A Reproducible, High Yield, Robust Wet Etch Etch-Stop Process Using Organic Acid – Peroxide Solutions.

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ABSTRACT

Continuous improvement has been key to the successful wet etch etch-stop process at Skyworks Solutions. Three conditions: device dimensions, etch chemistry, and etch tool directly affected the etched depth uniformity across a wafer. An unusual failure mechanism of the etch stop process was discovered while investigating a range of over etched devices. This failure mechanism was a perforation mode which standard profilometry would not reveal. The paper will show how the etch uniformity and yield is impacted by device geometry, etch chemistry, etch tool and surface pitting.

INTRODUCTION

There are two common methods of wet etching GaAs p-HEMT channel and gate recesses. One technique is manual iterative etching to a desired current target. This technique is time consuming, and requires a highly skilled operator to get accurate results. The other technique selectively etches the recess to an AlAs etch-stop layer in a single etch.[1] Uniformity (both cross-wafer and wafer-to-wafer) as well as selectivity to the stop layer are critical to a successful etch stop process.

In this investigation succinic/hydrogen peroxide and citric/hydrogen peroxide acid mixtures were evaluated to selectively etch recesses to AlAs etch stop layers.

Two etch tools were employed with different spray technologies as shown in Figure 1. The single wafer tool sprayed acid directly onto the wafer during the etch process. The multi-wafer tool applied the acid with multiple nozzles across a cassette of wafers, etching all wafers in the lot at one time.

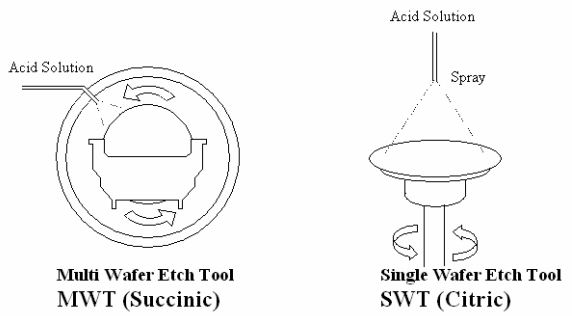

Figure 1

In order to determine the most robust process possible a 2X2 DOE was performed comparing etch chemistry and etch tool as independent variables and feature size and etch depth as dependent values.

The etched features were characterized by AFM, SEM, and electrical FET measurements. It was found that the etch uniformity and process reproducibility depended on mask feature size, etch chemistry and etch tool.

Based on the DOE results a process was developed that improved the productivity and yield of our p-HEMT manufacturing operations.

PROCESS DETAILS

The traditional manual etch process requires the operator to etch the wafers to target in multiple iterations. Each wafer is measured for a final current value. The time to process a lot is 2 – 4 hours of "operator touch time".

The simpler selective AlAs etch stop process, with only one etch, takes less than 1 hour and is totally automated.

Figures 2 and 3 show the impact that the more uniform etch stop process has on the Idss and Vp of a PCM test structure.

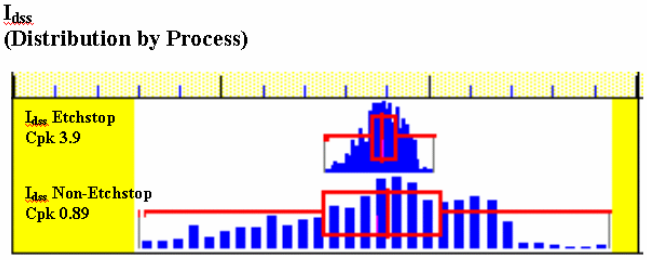

Figure 2

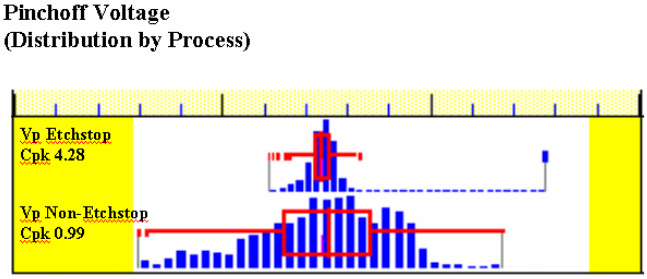

Figure 3

Cpk values for Vp and Idss demonstrate the etch stop process improvement over the non-etch stop process.

