Fleet matching performance for multiple registration measurement tools

Carl Zeiss SMS GmbH, 07745 Jena, Germany

ABSTRACT

Currently semiconductor industry drives the 193nm lithography to its limits, using techniques like double exposure, double patterning, mask-source optimisation and inverse lithography. These requirements trend to full in-die measurement capability of photomask metrology for registration. 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 is already well established in the market. To ensure in-die measurement capability, sophisticated image analysis methods based on 2D correlations have been developed.

A key component for registration tool users is the cross site manufacturing flexibility given by the matching capability of all its metrology tools. Therefore all PROVE® tools offer a tool matching procedure based on 2D Golden Grid references. In this paper we first review the optimal length standard and golden grid matching procedures of modern registration metrology tools. Systematic errors in fleet matching based on illumination differences, thermal expansion-based issues or line width roughness are addressed. The tool matching performance of PROVE® tools is demonstrated by comparing up to 7 different tools. All tools are well within accuracy and long-term repeatability specification which considerably reduces the statistical error contribution of the tool matching performance. For grid matched tools the final cross tool registration error is shown to be below 1nm.

Keywords: photomask metrology; registration; tool matching; fleet matching; golden grid; length standard; accuracy; long-term repeatability
1. MOTIVATION

Current semiconductor manufacturing for high-end devices is facing increasing costs. This trend is primarily driven by rising complexity for optical lithography and related processes. Moreover, the near future will certainly remain challenging due to the delay of alternative litho-technologies like EUVL. However, litho and process engineers as well as designers and mask makers got used to double patterning and double exposure schemes in order to shrink further features sizes and areas of chip layouts and cells. The reduced specifications for overlay control and the implementation of additional patterning steps have led to much higher demands for image placement control. This affects not only the writing and litho tools, it also impacts the related metrology tools needed to control and improve current and future equipment. Table 1 displays the actual performance requirements for overlay and image placement according to the latest revision of the ITRS roadmap.

![Table 1: Optical mask requirements for overlay and image placement according to the ITRS roadmap 2012 (http://www.itrs.net)](http://www.itrs.net)

The tightened specs as well the increasing amount of masks require more measurements, more sampling and therefore more registration metrology tools linked to the dedicated length standard. In fact, all linked tools should deliver and match the same measurement output within a significantly reduced tolerance. This goal can be achieved only when all tools meet stringent metrology specifications and operating conditions.

For this paper we focus on matching flows for state of the art optical mask and litho-technologies currently used for high-volume manufacturing. Processes and procedures using EUV masks or other alternative technologies have to be covered when available for mass production.

2. MASK REGISTRATION METROLOGY BY PROVE®

The development of PROVE® was requested and triggered by leading edge mask shops in order to address their need for an optical registration tool working at 193nm illumination wavelength in combination with significantly improved statistical performance parameters. Since project start in 2007 and market introduction in 2010, technical details and highlights have been presented at all major conferences [1-9]. Meanwhile PROVE® became a real roadmap enabler in its crucial role for the calibration of most advanced writing tools as well as its capability to detect phase and process related image placement errors not visible to other illumination wavelength then 193nm. With rapidly increased installed base, the implementation of a stable and reliable matching scheme within a PROVE® environment became essential while taking advantage of the superior metrology performance.

The paper is organized as follows: In section 3 we review a generalized procedure how the matching of different registration tool is currently performed. It may differ slightly from mask manufacturer to mask manufacturer due to their specific customer requirements or simply due to tradition. However, there are common logistical constrains as well as statistical and physical limits which will be emphasized and discussed. In section 4 we outline in more detail the
dedicated matching flow applied with PROVE® for 7 different PROVE® tools used in production while one tool is always used as a master tool. All presented results are based on customer inputs including statistical performance data. A short summary and acknowledgement conclude the paper.

3. METROLOGY TOOL MATCHING PROCEDURE IN A MASK SHOP

3.1 General procedure

Distance calibration

Usually the first step in the calibration procedure is to calibrate all metrology tools to the same length, the ‘Golden Length’. This procedure is called distance calibration. For the distance calibration each mask shop has a ‘Golden Mask’ which defines the ‘Golden Length’ in an appropriate way. The procedure and calculation method may vary from shop to shop, but after distance calibration has been applied successfully the measurement results on the ‘Golden Mask’ should show the same magnification on all metrology tools. Within PROVE® a distance calibration can be performed during alignment on the alignment marks. In particular, the measured distance between the alignment marks is calculated and compared to the nominal distance as defined in the alignment parameters of the job. Afterwards, a distance factor is calculated and applied to the calculation of each measurement point.

