Weighted least squares regression for advanced overlay control

Dana Klein\textsuperscript{a}, John C. Robinson\textsuperscript{b}, Guy Cohen\textsuperscript{a}, Chin-Chou Kevin Huang\textsuperscript{b}, Bill Pierson\textsuperscript{b}

\textsuperscript{a}KLA-Tencor Corporation Israel, Haticshoret St., Migdal Haemek 23100, Israel
\textsuperscript{b}KLA-Tencor Corporation, One Technology Drive, Milpitas, CA 95035, USA

Abstract

Controlling overlay performance has become one of the key lithographic challenges for advanced integrated circuit manufacturing. Overlay error budgets of 4 nm in the 2x node require careful consideration of all potential error sources. Overlay data modeling is a key component for reducing systematic wafer and field variation, and is typically based on ordinary least squares (OLS) regression. OLS assumes that each data point provides equally reliable information about the process variation. Weighted least squares (WLS) regression can be used to improve overlay modeling by giving each data point an amount of influence on the model which depends on its quality. Here we use target quality merit metrics from the overlay metrology tool to provide the regression weighting factors for improved overlay control in semiconductor manufacturing.

Keywords: Overlay, overlay analysis, overlay modeling, weighted least squares

1. INTRODUCTION

Lithographic process control and the reduction of parametric variability has been one of the key enablers in the progression of advanced integrated circuit manufacturing. Controlling overlay performance has always been an important factor and has garnered in increasing proportion of concern as the industry transitions to the 2x and 1x nodes. The ITRS roadmap [1], as shown in Figure 1 indicates 4.7 nm and below overlay error budgets are required, and for which there are no known manufacturable solutions. Given the shrinking overlay error budget, a careful consideration of all potential error sources is required. For overlay metrology, previously the primary industry focus has been on precision and matching whereas more recently the emphasis is turning to accuracy and the improvement of metrology tools, metrology tool recipes, metrology targets, and sampling [2]. This study focuses on improvements in the accuracy of overlay data modeling, which is a key component of overlay process control.

Figure 1. The ITRS Roadmap outlines the significant challenges of overlay in the coming years including 4 nm overlay error budgets for the 2x nodes. Shrinking overlay budgets indicate the need for improved performance and process control methods. White indicates manufacturable solutions exist, yellow indicates manufacturable solutions are known, and red indicates that there are no known manufacturable solutions.

\*John.Robinson@KLA-Tencor.com, +1-512-231-4221
Overlay data modeling is a critical part of overlay process control in advanced semiconductor manufacturing. Overlay process errors are measured in the X and Y direction at predetermined locations on the semiconductor wafer. Combined with the field and wafer coordinates, the data is spatially modeled for process disposition, process control, scanner fleet management, troubleshooting, continuous process improvement, and other tasks which are critical to maintaining overlay error budgets. Overlay data modeling is typically based on the scenario pictured in Figure 2a. Overlay data is analyzed using ordinary least squares (OLS) regression. OLS is well known in textbooks as a statistical technique to evaluate the relationship between a response variable and explanatory variables by minimizing the sum of squared distances between observed and predicted data points [3]. Each observed point has the same impact on the resulting estimators, and its influence is proportional to the square of the distance between the point and the model being used to describe the data.

An enhanced method is shown in Figure 2b. In this case additional target quality merit metric data from the metrology tool is incorporated into the analysis. The target quality merit is a quality score given to each overlay measurement in real time: the tool reports each overlay value together with its quality merit value [4]. The quality metric corresponds to the symmetry or asymmetry of the measured target. A target quality metric value of zero corresponds to optimal symmetry or best quality. The analysis then uses the standard overlay data in addition to the target quality metric data. In this case the analysis uses weighted least squares (WLS) regression. WLS is a well known statistical technique to evaluate the relationship between a response variable and explanatory variables by minimizing the sum of squared distances between observed and predicted data points multiplied by their individual weights [5]. With this method, high quality data would have higher impact on the resulting estimators than low quality data. Historically, the challenge has been to find suitable weighting factors for the analysis.

