Defining an optimal plasma processing toolkit for Indium Phosphide (InP) laser diode production

The properties of InP which combine a wide band gap with high electron mobility, make it a desirable semiconductor for the manufacture of optoelectronic devices. A key application is communication and this is expanding rapidly with increased data traffic.

InP enables the manufacture of components that can operate at high frequencies allowing higher volumes of data. In particular it offers compelling advantages for laser diode manufacture delivering excellent functionality at a competitive price. When design and fabrication is optimised InP lasers provide high spectral purity and optical power, over a wide temperature range. Furthermore the achievable wavelength range of 1100 – 2000 nm is optimal for fibre optic communications. Establishing cost-effective processing strategies for the production of InP lasers therefore directly supports the advancement of communications to support the ever increasing demand for data transfer.

In this white paper we examine the role of plasma processing technologies in InP laser diode manufacture focusing on the relative merits of inductively coupled plasma chemical vapour deposition (ICPCVD), plasma enhanced CVD (PECVD), reactive ion etching (RIE) and ICP-RIE. A primary aim is to highlight the relevant characteristics of different processes and show how they can be optimally applied, in combination, to efficiently fabricate high performance lasers.

Understanding InP laser diodes

In a laser diode, photons are spontaneously emitted when an electron and a hole recombine and interact with incoming electrons to produce more photons, propagating the process of resonance which ultimately produces a collimated laser beam. Direct band gap semiconductors such as InP with atomic structures that allow for the possibility of photon emissions are clearly a prerequisite for such devices. However the properties of the resulting laser, in particular its wavelength, are influenced not only by the band gap of the semiconductor but also by the physical structure of the device. Waveguides and gratings play an essential role in amplifying the light and controlling the wavelength band of the resulting laser.

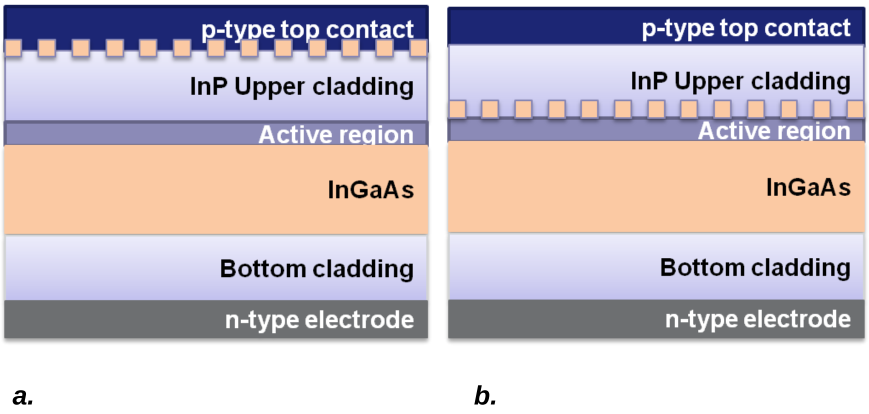


Figure 1: InP laser structure with a. surface distributed feedback and b. buried distributed feedback

Figure 1 shows the key features of an InP laser with surface and buried distributed feedback (DFB). Electron/hole recombination takes place in the active region with light contained by the higher refractive index of the cladding layers. Waveguides allow the light to be directed as required, while the DFB grating narrows the wavelength band, enabling exploitation of the core characteristics of the semiconductor to produce lasers with specific wavelengths for different applications.

All the material layers that form the basis of an InP laser are laid down using epitaxial growth techniques but the deposition, masking and etching steps used to incorporate the necessary waveguides and gratings are implemented using plasma processing methods. The defining characteristics of such features are smooth walls, a vertical side wall profile and precisely controlled depth. Surface roughness is associated with light scattering and absorption which reduces amplification relative to loss and consequently the intensity of the laser (power). In addition, smooth surfaces minimise contact resistance throughout the device maximising the conversion of power to light. Precise geometry is essential for wavelength control and in the case of a waveguide, retain the light in the correct layer of the device.

An array of plasma processing techniques is required with each optimally suited to different fabrication steps. These differ not only in their ability to answer to the requirements outlined above but also in practical aspects of industrial manufacture such as equipment and running costs, throughput and product uniformity.

