done using a 4µm stripe mask, etching 1.7µm deep and oxidation at 60 Volts. This results in a ridge as shown below.

![Figure 5.4 Laser Ridge, 4µm mask](image)

Measurements show a top GaAs part (the bright piece) that is 2.3 µm wide whereas the bottom of the ridge is 4.3 µm wide. It is clear that with this width, the depth of the active layer is crucial with respect to the ultimate ridge shape. When the same mask is used with the DHS which has a 3.25 µm deep active layer this results in a ridge shown in figure 5.5. Although etching hasn't reached the active layer, is the top of the ridge less than one micron wide. Etching deep structures therefore stresses the need for minimal under etching. As mentioned before this can be solved by better rinsing. Other techniques like Plasma etching should also be considered.
5.2.1 Field distributions

The light distribution of the SQW lasers is visible in the near field patterns in figure A26 of the appendix. Although the light appeared to be generated a little more than 0.1 \( \mu m \) below the bottom of the ridge, the confinement of light above threshold (7.2 mA, pulsed) is quite good.

The far field patterns in figure A27 show the asymmetry of the light beam produced above threshold. Both lateral and transversal far field distributions are the transforms of their near field equivalent and a the difference in beam waist results in a difference in radiation angle which can be observed in the figure.

With continuous operation it is possible to measure the spectrum of the lasers. This has been done at the Telecommunications Group by coupling the light into a single mode glass fibre that is connected to a spectral analyzer. The results in figure A28 show the spectra for 250 \( \mu m \) and 500 \( \mu m \) long SQW lasers. The plots clearly indicate the monochromatic behaviour of the lasers, the
linewidth is probably much less than the observed 0.1 nm; the resolution of the analyzer. The influence of the cavity length is visible as the line separation of the spectrum is inversely proportional to this length: $\Delta \lambda \approx \lambda^2/2nL$. The difference in power is caused by the difficult adjustment of the coupling of the light beams to the step index fibre. The difference of the central wavelengths from the designed value of 840 nm, is probably not the result of temperature effects in the (uncooled) lasers. Although the centre lines start shifting with higher currents (and temperature), is the stability above threshold relatively high. Moreover an increase of temperature results in an increase of wavelength so the deviation is probably caused by the small shift of the carrier distribution to a higher energy at increasing pumping rates. This deviation is higher with the 250 $\mu$m laser: with the same operation current, the current density in this laser is about twice as high as that of the 500 $\mu$m laser.

5.2.2 Threshold behaviour

Lasers of different lengths have been mounted. To achieve minimal threshold current, the L7 single quantumwell structure is used. Figure A29 shows the result of the P/I measurements. Using AuGeNi without titanium, good back contacts have been obtained resulting in a voltage of about 2 Volts at threshold. The data from figure A29 is shown in the table below.

<table>
<thead>
<tr>
<th>Laser</th>
<th>L $\mu$m</th>
<th>W $\mu$m</th>
<th>$I_{th}(cw)$ mA</th>
<th>$I_{th}(pl)$ mA</th>
<th>$dP/dI(cw)$ mW/mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQW(L7)</td>
<td>214</td>
<td>4.3</td>
<td>12.4</td>
<td>8.7</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>262</td>
<td></td>
<td>18.6</td>
<td>16.0</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td></td>
<td>13.1</td>
<td>10.1</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>505</td>
<td></td>
<td>10.8</td>
<td>7.2</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>605</td>
<td></td>
<td>14.2</td>
<td>9.2</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>750</td>
<td></td>
<td>44.1</td>
<td>37.4</td>
<td>0.11</td>
</tr>
<tr>
<td>4QW(L4)</td>
<td>250</td>
<td>4</td>
<td>30.7</td>
<td>27.1</td>
<td>0.4</td>
</tr>
<tr>
<td>DHS</td>
<td>250</td>
<td>4</td>
<td>75</td>
<td>57</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>8</td>
<td>-</td>
<td>56</td>
<td>0.27 (pl)</td>
</tr>
</tbody>
</table>

