# A Comparative Study of Fabrication of Long Wavelength Diode Lasers Using CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> and H<sub>2</sub>/CH<sub>4</sub>

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## ABSTRACT

We report comparatively on fabrication of two-section ridge-waveguide tapered 3 quantum well (QW) InGaAsP/InP (1300 nm) and 5 QW AlGaInAs/InP (1550 nm) diode lasers. Gas mixtures of  $CCl_2F_2/O_2$  and  $H_2/CH_4$  were used to form ridge-waveguide on the lasers with InP-based material structures. As known, chlorine- and hydro-carbon based gases are used to fabricate ridge-waveguide structures. Here, we show the difference between the structures obtained by using the both gas mixtures in which surface and sidewall structures as well as performance of the lasers were analysed using scanning electron microscopy. It is demonstrated that gas mixtures of  $CCl_2F_2/O_2$  highly deteriorated the etched structures although different flow rates, rf powers and base pressures were tried. We also show that the structures etched with  $H_2/CH_4$  gas mixtures produced much better results that led to the successful fabrication of two-section devices with ridge-waveguide. The lasers fabricated using  $H_2/CH_4$  were characterized using output power-current (P-I) and spectral results.

Keywords: Diode Lasers; Fabrication; Two-Section; Ridge-Waveguide; CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> and H<sub>2</sub>/CH<sub>4</sub>

## **1. Introduction**

InP-based devices have started to dominate opto-electronics because lasers and related devices with InGaAsP/InP and AlGaInAs/InP heterostructures are suitable for low-loss fibre communications and integrated optics. The fabrication of integrated optoelectronic devices necessitates pattern transfer techniques with a high degree of precision and a variable anisotropy, which is not achievable with wet etching process. Various dry etching techniques, such as plasma etching [1-2], reactive ion etching (RIE) [3-5], ion beam etching (IBE) [6-7], reactive ion beam etching (RIBE) [8-9], chemically assisted ion beam etching (CAIBE) [10-11] and inductively coupled plasma (ICP or RIE/ICP) etching [12] have been successfully used to fabricate InP-based devices to date. Of these techniques, RIE and ICP, which are well known and widely used dry-etching methods, provide higher anisotropy and better surface morphology when compared with other techniques. RIE of InP has been reported by using Cl<sub>2</sub>-based (halogen) chemistries [13-14] and methane (CH<sub>4</sub>)/hydrogen(H<sub>2</sub>) mixtures [15-16].

In this study, we have fabricated two-section In-GaAsP/InP and AlGaInAs/InP laser devices with ridge waveguide using chlorine- and hydrocarbon based gas

mixtures and reported the results comparatively.

## 2. Fabrication of the Lasers

The epitaxial structures used for the fabrication of twocontact devices are InGaAsP/InP (1300 nm) with three quantum wells (QW) and AlGaInAs/InP (1550 nm) five quantum wells (QW). These material structures are MBE grown at the IQE (Europe) Ltd [17]. The epitaxial layers were grown on a Si doped (3 x 10<sup>18</sup>) InP substrate. The material system contained an 0.8 µm n-type InP lower cladding layer, a 226 nm waveguide layer, a 25 nm In<sub>0.85</sub> GaAs<sub>0.33</sub>P quaternary etch stop layer, a 1.6 µm p-type InP upper cladding layer, a 50 nm In<sub>0.71</sub>GaAs<sub>0.62</sub>P transition layer and finally an 0.2 µm In<sub>0.53</sub>GaAs contact layer with Zn doped at a concentration of > 1.5 x 10<sup>19</sup> cm<sup>-3</sup>.