Introducing the core plasma processing technologies for InP laser fabrication

Plasma can be described as a fourth state of matter containing positive ions, electrons, radicals and non-ionised gas. Ionising a gas requires the input of significant amounts of energy (usually electrical or thermal) and the resulting plasma is highly energetic with properties which are well suited for well controlled semiconductor manufacture. These properties can be tuned through the manipulation of chemistry, by varying plasma composition or processing conditions such as pressure or wafer temperature offering exceptional flexibility to achieve and precisely control a very wide range of surface interactions. Furthermore because they contain free electrons, plasmas can be controlled both by electrical and/or magnetic fields within processing equipment. These inherent attractions have led to the commercialisation of highly productive and configurable plasma-based process tools for semiconductor device fabrication. Those utilising the following techniques are particularly valuable for InP laser fabrication:

PECVD – desirable film properties for a wide range of materials

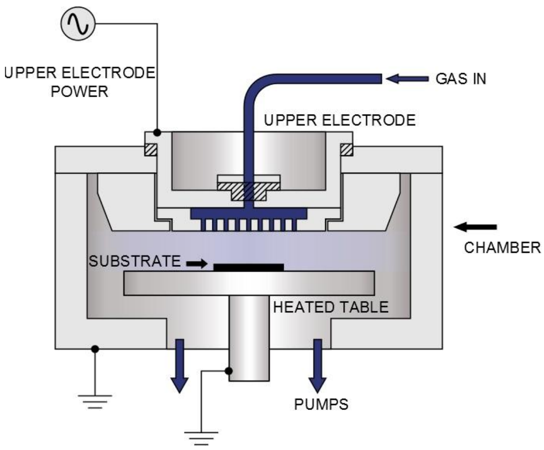


Figure 2: PECVD enables the deposition of high quality films at relatively low working temperatures

PECVD involves the reaction and deposition of ionised gases from a plasma onto a cooled substrate to form a film or coating.

Figure 2 shows the key features of a PECVD system. A gas mixture is pumped into the vacuum chamber via a 'showerhead' gas inlet in the top electrode and plasma is generated by the application of RF power. Deposition occurs on the substrate surface as radicals and ions from the plasma form material on the sample, with unused material pumped away. Operating pressures are typically in the region of 0.5 to 1.0 Torr.

PECVD can be used for an extremely wide range of materials, including SiO_x and SiN_x both of which are used for masking subsequent etch processes or passivation deposition in InP fabrication. It produces uniform high quality films, more specifically high density films with minimal pinholing, and enables the close control of material properties such as refractive index and hardness. Operating temperatures for PECVD processes typically lie in the range 90 – 650^{o}C with substrate temperatures ~300^{o}C used for processing InP.

ICP-CVD – Plasma deposition at low temperatures with minimal substrate damage

In ICP-CVD, as the name suggests, an ICP is used in place of the electrically generated plasma applied in PECVD processes (see figure 3). Inert gases are fed in at the top of the vacuum chamber and converted to plasma as they pass through the powered coil. A second gas feed point just above the substrate enables the separate introduction of reactant gases which trigger the formation of the film, along with dopants where required. RF biasing can be applied across the substrate table to manipulate the properties of the film. Operating pressures are typically in the region of 1 – 10 mtorr, far lower than for PECVD.

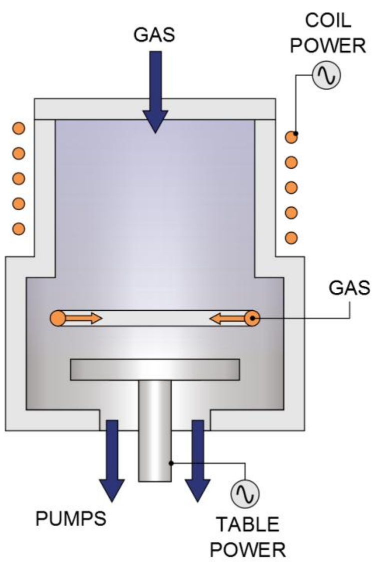


Figure 3: ICP-CVD enables low temperature

ICP results in a high density flux at the substrate surface. This enables the production of high quality films at lower temperatures than those achievable with PECVD. Operating temperatures for ICP-CVD processes are typically in the range 20 – 400^{o}C, though higher temperatures are accessible with the substrate typically maintained at a temperature of ~150^{o}C or less. This is an important advantage, particularly for certain Si-based materials. ICP-CVD is also associated with low substrate damage. This is attributable to the low ion energies associated with deposition and/or the remoteness of the plasma.

