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Thermally Enhanced Reactive Ion Beam Etching of InGaAsP

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A technique for thermally enhanced dry etching of InP, InGaAs, and InGaAsP has been developed using RIBE equipment with an ECR ion source and a sample temperature controller. The etching properties, such as etched surface flatness, etched wall verticality, and aspect-ratio, were drastically improved for these materials by heating the samples. Those properties were comparable to those for GaAs. The etching technique was applied to form cavity mirrors for InGaAsP laser diodes. The mirror reflectivity was almost equal to cleaved facets.

1. Introduction

Dry etching is expected to be a key technology in the future fabrication of various optical and electronic semiconductor ICs. With AlGaAs materials, excellent etching properties with smooth surfaces and high aspect-ratio have been achieved with reactive ion etching (RIE)[1-3] and reactive ion beam etching (RIBE)[4] techniques. However, for a InGaAsP material system lattice-matched to InP, satisfactory dry etching properties such as smooth etched surface and high enough aspect-ratio have yet to be reported. At room-temperature sufficient InP/mask materials etch rate ratios have not been obtained because the etch rate for the InP is about one tenth of that for GaAs and is about the same as that for mask materials. It has been reported that such reaction products as $InCl_2$ or $InCl_3$ remain on the sample surface after the etching at room-temperature[5]. They have relatively high boiling points as compared with $GaCl_3$ or $AlCl_3$, which are produced during the etching of GaAs or AlGaAs (See Table 1). Sample heating is effective, therefore, for improving the etching properties of InP, InGaAs, and InGaAsP. First experiment of the thermally enhanced etching of InP was performed by RIE[6]. However, in the case of RIE, sample temperature measurement and controle with thermocouple is essentially difficult because an anode electrode, on which the sample is located, has to be electrically connected to RF power supply. An increase in InP etch rate with sample temperature was also confirmed in the case of RIBE[7]. However, etching conditions have not been well optimized from the points of the etch rate, surface morphology, and sidewall verticality.

In this paper, we report thermally enhanced RIBE of InGaAs and InGaAsP as well as of InP. Smooth etched surfaces with an aspect-ratio as high as 10, comparable to that for AlGaAs, have here been obtained for the first time. Further, we have applied this technique to the formation of etched cavity mirror laser diodes.

2. Experimental

2.1 Etching equipment

Figure 1 is a schematic diagram of the etching system. The system is essentially composed of an etching chamber and a sample preparation chamber. The sample is moved between the two chambers with a magnetically coupled transfer rod. The equipment has an electron cyclotron resonance (ECR) ion source excited by the combination of microwave and magnetic field at a Cl_2 gas pressure of 1.0×10^{-3} Torr. It can be evacuated up to 5×10^{-7} Torr. The ion extraction voltage is controlled from 0 to 1kV by a dual grid extractor. A sample heater has been installed to allow adjustment of sample temperature from room-temperature to 250°C. For this study, the gas pressure and Cl_2 flow rate were fixed at 1.0×10^{-3} Torr and 3.4 sccm respectively.

2.2 Etching properties

Figure 2 shows the ion extraction voltage dependence of the etch rates of various electrical materials at room-temperature. As shown in Fig. 2, the InP etch rate is about one tenth of the GaAs etch rate and comparable to that of SiO_2. Therefore, sufficient etch rate ratios with respect to mask materials, such as SiO_2, were not obtainable under these etching conditions. This means sample surfaces would be covered by reaction products, like $InCl_3$, $InCl_2$, or InCl, which suppress the etching progress[5,6].

Figure 3 shows the substrate temperature dependence of the InP etch rate plotted with the ion extraction voltage as a parameter. The etch rate increased with substrate temperature because sample heating enhanced the removal of reaction products. It showed an abrupt increase at 170-190°C which can be considerd as a sublimation point for the above mentioned reaction products at the etching environment. It also increased with the extraction voltage. The smoothest surfaces were obtained at a 400 V ion extraction voltage.