The active layer in AlGaInAs structures contains five 6 nm Al<sub>0.24</sub>GaIn<sub>0.71</sub>As quantum wells sandwiched by 10 nm Al<sub>0.44</sub>GaIn<sub>0.49</sub>As barriers. The wells are surrounded in both directions with a 60 nm Al<sub>0.9</sub>GaIn<sub>0.53</sub>As buffer layer and a 60 nm intrinsic AlGaInAs step graded index region. Because AlGaInAs quaternary materials have a larger conduction band offset ( $\Delta Ec/\Delta Eg = 0.7$ ) compared to InGaAsP (( $\Delta Ec/\Delta Eg = 0.4$ ), termal stability and electron confinement in Al-quaternary quantum wells are better



than that of P-quaternary systems. Therefore, AlGaInAs QWs and barriers were used in our material system, allowing lasers to be operated without cooling. Our mask design incorporated 2 and 4  $\mu$ m wide straight waveguides tapering out at angles of 2°, as shown in **Figure 1**.

The etch mask, formed using standard photolithography process, contained 200 nm and 50 nm thick layers of sputtered  $Si_3N_4$  and evaporated Ni, respectively. The mask pattern was then transferred to the substrate by RIE with CHF<sub>3</sub>/O<sub>2</sub> (40/3 sccm) and HF. The fabrication result is shown in **Figure 2**.

#### 2.1. Formation of Ridge-waveguides

The ridge waveguide with a 1.7  $\mu$ m deep and 4  $\mu$ m wide was formed by dry etching InGaAs contact and InP upper cladding layers with a gas mixture of H<sub>2</sub>:CH<sub>4</sub> at a flow rate of 20:10 sccm and CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> at a flow rate of 19:1 sccm.

The stop-etch quaternary layer ( $In_{0.85}GaAs_{0.33}P$ ) is efficient to provide a precise control of etch depth. Dry etching was conducted in a parallel RIE at an RF power of 400 W and a process pressure of 0.75 mTorr. A maximum etch rate of 50 nm/min was observed in the RIE. A polymer layer accumulated in the chamber, requiring oxygen plasma (rf power 150 W, 50 sccm) cleaning after each run. In RIE process, etching occurs by both chemical due to the formation of volatile products and physical because of sputtering of surface by the ions. Etching result in a gas mixture of  $CCl_2F_2/O_2$  is shown in **Figure 3**.



Figure 1. Waveguide mask.



Figure 2. Formation of Si<sub>3</sub>N<sub>4</sub>/Ni mask.

As shown in **Figure 3**, the surface and sidewall has a sponge-like structure which proves that gas ions attacked and deteriorated the structure. When used hydrocarbon based gases ( $H_2$ :CH<sub>4</sub>), the etched structure exhibits much less roughness on the surface and sidewalls, as depicted in **Figure 4**.

A SiO<sub>2</sub> layer of 200 nm was then deposited using PECVD (plasma enhanced chemical vapor deposition) followed by the removal of the two-layered mask (SiO<sub>2</sub>/Ni) using  $H_2SO_4$  and HF. After applying contact window mask using a second photolithography process, the SiO<sub>2</sub> layer on the waveguide was removed by HF to confine the current injection to the ridge. Following a final photolithography process to form two-contact on the p-side, a 20 nm titanium and 200 nm gold metal alloy was used in the p-contact recipe. Then, the two contacts were defined by lift-off. The two sections, both monolithically integrated on a single laser chip, are called gain and absorber sections. Finally, a 14 nm Au, 14 nm Ge, 14 nm Au, 11 nm



Figure 3. Scanning electron microscope (SEM) photo of the etched structure using CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> gas mixtures.



Figure 4. SEM photo of the etched structure using  $H_2/CH_4$  gas mixtures.

Ni and 200 nm Au was deposited on the n-side after thinning the wafer to 100  $\mu$ m. Annealing at 400 °C for 1 minute was the optimum condition to obtain the best lasing characteristics since otherwise the devices gave very poor characteristics.

**Figure 5** shows the optical microscope image of the two-section device fabricated. Separation was deposited with  $SiO_2$  (green color) while the rest of the surface was evaporated with an alloy of Au/Ti (yellow color).