Table IV
The results in table IV are plotted out in figure A30. As was the case with the broad laser structures (fig. A10) a dependence of the threshold current is noticeable with respect to the cavity length. Because the single quantumwell structure has a relative low gain is the length of minimal current quite large: approximately 500 μm. The threshold current is very low at this point: 10.1 mA. The temperature rise in the lasers with continuous operation is visible as pulsed operation decreases the threshold current down to 7.2 mA/cm² for L = 505 μm. With this laser, a current density of about 330 A/cm² can be calculated. This is a reasonable value compared to the results of section 5.1 when side effects in the current distributions are taken into account. Better performance may be expected from more accurately etched ridges. The light output (for a single facet) in table IV still shows variation which is most probably due to non-uniformity among the different lasers caused by contamination of the facets. Also irregularities of the ridge shape are playing a more important role as the width is relatively small. Still a differential efficiency of 77% can be calculated from the laser with L=500 μm.

The best results achieved with other structures are also given in table IV. The LA structure (4 quantumwells) has a higher threshold current than a single quantumwell of the same geometry but this is not proportional to the number of wells, according to the results of section 5.2. Lasers made with the MOVPE DHS show much higher currents as is to be expected. This is not a fair comparison however since the ridges have been etched for 2 microns, 1 μm above the active layer, which probably resulted in poor index guiding. Ridges of 8 μm have been produced with 3 μm etching (figure 4.2) giving much better results. Although only pulsed operation was possible as a result of poor ohmic contacts, it is clear that the ridge shape does have a considerable influence on the threshold behaviour at these widths.

45
5.3 Laser arrays

Manufacturing of laser geometries other than the normal waveguides has been performed to see if lasers can be achieved with a higher light output. The method of ridge waveguides allows not only the variation of length and width, but also the entire shape of the ridge geometry. As the ridge is the etched copy of the resist pattern, the lithography is the only step to be changed.

The first structure tested is a laser array. The process of making the resist pattern is illustrated in figure 5.6.

![Lithography for the array pattern](image)

In the first step (fig. 5.6a) exposure of the resist layer with a 1-2 μm wide dark field stripe mask is performed repeatedly separated by intervals of 6 μm. This is done by shifting the sample this distance with the mask aligner, then exposing it again, releasing the sample and so on. Important is the uniform shift of the sample to obtain equal intervals. After a few exposures, the resist is developed, and a series of 4 μm stripes remains. To remove the rest of the resist, a second exposure is performed using a 16μm light field mask (fig. 5.6b). In this case, three stripes are the result but with enough dark field exposures and a wider light field mask, more can be made of course. After developing for the second time, the ridges can be etched (fig 5.6c) followed by the usual proceedings.
For coherent operation of the array, sufficient coupling is needed between lasers [Verd]. This is established by positioning the different lasers next to each other close enough. The ramp in the ridge edges cause some problem here. Although under etch compensates for the ramp, it is possible that the different ridges are not separated at the level of the active layer (the dotted lines in figure 5.6c). Sufficient separation is therefore needed, specially when the active layer lays deeply below the surface.

Figure 5.7 L7 3-ridge array, oxidized and stripped

With the SQW structure, arrays containing 3 and 5 lasers have been made. The results of the process are shown in the pictures in figures 5.7 and 5.8. Figure 5.7 shows the top view of a 3-ridge structure after oxidation and removal of the resist. An attempt was made to select two ridges of about the same width next to a wider ridge which is supposed to dominate the longitudinal mode of the array. But a deviation during alignment of the light field mask has caused a strong asymmetry in the structure. Figure 5.8 shows that etching emphasizes this effect as the difference in the width of the ridges seem to be greater than the difference between the resist stripes.
The problems with the aligning can of course be solved by developing a special light field mask containing the complete array design. Another problem appearing to be typical for these structures arises with cleaving of separate chips. It is almost impossible to cleave a laser with good mirror facets on both sides. During cleaving, the crack in the samples seems to be disturbed by a ridge. As this ridge is followed directly by another laser of the array, this disturbance becomes worse until there is no more facet plane. This effect has only been noticed with laser arrays. Since cleaving separately by hand hasn't given any trouble could the problem be solved by adjusting the cleaving procedure.

