Improving Registration Measurement Capability by Defining a 2D Grid Standard Using Multiple Registration Measurement Tools

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ABSTRACT

Currently all LMS IPRO pattern placement metrology tools are calibrated using a 1D length standard provided by a national standards institute (e.g. NIST or PTB), however there are no 2-D standards available with an uncertainty matching the requirements of mask manufacturing for the 22nm HP node and beyond. Therefore, the 2D stage coordinate system of the LMS IPRO systems is calibrated using KLA Tencor's proprietary combined correction technique.

With introduction of the LMS IPRO4 into high volume mask production at the AMTC, AMTC and KLA-Tencor MIE have demonstrated the capability to match IPRO3 and IPRO4 grids within 1.2 nm uncertainty [1]. Using the Golden Tool approach, we achieved a significant improvement in pattern placement measurement capability of previous generation measurement tools of up to 30%. This in turn leads to improved pattern placement metrology fleet capability and extended useful lifetime of capital equipment.

The use of multiple high end registration measurement tools enables the creation of a 2D coordinate system standard, which could be used for improved fleet matching and would help improve the capability of older generation pattern placement metrology tools by matching to this standard. Within this paper Golden Tool and Round Robin worldwide fleet matching approaches are compared and discussed.

Keywords: Pattern placement error, measurement capability, 2D grid artifact, matching, double patterning

1. INTRODUCTION

Technology development to meet the mask requirements for the 32nm half pitch node is almost finished and development for 22nm half pitch will follow within the next months. New lithography techniques such as EUV or Double Patterning Lithography place very tight demands on pattern placement metrology, resulting from a necessity to perform multiple exposures to form one pattern, or to align critical layers like contact and poly to avoid leakages and shorts. Mask to mask registration will be one of the most critical parameters for future advanced masks.

In photomask fabrication, the main contributors to image placement error are lithography processes and the metrology process itself [2]. Metrology error budget is typically 25% of the total image placement error (given a precision–to–tolerance ratio of 4). For the 45/32nm HP (half pitch) node, pattern placement metrology contribution is 1.0 nm to 1.5 nm. Thus, for future nodes it is expected that metrology error needs to be in the sub nanometer region.

With time-to-market at a premium for semiconductor manufacturers photomask makers value the flexibility to use multiple pattern placement measurement tools at one or more manufacturing sites. Consequently tool matching becomes a critical parameter. In a previous paper [3] approaches were discussed to improve fleet matching using the DEVA software HighGrid feature.

This work focuses on how to improve pattern placement measurement capability of 45nm and 32nm node metrology tools by introducing an artificial 2D grid standard. Different matching methodologies are compared, including Golden Tool matching, Round Robin matching and a KLA-Tencor MIE proprietary self calibration approach.

We will demonstrate that different matching methodologies potentially enable lifetime extension of 45nm/32nm node equipment beyond their specifications. In addition, improvements to the self-calibration strategy for the next-generation LMS IPRO5 22nm / 28 node pattern placement metrology system are mentioned.

2. EXPERIMENTAL SETUP AND ERROR MODEL

2.1 Error model and evaluation methodology

Measurement uncertainty basically consists of stochastic and systematic components. For this work, a variance model (ANOVA) approach [4] is employed, assuming independence of all error components.
LMS IPRO measurement repeatability is described by $\sigma_{Shortterm}$, whereas the reproducibility is described by $\sigma_{Longterm}$. Isotropy error component $\sigma_{Isotropy}$ describes the tool grid deviation from ideal Cartesian coordinate system.