Generally speaking ICP-CVD provides excellent coverage and is prized for delivering good conformality, particularly for deeper features.

RIE – flexible, simple directional etching

RIE is one of the simplest options for general plasma etching. As with PECVD, only one of the electrodes in an RIE system in charged, however in this instance it is the table on which the substrate sits (see figure 4). Gas enters the chamber through the top electrode and plasma is initiated by the application of RF power to the lower electrode. This results in the development of a negative self-bias on the table which influences the directionality of the etching. With this relatively simple set-up ion density and energy are both controlled via the same single RF source.

RIE can be used for chemical, ion induced or physical etching and is suitable for a wide range of materials including III-V materials such as InP. Rates can be increased by putting more power into the lower electrode thereby generating a higher DC bias. However, this simultaneously increases the energy with which ions impact the substrate increasing the risk of, for example, mask damage**.**

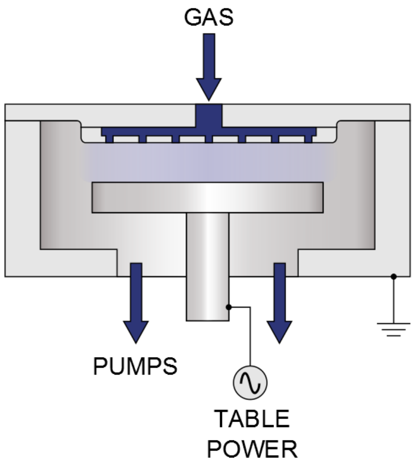
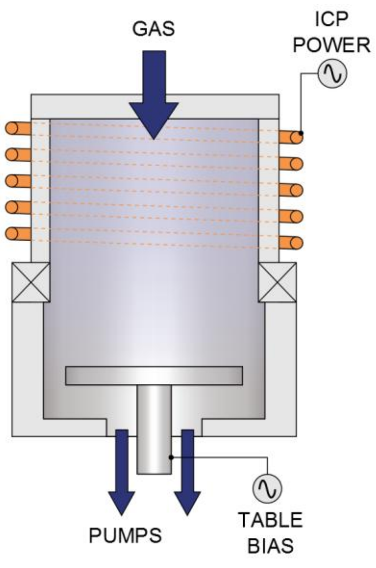


Figure 4: RIE is a flexible cost-effective option for directional etching

ICP-RIE – high etching rates coupled with accurate temperature control



The unique properties of ICP can be used to enhance the performance of RIE in an analogous way to its use in ICP-CVD. Figure 5 shows a schematic of an ICP-RIE system.

The high ion density of the ICP boosts etch rates without any accompanying increase in bias. ICP systems enable the independent control of ion density (RF power to the coil) and ion energy (RF power to the table) allowing ion density to be tuned to maximise etch rate while ion energy is minimised to reduce substrate damage and enhance selectivity. Furthermore higher plasma density is achieved at lower pressure enabling better control over selectivity, more directional etching and better profiles. Modern systems offer wafer clamping and helium cooling as standard which means that excellent temperature control can be maintained over a wide operating range.

Figure 5: ICP-RIE delivers high etch rates, at the same time allowing close control of the temperature of the substrate

Choosing an optimal processing technology for each fabrication step

An understanding of the different features of alternative plasma processing techniques aids assessment of their relevance and suitability for different stages of the InP fabrication process. Figure 6 shows the steps involved in the construction of a typical InP laser, highlighting the plasma processing techniques that are most suitable for each. While each step is important it is the InP Mesa/Ridge etch that is arguably most critical with the properties of the resulting waveguide having a defining impact on the quality of the finished laser. In the following sections we consider the selection of plasma processes for each step, with reference to example performance data. These data are derived from experience with Oxford Instruments systems in each specific application, either in laboratory and/or proof of performance studies (see call out box 'Working with Oxford Instruments') or within the manufacturing environment.

