In-die photomask registration and overlay metrology
with PROVE® using 2D correlation methods

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ABSTRACT

According to the ITRS roadmap, semiconductor industry drives the 193nm lithography to its limits, using techniques like double exposure, double patterning, mask-source optimization and inverse lithography. For photomask metrology this translates to full in-die measurement capability for registration and critical dimension together with challenging specifications for repeatability and accuracy. Especially, overlay becomes more and more critical and must be ensured on every die. For this, Carl Zeiss SMS has developed the next generation photomask registration and overlay metrology tool PROVE® which serves the 32nm node and below and which is already well established in the market. PROVE® features highly stable hardware components for the stage and environmental control. To ensure in-die measurement capability, sophisticated image analysis methods based on 2D correlations have been developed.

In this paper we demonstrate the in-die capability of PROVE® and present corresponding measurement results for short-term and long-term measurements as well as the attainable accuracy for feature sizes down to 85nm using different illumination modes and mask types. Standard measurement methods based on threshold criteria are compared with the new 2D correlation methods to demonstrate the performance gain of the latter.

In addition, mask-to-mask overlay results of typical box-in-frame structures down to 200nm feature size are presented. It is shown, that from overlay measurements a reproducibility budget can be derived that takes into account stage, image analysis and global effects like mask loading and environmental control. The parts of the budget are quantified from measurement results to identify critical error contributions and to focus on the corresponding improvement strategies.

Keywords: photomask metrology; registration; mask to mask overlay; second layer alignment; image analysis
1. MOTIVATION

PROVE® the next generation registration and overlay metrology system was successfully introduced into the market in 2010. It enables in-die measurement capability by means of high-resolution 193 nm optics, as well as optimized illumination for best contrast and pellicle compatibility. The basic specifications and measurement options are summarized in Table 1. Applying double patterning in particular requires rigorous manufacturing control over level to level registration in order to achieve the specified yield and device speed. The registration measurement on production features is therefore inevitable. Conventional image analysis schemes for small features suffer from optical proximity effects, low intensity profiles and resolution limitations due to given camera pixel sizes [9]. For PROVE®, Carl Zeiss has developed several new concepts to overcome these obstacles. For a different concept we refer to [10]. The current in-die registration performance of PROVE® for different substrates and specifications will be presented in chapter 3, followed by a detailed application study of mask-to-mask overlay measurements based on 2D correlation. Beside the demonstration of the measurement performance of the tool, the overlay results can be used to obtain an insight into different error budget contributions. Finally, the paper shows a customer example where PROVE® successfully measured the overlay between a poly layer mask and a contact layer mask.

![Figure 1: PROVE® – Photomask Registration and OVERlay metrology system. Picture of the PROVE® alpha tool at Carl Zeiss SMS GmbH in Jena, Germany.](image)

<table>
<thead>
<tr>
<th>PROVE® Specification</th>
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<tr>
<td>Short Term Reproducibility (3-sigma in nm)</td>
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<td>Complex tri-tone</td>
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<tr>
<td>Through Pellicle</td>
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</tr>
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</table>

Table 1: Basic specifications and measurement options for PROVE®

2. STATUS OF PROVE®

The history of PROVE® as a SEMATECH funded project goes back until mid 2007. The mask making community has been informed regularly about the progress at all major conferences [1-8]. Meanwhile, the project has reached its final status after meeting the SEMATECH specifications and the first five systems have been delivered to different customers. The tool is dedicated to the registration measurement of small features in particular and therefore employs high resolution optics with 193nm illumination together with patented correlation algorithms for image analysis. Nevertheless, the required registration specification as highlighted in Table 1 can only be reached with a well controlled and calibrated stage [4] and advanced correction algorithms for the optical beam path [11]. The stage as well as the optical beam path are in-house developments while the environmental control unit and the handling system are developed and delivered by OEM suppliers.

