

Resist Dispense Volume Reduction Using the Six Sigma Methodology

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Abstract

Process engineers pursue wafer fab cost reduction activities continually because of ongoing customer demand for lower cost devices. One of the highest costs in the photolithography process is the photoresist used to coat wafers. This process is also the most wasteful because more than 99% of dispensed resist is disposed as hazardous waste. The evaporated solvents in the resist are also environmentally hazardous and are controlled to tight environmental regulations.

This paper reviews how Skyworks Solutions' Newbury Park wafer fab used Six Sigma methodologies to cut resist costs, waste and emissions in half and still maintain a high level of product quality.

INTRODUCTION

The photolithography process begins when a few milliliters of photoresist coat a clean and dry wafer. Resist is dispensed onto the center of the wafer which then spins to spread and thin the resist to the desired thickness. If a coat process dispenses 2 ml of resist on a four-inch wafer to target a one micron resist coating, only 0.008 ml, or 0.04% of the dispensed resist volume remains on the wafer. The rest of the resist is spun off the wafer as excess. Since photoresist typically costs hundreds of dollars per liter, 99% waste of an expensive material can awaken any corporate accountant from a deep sleep. Reducing resist dispense volume without impacting process performance or product quality was the goal of our project. To be successful we had to identify and address the process factors that affect product quality in a systematic and thorough approach using valid statistical methods. For these reasons, we submitted this project to executive management for consideration as a Six Sigma project.

The completed project used Six Sigma methodologies to reduce the amount of resist dispensed on our wafers by more than 50% without adverse impact on our process performance or product quality.

PROCESS OVERVIEW

There are three primary components of a positive resist. The novolak resin is the patterning material. A diazoquinone photoactive compound changes to an acid when exposed to high intensity ultraviolet light and allows the resist to

dissolve easily in a basic developer solution. A solvent is the casting agent to control resist viscosity and the final resist thickness.

Once photoresist coats a wafer, the solvent evaporates quickly until about 30% of the solvent remains¹. The temperature of the wafer, the resist, the wafer chuck, and the wafer spin speed and airflow over the wafer all influence the solvent evaporation rate. Since the evaporation rate of the solvent controls the resist thickness, a change in the evaporation rate will affect the resist thickness uniformity.

However, the amount of resist dispensed has little effect on the coating thickness or thickness uniformity within a process window of approximately 0.5 to 7.0 ml. Resist dispense volumes below 0.5 ml do not coat our four-inch wafers completely. There is not enough resist to overcome the wafer surface tension resulting in uncoated triangular wafer sections. At dispense volumes above 7 ml resist uniformity starts to decrease again, presumably because of the higher solvent vapor content just above the wafer and the extra time needed to spin off the additional resist.

The challenge for the process engineer is to find the minimum resist dispense volume that can wet the wafer fully while providing a uniform and repeatable coating also.

Adding a solvent pre-wet step prior to resist coating will reduce the wafer surface energy and allow the engineer to reduce the resist dispense volume further. This change does add additional process complexity and more cycle time. We chose not to use a solvent prewet so that we could implement a solution quickly.

A SIX SIGMA APPROACH

A Six Sigma project should address one or more of the goals defined by the company as critical to the company vision and mission statements. Typically these goals address:

- cost reduction
- waste reduction
- a particularly challenging problem
- a process, design or quality improvement
- a manufacturing capacity improvement

The objectives of our project were to reduce the cost and waste of the resist coat process. We chose to reduce the resist dispense volume in two phases: first from 2.1 to 1.5 ml

and then from 1.5 to 1.0 ml. We divided the project into two phases so that we could realize the cost benefits from the first phase while evaluating further resist usage reduction in the second phase. For project requirements, the developed resist profiles, critical resist line width dimensions, and electrical test data using lower dispense volumes had to be comparable to our existing dispense volumes.

These objectives along with our business case, project scope, constraints, and assumptions, estimated cost savings based on this reduction, and preliminary project schedule defined our project charter. We selected internal customers from the wet etch, dry etch and photolithography process groups for the team to ensure that satisfactory responses to their concerns would be integrated into the final project solution. The project definition or “Define” stage of the Six Sigma project was completed when management approved the progress as part of a Tollgate review. A Six Sigma project has tollgate reviews after the completion of each of the five project stages. The team must meet the stage goals before it can start the next Six Sigma stage. Tollgate reviews also make sure management is aware of the team’s progress and continues to support the project.

