Pinpointing Causes of Overlay Metrology Uncertainty

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In this study, the contributors to in-field overlay metrology uncertainty have been parsed and quantified, with particular focus placed on the unmodeled systematics. These are the components which contribute to residuals in a linear model after removal of random errors. In addition, they are also those which tend to be the most challenging to quantify and are suspected to be significant in the model residuals. Study results show that even in a relatively "clean" front end process, the unmodeled systematics are the dominant residual contributor, accounting for 60% to 70% of the variance. Given the above results of in-field overlay behavior, new sampling and modeling methods are proposed which have the potential to improve the accuracy of modeled correctibles and lot dispositioning parameters.

Introduction

Layer-to-layer alignment in optical lithography is controlled by feedback of scanner correctibles provided by analysis of inline overlay metrology data from product wafers. These correctibles are parameters of linear overlay models describing the spatial dependence of overlay on field and wafer coordinates. Recent publications have reviewed the sources of uncertainty in overlay metrology by characterizing the contributors to the model residuals, i.e. the discrepancies between the modeled and measured values at the point of measurement. It has been observed that the most well characterized sources of error, typically the metrology tool contributors, are not necessarily the dominant contributors to model residuals. For the metrology engineer in the lithography cell, this represents an opportunity to improve the quality of correctibles and lot dispositioning parameters by broadening the scope of definition of the metrology problem. A wider list of sources of error should include all the components which appear in the schematic tree diagram in Figure 1.

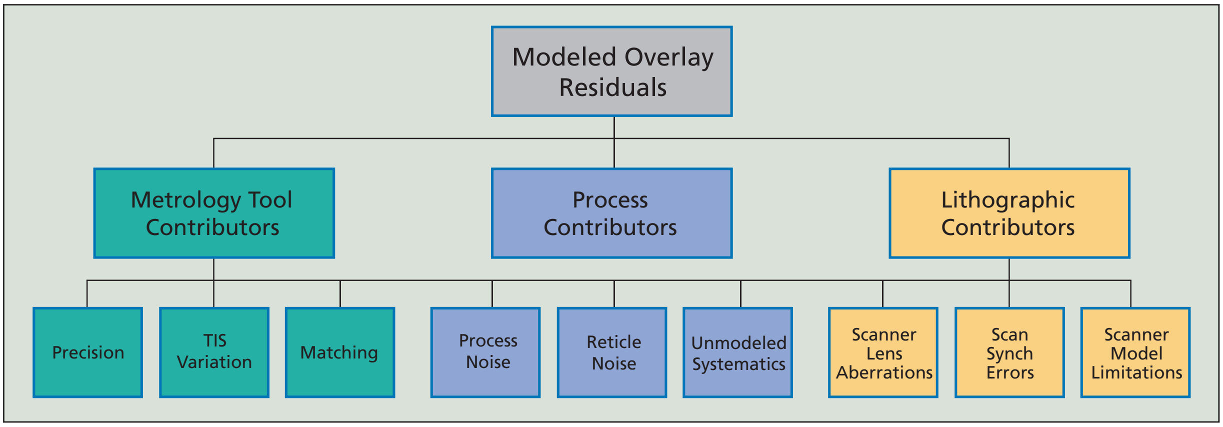

Figure 1. Schematic depiction of error contributors to overlay model residuals.

In this figure, the sources of uncertainty are grouped according to physical sources. Later we shall see that although this grouping is intuitive and didactic, it is not necessarily feasible to explicitly dissect the problem in this fashion, which leads to a proposal of an alternative breakdown.

The metrology tool contributors are quantified by a number of known methods and metrics[1], as shown on the left side of the tree diagram. The tool total measurement uncertainty (TMU), although not calculated by the same equation universally, is typically a sum squares of the 3 sigma precision, TIS variability and site-by-site matching. As we move from the left to the right of the diagram, the metrics and methods to quantify the contributors are not as well established[2]. In recent years, the process and lithographic contributors have become the focus of a number of studies[3], and new metrics have been proposed. In particular, Overlay Mark Fidelity has been proposed[4] as a method to independently quantify the random contribution of wafer and reticle manufacturing processes on metrology uncertainty. Work has also been reported quantifying the impact of scanner aberrations on pattern placement errors, i.e. the discrepancy between placement of design rule size features and larger features characteristic of the overlay mark[5]. In this work we have expanded the scope and attempted to quantify the other contributors in

Figure 1, specifically process-related unmodeled systematics, scanner-related unmodeled systematics, and intrafield reticle write errors.