In this study we demonstrate the improvements of using new target quality merit metrics from the Archer 300 LCM metrology tool in the K-T Analyzer overlay analysis solution. The goal is to provide enhanced overlay analysis for better process control in order to meet the stringent demands of the shrinking overlay error budget in the 2x and 1x nm lithographic nodes.

Figure 2. (a) The standard method where overlay metrology results are analyzed using ordinary least squares (OLS) regression. (b) The enhanced method where target quality merit information from the metrology tool are also included and analyzed in weighted least squares (WLS) regression.
2. METHOD

The goal of this study is to demonstrate the value of the target quality metric approach to improve overlay correctable accuracy using weighted least squares (WLS) for advanced lithography process control. In this study one Archer 300 LCM metrology tool was used with two distinct metrology recipes for the sake of comparison on the same wafers. The overlay tool recipe contains many parameters, including a color filter to adjust the illumination of the metrology target. In this study, one recipe used an optimized color filter, here called a “target compatible filter,” producing accurate results. Another recipe used another color filter, here called the “target incorrect filter,” producing results that are known to be biased for the sake of comparison. We then use a data analysis package, K-T Analyzer, to compare the results using both OLS regression and WLS regression method with the new quality metrics.

The models used in this study are linear. The wafer level model includes translation, scaling, and rotation (6 terms) and the field model includes magnification and rotation (4 terms) in a single pass regression. For direct comparison of the different cases we calculate the maximum modeled delta at the edges, as shown in Equation 1. In this study the wafer is 300 mm in diameter and the field is 30 mm in X and Y.

\[
\text{MaximumDelta} = \\
\text{Translation} \\
+ 150 \cdot (\text{Scaling}_{\text{Grid}} + \text{Rotation}_{\text{Grid}}) \\
+ 15 \cdot (\text{Magnification}_{\text{Field}} + \text{Rotation}_{\text{Field}})
\]

(1)

Another method of comparison is to consider the root-mean-square site-to-site matching. In the case of the original (or “raw”) overlay data this is straightforward. In the case of the modeled results, the models are evaluated at the measurement locations and are compared, as shown in Equation 2.

\[
\text{SRS} = \sqrt{\frac{(\text{OVL}_{\text{Compatible}} - \text{OVL}_{\text{Incorrect}})^2}{N}}
\]

(2)

In this study we perform the analysis for 2 case studies comprising 2 distinct sets of input data. In each case we compare the accurate target compatible filter data using OLS as the reference to the biased target incorrect filter data using OLS and WLS analysis for comparison.

3. FIRST CASE-STUDY

The target quality merit data for the first case-study is shown in Figure 3. For each overlay measurement in X and Y, there is a corresponding quality merit metric in X and Y, also in nm. The target compatible filter results show a narrow spread of +/- 2 nm, indicating that the corresponding overlay data is a good reference for the comparisons. The target incorrect filter results, however, show a wide spread of +/- 6 nm indicating that significant target asymmetry will bias the corresponding overlay results. The quality merit metric values are used as a weighting parameter in the case of WLS, and will be shown to compensate for the asymmetry detected when the incorrect filter was used.
Figure 3. Quality merit metrics are used as weighting factors in WLS. Each metric, represented here by a circle, represents the X and Y components of the quality merit metric, corresponding to the X and Y components of each overlay measurement in the data set. The solid green circles are for the target compatible filter results, and the hollow red circles are for the target incorrect filter results.

In Figure 4 the maximum modeled delta at the edges are shown as calculated by Equation 1. On the left we show the delta between the reference (target compatible filter results) using OLS and biased case (target incorrect filter results) using OLS. In this case differences of 8 nm and 7 nm are seen in X and Y, respectively. On the right we make a similar comparison, however, the biased case is enhanced with WLS using the quality merit metrics. The delta in X and Y are now below 6 nm showing a >25% improvement in the modeled results.

