Automated Skiplot Sampling for Photoresist Thickness Measurements

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Keywords: skiplot, sampling, statistics, photoresist, lithography

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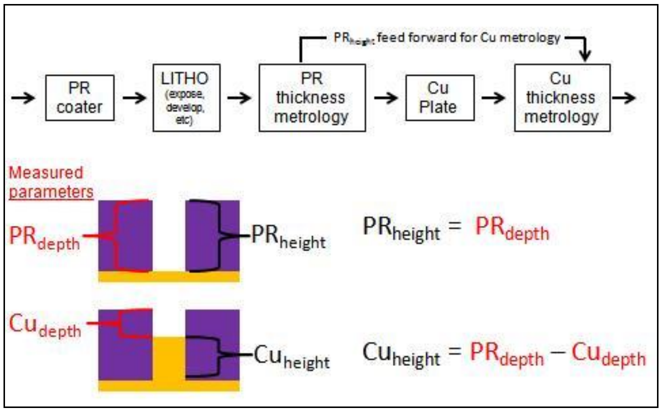
ABSTRACT

This paper describes how statistical methods were used to justify a substantial metrology reduction in Cu flip chip processing. A project overview is also given on how the skiplot sampling was tested, piloted, verified and implemented. Lastly, some discussion is given on how tool-chemical databases and MES lot histories can be combined to create an automated photoresist batch qualification system.

INTRODUCTION

Photoresist (PR) thickness control is a common concern in ultra-thick coatings (~100um). The thickness of the photoresist can play a role in the photoresist profile and for the case of copper (Cu) pillars, if the photoresist is too thin, it is possible to plate over the top of the resist which can result in the loss of Cu pillar feature size control. In our manufacturing line, a profilometry based PR thickness measurement is conducted on a test structure in the PCM (process control monitor) region on product wafers to ensure that the lithography module is in control. Furthermore, the measurement is *fed forward* to the Cu plating module as a reference thickness and is used to determine plated metal (Cu) thickness, Cu_{height}. See the figure below.

FIGURE 1.
OVERVIEW OF THE FEED FORWARD PR THICKNESS AND CU HEIGHT METROLOGY



In the early stages of our Cu pillar process when PR thickness control was relatively poor ($1\sigma = 1.7$um) , PR_{height} measurements were taken for every wafer in every lot. On average, the combined processing and queue time for each lot was approximately 3.5h. To make matters worse, the metrology tool is a manual P2 Tencor profilometer which requires constant operator intervention. After making numerous improvements to the PR thickness control, the team felt confident that a reduction in PR metrology could be achieved with minimal risk. The following is an overview of the steps that were taken to achieve this objective:

1. Characterize the sources of variation.
2. Determine an adequate sampling plan.
3. Test the effect of the sampling plan on downstream metrology using historical data.
4. Update the out of control action plan.
5. Pilot the sampling plan on a single product for a defined testing period.
6. Review the pilot data before implementing the change on other products.

Characterize the Sources of Variation.

All standard sources of variation were considered: the metrology tool, within-lot, lot-to-lot, tool-to-tool and PR batch variation. The only significant source of variation that would need to be accounted for was the photoresist *batch*. At the time of this study, a historical batch to batch variation of 1.5um had been observed for this photoresist. However, according to the photoresist vendor, we potentially could see a shift as high as 5um.

A potential shift of 5um in PR thickness upon introduction of a new resist batch could result in calculated plated metal heights that are out of spec if the shift in PR thickness were not taken into account (see figure 1, $Cu_{height} = PR_{depth} - Cu_{depth}$). Such an event, if taken as a true shift in plated metal height could lead to a series of unnecessary and problematic events (e.g., production lots going on hold, putting production tools down, rework through Cu plating, etc.) since wafers would be perceived as having Cu pillars either too tall or too short. Obviously, any excursions which occur at the end of wafer fabrication are particularly costly and any reduction in metrology must be done with a great deal of caution.