Each distribution includes over 5000 data points.

RESULTS

Four lots were processed, two in each tool, with the two different acids. Non-etch stop monitor wafers were included in each of the lots for etch depth measurements. Linear feature size of the test structures varied, from structure to structure, from 2 microns to 100 microns. AFM measurements were made to compare the etch depth uniformity of features across the monitor wafer. Five different areas on each wafer of each structure were measured.

A large difference was found in the etch depth uniformity between the MWT and SWT as a function of feature size regardless of etchant.[2] Figure 4 shows the variation in mean etch depth for the various combinations.

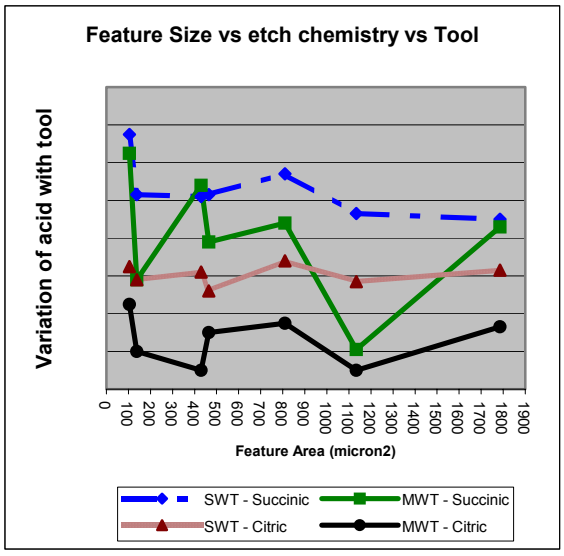

Figure 4

We found that the mean etch depth of the different device features was a function of feature area, etch chemistry and etch tool. Figure 4 shows the best results across the range of feature areas were obtained using the single wafer tool and citric acid based etchant.

The uniformity measurements also showed that the cross-wafer etch depth variation for a given feature was strongly dependent on etch tool and chemistry.

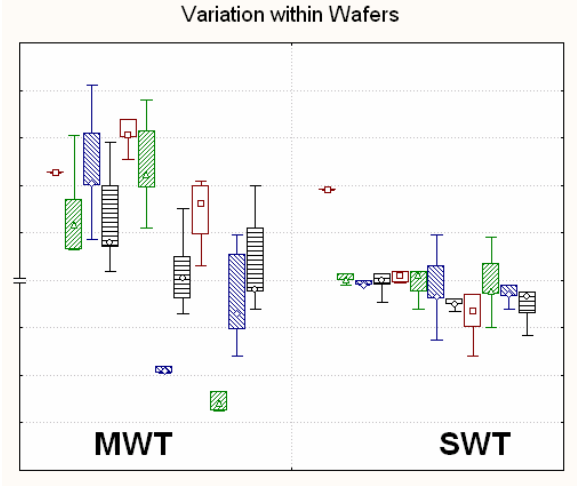

Figure 5

Figure 5 is a comparison of the best and worst process conditions for both tools-SWT with citric is much more uniform than the multi wafer tool. Each box represents a different area test structure.

Findings:

1. The SWT provides better uniformity than the MWT.
2. The citric acid provides better uniformity than the succinic acid.
3. The best combination was SWT with citric acid for etch uniformity and yield.

Etch Rate Stability

The same non-etch stop material used to determine etch depth uniformity was used to measure the etch rate of each acid. This etch rate was then characterized for stability with temperature and time.

The citric etch rate was found to be much more stable over a broader temperature range (11°C) than Succinic (2°C).