Experimental methods

A series of experiments was designed with the objective of independently characterizing and quantifying each of a number of uncertainty contributors. For this purpose, two specialized test reticle sets were designed and manufactured at AMTC using an e-beam write tool (Toshiba EBM 4000). The test reticles comprised a dense array of overlay features in both scan and slit orientations in the field. For each of the two reticle sets, the inner and outer features of the overlay mark were printed on the same reticle with a 50 mm offset and 650 mm offset, respectively. Wafers were printed using both a simple resist-resist process on an ASML/750s (248 nm ATHENA alignment system and Blue align reticle) and a short loop poly to active process, on an ASML/1100 (193 nm ATHENA alignment system and Blue align reticle). A number of different exposure and processing sequences enabled the independent quantification of the impact of different error sources; the details follow below.

Tool Contributors

All measurements where performed on the KLA-Tencor Archer AIM tool using standard non-segmented 27 mm AIM targets. Nine sites on all fields (21) where measured. Ten dynamic loops where performed, with each measurement performed at a wafer orientation of 0 and 180 degrees. 3*s over dynamic loops was calculated for each site. Precision (measurement repeatability) is defined as the pooled 3*s on all sites. TIS values were averaged per site (and per field) over all dynamic loops. TIS variability is defined as the 3*s across all fields and sites measured. Tool-to-tool matching is defined as the 3*s of site-by-site difference between two tools. When possible, 10 dynamic loops are measured on each tool, and the average over dynamic loops difference is used in order to eliminate the precision (repeatability) contribution from the tool-to-tool matching. TIS correction is also used on every measurement to decouple TIS variability from the tool-to-tool matching result. In the data set presented in this work, time constraints led to the removal of precision effects from one tool in the tool-to-tool matching data, leaving the matching variability estimate open to a slight upwards bias. This effect, however, is small due to the deep sub nanometer level of precision.

Overly Mark Fidelity

In order to quantify Overlay Mark Fidelity (OMF), an array of 4 closely packed, standard, non-segmented 27 µm AIM targets was measured. Nine sites on all fields (21) where measured in 10 dynamic loops. OMF of a single array is defined as 3*s over the four targets in the OMF array. Total OMF is defined as the pooled 3*s on all arrays. The total OMF can be further broken down into wafer and reticle components as defined in reference 4.

Intrafield Reticle Errors

Mask write registration error impact on overlay was also directly evaluated using a Leica LMS IPRO2 tool. One overlay mark was selected. Registration of its inner structure was measured on an 11x11 grid. Similarly, registration of its outer structure was measured on the same grid. The difference between the two registration measurements was used as an estimator of the contribution of reticle write error on overlay.

Scanner Stage Errors 1

Using test reticle 1 (named “overlay matching”), bar-in-bar targets were printed using a double exposure (650 µm shift of the same image between the two prints) in resist. These targets were measured on an Archer AIM tool at 49 points per field over 51 fields.

Using Archer Analyzer, two separate models were generated, one with an average intra-field model and one in which the intra-field model was allowed to vary by field. Under the assumption that in the process contribution in the double exposure resist, only print is negligible, the difference between the variance of the residuals is taken as an estimate of the scanner field-to-field systematic contribution.

Scanner Stage Errors 2

Using test reticle 2 (OCSLI FE) two exposure jobs, one standard and one non-standard, were created. Typically, the scanner will use the standard job for all layers of the same design (poly and active here). The non-standard job is used to obtain on the same wafers, all combinations of scanning direction. Two wafers were produced with the standard job in the active layer and the non-standard in the poly layer. Two wafers were also produced with the non-standard job in the active layer and the standard in the poly layer. Only inner dies can have a different scanning direction; outer dies will always scan in the same direction for leveling optimization. For each die, nine AIM 27 µm targets were measured. An analysis was performed to determine whether there is a statistically significant discrepancy between intra-field correctibles, which is correlated to scan direction.

