Implementation of End Point Detection for Compound Semiconductor Wafer Thinning Applications and Investigation of Gallium Arsenide Etch Rates and Surface Roughness

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Keywords: wet etching, gallium arsenide, etch stop layer, wafer thinning, bulk substrate removal, surface roughness, etch rates

Abstract

Accurate and precise control of wafer thickness is key to thermal management, packaging, and electrical performance. Recent trends for vertical cavity surface emitting laser (VCSEL), micro-light emitting diodes (µLED) and augmented reality (AR) applications show the need for greater process control. Two processes that drive development for these applications are wet etching a gallium arsenide substrate to a pre-determined thickness and completely removing the substrate. In this paper, the impact of etchant temperature on etch rate and surface roughness will be investigated for the first process. Completely removing the gallium arsenide (GaAs) substrate and stopping on an indium gallium phosphide (InGaP) etch stop layer using end point detection (EPD) will be demonstrated for the second process.

INTRODUCTION

Backside thinning a GaAs substrate from a starting thickness of 675 µm to a final thickness between 150 and 200 µm, without damaging the active side of the wafer, is a common approach to manufacture VCSEL devices. Deviations in the final substrate thickness can result in thermal, electrical, and packaging variabilities.[2] Thinning is typically achieved by mounting the device wafer to a carrier and grinding/polishing the backside until the desired final thickness is achieved. The grinding operation is typically followed by a wet etch to relieve residual stress in the wafer generated from the grinding process. An alternative approach to grinding/polishing is to thin the wafer to the desired thickness by wet etching[1]. This approach eliminates the mounting and grinding steps, resulting in a simpler process flow. The first goal of this paper was to demonstrate the impact of etchant temperature on GaAs etch rates and surface roughness.

A common alternative to targeting a final substrate thickness is wet etching to an etch stop layer. An etch stop layer with high selectivity to the GaAs wet etchant allows for the fast bulk removal of the substrate, protects the underlying epitaxial device layer and can be removed in a subsequent step. In a potential µLED process flow, transfer of the functional epi layers to an IC containing wafer can be achieved by wafer-to-wafer bonding and bulk GaAs substrate removal using this process.[3] Detection of this etch stop layer, indicating complete GaAs substrate removal, can be achieved using white light reflectometry end point detection and will be the second goal of this paper.

Single wafer wet etch tools provide advantages for these processes and several factors should be considered when selecting a tool. Compared to traditional wet benches or beaker level processing, single-wafer process equipment provides higher etch uniformities, more precise etch rates, and improved wafer-to-wafer consistency. Single-wafer process equipment also provides added benefits such as wafer-level end point detection, a feature not common on batch tools, which enables higher throughput and greater process control, further improving manufacturability. Here, a Veeco Instruments – Precision Surface Processing WaferEtch® 3302 single wafer etching system was used for all experimentation.

EXPERIMENTAL SETUP

Chemistry

A mixture of phosphoric acid (H_3PO_4, 85%), hydrogen peroxide (H_2O_2, 30%), and deionized water was used for the etchant. All chemicals were supplied by J.T. Baker and were of semiconductor/electronics grade.

Wafer type and film deposition

Six inch diameter, n-type, semi-insulating, double side polished, 675 µm thick gallium arsenide substrates with crystal orientation (100) were used as the primary substrate for etch rate and surface roughness studies. These wafers were misoriented 2-degrees towards [110]. For the second application, a 300 nm thick layer of InGaP was used which was deposited at a rate of 38 nm/min onto the frontside of a GaAs (100) wafer, which was misoriented 15-degrees towards [111]. Here, a Veeco Lumina® MOCVD reactor was employed for the deposition using a 7 x 6" configuration carrier. The growth temperature was at 680°C and the pressure was at 42 torr using trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminum (TMAl), PH_3 and AsH_3 as precursors. A 7 micron thick layer of gallium arsenide was then deposited on top of the InGaP at 100 nm/min to mimic a bulk layer. Using this approach avoided the bonding process and achieved the same end point detection result.

Tool and recipe setup

The temperature was controlled with a single heat exchanger to +/- 0.2°C and a constant flow rate of 1000 mL/min was maintained. The generic process flow for these experiments can be found in Table 1.

Table 1. Process flow for GaAs substrate etching.