After fine tuning and calibration, the PROVE® alpha tool at Carl Zeiss SMS GmbH had fulfilled all specifications and was ready for operation in mid 2009. Since then it was used for performance tests, application work and customer demonstrations. All results of this paper have been measured at the PROVE® alpha tool.
3. IN-DIE REGISTRATION MEASUREMENT RESULTS

3.1 Isolated features

At first we want to demonstrate the in-die measurement capability of PROVE® by means of small isolated features. For this, we measured on a Zeiss test mask (OMOG type) registration crosses with a design critical dimension (CD) of 85nm (Figure 2(a)). As mask structures are 4x demagnified, this is the first PROVE® measurement example of the 22nm node at wafer. The measurement was performed in reflection mode and on a 15x15 die array. An example for a PROVE® image of the 85nm cross is shown in Figure 2(b). The corresponding intensity profile of a single region of interest (ROI) is shown in Figure 2(c) and its contrast can be read off to be larger than 50%. For the measurement evaluation we used the standard threshold method which is sufficient as long as the cross bar length of the features is large enough to average enough pixels along the ROI.

![Figure 2](image)

Figure 2: PROVE® in-die resolution capability. According design clip (a), feature was a 85nm isolated line. (b) PROVE® image of the corresponding measurement with ROIs shown as black boxes. (c) The intensity profile of the measurement inside the ROIs shows a remarkable contrast of 54%.

Next we want to show the results for short-term repeatability and accuracy of this measurement. For 10 loops (repetitions of the 15x15 mask measurements) the distribution of 3σ values for registration for x and y is displayed in Figure 3, together with the maximum 3σ value over the mask which is 0.46nm in x and 0.44nm in y direction. These excellent results for the 22nm node are within PROVE short-term specification of 0.5nm. The accuracy of these results has been measured by two different mask orientations in the tool, 0° and 90°, and evaluating the confidence limit value of the results. This is displayed in Figure 4, from which we obtain an accuracy of 0.76nm in x and 0.95nm in y. Again, even for the 22nm node these values are within specification.

![Figure 3](image)

Figure 3: Results for short-term repeatability of 85nm cross (OMOG Mask, 10 Loops, 15x15 die array).

<table>
<thead>
<tr>
<th>Result Statistics</th>
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<tbody>
<tr>
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<td><strong>X [nm]</strong></td>
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<td>Dies Position</td>
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</table>
3.2 Dense features

Next, the in-die capability of PROVE® is demonstrated with a measurement of single contacts within a dense contact array. This is much more critical than isolated structures for two reasons. First, an array of dense pinholes can only be measured with an optical system that resolves the pitch of the structure. With PROVE® 193nm and NA 0.6 we can achieve here a theoretical pitch resolution of \( \lambda/(2NA) \sim 160\text{nm} \), which is sufficient for the 32nm node and below.

Second, with small contacts the standard threshold method will lose repeatability as it has been investigated by simulations \cite{8}. Therefore, we additionally perform a correlation measurement and we will compare the repeatability for both methods on the same data.

Our test mask for this experiment is an attenuated phase shift mask (MoSi) with a feature CD variation from 1µm down to 180nm on each of its 6x6 die array. The duty cycle was 1:1 such that pitches vary from 2µm down to 360nm. The mask has been measured in reflection mode with 10 loops in 0° mask orientation and 10 loops in 90° mask orientation.

From the 0° measurement we evaluate the short-term repeatability. For the threshold measurement the results are displayed in Figure 6(a). We observe repeatability around 0.6nm for structures down to 400nm feature size and worse repeatability for smaller features. This is related to the fact that the number of pixels dramatically decreases within the threshold ROIs. Thus, PROVE® 2D correlation is the better choice since the corresponding ROI contains and uses more pixels for image analysis \cite{8}. The experimental proof is shown in Figure 6(b), where the repeatability of the correlation measurement remains on a level of about 0.6nm for all feature sizes even down to 180nm. However, the measurement itself was not performed under optimal conditions caused by an experimental setup for the air flow at the PROVE® alpha tool in order to investigate environmental influences to the measurement. Therefore, only the y coordinate has repeatability within specification (< 0.5nm), whereas the x coordinate is slightly worse (< 0.65nm).