Aberration-induced Pattern Placement Errors

Using test reticle number 2 (OCSLI FE), over the top of the stack of interest (STI or POLY), simultaneous AIM targets (27 µm size) are exposed. Wafers were manufactured by a single lithography step. Metrology data acquired from these test vehicles were analyzed in order to characterize metrology performance of simultaneous AIM marks and to quantify pattern placement errors at multiple positions within the scanner field and their variability from field to field. In particular, the results of such measurement across the scanner slit and in the scan direction were analyzed to determine the magnitude and behavior of the PPE effect at 11 positions across the slit. The displacement value for each position is the average of 22 positions along the scan. This average along the scan virtually eliminates the contribution of random errors, which are in any case very small on single layer metrology structures.

Unmodeled, Systematic Field-to-Field Errors

Using the same short loop poly to active process described above, two layer wafers were printed using the OCSLI FE test reticle set. Overlay metrology was performed on non-segmented 27 µm AIM targets on the Archer AIM tool according to a dense (all fields, 9 sites) sample plan. Analysis was performed according to two different methodologies, as described below.

Results & Discussion

All the results of the independent metrology experiments for the standard and CMP+ wafers are grouped together in figures 2 though 5 below.

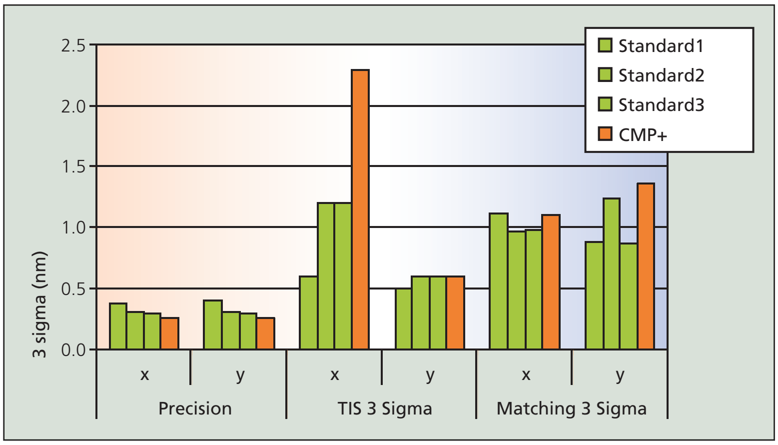

Figure 2. Tool uncertainty contributors, precision, TIS variability, and site-by-site matching variability as measured 27 µm AIM marks on poly to active process.

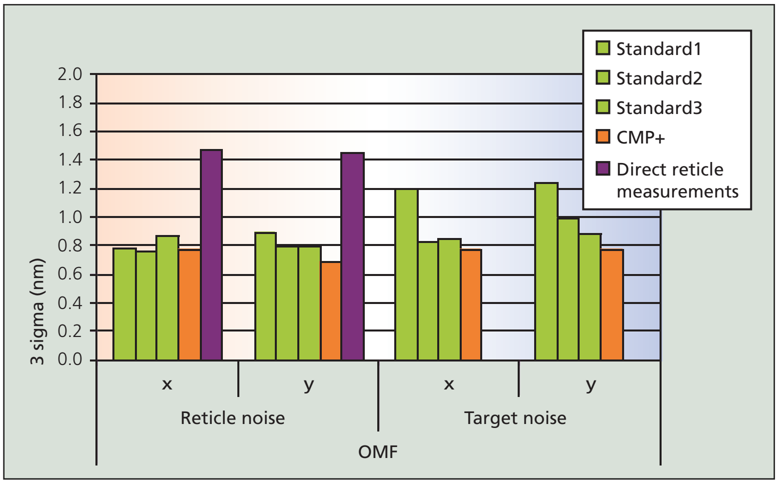

Figure 3. Reticle and target contributions to overlay mark fidelity as measured on 27 µm AIM marks on poly to active process. Direct reticle metrology results, obtained with the Leica iPRO tool, are added for comparison.