Figure 4. The MaximumDelta between the compatible filter data using OLS and the incorrect filter using OLS for both X and Y directions (left). The MaximumDelta between the compatible filter data using OLS and the incorrect filter using WLS for both X and Y (right). Notice a >25% improvement in the results of the incorrect filter when quality merit metrics are used in WLS.
In Figure 5 the site-to-site comparison results are shown based on Equation 2 for X and Y. Not surprising, the worst matching is for the original (or “raw”) data of 3.4 nm. There is a slight improvement when the two OLS models are compared (the models are evaluated at the measurement locations), due to the fact that the model averages out some of the variation of the intentional bias. The best case is when the biased data is analyzed with the WLS method based on the quality merit metrics. In this case we see a >25% improvement in site-to-site matching.

<table>
<thead>
<tr>
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<th>Raw vs Raw</th>
<th>OLS$<em>{fit}$ vs OLS$</em>{fit}$</th>
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<td>Orientation Y</td>
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Figure 5. Site-by-site overlay matching in the X and Y directions in nm between the correct filter and the incorrect filter: the raw (or original) data for both, OLS for both, and OLS for the correct filter vs. WLS for the incorrect filter. Notice there is a >25% improvement where the quality merit metrics are used in WLS.

4. SECOND CASE-STUDY

A second case-study was performed in order to gain additional confidence in the new methodology. In this case a different compatible filter was used and the same incorrect filter for comparison. The quality merit metrics are shown in Figure 6. In this case, the target incompatible filter results are again narrow (green circles), but have a spread of +/- 2.5 nm. The target incorrect filter results again vary by +/- 6 nm (red circles).

Figure 6. Quality merit metrics are used as weighting factors in WLS. Each metric, represented here by a circle, represents the X and Y components of the quality merit metric, corresponding to the X and Y components of each overlay measurement in the data set. The solid green circles are for the target compatible filter results, and the hollow red circles are for the target incorrect filter results.
For the second case-study we show the maximum delta at the edges and the site-by-site comparisons as was done in the first case study described above. For the maximum delta we see a >20% improvement and for the site-by-site we see >40% improvement when the quality merit metrics are incorporated in the WLS analysis.

Figure 7. The MaximumDelta between the compatible filter data using OLS and the incorrect filter using OLS for both X and Y directions (left). The MaximumDelta between the compatible filter data using OLS and the incorrect filter using WLS for both X and Y (right). Notice a >20% improvement in the results of the incorrect filter when quality merit metrics are used in WLS.

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<td>Orientation Y</td>
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Figure 8. Site-by-site overlay matching in the X and Y directions between the correct filter and the incorrect filter: the raw (or original) data for both, OLS for both, and OLS for the correct filter vs. WLS for the incorrect filter. Notice there is a >40% improvement where the quality merit metrics are used in WLS.
5. CONCLUSIONS

Improving lithographic process control is one of the key enablers to continue on the ITRS roadmap. The shrinking overlay budget in the 2x and 1x node requires looking at every possible source of error and every opportunity for improvement. When the overlay error budget is 4 nm, tenths of a nm count. Overlay modeling is a key component of overlay process control including process disposition, scanner control, scanner fleet management, root cause analysis, continuous process improvement, and the like. Ordinary least squares (OLS) regression has been the basis for overlay model analysis for many years. Other methods, such as minimizing the maximum error or robust regression methods have been proposed for process modeling [6, 7] but have not had widespread adoption as the core modeling engine (though robust regression, for example, is used for outlier removal). Weighted least squares (WLS) regression requires reliable additional information about the quality of the overlay targets.

One source of error is the asymmetry of the overlay metrology target, where new metrics have been developed to quantify the asymmetry on the Archer 300 LCM metrology platform [2, 4]. The quality merit metric and weighted least squares (WLS) regression has been successfully incorporated into K-T Analyzer. In this study we have shown that reliable quality merit metrics together with WLS methods can improve the accuracy in overlay modeling in a case where intentional asymmetry is induced. Future investigations will include application of these methods in high-volume manufacturing scenarios. This new technique can be a valuable addition to emerging industry practices.

REFERENCES