Next we calculate the accuracy of the measurement for each feature size by considering the confidence limit value between 0° mask orientation and 90° mask orientation. Again, for the threshold method (Figure 7(a)) the maximum confidence limit value is below 1nm for feature sizes larger than 500nm and increases for smaller features because of image analysis noise. In contrary, the correlation measurement which was performed on the same data yields a maximum confidence limit in specification (< 1nm) for all feature sizes down to 180nm as it can be seen from Figure 7(b). We emphasize that this is a first experimental proof of the performance gain of a registration measurement by means of PROVE® correlation methods.
In summary, we have shown the in-die registration measurement capability of PROVE® for isolated as well as for dense features. In the isolated case the challenging specifications of 0.5nm repeatability and 1nm accuracy are well achieved, even with 85nm features at mask. For the dense case we presented feature sizes down to a critical dimension of 180nm and we have shown that repeatability and accuracy specifications can only be achieved with PROVE® 2D correlation methods for features smaller than 500nm.

4. OVERLAY MEASUREMENT

4.1 Design of overlay measurement

Overlay is a critical demand of modern lithography since the shrinking of features on the wafer with .193nm illumination wavelength, as given by the ITRS roadmap (International Technology Roadmap for Semiconductors), can only be achieved with techniques like e.g. double patterning technology (DPT). According to [12], “for 32 nm node lithography using DPT a reticle to reticle overlay contribution target of ≤1.5nm has been proposed. Reticle based measurements have shown that this proposed target can be met for standard overlay features and dedicated DPT features”. In other words, mask-to-mask overlay must be ensured on every die and it has to meet challenging specifications of not much more than 1nm. A photomask overlay and registration tool like PROVE® has to achieve these specifications and it has to offer customer solutions for in-die overlay measurement and data analysis.

To demonstrate this we use two Chrome on Glass (CoG) test masks A and B with box-in-frame structures for critical dimensions of 200nm, 500nm and 1µm (Figure 8). All feature sizes are accessible within a single field of view. We emphasize the fact that PROVE® supports different measurements on a single field of view, all box and frame structures for all feature sizes are measured at once. Moreover, the definition of “ObjectPositions” within the DataPreparation-software allows measuring an entangled structure, like the frames in the upper row, without the inner boxes (Figure 9).
By means of the overlay structures measured on two different masks, we will show important application examples of photomask industry for a full field mask measurement (14x14 die array): the intra-field distances between two entangled structures (e.g. box in frame) on one mask (“second layer alignment” of mask process), the classical mask-to-mask overlay performed on equal structures on mask A and mask B and the mask-to-mask overlay between boxes on mask A and frames on mask B (as a typical example for double patterning). All measurement structures are summarized in Table 2.

![Figure 8: PROVE® image of overlay test structures.](image)

Figure 8: PROVE® image of overlay test structures.

![Figure 9: PROVE® application example for the measurement of entangled structures with 2D correlation method. Object positions given by the DataPreparation-software, defining the objects to be measured, are shown as green crosses.](image)

Figure 9: PROVE® application example for the measurement of entangled structures with 2D correlation method. Object positions given by the DataPreparation-software, defining the objects to be measured, are shown as green crosses.

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<tr>
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<td>Frame entangled</td>
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</tr>
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</table>

Table 2: Summary of overlay measurements.