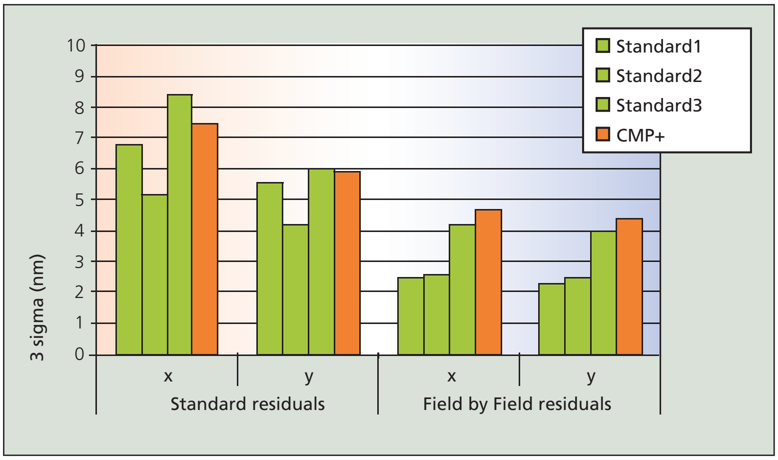

Figure 4. 3 sigma residuals, resultant from overlay modeling. Comparison shown between standard model residuals and the systematic residuals, as described in text.

The method chosen to analyze and group the data will now be described. In order to enable an unbiased representation of the relative contribution of each source, all the data will be compared in variance space. The procedure is shown diagrammatically in Figure 6. Firstly, the sources of uncertainty are broken down in random and systematic contributions. Moving from the left to right, the overlay mark fidelity contribution is broken down into the process and reticle contribution by a statistical method described in reference iv. The tool contributors are then calculated according to well known and excepted methods (see, for example, the ULSI microelectronics handbook of metrology). Methodologies for characterizing systematic contributors are less well established and the method used in this work will now be described. Using the data acquired as described previously, a standard scanner model was applied to the data using Archer Analyzer. After calculation of the inter-field model by standard linear regression, this model is subtracted from the overlay data at every measurement point. At this point two separate techniques are used to determine the intra-field model. In the first, the average intra-field model is determined by linear regression on the intra-field data averaged over all fields measured. In the second technique, each field is allowed to vary independently. If there were no additional sources of intra-field variability, then the residuals remaining after each of these methods would be equal to within the statistical uncertainties in the data. In practice, the second technique always yields significantly lower residuals. It is proposed that the difference in the residuals between these two models is an estimator for the unmodeled systematic field-to-field biases. Furthermore, it is assumed that these biases can be broken down into a process-induced contribution and a scanner-induced contribution.

In order to determine the relative contribution of the scanner and process components, the data obtained in the scanner error experiment described previously was analyzed in an identical modeling method described above. However, since this data was obtained from a resist double exposure process, the process contribution is considered to be neglible, leaving only the scanner-induced field-to-field variability. Under the assumption