5.3.1 Field distributions

As a result of the problems with the cleaving and breaking of the lasers, only a few 3-ridge arrays have been mounted and tested. A lateral near field pattern of the best laser is given in figure A31. This array consists of 3.0, 4.1 and 4.0 \( \mu \text{m} \) wide lasers (from left to right), separated by respectively 2 and 1.7 \( \mu \text{m} \), and is 440 \( \mu \text{m} \) long. The small laser on the left is slightly visible below threshold, above this point the lasers on the right and in the middle dominate the field pattern.
Of these two lasers the right one seems to be dominating (it starts lasing first) and appears to couple the field of the middle one into a second order mode. It seems that as a result of this the field of the central laser is pulled to the right side of the cavity.

From the far field distributions in figure A32 of the same laser it shows that the transversal far field is similar to that of a single ridge (fig. A27). The lateral field is however completely different and shows 4 peaks, also indicating a higher mode.

5.3.2 Threshold behaviour

In figure A33 a P/I-plot is given showing the results of the laser with continuous and pulsed operation. From this characteristic the following values can be extracted:

\[ L = 440 \mu m \quad w \approx 3 \times 4 \mu m \]

\[ I_{th}(cw) = 24 \text{ mA} \quad I_{th}(plsd) = 18 \text{ mA} \quad dP/dI = 0.25 \text{ mW/mA} \]

Compared with the single ridge lasers from 5.2 this is not a bad result considering the fact that the left laser is not functioning optimally. The light output is a bit low in comparison but this is probably the result of the poor mirror quality and one failing laser.

From these results it shows that good performance can be realized with ridge laser arrays since coupling of neighbouring ridges takes place. To do so a properly designed array mask is needed for developing the resist pattern in one step. Also the problems with cleaving of the laser chips need to be solved first.
5.4 Flared waveguide lasers

Another way of increasing the light output of the lasers is by diminishing the reflectivity of the front mirror. This can be realized by means of geometry as illustrated in the figure below.

In a normal laser the reflection on both sides of the cavity is the same causing a symmetrical distribution of light propagating forth and back (Fig. 5.9a). By broadening the cavity on one side, the light which can be considered as a plane wave starts to broaden also as a result of dispersion. The light reflecting at the wide facet of a flared waveguide is no longer a plane wave and therefore no longer directed mainly along the cavity. Because the amount of light propagating is no longer the same for both directions, the laser is supposed to radiate more at the flared side of the cavity than the other.

The flared structure has probably more loss than a regular cavity as the dispersed light will probably penetrate into the areas next to the flared structure more easily. Several configurations have therefore been processed in order to find the best performance. Figure 5.9b shows the different shapes and sizes
available on a light field mask. The tapered structures are meant to reduce the amount of loss and doing so, the threshold current.

5.4.1 Field distributions

Figure A34 of the appendix shows the near field pattern of a 12 µm wide tapered flared waveguide laser made with the L7 SQW structure. It clearly shows the broadening of the light beam at the front mirror above threshold. Because the lateral near field beam width is larger than the original narrow ridge lasers, the far field (figure A35) shows a slight decrease in the radiation angle.

5.4.2 Threshold behaviour

P/I measurements of several flared waveguide lasers have been performed. From these curves the following best values are obtained.

<table>
<thead>
<tr>
<th>l (µm)</th>
<th>t (mA)</th>
<th>L (µm)</th>
<th>W (µm)</th>
<th>w (µm)</th>
<th>I_{th(cw)} (mA)</th>
<th>dP/dI(cw) (mW/mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>0</td>
<td>172</td>
<td>26</td>
<td>6</td>
<td>45</td>
<td>0.15</td>
</tr>
<tr>
<td>24</td>
<td>45</td>
<td>176</td>
<td>26</td>
<td>6</td>
<td>16.4</td>
<td>0.40</td>
</tr>
<tr>
<td>23</td>
<td>12</td>
<td>212</td>
<td>12</td>
<td>6</td>
<td>14.4</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table V Results for the flared waveguide lasers