In the second Six Sigma stage, “Measure”, the project team collects and evaluates existing process data to create a baseline for future data comparisons. For our project data units, measurement equipment settings and measurement methodologies were documented in operational definitions. These documents were reviewed with operators so that future experimental data could be collected and compared in exactly the same way. We completed a Gauge Repeatability and Reliability (GR&R) study on the ellipsometer used to measure resist thickness and verified that the existing GR&R study on our Critical Dimension Scanning Electron Microscope (CD-SEM) was current.

To see how our resist dispense volumes compared to other gallium arsenide device manufacturers we conducted an informal survey during the 2006 ManTECH Conference (see Fig I). Figure I displays resist dispense volume data from Skyworks Solutions, Inc., Newbury Park, California as SKY A. Data from five other GaAs wafer facilities across the industry are labeled as B, C, D, E, and F.

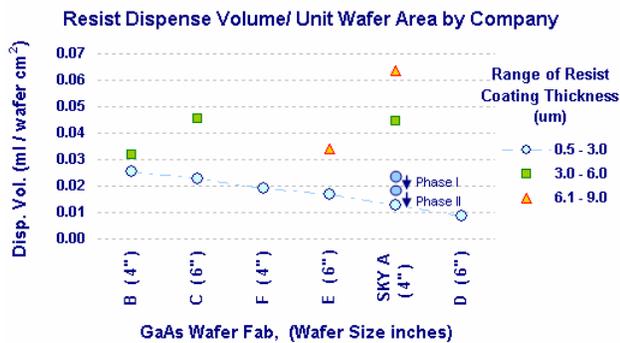


Fig I: 2006 Skyworks Industry Benchmark Survey on dispensed resist volume for three resist thickness ranges. Data normalized by wafer size.

None of the sites used a solvent pre-wet before resist dispense. These results show that there are large differences in resist volume usage within the industry. The scope of our project was confined to resist thicknesses between 1.25 um and 3.0 um. Data from company D indicated that we might be able to reduce the resist dispense volume for this thickness range down to 0.70 ml per wafer. We also discovered that we may have room to reduce the resist volume for our thicker resist coat processes.

After the Measure stage tollgate review with management we started the third Six Sigma stage, “Analyze”. The purpose of this stage is to review the existing process variables and find which of these variables can be adjusted to address the project goals best. To find the resist dispense lower process limit we coated 25 wafers at each of several dispense volumes from 0.5 ml to 2.1 ml per wafer (see FIGS. II, IIIA, IIIB).

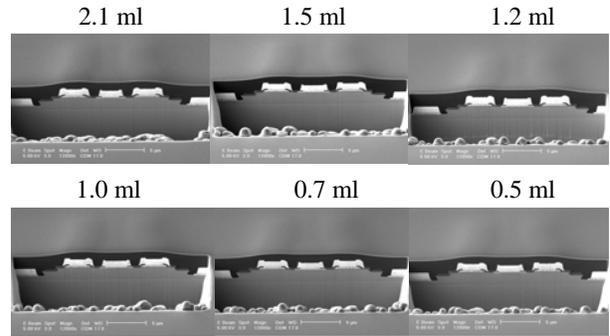


Fig II: 1.25 um Resist Thickness at Various Dispense Volumes

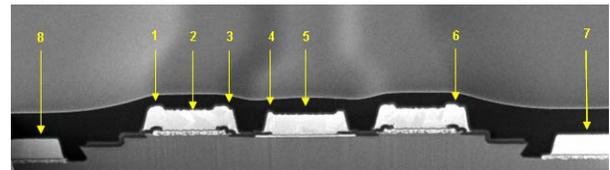


Fig IIIA: Measurement of resist uniformity over topography at eight transistor locations

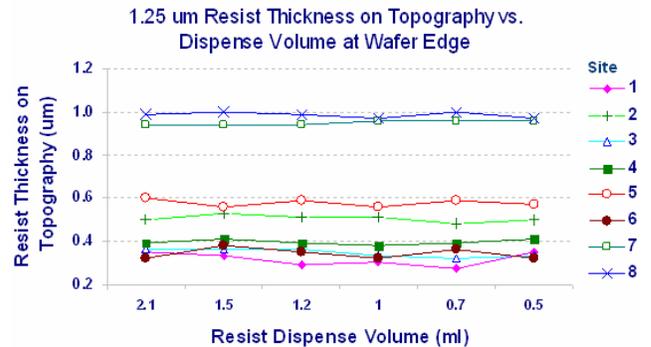


Fig IIIB: Resist Thickness on Topography at wafer edge for various resist dispense volumes.