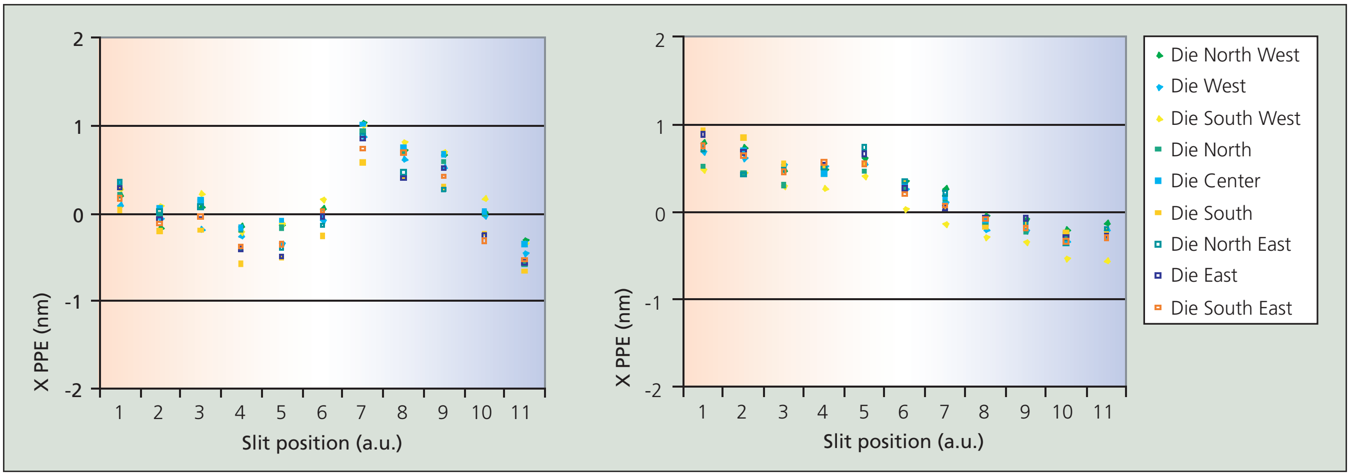

Figure 5. Pattern placement error dependence on slit position in x and y directions as measured by 27 μm simultaneous AIM marks on poly to active process, using poly step lithography conditions.

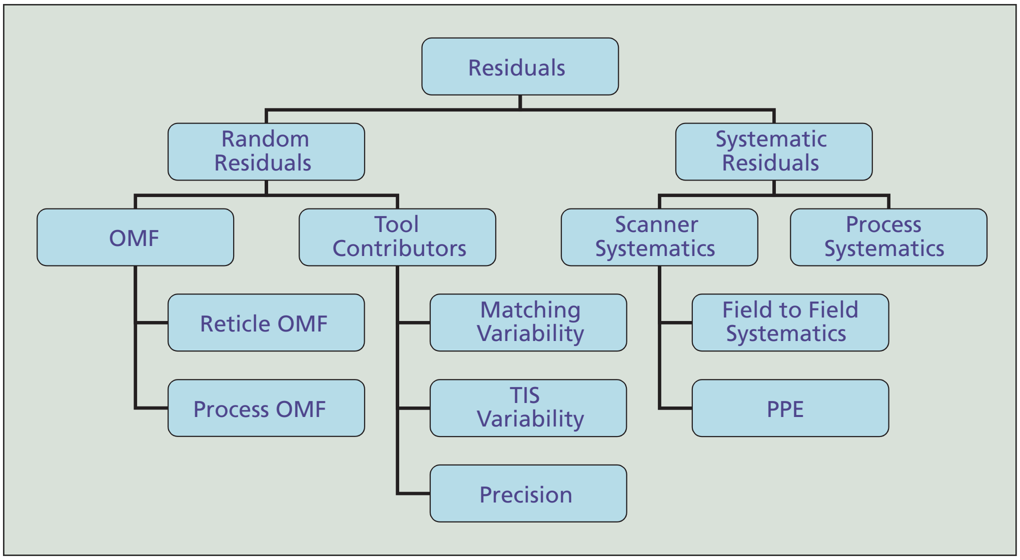

Figure 6. Residuals hierarchy, showing breakdown into random and systematic components.