Distance transfer

In general, during production process in a mask shop, the distance standard provided from the Golden Mask is not available at some tool at some instant. Therefore it is advantageous to transfer the golden length to a monitoring mask available at the tool at any time. The procedure is briefly described in Figure 1. The first step is to measure a grid on the monitoring mask of the tool including alignment and distance calibration on that mask. Secondly, the Golden Mask is measured, again with a previously performed distance calibration. The third step is to measure again the grid of step 1 on the monitoring mask, but with the still active distance calibration of the Golden Mask measured in step 2. The measurement will reveal a magnification difference when compared to the measurement of the first step. This magnification can be used to modify the alignment mark design positions of the monitoring mask job, such that a distance calibration on the monitoring mask yields the same distance as the distance calibration on the Golden Mask, as it can be cross-checked in a final verification step.

Figure 1: Procedure of distance transfer from the Golden Mask to some tool-specific monitoring mask and its verification.
**Tool matching**

Beside the ‘Length’ (magnification) the different metrology tools may show slightly different signatures in the measurement grid, depending on tool specific properties, like stage mirror surfaces, interferometer adjustment or other effects. Additionally, mask specific signatures may appear also, caused by interaction of mask properties and tool properties. If more than one metrology tool is used in the mask shop and the measurement results of these tools show deviations exceeding the overlay error budget, the appropriate signatures have to be compensated by a tool matching (TM) calibration, in a way that all tools show the same signature at the end. As there is no absolute grid available within the required accuracy, one metrology tool in the mask shop has to be defined as a ‘Master’. The grid measured by the Master is the Golden Grid for the mask shop which has to be matched well by all other metrology tools. Even if the Golden Grid measured by the Master is not perfect, the remaining overlay error will be in specification after applying tool matching if all other tools are matched to show the same signature.

![Figure 2: Schematic overview on tool matching procedure.](image)

### 3.2 Expected tool matching performance

The expected overall TM performance depends on several error (TME) factors. These error factors can be divided into 2 groups, the statistical errors and the systematic errors.

Please note that statistical errors (random errors – RE) are combined using the square root of the individual error terms, while systematic errors (SE) are added linearly.

\[
TME_{\text{overall}} = TME_{\text{random}} + TME_{\text{systematic}} = \sqrt{RE_{\text{tool1}}^2 + RE_{\text{tool2}}^2 + SE_1 + .. + SE_j} \tag{Eq.1}
\]
**Statistical Errors:**

The statistical error budget can be calculated from the long-term repeatability (LT) of the tools involved in tool matching. Long-term repeatability contains short-term repeatability and mask loading effects.

\[
TME_{\text{random}} = \sqrt{LT_{\text{tool1}}^2 + LT_{\text{tool2}}^2}
\]  
(Eq. 2)

In order to have good statistics, an average of some measurement loops is always recommended.

**Examples for systematic errors:**

There are several effects contributing to the systematic error budget of Tool Matching. We address some of them:

(a) **Thermal expansion coefficient (mask material property)**

The mask expands when getting warmer and shrinks when getting colder. The amount of changing the size depends on the thermal expansion coefficient \( \alpha \). If \( \alpha \) is known exactly, this effect can be compensated completely by a software procedure and using the right distance calibration. However, there is usually an uncertainty in the values given by the mask blank suppliers. Even the ULE (Ultra-low-expansion) - glass used for EUV mask blanks is specified with an uncertainty of the thermal expansion coefficient of \( \Delta \alpha \approx \pm 0.03 \text{ ppm} \). For quartz material it is expected to be even bigger.

\[
\Delta L = \Delta \alpha \cdot L \cdot \Delta T
\]  
(Eq. 3)

Using the equation (1) assuming an uncertainty of the thermal expansion coefficient of \( 0.03 \text{ ppm} \), a temperature difference of 0.5 °C between the tools and a measurement length of 0.14 m the length uncertainty (Magnification) can reach 2.1 nm (see Equation 4).

\[
\Delta L(\Delta T) = \frac{0.03 \cdot 10^{-6}}{K} \cdot 0.14 \text{ m} \cdot 0.5 \text{ K} = 2.1 \text{ nm}
\]  
(Eq. 4)

In order to minimize this value it is strictly recommended to have all environmental chambers of the metrology tools on the same temperature set point. Since tool to tool variations of the different metrology tools using the same set point are expected to be in the order of 0.05°K or smaller, the magnification error will be reduced by at least a factor of 10 to 0.2 nm. Thermal effects should affect all mask types in the same way as long as they use the same blank material. The variations are expected to come from small changes in raw material itself which may vary from lot to lot.