The measurement mode used here was transmission and we measured 10 loops on mask A in 0° mask orientation, 10 loops on mask A in 90° mask orientation and 10 loops of mask B in 0° mask orientation. For the long-term results, i.e. mask-to-mask overlay between mask A and different loads of mask B we present here the results of [9] for a 3x3 die array. All results have been obtained by using 2D correlation method for the image analysis for each feature.
4.2 Results of overlay measurement

Short-term repeatability and accuracy

For a proper performance analysis of the overlay measurement we evaluate in a first step the short-term repeatability and the accuracy for all features. We emphasize the fact that these results are for a true 14x14 die array on the mask, since similar data but for a 3x3 die array have been presented in [9]. The short-term repeatability has been evaluated on 10 loops as the maximum $3\sigma$ value of all 196 measurement sites with multipoint alignment applied. The final result is displayed in Figure 10(a). For the small 200nm boxes (contacts) we report a repeatability of 0.5nm, whereas for all larger features the repeatability is well below 0.4nm. These numbers are better than the ones for the corresponding contact measurement of Section 3.2 which is mainly due to the fact that we have isolated contacts here which exhibit a much better contrast. Moreover, the mask type is different compared to Section 3.2. The accuracy of all features has been evaluated on 10 loops in 0° orientation of the mask and 10 loops in 90° orientation of the mask as the maximum confidence limit value of all 196 measurement sites. The accuracy result is displayed in Figure 10(b) and it is well below the specification of 1nm, even for the 200nm boxes where the image analysis contribution to the overall error is somewhat larger. The quality of all results is a further proof of the performance gain in the image analysis by PROVE® 2D correlation algorithms.

Second layer mask process (intra-field distances)

Beside the respective repeatability of box and frame markers, intra-field overlay repeatability can be derived from the intra-field box-to-frame deviations. In the mask community this is often called “second layer alignment” and it is a typical measurement for the qualification of phase shift masks. We measured with PROVE® the box-to-frame overlay for the 200nm, 500nm and 1μm features on the 14x14 die array in transmission of mask A, see Figure 11(a). The mean registration result for the 0° mask rotation and for the 90° mask rotation (averaged over 10 loops, respectively) is shown in Figure 11(b) and (c). As expected, the registration pattern of the mask does not change with mask rotation in the tool.

Figure 10: (a) Short-term repeatability of all overlay features on mask A. (b) Accuracy of all overlay features on mask A derived from 0° and 90° mask orientations.

Figure 11: (a) Intra-field overlay measurement of the difference between frame position and box position of mask A. The corresponding registration results on the 14x14 die array over the complete mask for the 200nm box-in-frame structures for (b) 0° mask orientation and (c) 90° mask orientation.
The repeatability of this result has been calculated as the maximum 3σ value over all 195 sites and it is shown for each feature size in Figure 12. The repeatability is 0.5nm for the 200nm features and below 0.2nm for 500nm features and larger. These remarkable small values can be explained by the fact that stage noise is not present in intra-field distances. They contain the statistical sum of image analysis contributions for frame and box structures only (see chapter 4.3, for a detailed analysis). Because of PROVE® 2D correlation algorithms these image analysis contributions are small.

Figure 12: Results for the repeatability (max 3σ) of intra-field distance measurements of mask A for a 14x14 die array on the mask.

Mask-to-mask overlay

Next we want to show the results for mask-to-mask overlay of corresponding structures with the example of the frame structures on both masks (Figure 13(a) and (b)). The mean overlay error between mask A and mask B is visualized in Figure 13(c) for the 200nm frames and the full 14x14 die array.

Figure 13: (a) and (b) Mask-to-mask overlay measurement between frame structures on mask A and mask B for three feature sizes 200nm, 500nm and 1µm. (c) The corresponding overlay error of the 200nm features for one 14x14 die array on the masks.

The long-term repeatability of these results has been investigated in [9] by comparing 5 loads of mask B (10 loops each) with 10 loops of mask A and calculating the confidence limit value of these 5 overlay measurements. The final mask-to-mask long-term repeatability per feature size is shown in Figure 14. We can report excellent values for the maximum confidence limit of below 1nm long-term repeatability for all feature sizes.
Double Patterning

For double patterning, the registration of different features against each other has to be evaluated. In the present overlay example this can be tested with the overlay between frame and box structures Figure 15(a) and (b). The resulting registration plot for the overlay between 200nm boxes (mask A) and 200nm frames (mask B) for the 14x14 die array over the mask is shown in Figure 15(c). Obviously, this overlay error is almost the same as for the frame-to-frame overlay (see Fig. 13(c)) which demonstrates that a general mask writing error between mask A and mask B can be measured by different in-die features.