In case of self calibration, total measurement uncertainty (TMU) of a specific machine is described by:

$$\sigma^2_{Total} = \sigma^2_{Shortterm} + \sigma^2_{Longterm} + \sigma^2_{Isotropy} \quad (1)$$

For matched tools (all machines connected to the Golden Tool grid), the TMU is described by equation (2), with the Golden Tool grid uncertainty described by equation (3).

$$\sigma^2_{Total} = \sigma^2_{Shortterm} + \sigma^2_{Longterm} + \sigma^2_{Matching} + \sigma^2_{Grid} \quad (2)$$

$$\sigma^2_{Grid} = \frac{\sigma^2_{Shortterm}}{i} + \frac{\sigma^2_{Longterm}}{j} + \frac{\sigma^2_{Isotropy}}{k} \quad (3)$$

Grid error σ_{Grid} is estimated using Golden Tool variances, assuming the Golden Tool is the best performing machine; i indicates the number of repetitions used for short term measurement, j represents the number of days and k denotes the number of orientations used for isotropy measurement.

For variance and matching calculation first-order distortions were compensated. Calculations have been performed in mask coordinates.

2.2 Single tool results and measurement strategy

Four worldwide installed LMS IPRO4 systems were selected for this experiment. Each machine was self calibrated using the proprietary KLA-Tencor MIE (KT) “combined correction” method. Scale calibration was performed using national institute distance artifacts (NIST and PTB).

On machine IPRO4#A only, all experiments were repeated with an experimental version of KT's LMSCORR software. For simplicity, the self calibration of IPRO4#A using the experimental version is treated as a single tool and labeled IPRO4#E. Current version of LMSCORR software supports polynomial corrections up to 11th order.

To determine TMU from each machine and to measure each machine's grid, several measurements in 0° / 90° / 180° and 270° reticle orientation were performed and repeated on consecutive days (Table 1).

Table 1: Measurement strategy

	IPRO4#A	IPRO4#B	IPRO4#C	IPRO4#D	IPRO4#E
Cycles	5	4	5	5	5
Days	3	3	3	2	3
Orientations	4	4	4	4	4
Total measurements	60	48	60	40	60

Based on the ANOVA model [4], each tool's TMU has been calculated using one isotropy measurement run (0° / 90° / 180° / 270° measurements performed on one day) and 0° measurement runs on at least 2 days.

Table 2: Measurement performance according to ANOVA model

Mean 3 σ	IPRO4#A		IPRO4#B		IPRO4#C		IPRO4#D		IPRO4#E	
	X	Y	X	Y	X	Y	X	Y	X	Y
Short Term Error [nm]	0.53	**0.53**	0.41	**0.51**	0.52	**0.60**	0.39	**0.43**	0.51	**0.52**
Long Term Error [nm]	0.47	**0.64**	0.18	**0.33**	**0.17**	0.10	0.32	**0.36**	0.26	**0.53**
Isotropy Error [nm]	0.97	**1.02**	**0.87**	0.86	1.30	**1.31**	**1.05**	1.04	**0.98**	0.91
Total Measurement Uncertainty [nm]	**1.32**		**1.06**		**1.45**		**1.19**		**1.23**	

Overall TMU is well below 1.5 nm residual 3 σ error. Note that typical ANOVA based LMS IPRO4 performance is around 1.25 nm residual 3 σ . As required for further matching analysis, σ_{Grid} has been calculated for each machine, using the appropriate available isotropy measurement run.

Table 3: Grid uncertainty estimate based on ANOVA measurements

Mean 3 σ	IPRO4#A	IPRO4#B	IPRO4#C	IPRO4#D	IPRO4#E
Grid Error [nm]	0.73	**0.36**	0.53	0.44	0.57

In terms of TMU and also grid uncertainty, IPRO4#B is best performing machine (TMU ~ 1.1 nm, σ_{Grid} < 0.4 nm).

All measurements within this experiment have been performed on a binary test mask manufactured on binary MoSi material. Pattern layout is a 29 x 29 grid design. Measurements were performed on standard registration crosses with a nominal line width of 1.0 µm arranged in a 15 x 15 grid.

3. MATCHING CONCEPTS AND RESULTS

Improving registration measurement capability by matching older generation to new generation tools is a well known and proven method [1,3], but is this method capable to improve measurement capability of leading edge machines as well?