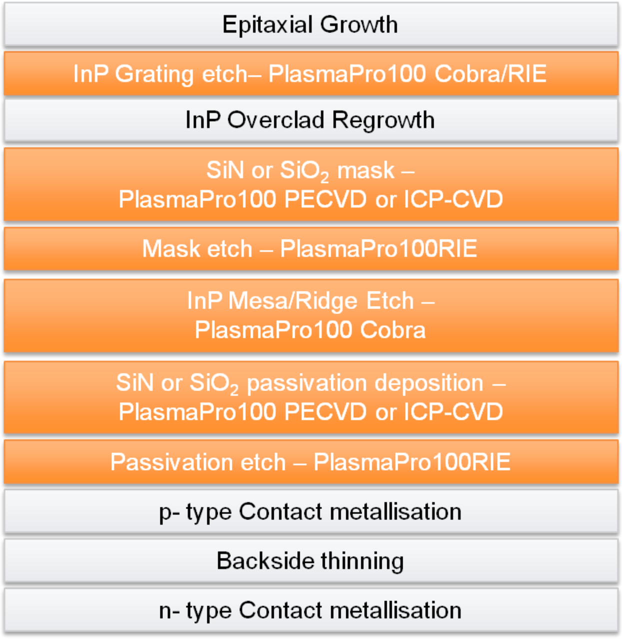


Figure 6: The processing steps involved in the fabrication of an InP laser with those implemented using plasma processing methods highlighted in orange

InP grating etch

InP grating etch is the first plasma processing step and produces the DFB grating. Here we are looking for:

- A shallow etch, typically in the order of 100 nm
- Precisely controlled depth
- Process compatibility with the use of photoresist
- Only moderate etch rates since this is a shallow etch and depth accuracy is essential

A photoresist mask is usually the easiest and least expensive option for the grating etch, with electron beam (e-beam) patterning delivering excellent line definition. However, erosion can be a problem with photoresist having a tendency to pull back from defined features as the etch proceeds. A SiO_x (or SiN_x) mask is the alternative. These thinner

Wafer Size (*2"single wafer*)	*RIE mode*	*ICP mode*
Process Gases	CH_4/H_2	
Etch depth	up to 100nm	
Selectivity (Oxide)	>10:1	>5:1
Selectivity (Photoresist)	>2:1	NA
Etch rate (nm/min)	>15	>50
Profile	>80 Mask profile >85°	>80 Mask profile >85°
Uniformity 2" size	<±2%	<±2%
Wafer to wafer	<±4%	<±4%

Table 1: Using ICP boosts the etch rate of RIE but results in lower selectivity in the InP grating etch

films enable a more selective etch than is achievable with a photoresist, simultaneously supporting a deeper InP etch with a good vertical profile. With either mask the etch itself can be made using either RIE or ICP-RIE (see table 1) using a methane/hydrogen process gas mixture.

In this application RIE and ICP-RIE perform similarly in terms of the profile delivered and uniformity. In all fabrication processes repeatability and uniformity both across a single wafer and from wafer to wafer, are carefully monitored since these are critical to the maintenance of consistent device quality. RIE, the simpler process, is notably slower than ICP-RIE but does offer more selective etching of the InP thereby preserving the mask. Since high rates are not essential RIE is most often the method of choice, primarily on the basis of simplicity.

An important aspect of etch control is endpoint determination (EPD); secure identification of the time at which etching should be cease because the grating has reached the required depth. One approach, with a well-controlled process, is to etch for a predetermined period of time but a more effective strategy is to employ in-process monitoring. Figure 7 shows the signal from a laser interferometer being used to monitor the advance of an etch through alternate layers of InP and InGaAsP. The refractive index of the material through which the etch is proceeding has a marked impact on the signal, providing clear evidence of progress through successive layers. Having established that to deliver a depth >75 nm this etch should stop in the No3 InP layer, close to the boundary of the No4 InGaAsP layer (which occurs at a total layer depth of 85nm), this signal can be used to automated EPD and streamline process control.