Step	Process	Time	Chemical	Speed (rpm)
1	Wet etch	60 seconds	Acid mixture	600
2	Rinse	20 seconds	DI water	200
3	Dry	45 seconds	N/A	1500

Metrology

Measuring the wafer thickness was performed on a Sentronics StraDex f24-300 sensor. The sensor performs the measurement by directing a laser at the substrate, upon which reflected light is detected from the top surface and refracted light is detected from the bottom surface. Film thickness can then be calculated from the interference pattern and the refractive index of the material. This sensor has a measuring wavelength of 1300 nm and a spot size of 24 µm. Gallium arsenide has an index of refraction of 3.66 at 1300 nm. Twenty-nine measurements were taken every 5 mm from -70 mm to 70 mm across the wafer diameter. These measurements were performed before and after etching. Radial measurements are more common in single wafer processing due to the rotational symmetry of spin processes.

Uniformity

Setup wafers were etched prior to this study to optimize the arm scanning profile in the wafer etch system, which directly impacts the etch uniformity. A linear arm scan (constant velocity at each arm scanning location) results in uniformities of approximately 10-15%, depending on the etchant, etchant temperature, and substrate. Hyperbolic motion allows the arm dispensing the etchant to change velocities while scanning across the wafer to ensure equal dwell time at each radial location. Without this feature, the etchant is dispensed for longer amounts of time at radii closer to the center of the wafer. Figure 1 is a graph showing the hyperbolic motion with the arm speeds used in this study to achieve an average uniformity of 2.6% non-uniformity at 50°C.

Arm Position (mm)	Scan Velocity (mm/sec)
4	125
12	123
20	119
28	113
36	105
43	96
51	86
59	74
67	62
75	50

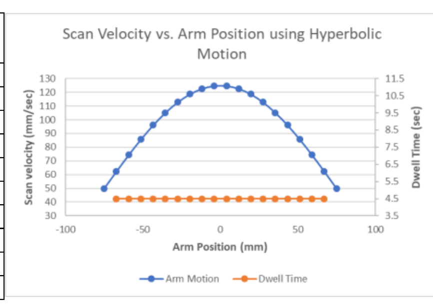

Figure 1. Hyperbolic motion of GaAs wet etching.

These values remained constant throughout the study to directly observe the impact of etchant temperature on etch rate and surface roughness. The arm scan is symmetrical with the same speeds used at the negative radial positions. For wafers with significant incoming thickness issues from previous processing steps, a custom arm scanning profile can be created in the software to further improve the uniformity.

Surface Roughness

A KLA Tencor P16+ stylus profile was used to acquire the surface roughness measurements. The profilometer setup used a 2.0 µm stylus radius, 400 µm scan length, 20 Hz sampling rate, 5 µm/sec scan speed, 2.00 mg applied force 60° stylus angle and 25 µm long wavelength cutoff. Five surface roughness scans were taken along the wafer radius every 14 mm and averaged together. The surface roughness was also investigated with a Bruker Dimension FastScan AFM, which yielded comparable numbers. Surface topography images provided below were captured with the AFM. Arithmetic average (Ra) was the roughness value used.

RESULTS

Etch Rates

Below is a sample dataset from experiments done to investigate the etch rate at 35°C for a one minute process (Table 2). The pre-etch wafer thickness and post-etch wafer thickness measurements are given at each diameter location. The difference between the two is the amount etched at that location. Each etch rate tests were repeated five times and the average delta across all 145 points determined the etch rate.

Table 2. Sample dataset of wafer thicknesses before and after etching at 35°C.

Diameter location (µm)	Pre Etch (µm)	Post Etch (µm)	Delta (µm)
-70000	608.902	594.104	14.798
-65000	609.546	594.905	14.641
-60000	609.895	595.409	14.486
-55000	610.121	595.810	14.311
-50000	610.225	595.967	14.258
-45000	610.591	596.210	14.381
-40000	610.713	596.297	14.416
-35000	610.696	596.263	14.433
-30000	610.696	596.019	14.677
-25000	610.382	595.792	14.590
-20000	609.947	595.305	14.642
-15000	609.668	594.817	14.851
-10000	609.512	594.556	14.956
-5000	611.131	596.733	14.398
0	610.861	596.385	14.477
5000	610.591	596.036	14.555
10000	609.355	594.591	14.764
15000	609.703	594.887	14.816
20000	610.086	595.462	14.624
25000	610.400	595.862	14.538
30000	610.592	596.141	14.451
35000	610.783	596.419	14.364
40000	610.800	596.471	14.329
45000	610.643	596.367	14.276
50000	610.434	596.071	14.363
55000	610.173	595.775	14.398
60000	609.912	595.375	14.537
65000	609.494	594.887	14.607
70000	609.233	594.556	14.677

As with most wet etchants, there is an exponential increase in etch rate with etchant temperature and that trend holds true with this study (Figure 2).