TABLE 1.
SOURCES OF PR THICKNESS VARIATION

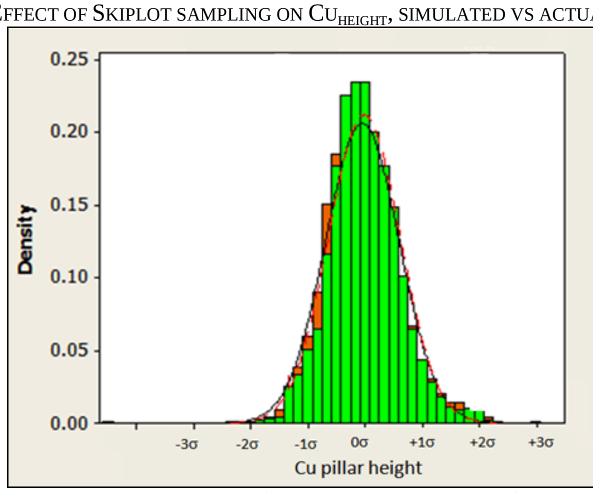
Source of variation	Variation
P2 Tencor Profilometer	0.33um (1σ)
Process variation (includes lot-to-lot, withing-lot, tool-to-tool)	0.63um (1σ)
PR batch	+/- 5.0 um (per vendor)

The above table of variations illustrates that each PR batch must be qualified, but once an average PR thickness of the batch is determined – that average may be used for all wafers coated with that batch. In other words, not all lots need to be measured. This sampling scheme is sometimes referred to as 'skiplot'. Using the sample size calculator in Minitab, a sample size of 80 wafers was selected (population std dev = 0.7um, margin of error = 0.33um, 2-sided confidence interval, confidence level of 99.99%). On average, the number of wafers able to be coated per PR batch was around 3000 wafers which therefore allows for a *substantial* reduction in metrology.

Test the Sampling Plan using Historical Data.

As mentioned before, a challenging aspect for this metrology step is that it not only ensures that the lithography module is in control, but in addition, the PR measurement is fed forward for downstream process control as well. Prior to implementation, to ensure that no significant shift would result from the skiplot sampling, 90 days of historical downstream data (i.e. Cu_{height}) was recalculated replacing the actual PR measurement with the batch averaged PR measurement; no significant shift was observed. (see Figure 2.)

FIGURE 2.
EFFECT OF SKIPLOT SAMPLING ON CU_{HEIGHT}, SIMULATED VS ACTUAL



Green = Cu_{height} distribution from measuring PR on all wafers.
Red = Cu_{height} distribution using skiplot sampling for PR thickness

Update the Out of Control Action Plan.

To prepare for an unexpected event in which a true PR_{height} shift occurs for any reason, the out of control action plan (OCAP) was updated to account for the reduction in metrology. In addition, the frequency of monitor wafer SPC measurements on the PR coater was increased from once every 48 hours to once per shift. The out of control action plan defines what to do if a failure is observed and is included in the production operation specifications. A benefit of a pre-defined OCAP is that it plans ahead for any worse case scenarios and clearly communicates to all production, engineering and management staff what actions are being done to respond to and contain any material affected by an excursion. For the updated OCAP, if any thickness failure is observed in the SPC monitor wafer, the skiplot condition at the metrology step for production wafers would be turned off and all lots not yet plated would get PR_{height} measured.

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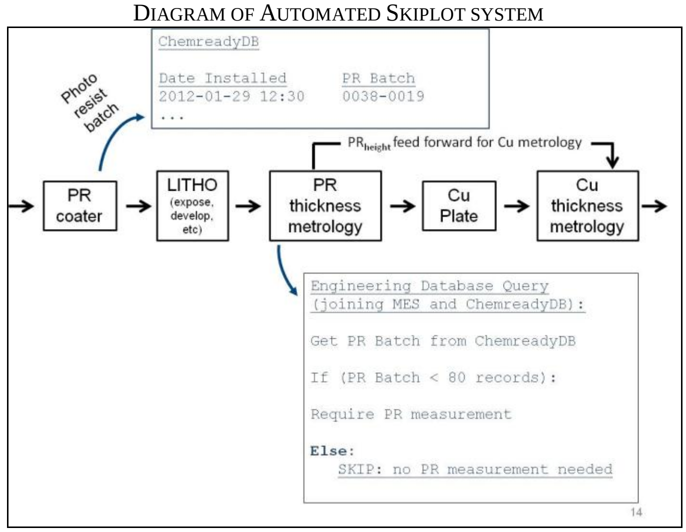
Automating the skiplot procedure