The basic idea is: if a high precision 2D grid standard is available, matching the high end metrology tools against this standard would improve measurement capability of all these machines.

One major issue is the missing high precision 2D grid standard. Typically a 2D grid artifact with a 10 nm gauge precision is provided with every LMS IPRO for calibration purposes, but 10 nm gauge precision is not suitable for 22nm node tool matching. Obviously, a more precise 2D grid standard has to be created.

Basically there are 3 different approaches to provide a 2D grid standard:

1. Golden Tool matching as a proven method,
2. Round Robin matching – derive a 2D reference grid by combining accurate measurements on multiple machines,
3. Self calibration ("combined correction").

For each option, the methodology is explained and matching results are presented. Finally all options will be evaluated in terms of performance improvements and cost. In addition, the self calibration concept for the next-generation LMS IPRO 22nm pattern placement metrology system is presented.

3.1 Golden Tool Matching

The Golden Tool concept selects the best performing tool as the reference for tool matching. A reference mask is measured on the Golden Tool and the reference mask grid is transferred to matched tools using the footprint technique [3]. The machine with the best measurement performance (IPRO4#B) was selected as the Golden Tool. The averaged grid from the Golden Tool (3 days, 4 orientations, 4 cycles per measurement run) served as the reference grid for tool matching, we will call it OPTI grid. The OPTI grid covers an area of 132 x 132 mm² (main field area).

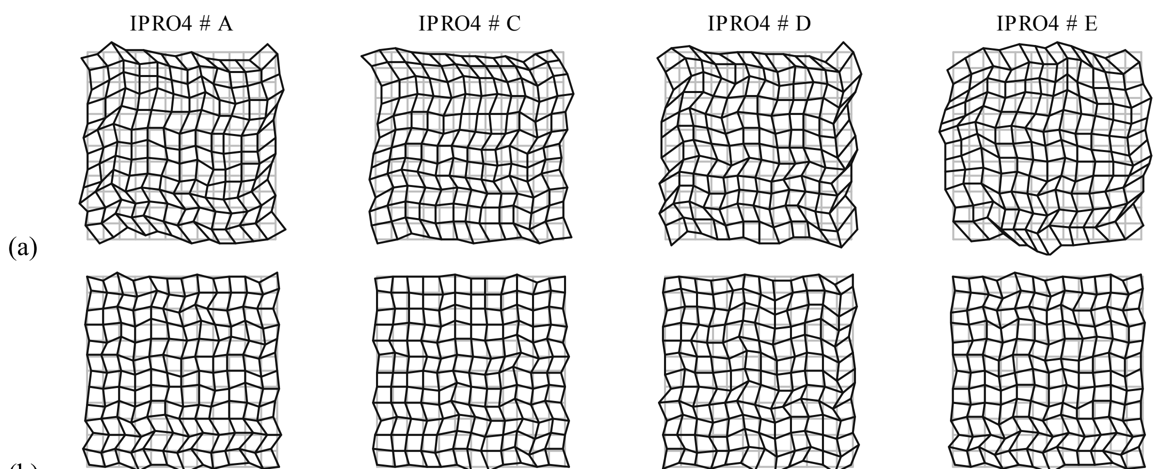


Figure 1: Matching grids with (a) 1st order (b) 7th order correction.

Golden Tool matching reveals individual systematic differences among all tools (Figure 1) used for this experiment. Since standard error is only valid for evaluation of random errors, range half will also be evaluated. First order matching of all IPRO4 machines to the Golden Tool OPTI grid is well around or below 2.0 nm (Figure 2).

2.0 nm matching error is not acceptable for 22nm lithography, so further optimization by using footprint technique (LMSCORR software) or HighGrid feature in LMS DEVA software is necessary. Results presented in Figure 2 demonstrate sub nanometer matching of different LMS IPRO4 machines using HighGrid function.