(b) **Mask writing effects**

For tool matching measurements it is essential to perform measurements with the same positioning and measurement settings on all tools involved. Not only the design coordinates of the measured sites must be the same, but also the region of interest (ROI) positions and dimensions. It is shown in Figure 3 that the selection of different ROIs on the bars of a marker cross feature may lead to errors of up to 3nm. For this particular example the error is concentrated on stripes over the mask area which indicates that a mask writing error by stitching may be the root cause for that difference. This effect has to be controlled carefully when PROVE® is matched to a registration metrology working with different wavelength and stages. However, for a proper PROVE® to PROVE® matching a unique image evaluation scheme can be used.
4. TOOL MATCHING PERFORMANCE OF PROVE®

4.1 Tool matching procedure of PROVE® tools

Tool matching allows mapping the PROVE® measurement results of one tool with other PROVE® tools of a specific mask supplier or even with the results of other metrology tools. For the PROVE® tool matching a special stage correction file will be created by the software PROVE® Calibration. This file must be used by a PROVE® system to achieve sufficient results for overlay requirements. The calibration file can be set globally in PROVE® Control or as a job property in PROVE® jobs.

For the creation of a tool matching calibration file similar measurements on both tools are required. Special care is taken to the following aspects:

- A sufficient measurement grid size and sampling
- The design coordinates of the measured sites must be the same.
- In order to eliminate mask errors from tool matching, identical ROI-positions and ROI-dimensions must be used in both tools.
- For noise reduction at least 3 loops are recommended in both tools.
- Tool matching to be performed in one orientation (0° is recommended).
- All tools should be distance calibrated to the same mask.
- Same chamber temperature (set point) of tools to be matched is recommended

The measurement results from the ‘Master’ (reference file) have to be provided according to the measured design coordinates. The data have to fit together, i.e. for each measured data point in PROVE® the reference data should have a reference value. An example for a suitable data table used as reference input in PROVE® Calibration is given in Figure 4.
4.2 Statistical performance data

For an estimation of the statistical error described in Section 3.2, the short-term and long-term repeatability of the individual tools have to be known. For a state-of-the-art registration measurement tool as PROVE®, the short-term repeatability derived as maximum $3\sigma$ values of all measurement is well below 0.5nm and the long-term repeatability over different loads derived as maximum confidence limit value is well below 0.7nm. Moreover, all PROVE® tools are self-calibrated [4] and achieve accuracy specifications measured over 4 mask orientations of less than 0.8nm maximum confidence limit. However, although in specification, short-term, long-term as well as nominal accuracy data may differ from tool to tool caused by different tool and operating conditions. This is shown in Figure 5, Figure 6 and Figure 7. Assuming a long-term repeatability of 0.7nm and matching between PROVE® tools with all systematic effects suppressed, one expects from Equation 1 and 2 a tool matching error below 1nm. This error can be further reduced by a proper averaging of tool matching measurements.

Figure 5: Short-term repeatability of different PROVE® tools on the same Golden Mask. Measured data based on 10 loops over a 15x15 die array
Golden mask matching

In this section we compare 7 different PROVE® tools used in production at customers site. We take tool 1 as ‘Master’ and tool 2…7 as ‘slave’. The corresponding short-term and long-term repeatabilities are shown in Figure 5 and Figure 7. At first the polynomial order \( n \) of the tool matching correction for the given measurement data has to be analyzed. Therefore we perform a tool matching fit with 2D polynomials for increasing order \( n \) and compare the residual error of the fits with the magnitude of the arising calibration fields. This is shown in Figure 8 for the example of slave tool 7. For all data, the average of 10 loops of tool 1 has been chosen as reference and we compared 10 loops of tool 2…7 against this.