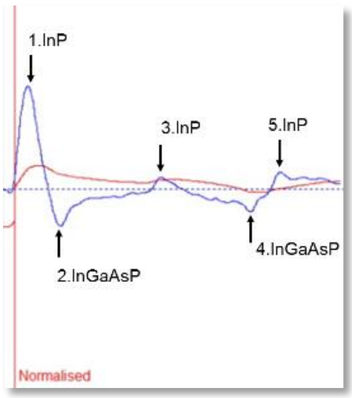


Figure 7: Laser interferometry can be used for endpoint determination to precisely control etch depth within the manufacturing environment

Grating Epi Structure		Thickness (nm)
1. InP	n = 3.17	15
2. InGaAsP	n = 3.3	30
3. InP	n = 3.17	40
4. InGaAsP	n = 3.3	20
5. InP	n = 3.17	50

Index @ 1310nm

Masking and etching the InP Mesa/Ridge

The InP Mesa/Ridge etch forms the waveguide for the laser and is significantly deeper than the grating etch, up to 5 or 10 µm. This step has a defining influence on laser quality and is the most demanding in terms of plasma processing technology choice and processing conditions. Key requirements are:

- A high etch rate
- Highly anisotropic etching to achieve a deep, vertical-walled profile
- High selectivity to SiO_x/SiN_x, the most commonly used materials for masking

Attainment of a deeper etch in an acceptable processing time necessitates higher temperature processing, typically in excess of around 160°C. At these temperatures the $InCl_x$ formed from the chlorinated gas chemistry becomes volatile so etching occurs. Unfortunately using photoresist is not possible at it burns, so a dielectric mask is required. The fabrication of this mask is the first step in the development of the InP Mesa/Ridge.

Fabricating the InP Mesa/Ridge mask

The choice of material for the InP Mesa/Ridge mask typically lies between SiN_x and SiO_x. SiN_x has a tendency to facet less resulting in a good right-angled profile with less pronounced rounding than is observed with SiO_x and is often the preference. Faceting is where the top corners of a masking pattern are eroded faster than the planar surfaces and can compromise mask quality. In either case the mask is patterned using photoresist, which is then removed prior to etching of the InP through the SiN_x/SiO_x. Residual mask is subsequently removed in a final step.

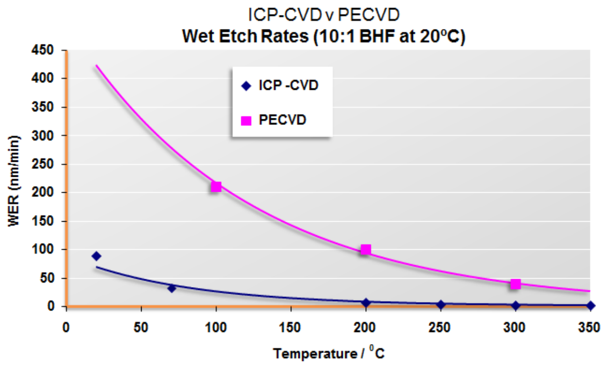
Choice of technique for mask deposition is usually based primarily on film quality, though deposition rate is also important. High film quality, more specifically high film density, is associated with high selectivity during the subsequent etch and is quantified for comparative purposes via wet etch rates (WERs), measured under standardised conditions using potassium hydroxide or buffered HF (buffered oxide etch - BOE).

A further consideration is the need for hydrogen-free deposition. In certain circumstances hydrogen can change the stoichiometry of InP during processing, thereby influencing the performance of the device. Removing any possibility of hydrogen evolution by avoiding the use of ammonia for example as a deposition gas is common practice.

Table 2 contrasts the operating conditions for PECVD and ICP-CVD, the alternative processes for mask deposition. PECVD is the faster process and usually the preference except in applications where there is a temperature limitation. Here the lower operating temperature of ICP-CVD is an advantage that more than offsets the somewhat lower deposition rates obtained. Both PECVD and ICP-CVD can be deployed with low hydrogen process chemistries where required.

	PECVD	ICPCVD
Recommended temperature range	90°C – 650°C	20°C – 400°C (higher temperatures possible)
Equivalent temperature	~300°C	~100°C
Stress control methods	SiNx – LF power, He addition, power, pressure SiOx – SiH_4, power	All film types, process conditions, e.g. ICP power, pressure.
Process pressures	600 – 3000mTorr	2 – 30mTorr
Power ranges	20 – 1000W	150W – 2000W
Deposition rates	7 – 1200nm/min	6 – 150nm/min

Table 2: PECVD delivers high SiN_x/SiO_x deposition rates but requires higher operating temperatures which can be a limitation for some devices