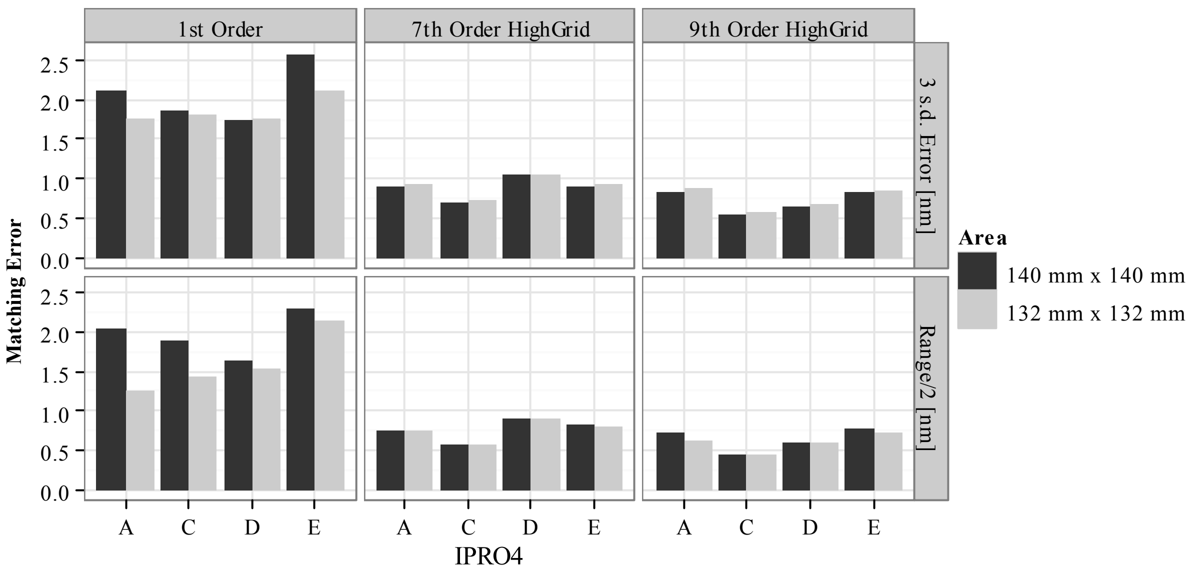


Figure 2: Golden Tool pattern placement matching error results by correction method and image area. Sub-nanometer matching can be achieved using footprint or HighGrid correction techniques.

Root causes for slight systematic grid distortions (e.g. s-bow distortion) are individual tool hardware differences, material differences (e.g. 5" mask border exclusion at combined correction) and different correction/monitoring processes at each side. The substantial difference between IPRO4#E and all other machines is caused by a different software implementation of the combined correction polynomial model.

3.2 Round Robin Calibration

One can optimize the grid without having a high precision 2D grid artifact for calibration by simply averaging over all available tool grids and using the averaged grid as a reference for matching. Only machines with a TMU < 1.5 nm residual 3σ ($\sigma_{Longterm}$ < 0.7 nm and $\sigma_{Isotropy}$ < 1.3 nm) should be selected for grid averaging. The following procedure was applied to derive self-made 2D grid artifact:

- Each machine was self calibrated for best accuracy;
- Measurements were taken according to Table 1: Measurement strategy;
- Averaging over repeats, orientations and days was performed to create single machine OPTI grids;
- Averaging all machine specific grids and thus create Round Robin OPTI grid was saved as Round Robin grid.

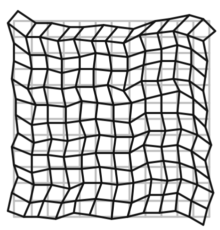
Averaging over all participating LMS IPRO4 machines reduces the grid uncertainty σ_{Grid}, which in consequence will slightly improve the TMU of tools connected to the Round Robin artifact.

After establishing the Round Robin grid, a matching cycle has to be performed for each machine. Here, LMSCORR software (footprint correction) or DEVA Software using HighGrid feature could be employed.

