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# High-Speed Plasma Etching of Gallium Oxide Substrates Using Atmospheric-Pressure Plasma with Hydrogen-Helium Mixed Gas

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**Abstract.** In addition to silicon carbide (SiC) and gallium nitride (GaN), gallium oxide ($Ga_2O_3$) is attracting attention as a widegap semiconductor material. $Ga_2O_3$, unlike SiC and GaN, is not as hard, but has strong cleavage properties, making highly effective mechanical machining difficult. Thus, the processing of $Ga_2O_3$ by high-speed etching employing atmospheric-pressure plasma was studied. An extremely high removal rate of 60 μm/min was obtained due to basic processing experiments using hydrogen gas instead of toxic and corrosive chlorine gas as the reaction gas.

## Introduction

In addition to silicon carbide (SiC) and gallium nitride (GaN), gallium oxide ($Ga_2O_3$) has recently attracted increased attention as a widegap semiconductor material for a sustainable society. Not only is it expected to have high durability and low on-resistance due to its large energy bandgap and breakdown electric field, but bulk crystals are also grown using the melt growth approach, which enables the production of high-quality, large-diameter substrates at a low cost. Based on β-$Ga_2O_3$, the development of lateral transistors and Schottky barrier diodes has already been achieved [1], and a vertical transistor has been successfully prototyped and demonstrated in operation [2]. Although $Ga_2O_3$ is not a hard material compared with SiC and GaN, it has two strong cleavage directions that increase the risk of cracking and cleaving during mechanical processing. Therefore, we propose using plasma chemical vaporization machining (PCVM) instead [3,4], a nonmechanical high-speed plasma etching using high-pressure plasma for the high-speed processing of $Ga_2O_3$ without fear of cracking and cleaving. In this study, we present some preliminary experimental findings of applying PCVM with a hydrogen–helium mixture gas for $Ga_2O_3$ processing.

## Experimental Setup

Generally, chlorine gas is employed for etching gallium-based materials, and it has also been employed for GaN processing by PCVM [5]. However, since chlorine gas is corrosive and poisonous, hydrogen was used as an alternative gas in this experiment. Preliminary experiments using the setup shown elsewhere [6] confirmed that $Ga_2O_3$ could be etched by PCVM using hydrogen gas. However, in the experiment employing power as a parameter, a phenomenon was observed in which the removal rate began to decrease when a certain amount of power (150 W) was applied, which is an unusual phenomenon. The same experiment was conducted while cooling the sample table from the outside, considering that the processing speed may have decreased due to the increase in sample temperature. Then, the removal rate increased under all conditions, and no decrease in the removal rate was observed even at 150 W (Fig. 1). Since sample temperature was discovered to be a crucial

parameter, an experimental apparatus with a water-cooling system was fabricated to enable the measurement of sample temperature during PCVM processing.

Figure 2 illustrates a schematic of the apparatus. A β-$Ga_2O_3$ (100) substrate with a size of 5 × 8 $mm^2$ was employed. Hydrogen gas diluted to 10% with helium was supplied through a pipe electrode using a mass flow controller after setting the sample and evacuating the system. The processing pressure and processing gaps were set to atmospheric-pressure and 0.2 mm, respectively. A 13.56 MHz radiofrequency (RF) power was supplied to the electrode, and plasma was generated between the pipe electrode and the sample surface. A thermocouple was embedded in the sample holder to measure the sample temperature. Cooling water was run through the electrode and the sample holder, and the sample temperature during PCVM processing was controlled by adjusting the amount of cooling water. The processed samples' surface was measured using a stylus-type surface profiler, and the removal rate was calculated by dividing the maximum removal depth by the processing time.

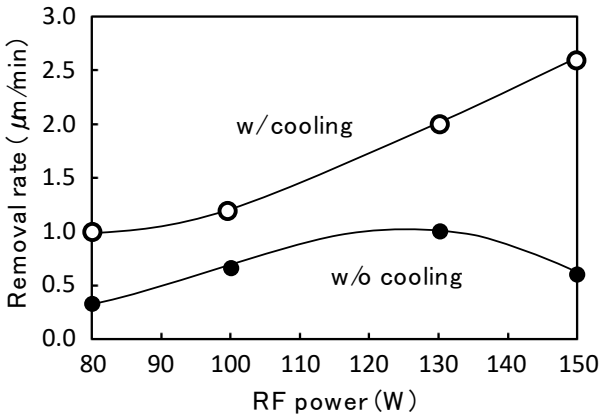


Fig. 1. Preliminary results of the dependence of removal rate on radiofrequency (RF) power.

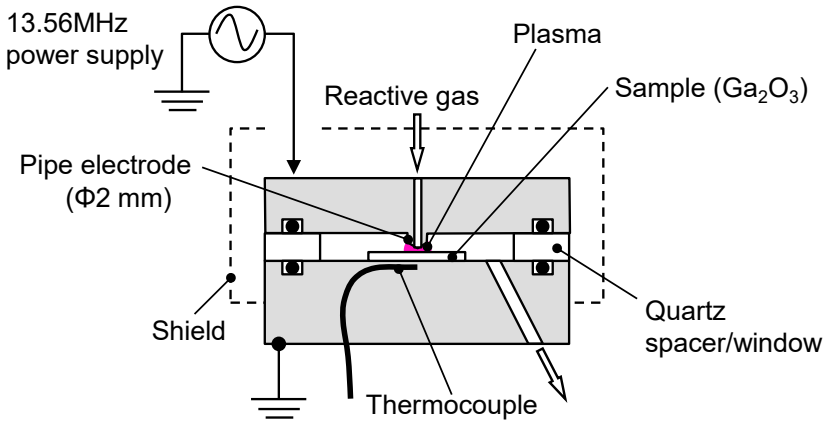


Fig. 2. Schematic of plasma etching apparatus.