The morphology of etched surfaces degraded at temperatures over 200°C and under 150°C as shown in Figure 4. The smoothest etched surface was obtained in the temperature range of 170-180°C. In this range, optimum for the morphology, the InP etch rate was enhanced to about ten times as fast as that at room-temperature, while the etch rate for SiO_2 remained the same as at room-temperature. In this way, the InP-to-SiO_2 film etch rate ratio became about 10 to 1.

From the above results, the best etching property was determined to be at substrate temperatures of 170-180°C and an ion extraction voltage of 400 V. Figure 5 shows an SEM picture of InP walls and square pillars etched under those conditions. The wall thickness and height were 1 µm and 10 µm, respectively (Fig. 5(a)), which resulted in an aspect-ratio as high as 10. No crystallographic orientation dependence for etched profile was observed (Fig. 5(b)). The etched wall was smooth and vertical. With those results it was confirmed that the etching conditions were well optimized in thermally enhanced RIBE.

2.3 Application to device fabrication

One of the most interesting applications of this technique is the formation of laser cavity mirrors. The etching properties for InGaAs and InGaAsP (λg=1.3 µm) were also studied for that purpose. The etch rates and surface morphologies of InGaAs and InGaAsP(λg=1.3 µm) showed the same temperature and ion extraction voltage dependence. Figure 6 shows the In mole fraction (x) dependence of the $In_xGa_{1-x}As_yP_{1-y}$ etch rate. The $In_xGa_{1-x}As_yP_{1-y}$ etch rate decreased with increasing In mole fractions. The etching properties for various InGaAsP compounds compositions were almost similar, except for a slight difference in etch rates and surface morphologies. The InGaAs surface was slightly smoother than that for InP at all temperatures. We then applied this technique to the fabrication of laser diodes with etched cavity mirrors. Figure 7 is an SEM picture of an etched laser cavity. Smooth surfaces were obtained, except for a slight vertical corrugation whose height is small enough with respect to the optical wavelength. For the etching mask, hard baked AZ-1350 photoresist was used. Smoother surfaces might be obtained by the improvement of the mask lithography process. Figure 8 shows the L-I characteristics of a BH-LD with one facet etched and the other cleaved. The etched facet has comparable reflectivity to the cleaved facet, evidenced by almost exactly the same slope efficiencies for both facets.

3. Conclusion

A thermally enhanced RIBE technique for InGaAsP has been developed. The InGaAsP etch rate increased dramatically with sample heating. Smooth etched surfaces, vertical walls, and high aspect-ratio etching, comparable to that for GaAs, were attained under optimized etching conditions: sample temperatures of 170-180°C, ion extraction voltage of 400 V with gas pressure of 1.0×10^{-3} Torr. Laser diodes formed with one etched mirror and another cleaved were examined. We estimate the reflectivities of etched surfaces to be equal to those of cleaved facets.

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Table 1 Boiling points of various III, V-chlorides.

Reaction products	Boiling points	Reaction products	Boiling points
$AlCl_3$	183	PCl_5	162
$GaCl_2$	535	PCl_3	76
$GaCl_3$	201	$AsCl_3$	130
InCl	608		
$InCl_2$	560		
$InCl_3$	600		

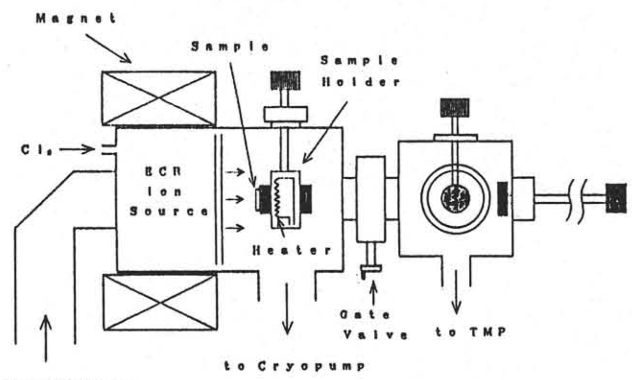


Fig. 1 Schematic diagram of RIBE equipment, including installed sample heater.