It can be seen from Figure 8 that the residual error decreases with increasing \( n \), since measurement data can be fitted more accurately. However, at the same time the magnitude of the calibration pattern increases due to oscillations of the polynomial, as it can be seen for \( n = 13 \). The adequate fit order can be determined by the point where the calibration
pattern does not show large oscillations but residuals are sufficiently small. For tool 7, this would be the case for $6 < n < 12$, where an order of 12 has been finally chosen.

![Figure 8: Analysis of adequate polynomial fit order for tool matching between PROVE® tool 1 and PROVE® tool 7.](image)

The same procedure has been applied to the tools 2…6. The results of the tool-matching calibration and the corresponding xy-residuals are shown in Figure 9 and the corresponding amplitudes in Figure 10.

<table>
<thead>
<tr>
<th>Tool 2</th>
<th>Tool 3</th>
<th>Tool 4</th>
<th>Tool 5</th>
<th>Tool 6</th>
<th>Tool 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>9</td>
<td>12</td>
<td>9</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

![Figure 9: Tool matching calibration patterns and residual errors of matching for PROVE® tool 1 (reference) versus PROVE® tools 2…7. In all cases, the calibration measurement was on a 15x15 die array of an OMOG type Golden Mask for a 140mm x 140mm mask area.](image)

![Figure 10: Tool matching residual errors of Golden Mask tool matching procedure for PROVE® tool 1 (reference) versus tool 2…7.](image)
From this data we can identify two different tool states which can be attributed to different hardware properties of the tools to be matched. However, after proper calibration all tool matching residual errors can be made smaller than 0.65nm.

**Tool matching verification**

The next step in the tool matching process is a verification of the tool matching by a different mask, e.g. a production mask. Therefore we measured a 15x15 grid on a phase-shifting EAPSM mask on the master tool 1 and slave tool 7, with the 12th order tool-matching file derived in the previous step as input for tool 7. It is important to note that the grid points should differ in design from the Golden Mask design positions for a reasonable verification.

![Figure 11: Difference between Tool 1 and Tool 7 on verification mask (EAPSM) for a 12th order tool matching calibration applied to Tool 7.](image)

As it can be seen in Figure 11, the remaining difference between both tools is well below 1nm as required for most advanced technologies and nodes.

### 4.4 Higher Polynomial Fit Order for Larger Grids

To correct for higher error patterns, larger grids have to be measured. We present here a customer tool matching example, where a 47x47 grid has been used for tool matching between two PROVE® tools selected from the above mentioned tool set. For verification a 37x37 grid has been used.

**Golden Mask matching**

To identify the correct polynomial fit order of the tool matching calibration, one can repeat the analysis from the previous section and compare the decrease of the residual maximum value with the increase of the tool matching correction maximum value. We identified an optimal polynomial order of $n = 15$ for the calibration. The corresponding calibration pattern and residual pattern of a 15th order calibration is shown in Figure 12.
Figure 12: (a) Resulting tool matching calibration pattern (15th order) and (b) corresponding residual error for the customer example of a 47x47 tool matching calibration grid. The 3σ value of the residual error is below 0.5nm.

Tool matching verification

Again, following Figure 2, the final verification of the tool matching correction on a production mask is the last step in the procedure. The customer measured therefore a 37x37 grid on a CoG mask on both tools.

Figure 13: Difference between two customer tools after applied tool matching procedure on a 37x37 grid of a production mask.
Figure 13 displays the final verification result for this production mask with applied tool matching and different grid size and design positions compared to the Golden Mask measurement. The $3\sigma$ matching performance is $0.63\text{nm}$ in x and $0.60\text{nm}$ in y and thus well below 1nm.

5. SUMMARY

In the previous chapters we have elaborated in detail the technical and physical constrains for a proper registration tool matching as needed for most advanced litho-technologies. A practical example for 7 tools located at different sites has been outlined and discussed. The final matching performance depends not only on a reliable and repeatable manufacturing process for critical parts within the metrology core of each PROVE® tool. It relies even more on operating conditions like constant and equal clean room temperatures and blank materials. Nevertheless, well controlled flows, processes and operation condition enable tool to tool matching results well below 1nm. Validation and monitoring of these numbers have to be done continuously. Inevitable for reliable matching performance data are superior specifications, in particular for long-term repeatability which is most relevant for production purposes.

6. ACKNOWLEDGEMENT

The authors like to thank all PROVE® customers around the world for providing input for this paper. In particular we like to thank the metrology team at INTEL Mask Operations for their data and continuous support.

7. REFERENCES