### 3. Characterisation Measurement Results

The laser was driven by a pulse generator, output of which was applied to a current probe to obtain current from the pulse generator. A digital oscilloscope was used to monitor the output of the current probe. Output powercurrent (P-I) measurements were carried out using an optical powermeter via an optical sensor. A single-mode fiber and an optical spectrum analyser were used to obtain spectral measurements from the laser.

**Figure 6** shows P-I result of the laser fabricated using  $CCl_2F_2/O_2$  gas mixtures. As seen in this figure, output power is very low and the laser is operating like an light emitting diode. P-I result of the device, in which  $H_2/CH_4$  gases are used, is shown in **Figure 7** that demonstrates much better result. As seen, the threshold current is around 40 mA.





Figure 5. Microscope image of two-section device.

Figure 6. P-I result of the laser etched by using  $\text{CCl}_2\text{F}_2/\text{O}_2$  gas mixtures.



Figure 7. P-I result of the laser etched by using  $H_2/CH_4$  gas mixtures.



Figure 8. Optical spectrum of the laser.

**Figure 8** shows the spectrum of the laser fabricated using AlGaInAs/InP (1550 nm) in which ridge-wave-guide was fabricated using  $H_2/CH_4$  gas mixtures.

#### 4. Conclusions

We showed the fabrication of two section tapered waveguide lasers with InGaAsP/InP and AlGaAsP/InP structures using gas mixtures of CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> and H<sub>2</sub>/CH<sub>4</sub>. It is demonstrated that smooth surface and sidewall structures were obtained using H<sub>2</sub>/CH<sub>4</sub> gas mixtures. However, it was also observed that the use of gas mixtures of CCl<sub>2</sub>F<sub>2</sub>/O<sub>2</sub> caused very rough structures that resulted in the failure of the laser devices. The lasers fabricated using hydrocarbon chemistries produced much better results with threshold current of ~40 mA. It can be concluded that the fabricated long wavelength diode lasers with 1550 nm wavelength can be used in fiber optic communication systems.

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#### REFERENCES

- D. E. Ibbotson and D. L. Flamm, "Plasma Etching for III-V Compound Devices.2," *Solid State Technology*, Vol. 31, 1988, p. 105.
- [2] J. W. Lee, J. Hong, C. R. Abernathy, E. S. Lambers, S. J. Pearton, W. S. Hobson and F. Ren, "Cl<sub>2</sub>/Ar Plasma Etching of Binary, Ternary, and Quaternary In-Based Compound Semiconductors," *Journal of Vacuum Science & Technology B*, Vol. 14, No. 4, 1996, pp. 2567-2573. doi:10.1116/1.588769
- [3] J. Hommel, M. Moser, M. Geiger, F. Scholz and H. Schwiser, "Investigations of Dry Etching in Al-GaInP/GaInP Using CCl<sub>2</sub>F<sub>2</sub>/Ar Reactive Ion Etching and Ar Ion Beam Etching," *Journal of Vacuum Science & Technology B*, Vol. 9, No. 6, 1991, pp. 3526-3529. doi:10.1116/1.585837
- [4] S. Allen and P. Silverberg, "Methane-Hydrogen III-V Metal-Organic Reactive Ion Etching," *Semiconductor Science and Technology*, Vol. 6, 1991, pp. 287-289. doi:10.1088/0268-1242/6/4/010
- [5] J. W. Mcnabb, H. G. Craighead, H. Temkin and R. A. Logan, "Anisotropic Rective Ion Etching of InP in Methane/Hydrogen Based Plasmas," *Journal of Vacuum Science & Technology B*, Vol. 9, No. 6, 1991, pp. 3535-3537. doi:10.1116/1.585839
- [6] Y. Yuba, K. Gamo, H. Toba, X. G. He and S. Namba, "Ion Beam Etching of InP. I. Ar Ion Beam Etching and Fabrication of Grating for Integrated Circuits," *Japanese*. *Journal of Applied Physics*, Vol. 22, No. 7, 1983, pp. 1206-1210. doi:10.1143/JJAP.22.1206
- [7] R. A. Mikhnev, S. K. Shtandel, M. I. Martynov and E. D. Olshanskii, "How Ion-Beam Etching Affects the Surface Quality of Optical Articles," *Journal of Optical Technology*, Vol. 66, No. 12, 1999, pp.1032-1034. <u>doi:10.1364/JOT.66.001032</u>
- [8] W. Katzschner, U. Niggebrugge, R. Lofflerr and H. Schroter-Janssen, H., "Reactive ion beam etching of InP with N<sub>2</sub> and N<sub>2</sub>/O<sub>2</sub> mixtures," *Applied Physics Letters*, Vol. 48, No. 3, 1986, pp. 230-232. doi:10.1063/1.96566
- [9] F. Frost, A. Schindler and F. Bigl, "Reactive Ion Beam Etching of InSb and InAs with Ultrasmooth Surfaces," *Semiconductor Science and Technology*, Vol. 13, 1998,