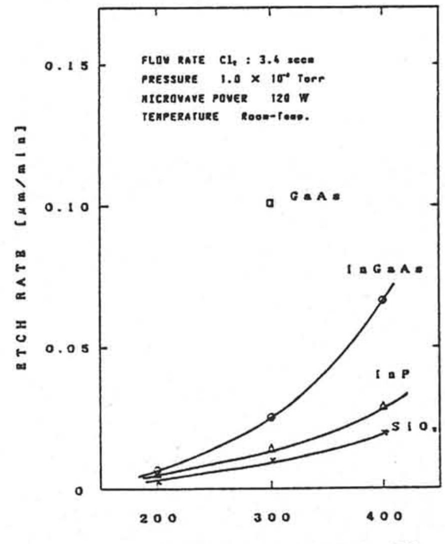


Fig. 2 Measured etch rates for various electrical materials as a function of the ion extraction voltage at room-temperature.

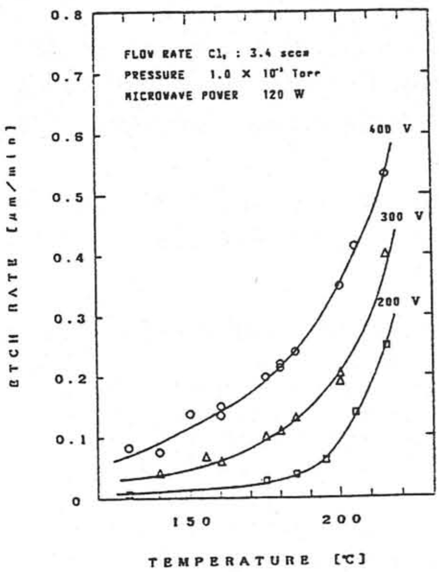


Fig. 3 Measured InP etch rates as a function of the sample temperature.

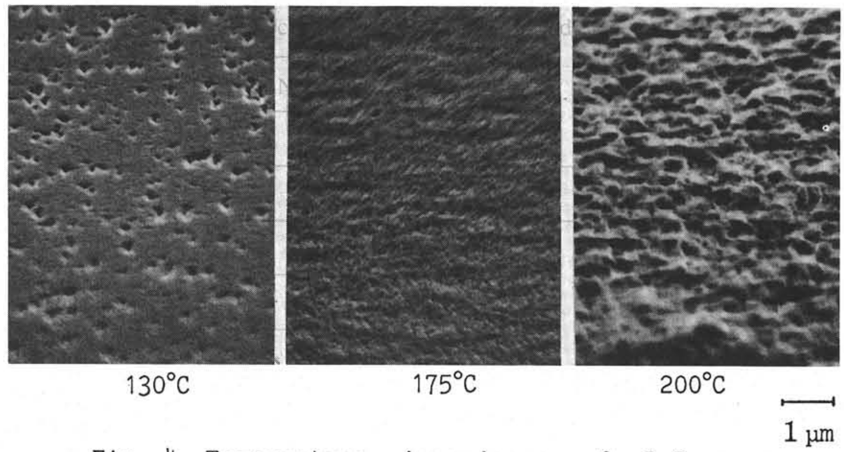
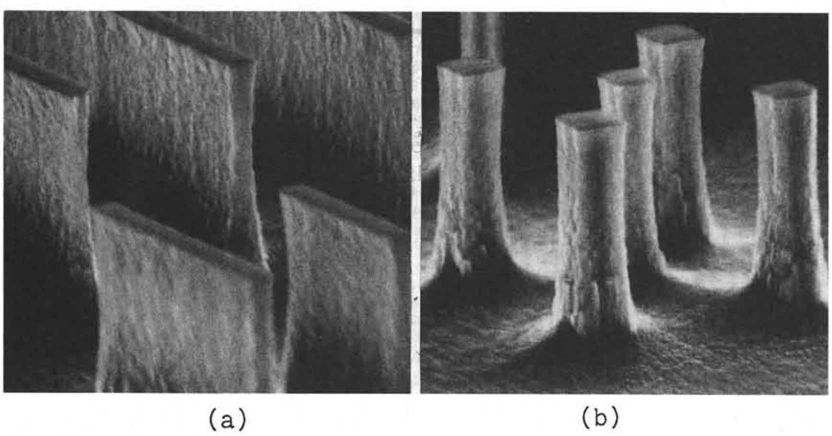