The long-term repeatability of double patterning registration has been investigated by considering 5 loads of mask B (10 loops each) and comparison with 10 loops of mask A. The maximum confidence limit of the registration error is below 1.1nm (Figure 16), where these results are again only for a 3x3 die array over the mask [9]. Note that for this kind of repeatability three different error contributions sum up: the loading effects of mask B, the image analysis and stage effects of mask B for the frame structure and the stage and image analysis effects of mask A for the box structure. Because of the contributions of mask A measurements, the long-term repeatability of double patterning is somewhat larger than a standard long-term repeatability, where only loading effects and image analysis effects of a single mask contribute.
4.3 Error budget investigation

In this section we use the previous results for mask-to-mask overlay repeatability and short-term repeatability to separate inherent error contributions of such a measurement. The motivation is that only a detailed error analysis allows the specific improvement of the measurement tool.

We consider the mask to mask overlay between different sets of markers, located on corresponding masks A and B, respectively. The mask to mask overlay repeatability budget $\sigma_{\text{MMOV}}$ is split up to local effects like stage position noise $\sigma_{\text{stage}}$ and image analysis repeatability $\sigma_{\text{IA}}$ and to global effects like mask loading and stationarity of climatisation and heating $\sigma_{\text{global}}$, see Figure 17.

The idea of PROVE® supported overlay error budget analysis can be summarized by two main steps:

I. Assess the expected quantity of cumulative local repeatability $\sigma_{\text{local}}$ including a separation of the main contributions $\sigma_{\text{stage}}$ and $\sigma_{\text{IA}}$. Repeat this for all marker types (here: box and frame structures) to be involved into later experimental overlay investigation.

II. Perform a set of mask-to-mask overlay measurements to get total error $\sigma_{\text{MMOV}}$ and from this deduce to $\sigma_{\text{global}}$.

Figure 17: Model for mask to mask overlay repeatability budget driven by both local and global effects.

Local effects by short-term repeatability

Consider a short-term measurement of the above overlay mask structures. Beside the respective repeatability of box and frame markers, the intra-field overlay repeatability has been derived from the intra-field box-to-frame distance. In the mask community this is often called “second layer alignment”. The local error budget can be modeled by the following equations:
\[ \sigma_{\text{shortterm.Frame}}^2 = \sigma_{\text{IA.Frame}}^2 + \sigma_{\text{stage}}^2 \]  
\[ \sigma_{\text{shortterm.Box}}^2 = \sigma_{\text{IA.Box}}^2 + \sigma_{\text{stage}}^2 \]  
\[ \sigma_{\text{intrafield}}^2 = \sigma_{\text{IA.Frame}}^2 + \sigma_{\text{IA.Box}}^2 \]  

(Eq. 1)

These are three equations for the three unknowns \( \sigma_{\text{IA.Frame}} \), \( \sigma_{\text{IA.Box}} \) and \( \sigma_{\text{stage}} \). Thus, by the set of equations 1, stage and image analysis contributions can be separated. Clearly, the image analysis parts will depend on feature size and the stage contribution may depend on mask field position.