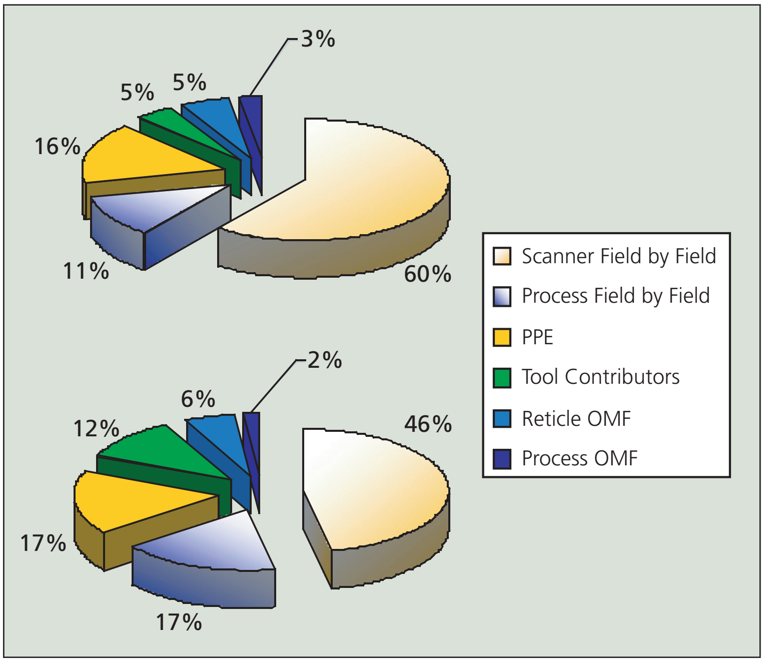

Figure 8. Breakdown of sources of overlay metrology uncertainty; left: standard process wafers, right: CMP+ wafer. The pie chart represents the weight of each contributor in variance space.

that the size of this contribution is constant, independent of process, this same component (in variance space) will be present in the poly to active data. After removal of all other components from the standard residuals, the remaining component is attributed to process systematics. One more important result was obtained from the experiment described earlier. By analyzing data from wafers exposed with differing scan directions, no clear correlation was found between scan direction and intra-field correctibles. The final breakdown of sources of uncertainty according to this technique, for the standard wafers (averaged) and for the CMP+ wafer, is shown in Figure 8. From these pie charts, a number of conclusions can be drawn.

Sampling & Modeling

It is clear from the preceding section that the major contributor to the model residuals is field-to-field systematics. This indicates that there exists an additional physical phenomena not accounted for by the average intra-field model. This implies that the traditional overlay model in which all fields are averaged to give a single intra-field model may potentially lead to non-optimal lot dispositioning criterion and correctibles.

Lot Dispositioning

The Maximum Predicted Overlay (MPO) based on the traditional model may potentially send good lots to re-work or pass on bad lots. In order to reduce this risk, it is proposed that intra-field model variation be accounted for on a field-by-field basis, removing the bias built into the model. One method is to introduce high order terms into the interfield model and remove the bias before intra-field analysis. This is appropriate in a case when wafer level processes such as CMP, etch, or deposition introduce high order wafer level signatures. An alternative method is to allow the intra-field model to vary field by field. This is more appropriate for scanner-dominated sources of high order error. Such methodologies require appropriate, generally denser, sampling schemes.

Correctibles

In cases where the physical origin of this systematic signature can be identified, then the model can be expanded to reflect all the physical mechanisms responsible for the overlay error. The physical sources can be broken down into scanner-related and process-related phenomena. In the latter case, this opens up the prospect in the future of overlay correctibles feedback (or feed-forward) to process tools outside the litho cell. Such enhanced modeling is beneficial only to the extent that control knobs in either the scanner or in the process tool are available and strongly correlated to the new correctibles.

Conclusions

A method has been developed for identifying and quantifying individual contributors of overlay metrology uncertainty. Using this methodology, for the front end case characterized in this work, the residuals are indeed dominated by systematic contributors. For a high-fidelity front end process, the unmodeled systematic residual contribution is primarily due to scanner effects. Although there is a clear PPE signature, its magnitude is significantly less than the field-to-field systematic variability. Turning to the random contributors, in the standard wafer case the process- and tool-induced contributors are comparable in magnitude, while in the CMP+ case the tool contributor increases significantly due to TIS 3 sigma. Of the process random contributors, the wafer component is significantly larger than the reticle component, which was shown by two separate techniques to be a minor contributor. It is proposed that the dominance of systematic biases in the data indicate an opportunity for implementation of alternative modeling methods and denser sampling schemes to reduce bias in lot dispositioning criteria. One such method has been proposed. This will be further explored in subsequent publications.

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