Overlay control methodology comparison: field-by-field and high-order methods

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Abstract

Overlay control in advanced integrated circuit (IC) manufacturing is becoming one of the leading lithographic challenges in the 3x and 2x nm process nodes. Production overlay control can no longer meet the stringent emerging requirements based on linear composite wafer and field models with sampling of 10 to 20 fields and 4 to 5 sites per field, which was the industry standard for many years. Methods that have emerged include overlay metrology in many or all fields, including the high order field model method called high order control (HOC), and field by field control (FxFc) methods also called correction per exposure. The HOC and FxFc methods were initially introduced as relatively infrequent scanner qualification activities meant to supplement linear production schemes. More recently, however, it is clear that production control is also requiring intense sampling, similar high order and FxFc methods. The added control benefits of high order and FxFc overlay methods need to be balanced with the increased metrology requirements, however, without putting material at risk. Of critical importance is the proper control of edge fields, which requires intensive sampling in order to minimize signatures. In this study we compare various methods of overlay control including the performance levels that can be achieved.

Keywords: Overlay, overlay analysis, overlay modeling, high order overlay

1. INTRODUCTION: HIGH ORDER VS. FIELD BY FIELD

The increasing challenges of advanced photolithography and the decreasing allowable overlay error budgets require going beyond the linear overlay modeling that has been the standard for many years. Going beyond the linear regime for both equipment control and process control requires careful consideration of the trade-offs of improved scanner performance versus the extensive sampling that is required. In this study we consider a double patterning lithography (DPL) technology to achieve half pitch resolution of 28 nm, and below, using a 193i immersion exposure tool. To meet the 28 nm performance, the single machine overlay spec is set to less than 4 nm.

In order to achieve the required tight overlay spec in a production environment, there are three correction methods that are commonly used by lithography engineers: (1) high order control, (2) linear control with static field x field correction (FxFc), and (3) high order control with static FxFc. The objective of this study is to compare the overlay correction results among these three commonly used methods and the standard linear control method.

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Figure 1. High order control: dynamic lot-by-lot high order correction. High order control cannot correct field scan direction or routing signatures.

In traditional linear control, overlay data is modeled using the $K_1$ to $K_6$ terms as shown in the polynomial equations shown below. For today’s state-of-the-art immersion scanner the available high order wafer grid knobs can be up to a 5th order polynomial, however, 3rd order ($K_1$ to $K_{20}$) is the most commonly used mode in production environments due to its robustness to process noise.

$$X_{\text{OVL}} = K_3 + K_4 x + K_5 x^2 + K_6 x y + K_{11} y^2 + K_{13} x^3 + K_{15} x^2 y + K_{18} x y^2 + K_{20} y^3 + ..$$

$$Y_{\text{OVL}} = K_3 + K_4 x + K_6 y + K_8 x^2 + K_{10} x y + K_{12} x^3 + K_{14} y^3 + K_{16} y^2 x + K_{18} x y^2 + K_{20} x^3 + ..$$

where $x$, $y$ are wafer or field coordinates

Overlay distortion patterns that follow a low frequency smooth curve usually can be modeled and corrected by scanner knobs as shown in Figure 1 (top) using high order models. For irregular overlay scan-direction or routing signatures, however, it will not be well modeled or corrected by typical high order models as shown in Figure 1 (bottom). In this case the un-modelable residual might exceed the required overlay control spec.

To overcome the limitations of polynomial modeling, if the un-modeled signature is common to all similar wafers within the lot and lot-to-lot, one can generate average un-modeled overlay distortion signatures and use it as a static field by field correction (FxFc) lookup table. This table can be applied on top of the dynamically (per lot) polynomial modeled overlay corrections. There are two commonly used methodologies for applying the FxFc as shown in Figures 2 and 3. Of course, to obtain the FxFc lookup table, a full-field sampling across several wafers and lots are required in order to create the averaged common signatures. The FxFc signature will additionally need to be periodically updated. Depending on process stability, the update frequency could be as long as between monthly scanner PM, or every 10 days, or even as short as every several lots depending on the level of variability.
Figure 2. Linear plus field by field correction (FxFc). A static signature correction applies to all lots. Typically the FxFc file is updated periodically from every 10 days to every month.

Figure 3. High order correction (HOC) plus field by field correction (FxFc). A static signature correction is applied to all lots. HOC removed the modeled HO process signature.
The unmodeled systematic overlay component in our study, as described above, will be called “process signatures.” The process that causes these signatures could be lithography, etching, thermal or CMP process. The process signature could vary from lot-to-lot due to process instability as shown in Figure 4.

Since the process signature may vary from lot-to-lot, a static FxFc has to be generated by taking the common signature by averaging process signatures from a meaningful number of lots. Figure 5 illustrates generating a composite process signature from N lots. At each field, a common single vector component was taken by averaging all the vectors from the N lots as displayed as a red vector in the figure. As one can see, the associated deviation from the average vector is the residual of correction. The larger the deviation from averaged vector, the less effective the FxFc results will be. Hence the 3 sigma deviation among all the lots at each field is used to quantify the process signature uncertainty or the FxFc effectiveness. The size of bubble plot for each field presents the X and Y combined uncertainty. The larger the bubble, the less effective the FxFc will be.
3. **CASE STUDY**

In this experiment we chose a double patterning lithography (DPL) 28 nm process node. The scanner was a 193i immersion scanner. For the study we had a total of 7 lots, some with 1 wafer and others with 2 for a total of 11 wafers exposed over a period of 10 days on the same scanner chuck. The metrology tool is an Archer 300 metrology system. All fields were measured, and 5 sites were measured in each full field. The data was analyzed in K-T Analyzer using the HOC Package and HOC On-line. Four control scenarios were studied: (1) linear, (2) HOC, (3) linear + constant FxFc1, and (4) HOC + constant FxFc2.