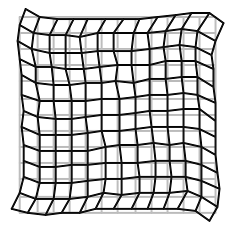
Two matching procedures are possible now:

1. matching to round robin using 0° measurements
2. matching to round robin using 0° / 90° / 180° / 270° orientation averaging

Most intuitive and common matching procedure is comparing 0° single tool measurements with Round Robin artifact, because most product measurements are performed in 0° orientation. Improving matching in 0° mask orientation only leads to decreased IPRO accuracy. With rising 22nm node demand, it might worth to investigate how orientation averaging could improve the calibration and product measurement [2] for double patterning applications.



(a) 0° matching



(b) matching with orientation averaging

Figure 3: Matching grid for best performing IPRO # B

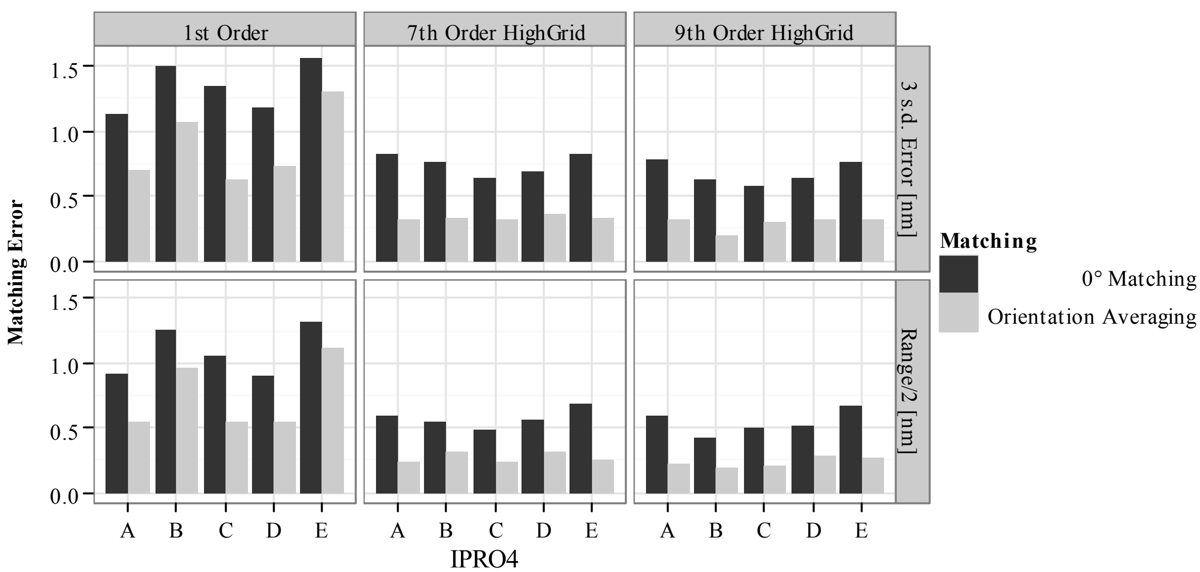


Figure 4: Round Robin matching error comparing 0° results and orientation averaging technique results.

2D grid Round Robin potentially attenuates the gap between best matching and optimized accuracy performance for LMS IPRO4 systems. Thus, having small isotropy error and good matching to a grid standard might become possible. This has not been proven yet and will be part of further investigations. The Round Robin matching cycle should be performed on an annual basis.

3.3 Self - calibration of single tools

How does self calibration compare with golden grid and Round Robin methods in terms of matching?

Self calibration is a method to improve the calibration of a gauge and a measurement system by using an imperfect artifact and the roughly calibrated measurement system itself [5]. This method is commonly used for XY stage calibration in electron beam lithography systems and metrology systems [6,7,8]. Combined with a distance artifact [9], self calibration is used to minimize the deviation of the LMS IPRO coordinate system from ideal Cartesian coordinate system. In a perfect world, comparing self calibrated grids should result in zero difference, and in reality only random error should be observed.