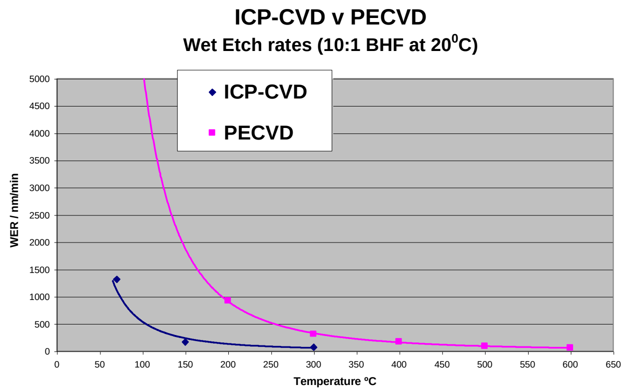


Figure 8: Wet etch rates highlight the higher quality of SiN_x films (upper graph), relative to SiOx analogues (lower graph), and the ability of ICP-CVD to deliver high quality films at low processing temperatures

Figure 8 compares WERs for both SiN_x and SiO_x films made by PECVD and ICP-CVD. In terms of film quality the SiN_x films are superior to those fabricated from SiO_x, regardless of processing technique. However, the films deposited by ICP-CVD are superior to those deposited by PECVD as well as exhibiting performance that is less temperature dependent. In all cases film quality improves with processing temperature but this effect is particularly modest with ICP-CVD SiN_x films, which exhibit excellent quality when manufactured at very low temperatures.

RIE is typically used for etching of this mask as it offers a simple cost effective option for this relatively undemanding application, where etch rates tend are not critical. Figure 9 shows the results of using RIE to etch a SiN mask. This etch was carried out using a SF_6-CHF_3 process using a PlasmaPro 100 RIE. An excellent vertical feature was achieved; this is essential to create a vertical InP profile during the following etch step.

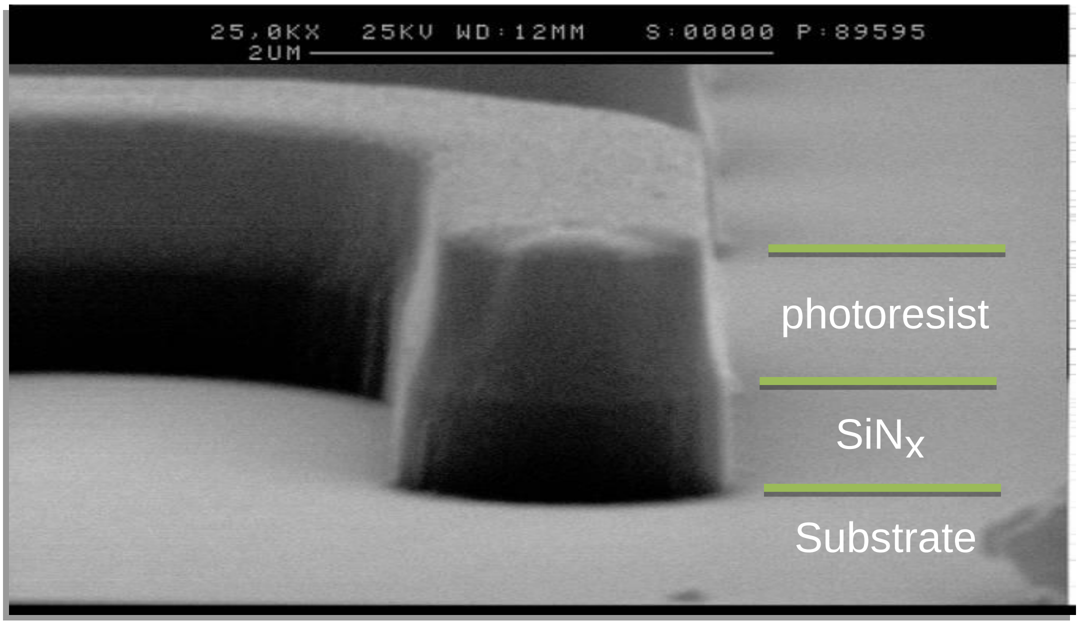
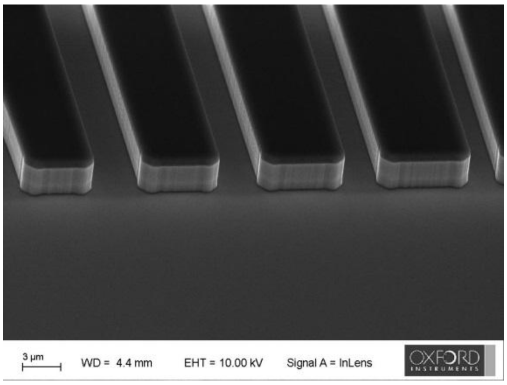