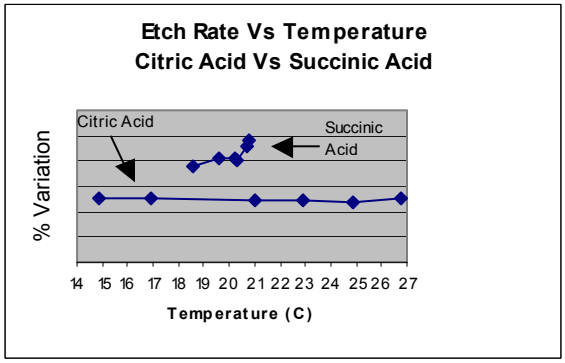

Figure 6

Temperature stability of the etch is important when trying to establish a robust process having excellent wafer uniformity.

However, etch rate versus time is most critical. It was discovered that the succinic acid etch rate does not stabilize until 12 hours after adding the H2O2. The etch rate after

mixing succinic acid is 4 – 5 A/sec. When the solution has aged for 12 hours the etch rate increased to a range of 10 – 20 A/sec. Etch Rate stability and specification for wet etch process is +/- 1.5 A/sec.

The citric acid etch rate was found to be stable at 11-14 A/sec within an hour after mixing and remains stable for at least 48 hours. A stable and predictable etch rate greatly simplifies the calculation of etch time for the automated etch process. The operator can select an etch program based on the product type and process step without having to calculate an etch rate or etch time for each lot. The low etch rate also allows for good controllability of the etch.

Etch Pit Formations

Regardless of etch chemistry and tool an over-etch beyond the calculated time must be performed to compensate for any remaining non-uniformities in the process. Both solutions produced specular etched surfaces in GaAs and AlGaAs using conservative over-etch conditions. When the percent over etch was too high 30-40 nm diameter etch pits were observed on the channel surface as shown in Figure 7. A sharp drop in device current and yield was also seen when these pits were observed.

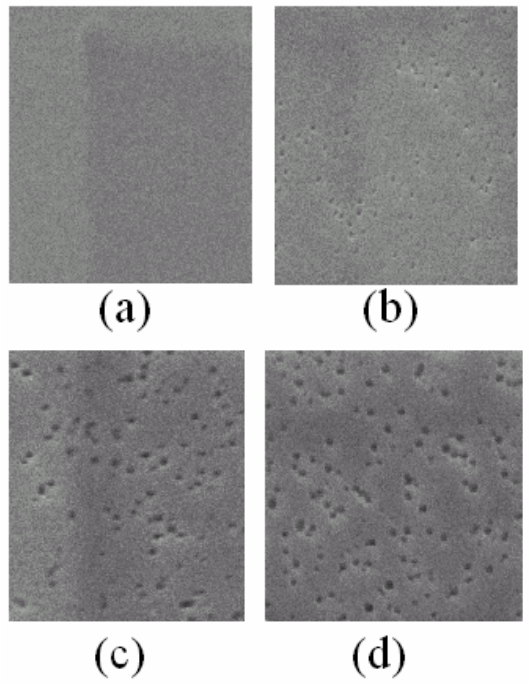

Figure 7
SEM images of the etched surface. All images were obtained at 50,000 X.
(a) 30% over-etch (b) 40% over-etch
(c) 50% over-etch (d) 60% over-etch

The SEM photographs show that depth measurement by standard profilometry alone is not adequate to determine selectivity of the etchant to the AlAs layer. Selectivity must be determined by a profilometry measurement and a SEM inspection.

These pits in the channel surface are formed when the AlAs etch stop layer is perforated by the etchant. Figure 8 shows a cross-sectional TEM of a normally etched device with an intact AlAs etch-stop layer. As the over-etch is increased the surface morphology of the AlAs etch stop is degraded, resulting in nm-scale holes that cause damaging pits, as shown in the second device cross-section in Figure 9.