No specific reference grid is required for self calibration matching evaluation. Figure 5 presents the matching grids for each unique tool combination, where the first letter indicates the reference and the second letter the matched tool.

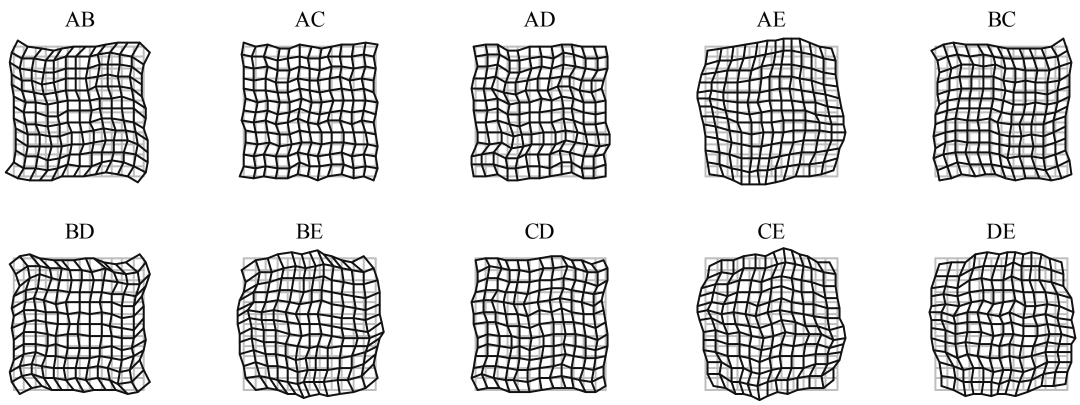


Figure 5: Self calibrated IPRO matching grids, 132 mm x 132 mm measurement area.

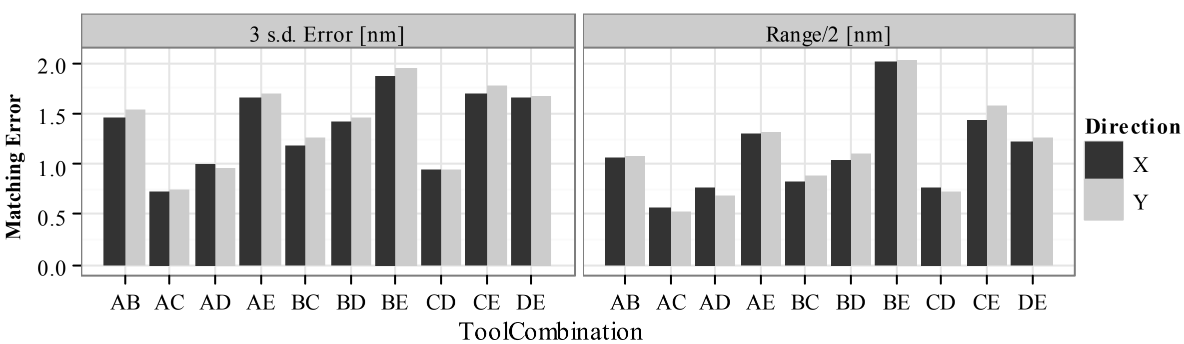


Figure 6: Matching results for self calibrated systems, 132 mm x 132 mm mask image field.

Self calibration matching for current LMS IPRO4 systems was equal compared to the Golden Tool matching performance (Residual 3σ error and range/2 error components). Nevertheless, Figure 6 shows that sub nanometer matching is possible using the self calibration approach for 3 out of 10 unique tool combinations (AC, AD and CD).

To have all tools within a fleet as closely matched as possible, there is currently no other option than using matching concepts like Golden Tool or Round Robin.

Rotationally symmetric grid distortions seem to be the root cause for matching errors beyond 1.0 nm, regardless of the evaluation criteria like 3σ or range/2.