An average etch rate of 6.37 µm/min was obtained with an etchant temperature of 20°C, 14.56 µm/min with 35°C etchant and 27.73 µm/min with 50°C etchant. Fitting these values to an exponential regression gave the equation below and a R^2 value of 0.9949, indicating an accurate fit and trend.

$$y = 2.463e^{0.049x}$$

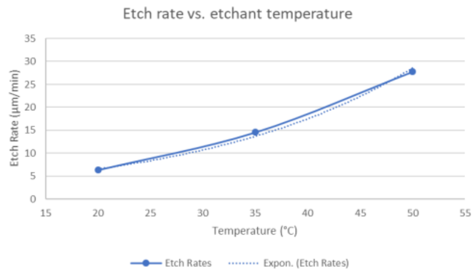

Figure 2. GaAs average etch rates at 20°C, 35°C, and 50°C etchant temperatures.

Etch Uniformity

Etch uniformities are also of great importance, especially when considering the selectivities of the etch stop layer etch rate to the bulk wafer thickness etch rate. Uniformities were calculated for each of the five runs at each etchant temperature and are given below (Table 3).

Table 3. Etch uniformities at 20°C, 35°C, and 50°C etchant.

Temperature	20°C	35°C	50°C
Run 1	3.56%	2.76%	2.80%
Run 2	2.30%	2.40%	2.82%
Run 3	2.80%	1.83%	2.44%
Run 4	2.47%	1.76%	2.59%
Run 5	2.37%	1.76%	2.25%

Surface Roughness

The average roughness from the five radial surface roughness scans taken on the stylus profilometer are given below (Table 4). There is a clear trend of increasing roughness with increasing etchant temperature.

Table 4. Surface roughness values before and after etching using a stylus profilometer.

Etchant Temp. (°C)	Before Etch Roughness (nm)	After Etch Roughness (nm)
20°C	1.108	2.619
35°C	0.962	4.043
50°C	1.008	8.987

Three scans were taken along the radius of the same wafers using an AFM and the average roughness values are given below (Table 5). Direct comparison of 1-D and 2-D surface roughness measurements are not possible, but the trends of increasing surface roughness with increasing etchant temperature was confirmed

Table 5. Surface roughness values before and after etching using an AFM.

Etchant Temp. (°C)	Before Etch Roughness (nm)	After Etch Roughness (nm)
20°C	1.22	2.69
35°C	1.23	7.37
50°C	1.25	14.89

AFM topography images show the initial pre-etched, low roughness surface (Figure 3, left) and an image from the 20°C etched wafer (Figure 3, right).

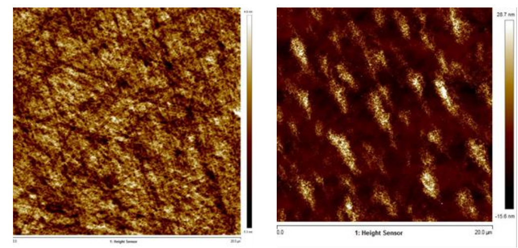

Figure 3. GaAs etch rates at 20°C, 35°C, and 50°C etchant temperatures.

In addition to the stylus profilometer and AFM roughness measurements, the topology of the post-etch surface was inspected in a SEM (Figure 4).

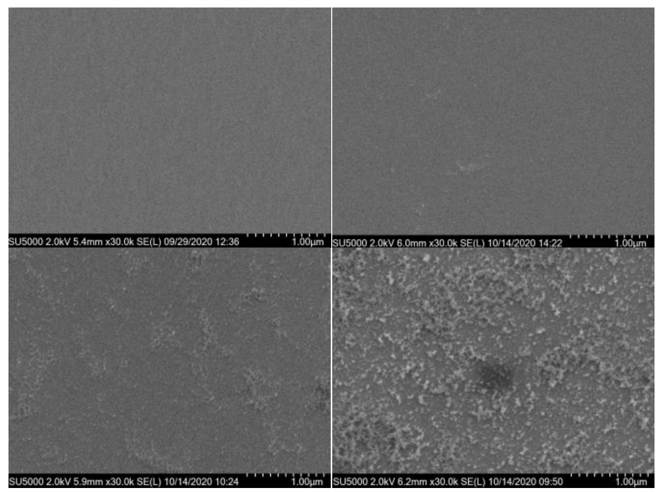

Figure 4. SEM image of GaAs surface etched at 20°C (top right), 35°C (bottom left), 50°C (bottom right) and a control without etching (top left).

The top left image of Figure 4 shows an unetched wafer with no discernable topology. The other three images show that the roughness is not uniform after etching, indicating some areas could yield low roughness values even though surrounding areas could be rough and vice versa.