pp. 523-527. doi:10.1088/0268-1242/13/5/014

- [10] Bharadwaj, L. M., Bonhomme, P., Faure, J., Balossier, G., and Bajpai, R. P., "Chemically Assisted Ion Beam Etching of InP and InSb using Reactive Flux of Iodine and Ar<sup>+</sup> Beam," *Journal of Vacuum Science & Technology B*, Vol. 9, No. 3, 1991, pp. 1440-1444. doi:10.1116/1.585447
- [11] J. Daleiden, K. Czotscher, C. Hoffmann, R. Kiefer, S. Klussmann, S. Muller, A. Nutsch, W. Pletschen, S. Weisser, G. Trankle, J. Braunstein and G. Weimann, "Sidewall Slope Control of Chemically Assisted Ion-Beam Etched Structures in InP-Based Materials," *Journal of Vacuum Science & Technology B*, Vol. 16, No. 4, 1998, pp. 1864-1866. doi:10.1116/1.590099
- [12] S. Bouchoule, L. Vallier, T. Chevolleau and C. Cardinaud, "Effect of Cl2- and HBr-based Inductively Coupled Plasma Etching on InP Surface Composition Analyzed Using in Situ X-Ray Photoelectron Spectroscopy," *Journal of Vacuum Science & Technology A*, Vol. 30, No. 3, 2012, pp. 31301-31312.
- [13] J. Hommel, M. Moser, M. Geiger, F. Scholz and H. Schwiser, "Investigations of Dry Etching in Al-GaInP/GaInP Using CCl<sub>2</sub>F<sub>2</sub>/Ar Reactive Ion Etching and Ar Ion Beam Etching," *Journal of Vacuum Science & Technology B*, Vol. 9, No. 6, 1991, pp. 3526-3529. doi:10.1116/1.585837
- [14] J. W. Lee, J. Hong, C. R. Abernathy, E. S. Lambers, S. J. Pearton, W. S. Hobson and F. Ren, "Cl<sub>2</sub>/Ar Plasma Etching of Binary, Ternary, and Quaternary In-Based Compound Semiconductors," *Journal of Vacuum Science & Technology B*, Vol. 14, No. 4, 1996, pp. 2567-2573. doi:10.1116/1.588769
- [15] S. Allen and P. Silverberg, "Methane-Hydrogen III-V Metal-Organic Reactive Ion Etching," *Semiconductor Science and Technology*, Vol. 6, 1991, pp. 287-289. doi:10.1088/0268-1242/6/4/010
- [16] J. W. Mcnabb, H. G. Craighead, H. Temkin and R. A. Logan, "Anisotropic Rective Ion Etching of InP in Methane/Hydrogen Based Plasmas," *Journal of Vacuum Science & Technology B*, Vol. 9, No. 6, 1991, pp. 3535-3537. doi:10.1116/1.585839
- [17] B. Cakmak, T. Karacali and M. Biber, "Investigation of Q-Switched InP-Based 1550 nm Semiconductor Lasers," *Optics and Laser Technology*, Vol. 44, 2012, pp. 1593-1597. doi:10.1016/j.optlastec.2011.11.043