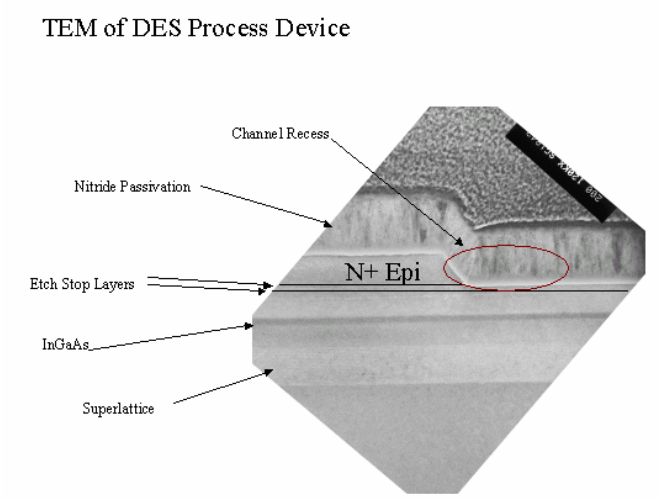

Figure 8
FIB TEM of Channel Layer without Pits
Excessive over etch leads to perforation of etch stop layers

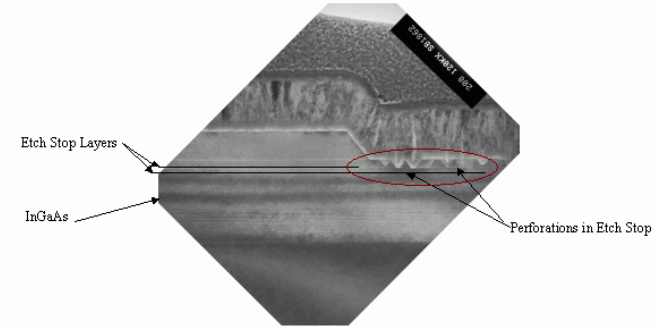

Figure 9
FIB TEM of Channel Layer with Pits

The requirement to limit over-etch so that etch pits and their associated device degradation are prevented further

emphasizes the need for an extremely uniform etch to achieve a robust, high yield process.

Contact Angle

In an attempt to understand causes of the chemistry effect on uniformity, contact angle for both solutions was measured. The results showed that the contact angle for citric acid was 11 degrees while the contact angle for succinic acid was 62 degrees. Low angles indicate that the liquid spreads, or wets well, while high angles indicate poor wetting.

CONCLUSIONS

A robust wet etch high yielding etch-stop process has been developed. The process dependence on feature size, etch chemistry and etch tool was characterized. This process uses a citric acid/peroxide mixture to achieve a controllable etch rate with high selectivity. The etch rate is stable over time which simplifies the manufacturing process. The new etch stop process allows the operator to select a program from an automated tool without having to make an etch time calculation for each lot.

The failure mode of the AlAs stop layers to selective etchants was studied. Using high over-etch conditions we found that 30-40 nm perforations in the stop layer can result in channel etch pits and a significant degradation in device parameters. This degradation can occur while the bulk of the AlAs layer is still intact. Both profilometry and detailed SEM inspection must be used to establish true selectivity of the etch to AlAs.

This study has resulted in improved productivity and yield in our manufacturing line. Production lots using this etch-stop process frequently yield above 95% at RF Onwafer Circuit Test.

The combination of a low etch rate, highly selective, stable and uniform etch chemistry with optimum tool and over-etch conditions has resulted in a high yield, reproducible and robust wet etch process.

ACKNOWLEDGEMENTS

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ACRONYMS

AFM: Atomic Force Microscope
DOE: Design Of Experiments
FET: Field Effect Transistor
GaAs: Gallium Arsenide
MBE: Molecular Beam Epitaxy
MWT: Multi Wafer Tool
PCM: process control monitor
p-HEMT: Pseudomorphic High Electron Mobility Transistor
SEM: Scanning Electron Microscope
SWT: Single Wafer Tool
TEM: Transmission Electron Microscopy