Smooth, Anisotropic Etching of Indium Containing Multi-layer Structures Using a High Density ICP System

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Abstract

In recent years, indium phosphide (InP) and other In-containing materials (e.g. InGaAs, InAlGaAsP) have extensively been used for fabrication of optoelectronic devices. To reduce the processing cost, high yield manufacturing processes are required for the volume production. In this paper, we present results for a production-worthy process producing an anisotropic, smooth and notch-free features using a high density Inductively Coupled Plasma (ICP) system. InP etching rates of up to 2.0 μm/min with selectivity to oxide or nitride hardmask materials of 30:1 are reported. An excellent uniformity over 4" wafer was achieved. In this study, an endpoint detecting system OES (optical emission spectroscopy) was also utilized to monitor the etching process.

INTRODUCTION

Indium containing multi-layer structures (including InP, InGaAs and InGaAsP) are now prevalent material systems for the fabrication of long wavelength optical devices, such as lasers and other waveguide structures. Due to the difficulties associated with dry etching In-based materials, the manufacturing has traditionally been low volume at high cost. Recently this technology has migrated toward high volume production to reduce these processing costs[1]. A more mature dry etching process is key to make it possible for mass production of InP-based materials.

Typical methods for dry etching In-containing materials involve the use of hydrocarbon (CH_4/H_2-based) and halogen-based (Cl-, Br- and I-) plasmas. CH_4/H_2 chemistry results in a smooth surface due to the near equal removal rates of $In(CH_3)_3$ and PH_3, volatile byproducts. Although CH_4/H_2-based plasmas have been widely used to etch InP, the etching rate is considered slow at ~ 500 Å/min for the depth of structures utilized and polymer deposition causes contamination of both the etching module and the samples. The slow etching rate and the unstable chamber condition will not be acceptable for high-volume manufacturing. Chlorine chemistry is an alternative to etching In-based materials. Elevated temperatures are typically required to obtain high etching rates and acceptably smooth surfaces. The use of Cl_2-based chemistries at substrate temperatures of 225 °C to etch InP/InGaAsP with smooth surfaces and high etching rates has been previously reported [2].

Br-based chemistries, such as HBr and Br_2, have also been reported to etch In-based materials. Volatile $InBr_3$ byproducts are produced at lower substrate temperatures, thus increasing the range of device manufacturability. This work presents HBr-based chemistries using a high density plasma ICP system to provide an inherently anisotropic, smooth and notch free etching process. The effects of substrate temperature, RIE power and ICP power on the etching performance are discussed. Indium containing multi-layer structures were etched at rates of 2.0 μm/min with extremely smooth and clean surface (surface roughness < 2.0 nm RMS). The etch selectivity to hard masks (SiO_2 or SiN_x) was greater than 30:1. This technology also provides an excellent uniformity for 4 inch InP wafers. In this work, optical emission spectroscopy was utilized to monitor the process and determine process endpoint.

EXPERIMENTAL

All experiments were performed in a commercially available Unaxis SLR ICP system equipped with mechanically clamping and He backside cooling. In this system, a high-density plasma is generated by a 2 MHz coil with the ion energy being controlled by a 13.56 MHz RF biased cathode. Gas flow rates are controlled by precision mass flow controllers. The substrate temperature is controlled between 20 – 200 °C using backside He cooling. An Unaxis Spectraworks optical emission spectrometer is used to monitor the etching progress. The OES system has a spectral range was 200 – 800 nm with a resolution of 1 nm. The plasma emission is coupled to the spectrometer through a sapphire reactor viewport and a silica optical fiber.

The materials used in these experiments included both pieces and 4 inch bulk InP wafer and epitaxial InGaAs/InP/InGaAsP wafers. Mask patterns for etching were either photoresist or dry etched SiO_2. Surface morphology was measured using atomic force microscope (AFM) and etched profile was examined by scanning electron microscope (SEM). All depth measurements were performed using a Tencor P-11 step profilometer.

RESULTS and DISCUSSION

A) HBr

Etched profile and smoothness of the sidewall and floor surfaces are often key issues associated with the optoelectronic device performance through their effect on light scattering and epitaxial regrowth. High etching rates are critical to achieve satisfactory wafer throughput. Due to the relatively low volatility of indium byproducts, substrate temperature is an important control factor in determining etching rate, etched profile, and surface morphology. Figure 1 illustrated substrate temperature effects on the InP etching rate and selectivity to (SiO_2) mask material. Examples of substrate temperature effects on the etched profile are shown in Figure 2.

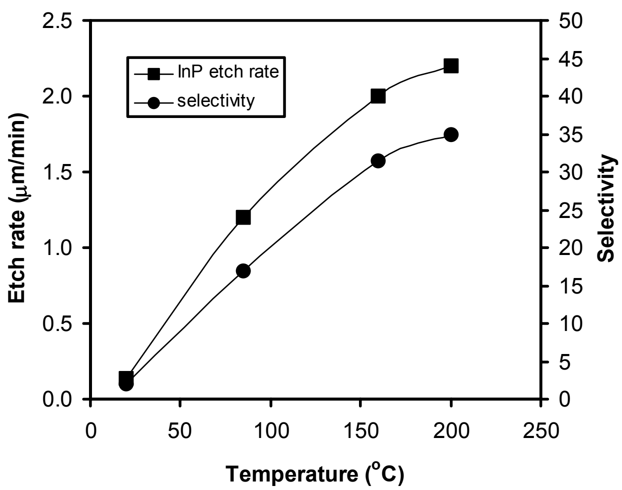

Figure 1. Effects of substrate temperature on the etch rate and selectivity.