Figure 9: RIE can be used, along with photoresist, to fabricate a high quality SiN_x mask for etching of the InP Mesa/Ridge

The InP Mesa/Ridge etch

For the InP Mesa/Ridge etch, ICP-RIE is typically the technology of choice because of its capacity to deliver high etch rates, vertical etch profiles and smooth etch surfaces important for low loss from light scattering. Chlorinated process chemistry is typically chosen for this etch as it results in highly anistropic, smooth etch profiles.



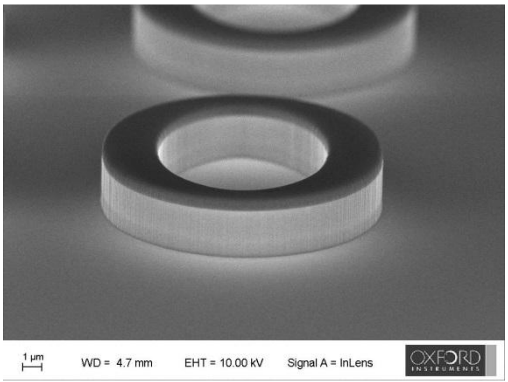


Figure 10: Using chlorinated process chemistries, ICP-RIE is unrivalled for delivery of the precise profiles and smooth surfaces required for the critical InP Mesa/Ridge etch

The optimal application of chlorine-based recipes requires the careful balancing of gas composition and temperature to control the volatilisation rate of the $InCl_x$ compounds formed during etching. The low volatility of $InCl_x$ allows desirable highly anisotropic etching to achieve a deep, vertical-walled profile but if volatility becomes too low then deposition occurs on the developing surfaces increasing roughness. On the other hand, excessive evaporation rates are associated with undercutting. Temperature is optimised to control these effects with chlorine-based InP etching processes tending to operate in excess of 160^{o}C

In fact, two different chlorine-based plasma chemistries are suitable for this etch – methane/hydrogen/chlorine or a chlorine/argon alternative. These processes differ significantly in the level of temperature control required, which in turn impacts the clamping applied to the device, an important practical consideration. With the methane/hydrogen/chlorine option, heat is supplied by the plasma and the wafer simply sits on the electrode. Thermal contact to the lower electrode is minimal and the wafer temperature is elevated high enough by the plasma for the $InCl_x$ to become volatile under ion bombardment.

In contrast, with the chlorine/argon process, more precise temperature control is required and the wafer is consequently mechanically clamped to the electrode, a layer of helium between the two enhancing heat transfer. Mechanical clamping is the topic of much debate in the industry, prized for the control it offers but disliked because of the potential for wafer breakage. Better options that address these concerns are therefore an important goal for ongoing process development. The operating temperature for this process is typically in excess of 160^{o}C.

Etch rate	>500nm/min
Selectivity	>15:1
Uniformity (2mm EE)	<+/-2%
Repeatability	<+/-2%
Side wall	smooth
Surface	smooth

Etch rate	>750nm/min
Selectivity	~20:1
Uniformity (2mm EE)	<+/-2%
Repeatability	<+/-2%
Side wall	smooth
Surface	smooth

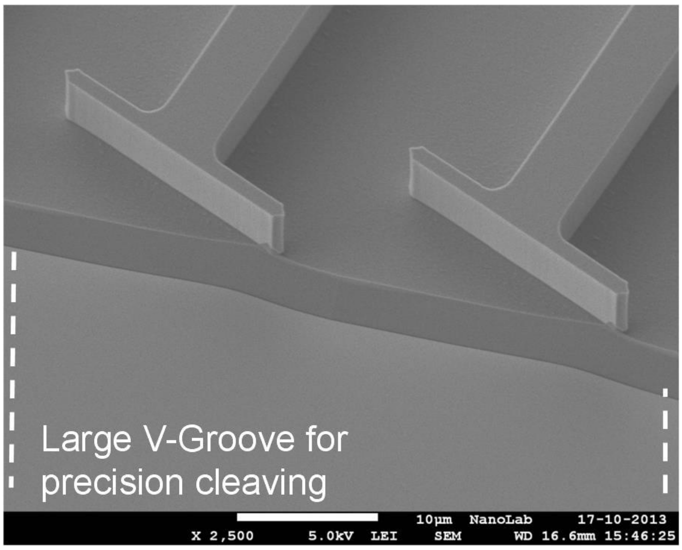
Table 3: Performance data for the argon/chlorine chemistry (right) show that it delivers a higher etch rate and higher selectivity than the methane/hydrogen/chlorine alternative (left)