To ensure that no lots escape the lithography module coated with a PR batch that is not qualified, an automated system was put in place that queries both lot history and tool PR batch history. When a lot reaches the metrology step coated with an unqualified photoresist batch, the automated system will flag the lot for required thickness check.

The following diagram illustrates the automated skiplot system.

FIGURE 3.
DIAGRAM OF AUTOMATED SKIPLOT SYSTEM



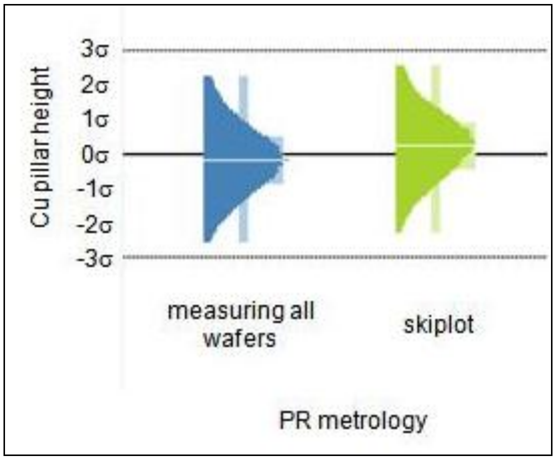
There are two main components to the system. The first component is that all PR batches loaded onto the coaters are logged in our internal tool-chemical database (called "ChemreadyDB"). Secondly, at the point of PR_{height} measurement, the operator scans the production lot ID into a web-based data entry form. The host program then queries both the ChemReadyDB and the MES lot history to determine what PR batch was used to coat the lot. It also queries if the lot has been qualified (i.e. are there 80 PR_{height} data entries for the PR batch used?). If so, the average of those 80 wafers will be used for the $PR_{hreight}$ of that lot. If not, the host system will communicate to the operator that the lot must be measured.

Pilot the skiplot procedure and review the results.

With all the aforementioned steps completed, the skiplot sampling scheme was piloted on a single product mask for a testing period of four weeks. The duration of this period of time allowed for a transition of PR batches which was useful in debugging the skiplot query code described in Figure 3.

In addition to this profilometer based metrology, 3D AOI (Automated Optical Inspection) is also conducted on product wafers which gives a more thorough characterization of actual bump heights in the die. A box plot comparison of the 3D AOI pillar height data is shown in Figure 4 along with the pillar height distribution histograms, indicating no significant shift. Based on this successful result, the skiplot method was rolled out to other masks.

FIGURE 4.
BOXPLOT COMPARISON OF 3D-AOI CU PILLAR HEIGHT BEFORE AND AFTER PR SKIPLOT IMPLEMENTATION



CONCLUSION

We have achieved greater than 90% reduction in PR_{height} metrology for our Cu pillar layer; saving several thousands of hours of cycle time and freeing up half of the time of an operator per shift. Since implementing this skiplot procedure, no unintended consequences have been encountered. As should be done anytime skiplot is implemented, in response to the reduction in metrology since production wafers are not being as closely monitored, the out of control action plan for PR thickness was updated and is documented in our production specifications.

ACRONYMS

AOI	Automated Optical Inspection
Cu	Copper
MES	Manufacturing Execution Systems, information technology systems that manage manufacturing operations in factories
OCAP	Out of Control Action Plan
PCM	Process Control Module
PR	Photoresist
SPC	Statistical Process Control

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