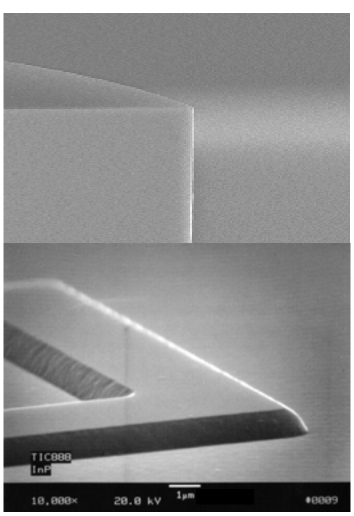

Figure 2. Effect of substrate temperature on the etched profile with HBr chemistry. (top 160 °C; bottom 20 °C)

In the room temperature region (< 30 °C), the InP etching rate is quite low ~ 1000 Å/min; however, very smooth surfaces (RMS < 2.5 nm) were obtained[3]. The etched profile is positively sloped 45°; despite using a vertical mask. It has been observed that photoresist is prone to erosion during dry etching (Figure 2, bottom). It is believed the physical component is the major factor in the etch mechanism within the room temperature region.

The InP etching rate and selectivity to mask was enhanced with the increasing substrate temperature. The surface starts to become rougher as temperature increases due to the imbalance of volatility of by-products $InBr_3$ and PH_3 at this temperature range. When the substrate temperature is increased above 150 °C, the surface became smooth again because volatility of byproducts is balanced. Generally, temperatures greater than 150 °C are necessary to achieve high etching rate (2.0 μm/min) and selectivity (30:1) with smooth morphology. In Figure 2 (top), a highly anisotropic profile is obtained at high temperature processing with hard baked photoresist mask; while an undercut profile is evident if SiO_2 is used. We suspect photoresist is redeposited on the sidewall, thus eliminating undercutting.

B) HBr/CH$_4$ -based

Since HBr chemistry tends to undercut InP with the SiO_2 hardmask, it may be necessary to passivate the sidewall and prevent the lateral etching. CH_4 is often used for this purpose in a wide range of processes, and has applicability with the HBr based InP etch.

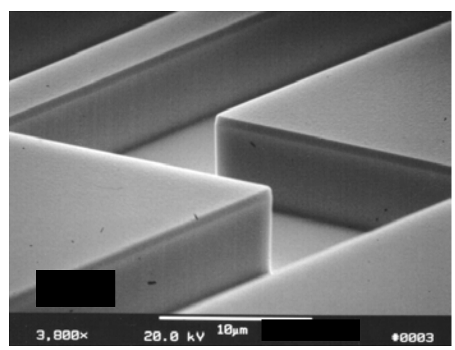

Figure 3. SEM of InP after etching with HBr/CH_4 chemistry

Figure 3. illustrates a near 90°, smooth etch being achieved with HBr/CH_4 based plasma at 160 °C. The InP etching rate and selectivity to the oxide hardmask are 1.2 μm/min 15:1 for this process. The extent of chamber contamination resulted from polymerization will strongly depend on the amount CH_4 used and etching time. The results showed relatively stable chamber condition due to the low CH_4 concentration used in this process and the short etch time.

C) HBr/N_2

Although CH_4 addition can be beneficial in etching In-based materials, the effects on the chamber are a concern when considering high volume production. Therefore, an alternative chemistry to replace CH_4 is needed for sidewall protection during etching. The addition of N_2 has been reported to enhance the verticality of the etched profile for frontside GaAs/AlGaAs selective etching process[4]. In this study, N_2 was utilized in conjunction with HBr to produce anisotropic InP features. Figure 4 (top) shows bulk InP ridge waveguide structures etched using HBr/N_2 based process at substrate temperatures of 160 ^oC. This chemistry produces a vertical profile as well as smooth sidewall and floor surfaces (RMS < 2 nm). Figure 4 (bottom) demonstrates similar results on feature size down to near 1 μm. The InP etching rate and the selectivity to the oxide is 2.0 μm/min and 30:1 for this process. Note a vertical profile and smooth surface obtained from this process will assist in maximizing waveguide performance transmission for optoelectronic devices.