## Results and Discussion

**Temperature Dependency.** Experiments on the dependence of processing speed on sample temperature were performed employing an rf power of 130 W, gas flow rate of 75 sccm, processing time of 5 min, and sample holder temperatures of 30°C, 50°C, 70°C, and 100°C. Figure 3 shows the results. When the temperature of the sample holder was 50°C, the removal rate reached its maximum value. It is reported that the etching of silicon using hydrogen gas has a similar maximum value because of a decrease in the number of hydrogen radicals reacting with the surface atoms of the sample due to desorption or the internal diffusion of hydrogen as the temperature increases [6]. It is assumed that a similar phenomenon occurred in this experiment.

**Gas Flow Rate Dependency.** The dependence of the removal rate on the gas flow rate was examined employing an rf power of 130 W, sample holder temperature of 50°C, a processing time of

3 min, and gas flow rate of 75, 100, 500, 1000, and 2000 sccm. Figure 4 shows the results. As the gas flow rate increased, the removal rate increased and reached a maximum rate of about 60 μm/min at 500 sccm. Figure 5 illustrates the surface profile of the sample at 500 sccm. In just 3 min of processing, a depth of about 200 μm was achieved. As the gas flow rate was further increased, the processing speed began to decrease. The reason for this is as follows: since the experiment was conducted with constant power, the supplied hydrogen gas was sufficiently decomposed up to 500 sccm; above 500 sccm, however, the power was insufficient and the plasma density decreased.

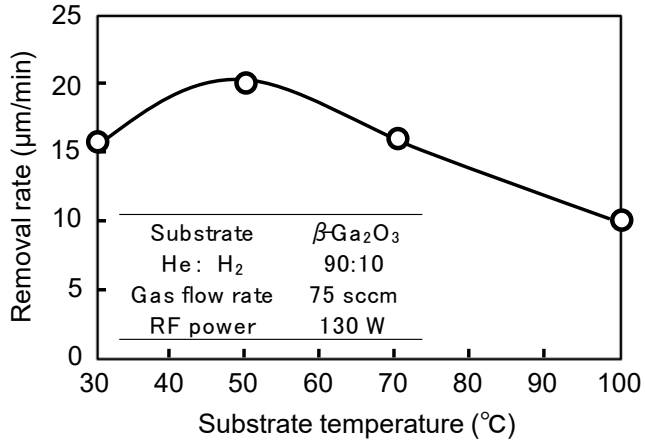


Fig. 3. Dependence of the removal rate on the substrate temperature.

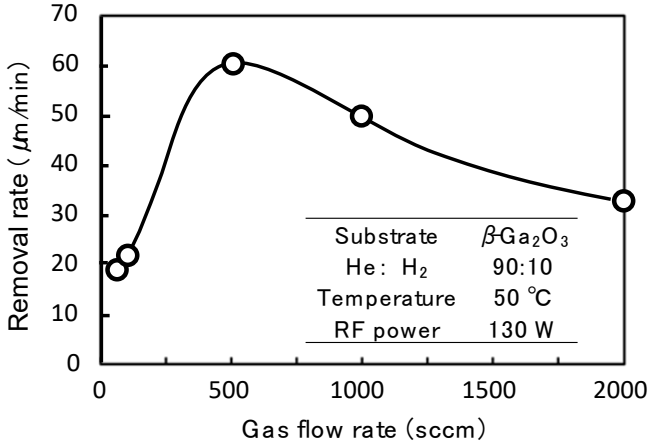


Fig. 4. Dependence of the removal rate on gas flow rate.

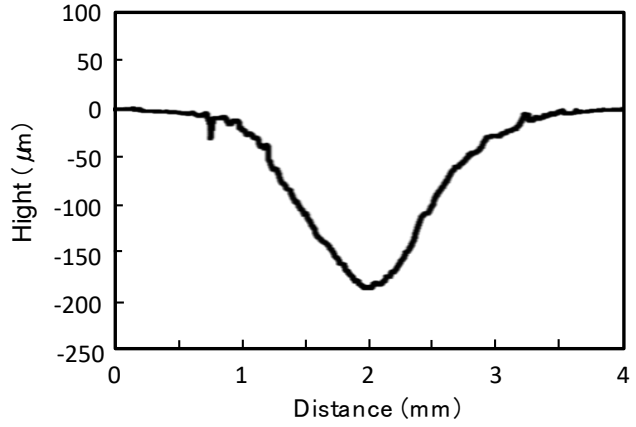


Fig. 5. Surface profile of the sample at 500 sccm in Fig. 4.

Regarding surface roughness, the surfaces that were mirror-like before processing were all cloudy after processing. Qualitatively, as the gas flow rate increased, the tendency of cloudiness decreased,

indicating that the ejection of reaction products out of the plasma is crucial to keep the processed surface clear. However, further studies are necessary to improve the surface roughness of the processed surface.

## Summary

From the findings of the above experiments, $Ga_2O_3$ substrates can be processed by PCVM employing a hydrogen–helium gas mixture. Although the experiment was conducted on a small area, it was discovered that an extremely high removal rate of around 60 μm/min could be achieved. In the future, we intend to examine processing the entire substrate surface for applications, such as the backside thinning process, with studies on improving surface roughness.

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