Only three of the four flare types have been successfully measured. The total length of the lasers (±250 µm) is shorter than the optimal value found in section 5.2. This is probably the reason why the rectangular shaped flares gave poor results showing high threshold currents and low light output. High internal absorption as mentioned earlier is probably the cause of this. The tapered laser shapes show much better results and therefore seem to have less problems with absorption. When the light output is compared to that of narrow ridges it can be concluded that with a longer total cavity and an optimal taper region (maximal dispersion in a minimal area), a flared waveguide can be designed with a larger light output.
6 Conclusions and recommendations

In the process of making ridge waveguide lasers, several problems have arisen. The greater part of them has been solved, resulting in well working devices. For some process steps however, improvement is still desirable.

6.1 Manufacturing process

The measurement of dope profiles was found to be insufficient for the purpose of establishing the location of the active layer since the realization of a proper waveguide requires information about the optical properties more than the electrical. In this respect better results have been obtained by inspection of the aluminium concentrations with a scanning electron microscope in backscattering mode. For inspections during processing, a good technique has been found to be the oxidation of cleaved facets. The colour of the oxide reveals the aluminium concentration of the different layers as well as the doping type. Polishing a ramp through the top layers followed by oxidation may give more detailed information. It is also worth the effort investigating the possibility of ellipsometry for measurement of the aluminium percentages.

The creation of ridges by wet etching has been found to be well controllable. In case of etching narrow and deep structures, the ridge shape however presents some difficulties mainly caused by under etching during rinsing in water. Rinsing in methanol fails as it dissolves the photo resist. Perhaps the methanol can be treated in a way to prevent this. So far, 4 μm wide ridge lasers with a height of 2μm have been etched successfully and show good light confinement.

Good contacts have been obtained on the p-type top layers by deposition of platinum and gold. The attachment of the metallization on the oxide layer has been highly improved by baking the oxide in the RTA and by application of titanium. Also bonding has been improved by a titanium buffer layer. N-type back contacts consisting of a gold germanium nickel alloy showing good results. To enable bonding on the back, the application of a titanium buffer layer has been tried but this causes poor alloying. Better results may be gained by deposition of the titanium and top gold layer only after alloying. For minimal resistance, research is needed to find the optimal annealing temperature and duration for both top and back contact.
Friction between lasers after cleaving complete samples may cause some damage to the mirrors. To reduce this problem, bars need to be broken separately. Mounting on DIL packages gives sufficient results for pulsed operation. Also small lasers with low heat production can be operated continuously. For mounting on top of heatsinks, bonding on top of the backside is preferable which emphasizes the need for a good back contact.

6.2 Laser performance

Several type of ridge waveguide lasers have been produced with the MQW structures provided by the Solid State Physics group. First of all, broad area lasers have been made of different lengths. Measurements of the current densities at threshold and the differential efficiency show good performance. Values of about 7 cm\(^{-1}\) have been found for the total internal absorption of all the structures. A transparency current density of 74 A/cm\(^2\) was found for the SQW structure. This value seems to increase less than proportional to the number of quantumwells. This may be the result of better overall confinement of light or an improved carrier distribution in the structures with more quantumwells. Further investigations are recommended to explain this behaviour.

Narrow ridge lasers with a width of 4 \(\mu\)m have been made using the SQW structure. Best results have been gained with a length of 0.5 mm. The measured threshold currents are 7.2 mA for pulsed and 10.8 mA for continuous operation. The latter value may be reduced by mounting the lasers with the ridge on top of a heatsink. 4QW lasers also show good results indicating again a less than proportional increase of threshold current with respect to the number of quantum wells.

The laser arrays that have been made show promising results. Problems arise with the manual positioning during mask alignment causing non-uniformity among separate lasers. Also the cleaving of these lasers seems difficult. Improvement of this combined with the use of a specially designed mask should yield good performance.