Preliminary results showed that a 0.7 ml dispense volume gave acceptable and repeatable resist uniformity values. Cross sections of ring transistors coated with 1.25 microns of resist showed that the coating over topography was comparable for all resist dispense volumes.

Despite good resist coverage over topography, the 0.5 ml dispense volume did not coat some wafers completely. Data from the 0.7 ml coating was stable over short periods of time, but if it drifted toward 0.5 ml over a longer time period the process would be unstable. To allow a process buffer we selected a 1.0 ml dispense volume for our project's second phase target.

Using an Ishikawa Fishbone Diagram created in the Define stage, we listed and prioritized the variables we believed had the largest impact on resist uniformity control. This diagram displays the critical process output variable as the head of a fish. The spines of the fish are all of the process characteristics that affect this output variable. The highest ranked variables in a Pareto graph indicated which variables to consider in our experiments.

One variable, resist dispense methodology, was a high ranking factor. Our previous process used a combination of a static + dynamic = "stamic" resist dispense. The wafer does not spin initially but before dispensing is complete, the wafer starts to spin to spread the resist. Although initial tests suggested that the stamic dispense might improve resist coating uniformity, there was no statistical difference detected between dynamic and stamic dispenses when we completed a statistical t-test on resist thickness data from larger wafer samples for resist volumes of 2.1, 1.5 or 1.0 ml.

We also suspected that resist temperature might affect resist coating uniformity differently at different dispense volumes. An experiment that adjusted resist temperature by +/-1 deg. C showed the only significant difference in resist thickness uniformity between resist dispense volumes was at a -1 degree resist temperature setting (see FIG IV), which negatively impacted the uniformity. While the result was significant for the lowest temperature, our coater tracks have resist temperature controls with alarm setpoints at +/- 0.5 deg. C that prevent temperature drift.

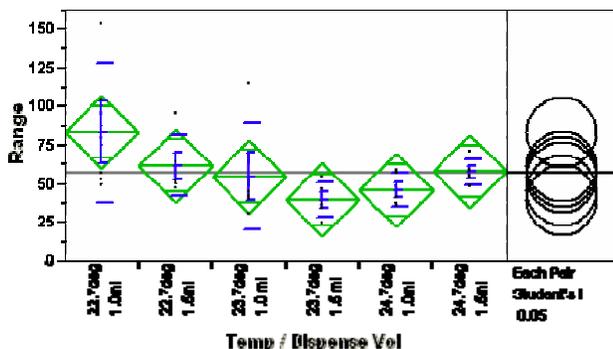


Fig IV: T-test comparison of Dispense Volume vs. Resist Temperature.

We also evaluated resist nozzle radial placement variation by +1 or - 2 mm and by height +/- 1.5 mm from the standard nozzle position. The t-test analysis of this data did not show any statistically significant differences between the dispense volumes for the various nozzle positions.

We applied the different dispense volumes on product wafers to test the effects of resist coating over standard topography. To test our dispense volume change with more aggressive, non-standard topography using larger step heights we used wafers from our final process layer (see Fig V).

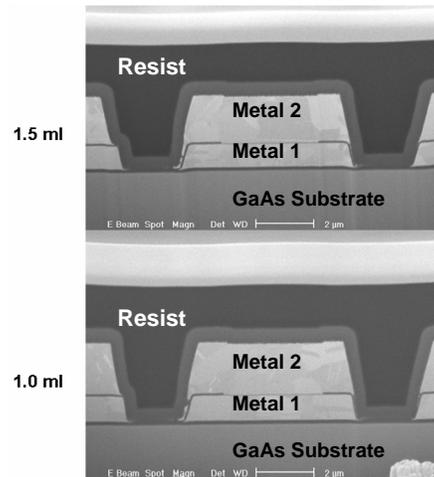


Fig V: Cross sections of 2.5 um resist coating with 1.5 and 1.0 ml resist dispense volumes over non-standard topography.

Cross sections at the center and the edge of several wafers coated with the 1.5 and 1.0 ml resist volumes confirmed that the 1.0 ml dispense volume were comparable to those with the 1.5 ml dispense volumes. A week later we repeated these tests as part of a confirmation experiment with similar results.