![Linear control process signature](image1)

![High order control process signature](image2)

Figure 6. Linear process signature vs. high order process signature. High order control removed part of the process signature.
As defined in the previous section, the process signature is the un-modeled systematic overlay wafer component. Therefore for a given set of data, by using either a linear or high order to model, the remaining un-modeled systematic component will be different. Hence, a linear control process signature will be different from a high order process control signature for a given set of data. Figure 6 illustrates the signature differences between the 2 modeling methods. As one can see the linear control process signature in top of Figure 6, the process signature varied significantly from wafer-to-wafer. The process variations for each wafer could, however, be modeled or corrected by high order control. As a result, the process signatures of HOC are more stable and are smaller in magnitude.

The process variation between wafers also can be quantified by using source of variation (SOV) methodology provided by K-T Analyzer as shown in Figure 7. In the SOV plot, the overlay linear residual was decomposed into 3 major components: the systematic wafer non-linear from process, the systematic field non-linear from exposure and the un-modeled random component. The wafer process signature can vary significantly between wafers.

![Figure 6](image)

Figure 6. Source of variation (SOV) analysis for non-linear components. Non-linear process signature has a large variation between lots, which implies ineffective FxFc results.

![Figure 7](image)

Figure 7. Source of variation (SOV) analysis for non-linear components. Non-linear process signature has a large variation between lots, which implies ineffective FxFc results.

![Figure 8](image)

Figure 8. Process signature uncertainty: after each lots linear systematic component was removed. The ellipses indicate variation at each field. Large ellipses indicate ineffective FxFc for that field.
By overlapping the 11 wafers’ non-linear process signature together as showed in Figure 8 (left), one can see the process variation is very significant. The common signatures or the FxFc lookup map is plotted by taking the average of all the wafers as shown in Figure 8 (center). Using the process signature uncertainty defined in previous section, the process signature uncertainty associated with the non-linear FxFc data is shown in Figure 8 (right). For fields with uncertainty greater than 3nm, the bubbles are filled solid to emphasize ineffective correction at that particular location. As one can see, the wafer edge fields were very unstable. Unexpectedly many of the fields near the wafer center were also unstable. It is very clear from the process signature uncertainty bubble plot that the linear modeling combined with FxFc control methodology could not deliver effective correction results.

![Figure 8](image1)

Figure 8. Source of variation (SOV) for non-linear components to further separate components of variation. In this case the high order component could be removed by HOC control and the process signature became much smaller and more stable.

If we further decompose the non-linear overlay residual to include 3rd order wafer component, the un-modeled systematic component is much smaller and more stable as shown in Figure 9 as the “wafer > 3rd order systematic” component. The process signature uncertainty associated with the averaged FxFc created from HOC residuals was significantly reduced as shown from the bubble plot in Figure 10 (right). It also illustrates that more effective correction results can be achieved by using the HOC + FxFc methodology.

![Figure 9](image2)

Figure 9. Source of variation (SOV) for non-linear components to further separate components of variation. In this case the high order component could be removed by HOC control and the process signature became much smaller and more stable.

![Figure 10](image3)

Figure 10. Process signature uncertainty after the HOC systematic component was removed for each lot. Ellipses indicate variability for each field. Wafer edge fields have larger uncertainty, so FxFc will be less effective at the edges.
By combining the non-linear and high order removed process signature, as shown in Figure 11, it can be seen that the uncertainty of the process signature is improved by HOC removal.

Figure 11. The uncertainty of the process signature is improved by HOC removal.

![Non-linear process signature uncertainty bubble plot](image1)
![High order removed process signature bubble plot](image2)

Remove HO component
Overlap

Figure 12. Correction comparison for the 11 wafer averaged residual 3 sigma in nm. Commonly used HOC or “linear + FxFp1” is insufficient to meet 4 nm overlay budget. High order control combined with FxFc2 was the most effective method to achieve 4 nm OL production requirements.

![Correction Result Comparison X-direction](image3)
![Correction Result Comparison Y-direction](image4)
4. SUMMARY AND CONCLUSIONS

It is clear that going to advanced process nodes with sub 4 nm single tool overlay budgets is a challenge requiring advanced techniques. It requires a careful analysis of the sources of variation (SOV) and the available correction methodologies. An analysis tool, such as K-T Analyzer can provide meaningful insights into the various trade-offs.

In this study, HOC combined with FxFc, as shown in Figure 12, was the most effective methodology among the four evaluated methods to achieve the 4nm overlay requirement. Linear control was incapable of meeting the 4nm overlay requirement. High order alone or linear with FxFc was not sufficient to meet requirements either. Process Signature Uncertainty (PSU) for FxFc was introduced to evaluate the field-by-field correction efficiency. By using high order control, which removed the high order component from the process signature, FxFc would become much more effective than linear based FxFc method.

REFERENCES