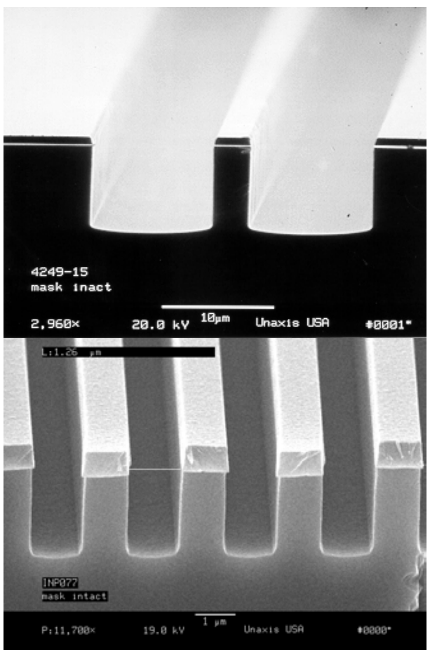

Figure 4. SEM of InP after etching with HBr/N_2 chemistry

Table I summarized the process trend associated with HBr/N_2 plasma in the ICP system. The InP etching rate increases with increased HBr percentage, RIE and ICP power. This suggests that both the generation of Br radicals and ion energy will increase the InP etching rate. The selectivity to SiO_2 hardmask material decreases with increasing HBr percentage and RIE power. The verticality of the etched profile is enhanced with increasing N_2 percentage, RIE and ICP power.

TABLE I
Process trend for InP etching with HBr/N_2 in ICP.

	Etching Rate	Selectivity to mask	Profile
HBr/N2 ratio ↑	↑	↓	↓
RIE ↑	↑	↓	↑
ICP ↑	↑	-----	↑

The difficulties associated with dry etching of multi-layer structure containing various III-V compounds (InGaAsP for example) are the notch formation and surface roughness due to the difference in the volatility of their byproducts. Certain post-etch processing steps such as deposition, metallization and epitaxial regrowth can be hindered by sidewall notch formation. Equal removal rates for these layers is necessary to obtain notch-free profiles and smooth surfaces. Figure 5 demonstrates the results of applying HBr/N_2 etching process to ridge waveguide (bottom) and ring oscillator devices (top). Both structures are composed of epitaxial InGaAs, InP and InGaAsP layers. Note the absence of any notching at interfaces among these epitaxial structures following dry etching, as well as the very smooth floor and sidewall surface using this process. The average etching rate of the whole epitaxial structure is very close to that of bulk InP, which implies a selectivity of near 1:1 for these materials.

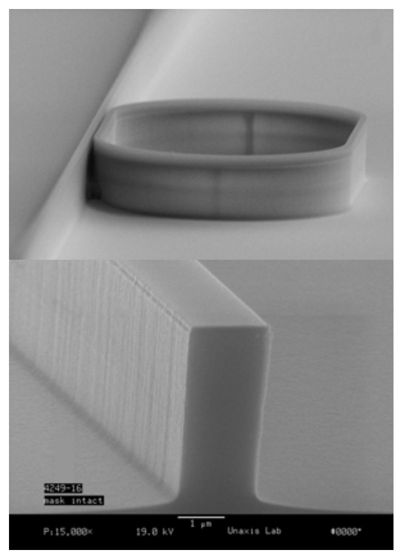

Figure 5. SEM of multi-layer etching with HBr/ N_2 chemistry. (top: ring oscillator; bottom: ridge waveguide)

In this study, OES was utilized to monitor the etch depth in the epitaxial structures. In order to set up the emission endpoint algorithm for this application, it is necessary to collect emission spectra for epitaxial structure with different compositions and construct a difference plot to detect more subtle changes between these spectra. The difference plot confirms that the Ga line and In line are the most useful monitoring peaks for endpoint detection due to the large changes between the two spectra. Therefore, [Ga]/[In] ratio was utilized to monitor the process. Using this algorithm, an endpoint signature for the etching process of optoelectronic devices with epitaxial InGaAs and InP layers is shown in Figure 6. A well-developed signature corresponding to the etch depth along with the varied Ga and In concentrations within the structure is clearly evident.

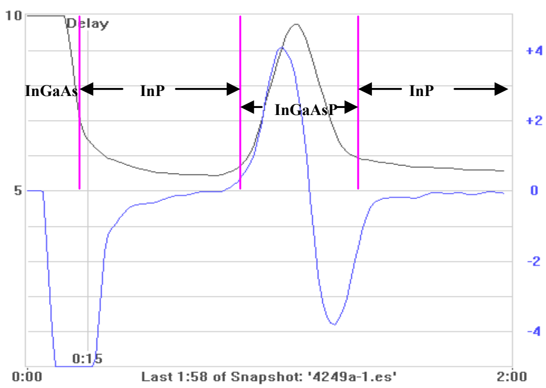

Figure 6. Optical emission intensity as a function of etch time for optoelectronic device processing.

CONCLUSIONS

In this study, we present HBr/N_2 based dry etching process producing anisotropic (90 ± 1°), smooth (RMS < 2.0 nm), and notch-free features of In-containing multi-layer structures using a high density ICP system for optoelectronic devices manufacturing. The InP etching rate and selectivity to oxide hardmask material using this chemistry at high temperature is 2.0 μm/min and 30:1, respectively. In addition, excellent uniformity values (≤ ±5%) for full 4" wafers are achieved. A clear endpoint signature using OES to monitor the multi-layer etching process is demonstrated. Clean processing condition, high etching rates and excellent uniformity combined with endpoint system monitoring the process will make it possible to move optoelectronic devices from R&D/low volume into high volume manufacturing.

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