Finally flared waveguide lasers have been produced. Especially tapered waveguides seem to function properly and show high light output. Rectangular waveguides show less good results, probably due to short cavity lengths. With optimal geometry design improvements are probably achievable.
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Appendix: Figures

Figure A1 Transversal near field pattern, L7 SQW-laser
W = 30μm L = 340μm (light output not to scale)
Figure A2 Lateral near field pattern L6 3QW-laser
W=30µm L=300µm (light output not to scale)
Figure A3 Lateral near field pattern L7 SQW-laser
W = 50μm L = 340μm (light output not to scale)
Figure A4 Example P/I-measurements L5 2QW-lasers
W=30/50μm L=300μm
Figure A5 Example P/I-measurements L8 4QW-lasers
W = 30/50μm L = 700μm
Threshold Current L7
1 Quantumwell

- w=30
- w=50

Threshold Current L5
2 Quantumwells

- w=30
- w=50

Figure A6

Figure A7
Threshold Current L6
3 Quantumwells

\[ I_{th} [\text{mA}] \]

\[ L [\mu \text{m}] \]

Figure A8

Threshold current L8
4 Quantumwells

\[ I_{th} [\text{mA}] \]

\[ L [\mu \text{m}] \]

Figure A9
Threshold Current L7/5

\( w = 30 \, \mu m \)
- L7: 1 QW
- L5: 2 QW's

Figure A10

Threshold Current Density L7
1 Quantumwell
- \( w = 30 \)
- \( w = 50 \)

Figure A11
Threshold Current Density L5
2 Quantumwells

- w=30
- w=50

Figure A12

Threshold Current Density L6
3 Quantumwells

- w=30
- w=50

Figure A13
Threshold Current Density L8
4 Quantumwells

Figure A14

Differential Efficiency L7
1 Quantumwell

Figure A15
Figure A16

Differential Efficiency L5
2 Quantum wells

\[ \begin{array}{cc}
\bullet & w=30 \\
\triangle & w=50 \\
\end{array} \]

Figure A17

Differential Efficiency L6
3 Quantum wells

\[ \begin{array}{cc}
\bullet & w=30 \\
\triangle & w=50 \\
\end{array} \]
Differential Efficiency L8
4 Quantum wells
• w=30 ▲ w=50

Figure A18

Internal Loss L7
1 Quantum well
• w=30 ▲ w=50

Figure A19
Internal Loss L5
2 Quantumwells

\[ \bullet \quad w=30 \quad \triangle \quad w=50 \]

Figure A20

Internal Loss L6
3 Quantumwells

\[ \bullet \quad w=30 \quad \triangle \quad w=50 \]

Figure A21
Internal Loss L8
4 Quantumwells

![Graph showing internal loss L8 with 4 quantum wells.]

- w=30
- w=50

Figure A22

Internal Loss

- measured
- ai'=7.7

![Graph showing internal loss with number of quantum wells on the x-axis and ai in [1/cm] on the y-axis.]

Figure A23

A 14
Figure A24

Current Densities at Threshold

$J_\text{th} [\text{A/cm}^2]$

Number of quantum wells

Figure A25

Nominal Transparency Current Density

$J_{\text{nom}} [\text{A/\mu mcm}^2]$

Number of quantum wells
Figure A26 Lateral near field pattern L7 SQW-laser
$W=4.3 \mu \text{m}$ $L=500 \mu \text{m}$ (light output not to scale)
Figure A27 Lateral and transversal far field pattern L7 SQW-laser
$W=4.3\mu m \ L=500\mu m$ (arbitrary scales)
Figure A28 SQW Laser spectra. Top: L = 250 µm, bottom: L = 500 µm.
Figure A29 P/I measurements L7 SQW-lasers, w=4.3 µm
Threshold Current L7
SQW lasers w=4.3μm

Figure A30
Figure A31 Lateral near field pattern SQW 3 ridge array laser, L=436μm (light output not to scale)
Figure A32 Lateral and transversal far field patterns SQW 3 ridge array laser L=436μm (arbitrary scales)
Figure A33 P/I measurement SQW 3 ridge array laser, L=436 μm
Figure A34 Lateral near field pattern SQW flared waveguide laser, w=6μm W=12μm (light output not to scale)
Figure A35 Lateral and transversal far field patterns SQW flared waveguide laser, \( w=6\mu m \) \( W=12\mu m \) (arbitrary scales)
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