Table 3 shows data for the performance of the two alternative process chemistries applied in the InP Ridge/Mesa etch. In terms of profile, repeatability and uniformity they are closely similar, however, the higher temperature argon based process delivers a higher etch rate and higher selectivity.

As with the grating etch, EPD within the manufacturing environment can be enhanced for this etch using embedded monitoring technology. Here, optical emission spectroscopy has proven application and can be used to analyse the plasma, as the etch proceeds, to monitor progress. When integrated with processing software such analysis helps manufacturers to achieve maximum throughput and highly consistent product quality.

ICP enhanced etching - proven performance for the most demanding of applications

The InP Mesa/Ridge etch is widely recognised as the most critical of the plasma processing steps associated with InP laser fabrication. The properties of the resulting waveguide are performance-defining for the finished laser and the requirements for precise conformality and smooth walls over a deep etch create a demanding technical challenge. Work by researchers at the Phototonic Integration Group at Eindhoven University of Technology demonstrates the ability of ICP-enhanced etching processes such as ICP-RIE to answer to this challenge.*



SEM micrographs of etched facet waveguides produced using an ICP-based etching process illustrate the exemplary characteristics of the resulting structures

A study was carried out to fabricate etched facet waveguides to support the advanced packaging of phototonic integrated circuits (PICs). Both straight and angled facet waveguides were successfully fabricated using a single ICP-based etching step and the resulting structures were characterised to compare the quality of the etched-facet waveguides with cleaved-facet analogues. The results showed that the ICP etching process produced smooth, vertical waveguide facets with excellent light transmitting performance, comparable to that of the cleaved-facet waveguides.

*_Lemos Alvares Dos Santos, R.M et al 'Fabrication and characterization of etched facets in InP for advanced packaging of Photonic Integrated circuits'_

Published in: Proceedings of the 19th Annual Symposium of the IEEE Photonics Benelux Chapter, 2-4 November 2014.

Passivation deposition and etch

The final plasma processing step InP laser fabrication is the deposition of a passivation layer and associated etching to enable electrical contacts to be implemented as required. SiN_x or SiO_x are again the materials of choice and this step has much in common with the preceding mask deposition. The technology choice typically comes down to PECVD or ICP-CVD with the latter preferred for temperature sensitive applications. Film quality at this point in this process is directly associated with protection of the device, with higher density films resisting the ingress of water more effectively and enabling the application of higher voltages prior to breakdown. The final etching step is typically implemented using simple RIE, as with the mask etch.

In conclusion:

Fabrication of the waveguides and gratings that deliver desirable performance in an InP laser diode requires the considered use of a range of plasma processing techniques. A suite of powerful and flexible plasma processing tools enable laser manufacturers to efficiently apply these techniques to achieve the deposition, masking and etching that is essential for the precise control of feature characteristics. A basic understanding of the strengths and limitations of these tools helps manufacturers to consistently produce the precisely controlled, smooth vertical profiles associated with exemplary device performance while simultaneously maximising throughput and minimising the cost of production.

Working with Oxford Instruments: Knowledgeable support, proven performance

With more than 6000 process recipes in our database we have unrivalled experience in the application of plasma processing techniques. Each new customer request tends to come in the form of a detailed specification defined in terms of, for example, a specific vertical profile, etch depth and/or surface roughness. We apply our expertise to develop the optimum process chemistry for the task, focusing not only on consistent delivery of the required quality but on also on critical manufacturing metrics such as throughput and equipment cost. We then robustly test the proposed strategy. Rigorous evaluation of the resulting samples is part of the ongoing dialogue we have with every customer to ensure that each solution offered is optimally tailored to the specific application.