A similar experiment evaluated potential impacts of dispense volume on developed resist line profiles. Platinum was deposited over the resist in-situ in the SEM to prevent

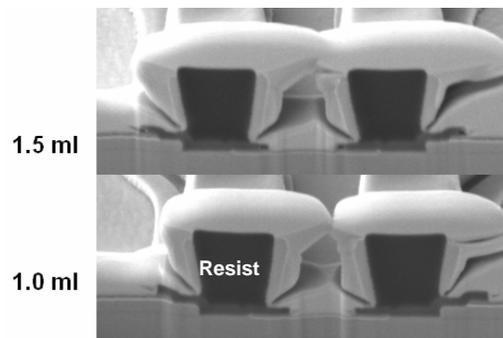


Fig VI: Developed Resist Profiles using Two Resist Dispense Volumes.

resist deformation and electron beam charging (See Fig VI). These cross section results indicated that the experimental wafer profiles were comparable to control wafer profiles.

In the fourth Six Sigma stage, "Improve", we implemented our process change on a limited production sample. Three production lots were split between odd (experiment) and even (control) wafers with the new 1.0 ml and the standard 1.5. ml dispense volumes, respectively. At each resist coat processing step for each lot we measured the critical dimensions (CD) from two wafers at each dispense volume on our CD SEM. Data analysis at each process layer showed that the critical dimensions for most process layers were not statistically different between the two resist dispense volumes. For the few process layers that showed a significant difference the difference was within the CD SEM resolution tool measurement error. Analysis of electrical test data between the control and experimental wafers also showed that most of the parameters were not statistically different. For the few test parameters that did show a statistical difference we compared the experimental data with the electrical parameter production lot historical data. In each of these cases, the historical variation of the electrical test parameter was considerably greater than the differences detected between wafer experiment groups.

Even if all of the data for the new process was equivalent to our existing process, we still had the potential to ignore concerns of customers downstream of our process. We solicited input from these customers by enlisting their help to complete a Failure Mode and Effects Analysis (FMEA). An FMEA is a systematic review of potential process failures to determine the potential causes of each failure². For each cause, the team must brainstorm what potential controls can be introduced so that the failure does not occur. For causes that occur frequently or have a low chance of detection or prevention the FMEA team must assign actions to try to reduce the frequency of the occurrence of the cause, or improve the prevention or detection of the failure mode. The FMEA is not complete until the team determines that the occurrence of the potential failures was reduced and/or the detection or prevention of the failure was improved as a result of the completed FMEA actions. A completed FMEA should also trigger a review of the Process Control Plan. Any new process parameter or one considered critical to the process output must be listed in the Process Control Plan, along with documented process controls.

We reviewed our existing resist coat Process Control Plan to make sure that equipment and process controls were in place and were documented for each of the critical process control characteristics.

Management approved the experimental data, the FMEA data and the Process Control Plan as part of the Six Sigma Improve stage Tollgate review. After completing this milestone we released the process change on one of our coater tracks as part of a pilot production ramp.

In the final Six Sigma stage, "Control", the team must monitor a newly released process for stability over time. New and existing process controls must be able to prevent or detect any significant process shift.

We verified that Out-of-Control Action Plans were in place for all known process failures to direct production technicians to the appropriate response procedure should a process fail.

Our process capability indices for our critical dimensions and our resist thickness control charts for the coater track with the new process did not shift after one month of production. We released the process on the remaining coat tracks and monitored the critical controls on all tracks for another month. The control charts for these critical process characteristics, the critical dimension control charts and the process capability indices did not show any shift due to the process change. Review of our electrical test data also did not show any test data shifts after this process was released.

We stored all of the project data in a central repository, referenced by a storyboard that included links to all of the data, reports, actions taken and improvements made. We shared what we learned in Newbury Park with our other facilities. As part of the closing activities of the Control stage, we identified what other projects would provide the next best process improvements and cost savings.

CONCLUSION

We reduced our resist dispense volumes for our resist and our resist waste by 50% without impacting our product quality by using Six Sigma methodologies. This systematic approach ensured that we addressed the concerns of our internal customers *before* the process change was implemented into production. This project generated considerable cost savings, reduced emissions and reduced hazardous waste. We believe that our corporate accountant can sleep a little more soundly, at least for now.

REFERENCES

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- [2] Le Saux, Daniel, *The Effective use of Process Control Plans and Process Failure Mode and Effects Analysis in a GaAs Semiconductor Manufacturing Environment*, pp. 31-34, 2006 CS MANTECH, April 2006.

ACRONYMS

CD: Critical Dimension
CD SEM: Critical Dimension Scanning Electron Microscope
FMEA: Failure Mode and Effects Analysis
DMAIC: Define Measure Analyze Improve Control,
The five stages of a Six Sigma project.