**Global effects by long-term repeatability and mask-to-mask overlay repeatability**

Next we consider the global contributions to the mask-to-mask overlay repeatability, e.g. loading effects and mask climatisation. These global effects can be accessed by two different possibilities: from the long-term repeatability of a single mask or from the mask-to-mask overlay repeatability:

\[ \sigma_{\text{longterm.Frame(Box)}}^2 = \sigma_{\text{shortterm.Frame(Box)}}^2 + \sigma_{\text{global}}^2 \]  
\[ \sigma_{\text{MMOV}}^2 = \sigma_{\text{longterm.Frame}}^2 + \sigma_{\text{longterm.Box}}^2 = \sigma_{\text{intrafield}}^2 + 2 \left( \sigma_{\text{stage}}^2 + \sigma_{\text{global}}^2 \right) \]  

(Eq. 2)

From the knowledge of short-term, intra-field and stage contributions based on the previous paragraph, \( \sigma_{\text{global}} \) can be calculated by either the first or the second of both equations.

**Error budget results**

Using the results of section 4.2, the error budget is now accessible. First, we derive the stage noise and image analysis noise contributions by means of the equation system 1 and the results of short-term repeatability and intra-field distance repeatability. Next we use the results for mask-to-mask overlay repeatability to separate the loading effects through equation 2. The final result is that loading effects dominate the cumulative error budget and thus have to be addressed preferably. Due to the 2D correlation method, pure image analysis noise is smaller or equal than stage noise contributions:

\[ \sigma_{\text{global}} \geq \sigma_{\text{stage}} \geq \sigma_{\text{IA}} \]  

(Eq. 3)

This analysis provides an important insight into the error budget of any metrology tool. It will drive the further improvement of registration metrology with PROVE®.

### 4.4 Customer example: Overlay between poly layer and contact layer

A major request for modern registration tools is the overlay measurement between in-die features for the polysilicon (poly) layer and for the gate layer (contact layer) of a wafer. With PROVE® we performed such a measurement between a customer mask A, containing the in-die features on the poly layer (Figure 18(a)) and a customer mask B containing the contact layer features (Figure 18(b)). First we can report that PROVE® has well resolved and measured all 4032 positions of both masks given by the customer. Moreover, the expectation of the customer for a Gaussian error distribution of the registration error could be met. This error distribution is shown in Figure 18(c) and it provides valuable information about the mean overlay error and its deviation between poly layer mask and contact layer mask. As the nature of the error distribution is Gaussian it can be derived that no dominant varying systematic measurement errors are present. This shows the excellence of the PROVE® metrology tool.
5. SUMMARY

The present paper summarizes the in-die registration and overlay measurement capability of the photomask registration and overlay measurement system PROVE® at Carl Zeiss. The metrology tool provides excellent feature resolution by its 193nm illumination system down to 32nm node features and reaches the major specifications for repeatability (< 0.5nm) and accuracy (< 1nm) on isolated and dense in-die features. For the first time it has been experimentally proven that for small in-die features this can only be achieved by 2D correlation algorithms of PROVE®.

Moreover, the paper presents an application study for mask-to-mask overlay registration structures on a 14x14 die array. It is shown that overlay structures can be precisely measured by means of 2D correlation algorithms, even if they are entangled, e.g. box-in-frame structures. We obtain a short-term reproducibility of below 0.5nm down to 200nm line-width and an accuracy of below 0.9nm. In addition, the mask-to-mask overlay reproducibility between two test masks has been measured for all combinations of boxes and frames and it is below 0.9nm. From these results a cumulative error budget can be derived which allows a separation of error contributions for image analysis, stage and global loading effects. The results help to identify critical error components and they will lead to the further improvement of registration metrology with PROVE®.

Finally we presented a customer application example that shows an overlay measurement between a poly layer mask and a contact layer mask with PROVE®. Such type of measurement is one of the most important requirements of modern mask metrology. The in-die features on both masks could be very well resolved and more than 4000 positions on both masks have been measured. The resulting overlay error distribution is in accordance with the customer’s expectation.

6. ACKNOWLEDGEMENT

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7. REFERENCES


Figure 18: (a) PROVE® image of poly layer (mask 1). (b) PROVE® image of contact layer (mask 2). (c) Resulting overlay difference distribution with Gaussian fit (red line). Units have been omitted for confidentiality reasons.