Fig. 4 Temperature dependence of InP surface morphology. The extraction voltage was 400 V.



ETCHING CONDITIONS
Temperature 180°C
Flow rate Cl_2: 3.4 sccm
Pressure 1.0×10^{-3} Torr
Ion extraction voltage 400 V

5 µm

Fig. 5 SEM pictures of the processed InP substrate.

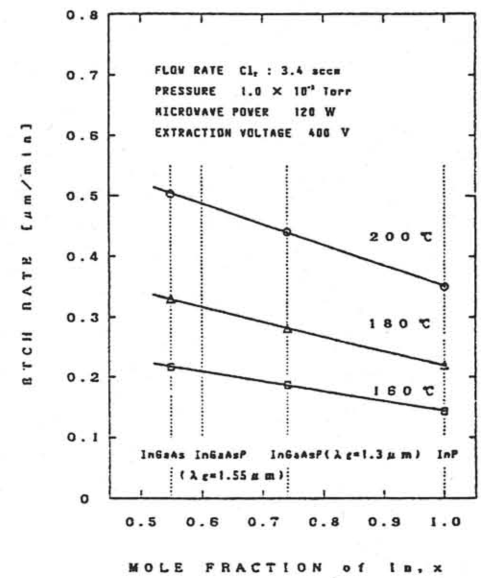


Fig. 6 Measured $In_xGa_{1-x}As_yP_{1-y}$ etch rates as a function of In mole fraction (x).

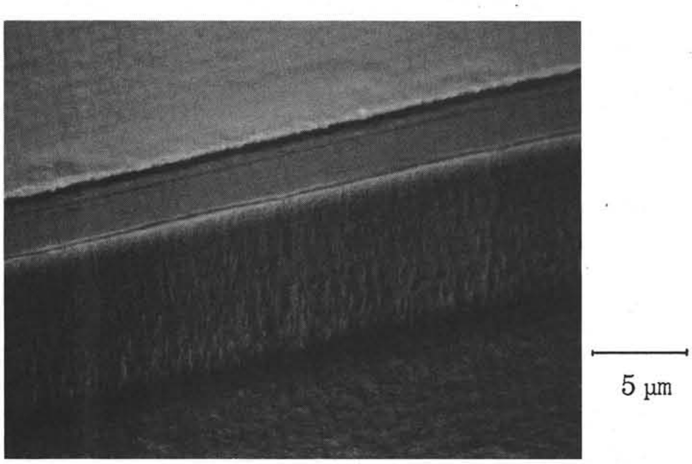


Fig. 7 SEM picture of fabricated laser diode using this technique.

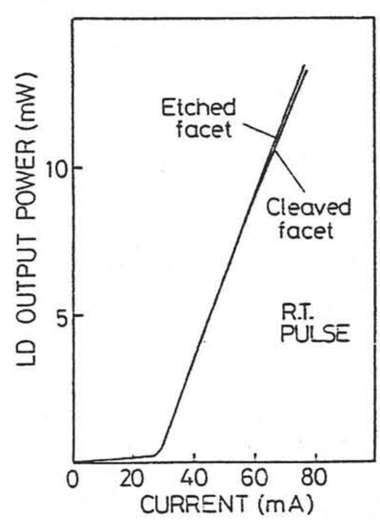


Fig. 8 L-I curves of InGaAsP/InP BH-LD with one facet etched and the other cleaved.