The basic root cause for the remaining errors can be found within the LMS IPRO4 combined correction method. This method uses a 5” plate to correct for rotation symmetrical errors and is sufficient for the most critical exposure field area of the mask. But as 5” plate is smaller than a 6” standard reticle, the outer area measurement locations, especially the corner measurements, do typically suffer from insufficient correction quality. Considering the critical exposure field area of the mask only, this effect becomes neglectable.

To support best grid accuracy and matching also outside of the exposure field areas of the mask, the next-generation LMS IPRO will offer a new combined correction method. This method will utilize one 6” mask to execute a combined correction. Multiple orientation measurements at different locations on the metrology system will be used to establish an enhanced registration self calibration grid.

3.4 Final comparison of Matching Methods

It was found that the 3 matching methods provided comparable 1st order matching results in terms of residual 3σ and range/2. All LMS IPRO4 machines matched within 2.5 nm 3σ, even in a self calibrated state.

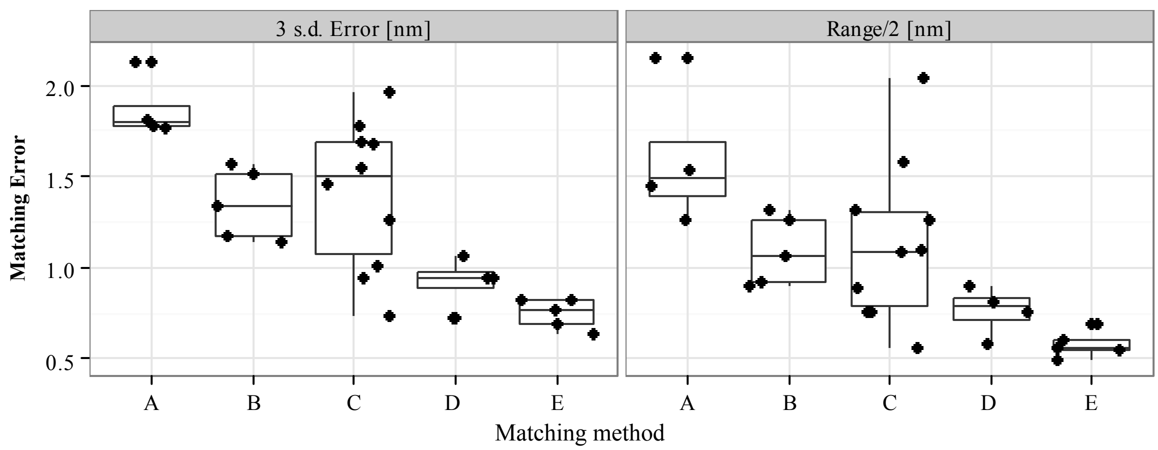


Figure 7: Comparison of all matching results.
A = Golden Tool, B = Round Robin, C = Self-Calibration, D = 7th Order Golden Tool, E = 7th Order Round Robin

Based on the ANOVA approach introduced in section 2.1, measurement capability for each machine and strategy was calculated according to equations (1) and (2). For Golden Tool matching capability calculation, grid uncertainty from IPRO4 # B OPTI grid was used.

For Round Robin grid error calculation, final grid error was the average over individual tool grid error divided by $\sqrt{5}$ (number of systems used to define the average grid).

Using self calibration only, current LMS IPRO4 systems residual matching error is below 2.0 nm. Golden Tool and Round Robin methods gave comparable results with 1st order correction. Applying matching functions, like DEVA HighGrid or Footprint, improved matching results below 1.0 nm can be achieved for Golden Tool and Round Robin methods. Even though comparison of self calibrated grids revealed systematic differences between individual grids, self calibration potentially enables sub nanometer matching without application of higher order corrections.

Table 4: Measurement capability calculated for each machine and each matching strategy.