The profilometer surface roughnesses were then plotted against etchant temperature so a comparison could be made to etch rate (Figure 5). Applying a linear regression fit to the data produced a R^2 value of 0.907. Modifying the fit to a 2^{nd} order polynomial gave a fit of 1, but more data is needed to verify this fit.

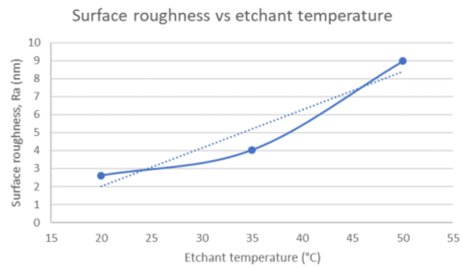

Figure 5. Surface roughness values at 20°C, 35°C, and 50°C etchant temperatures.

The surface roughness observed is attributed to the formation of a film, rather than porosity of the wafer surface, based on the morphology observed in the SEM images. This film was theorized to be a gallium oxide or arsenic oxide. One of the 50°C samples, with significant surface roughening due to the film, was exposed to phosphoric acid as a solution to remove the film. Surface roughness values were obtained after exposure to phosphoric acid and the values are given below (Table 6). These five measurements were taken radially on the same wafer, which was etched at 50°C. The post phosphoric acid treatment surface roughness values are much closer to the before etch roughness measurements.

Table 6. Surface roughness values before etching, after etching, and after phosphroic acid treatment.

Radial Measurement #	1	2	3	4	5	Average
Pre wet-etch	1.046	1.011	0.986	0.995	1.001	1.008
Post wet-etch	3.132	10.605	7.796	7.964	15.440	8.987
Post phosphoric exposure	1.902	1.791	1.809	2.383	2.362	2.049

End Point Detection

All the above is pertinent to the first goal of this paper where a certain wafer thickness is desired. When the entire GaAs substrate is to be removed, the end point detection of an InGaP etch stop layer can be utilized to ensure consistent wafer-to-wafer processing. The EPD system on the WaferEtch® 3302 system continually monitors the RGB (red, green blue) and HSV (hue, saturation, value) color spaces while the wafer is being etched. Once the software detects a significant change in any of these channels, the wafer is immediately quenched with deionized water to stop the etch process.

In this particular process of bulk etching a GaAs wafer and stopping on a layer of InGaP, the hue channel (yellow line, Figure 6) demonstrated the most significant end point signal. A hue value of approximately 60 bits is obtained from sample numbers 1 to 8 while the wafer is being etched. As soon as the GaAs layer is etched through, the hue channel increases to approximately 210 bits indicating the etch is complete.

The other channels (red, green, blue, saturation, and value) did not show a significant end point signal in this particular application but are known to work well in other applications such as copper under bump metallization (UBM) etching. The advantages of using an EPD system is that it can account for wafer thickness variations from the manufacturer and can be used as an indicator of when the etchant needs to be replenished or replaced.

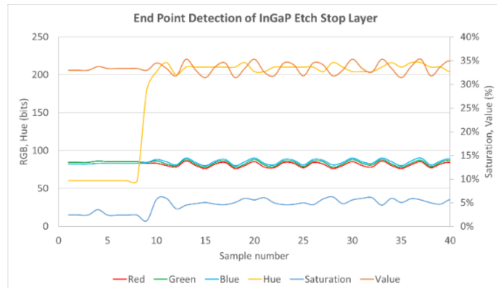

Figure 6. End point detection of InGaP etch stop layer.

CONCLUSIONS

The characterization of surface roughness and etch rates as a function of etchant temperature was successfully demonstrated on gallium arsenide wafers using a phosphoric acid/hydrogen peroxide mixture. A maximum gallium arsenide etch rate of 27.73 µm/min was achieved at a temperature of 50°C. A custom arm scan profile was used to achieve etch uniformities of 3% and lower at 20°C, 35°C, and 50°C. The surface roughness (Ra) increased to a maximum of 15.440 nm after exposure to 50°C etchant but this was attributed to the formation of a film on the surface. It was shown that exposure to phosphoric acid can remove this film and the surface roughness decreases back to a value more comparable to the starting roughness value.

End point detection of an InGaP etch stop layer was demonstrated when bulk etching a GaAs substrate. This setup enabled consistent removal of the GaAs wafer without etching through the InGaP etch stop layer and potentially damaging the epitaxial layers. Other applications such as substrate stress relief and alternative material etching (GaN, AlGaAs, InP, InGaAsP, etc.) are possible but outside the scope of this paper. Future studies will investigate the oxide formation in more detail.

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