All numbers are residual 3σ in [nm].		LMS IPRO4 System				
		A	**B**	**C**	**D**	**E**
Tool specific	Short	0.53	0.51	0.60	0.43	0.52
	Long	0.64	0.33	0.17	0.36	0.53
	Grid	0.73	0.36	0.53	0.44	0.57
Self Calibration	Isotropy	1.02	1.06	1.31	1.05	0.98
	Total	1.32	1.06	1.45	1.19	1.23
Golden Tool Matching	Grid	***0.36***	***undefined***		***0.36***	
	Matching (7^{th} order)	0.94		0.73	1.06	0.94
	Total	**1.31**	1.06	**1.02**	**1.25**	**1.25**
Round Robin Matching	Grid			***0.16***		
	Matching (7^{th} order)	0.82	0.76	0.64	0.69	0.82
	Total	**1.18**	**0.99**	**0.91**	**0.90**	**1.12**
Improvement over self calibration	Golden Tool	1 %	reference	29 %	- 5 %	- 2 %
	Round Robin	**10 %**	**7 %**	**37 %**	**24 %**	**9 %**

The Round Robin method resulted in improved tool matching compared with Golden Grid and self calibration methods. Use of higher order corrections further improved Round Robin matching, to the sub nanometer region for LMS IPRO4 tool generation.

Compared to self calibration only, a TMU capability improvement by up to 37% was achieved using the Round Robin matching technique. A TMU < 1.0 nm was achievable with LMS IPRO4 tool generation. Benefits and costs for each matching strategy are compared in Table 5.

4. SUMMARY AND OUTLOOK

We were able to demonstrate that matching techniques can be used to extend the measurement capability of the LMS IPRO4 tool generation beyond their factory specifications. Capability improvements (i.e. reduction of TMU) of up to 37% were achieved by Round Robin matching.
Using ANOVA methodology for TMU evaluation, a measurement capability of ~ 1.0 nm residual error was achieved with the LMS IPRO4 pattern placement measurement system.

Using **Round Robin** matching combined with an artificial 2D grid standard, enables sub nanometer matching for different LMS IPRO4 machines to this grid standard. Performance improvement by using Golden Grid matching was negligible for most machines: only one machine showed a significant performance improvement.
Nevertheless, Golden Tool matching remains a proven method for matching older generation registration tools to latest available tool generation. This technique enables capability extension of older generation LMS IPROx tools applying golden grid of latest available LMS IPRO generation, e.g. LMS IPRO4 in this evaluation.

We also demonstrated that KLA-Tencor's combined correction method potentially enables sub nanometer matching and below 1.0 nm residual measurement capability as well. Currently, self calibration matching is limited due to systematic grid distortions, caused by an imperfect self calibration method. With the next generation of LMS IPRO tools, a new combined correction method is planned which will address the systematic grid distortions that have been found.

Table 5: Comparison of matching techniques in terms of effort and performance

	Self calibration	**Golden tool calibration**	**Round robin calibration**
Grid definition	Single machine, 0°/90°/180°/270° average	Golden tool OPTI grid file	Average among several golden tool OPTI grids
Grid accuracy	Limited to single systems accuracy. -	Limited to latest available LMS IPRO system. o	Based on all available machines within round robin network. +
Fleet matching performance	Limited and based on single machine accuracy. -	Optimized +	Optimized +
Effort to establish	Small +	Small +	Collaboration among different sites or even customers needed. -
Effort to maintain	Small +	Medium o	Round robin mask need to be "cycled" through the network of tools connected. -
Application use case	Single tool in one mask shop.	Tools of various generations in one mask shop.	Tools of various generations in different mask shops or even different companies.

5. ACKNOWLEDGEMENTS

AMTC is a joint venture of Globalfoundries and Toppan Photomasks, and gratefully acknowledges the financial support by the German Federal Ministry of Education and Research BMBF under contract numbers 13N9675 (ANTARES) and 13N9946 (CDuR32).

The author is thankful for the R project providing such an extensive environment for statistical computing under the GNU General Public License.

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