Registration Measurement Capability of VISTEC LMS IPRO4 with Focus on Small Features

Christian Enkrich[a], Gunter Antesberger[a], Oliver Loeffler[a],
Klaus-Dieter Roeth[b], Frank Laske[b], Karl-Heinrich Schmidt[b], Dieter Adam[b]

[a] Advanced Mask Technology Center GmbH & Co KG,
Raehnitzer Allee 9, 01109 Dresden, Germany;
[b]Vistec Semiconductor Systems GmbH,
Kubacher Weg 4, 35781 Weilburg, Germany

ABSTRACT

The development of the 45-nm node manufacturing process at leading edge mask shops is nearly finished. In order to reach the required registration measurement performance with a precision to tolerance value of P/T = 0.25, the measurement error may not exceed 1.2 nm according to ITRS roadmap. This requires the latest generation of registration measurement tools. In addition, the demand for measuring very small features increases – for standard pattern placement measurements, as well as special engineering tasks, e.g., the position measurement of single contact holes.

In this work, the error of pattern placement measurement on an LMS IPRO4 is determined using an analysis of variance methodology (ANOVA). In addition we analyze the capability as a function of the critical dimension (CD) of the registration feature. The results are compared to the previous tool generation.

Keywords: registration metrology, ANOVA, double patterning technology, in-die measurement, small feature

1. INTRODUCTION

The LMS IPRO4 is the state-of-the-art mask registration metrology system available. The standard acceptance test of the tool focuses on common registration marks of 1 μm line width and a cross length of several microns. However, since double patterning is considered as the highest potential technology for the 32-nm node,[1–3] several leading edge mask user already request the capability to measure registration on significantly smaller structures which fit into the active area of the circuit.[4] In addition, it is assumed that during some process steps in wafer manufacturing as e.g. CMP, any larger structures in the neighbourhood of smaller features may generate killer particles. Therefore it is preferred to use smaller features for registration metrology.

In order to support our mask user's request to measure on significantly smaller structures, we investigated the performance of the metrology system on structures between 80 nm and 1 μm wide for the contrasts of Chrome and MoSi against quartz, respectively. We compared the results achieved on both AMTC's in-house systems LMS IPRO3 and LMS IPRO4. The IPRO3 was the beta-site system installed in 2005 and the IPRO4 was the first installation of the most actual generation and took place in summer 2007. Both metrology systems are qualified together with AMTC's customers using the analysis of variance (ANOVA) based evaluation method as first presented in autumn 2006.[5] Obviously, this investigations here use the same evaluation approach to prove the overall metrology capability of the IPROx systems.

This paper is structured as follows: First we briefly review the ANOVA to evaluate the registration measurement error. This methodology is used in the following two sections: In Section 3 we evaluate the actual tool performances of IPRO3 and IPRO4 on standard registration features. In Section 4 we extend the experiments and show the measurement capability of both tools on smaller features for different materials and tones.

Further author information: (Send correspondence to Christian Enkrich)
Christian Enkrich: E-mail: Christian.Enkrich@amtc-dresden.com, Telephone: +49 351 4048 334
Klaus-Dieter Roeth: E-mail: Klaus-Dieter.Roeth@vistec-semi.com, Telephone: +49 6471 910 2673

Photomask and Next-Generation Lithography Mask Technology XV,
edited by Toshiyuki Horiuchi, Proc. of SPIE Vol. 7028, 70282Y, (2008)
0277-786X/08/$18 · doi: 10.1117/12.793104

2. MEASUREMENT ERROR DEFINITION

For the definition of the registration error we refer to the proposal we made in Ref. 5. Here, an analysis of variance (ANOVA) is used to evaluate and separate the different error components, which are:

- Short-term repeatability: Direct comparison of multiple successive measurements. Assumed as stochastic noise, denoted by σ_{short}
- Long-term reproducibility: Comparison of measurements taken on different days, including mask loading and unloading cycles. The observed tooldrift behaviour does not show any systematic error over time. Thus, it is modelled as a random variable characterized by a standard deviation σ_{long}
- Isotropy: Coordinate system deviation from Euclidean metric, due to imperfect stage correction, ceramic frame and reticle variations, denoted by σ_{iso}

The first two error components are valid for all tools, the last one is only used for the *golden tool*, which serves as the reference tool. All other tools are matched to this tool, thus, instead of the isotropy error two other error components are applied:

- Matching: Difference between the measurements on the *golden tool* and the *matched tool*, denoted by σ_{match}
- Grid: Accuracy of the grid measurement on the *golden mask*, which is used to match the tools, denoted by σ_{grid}

As an independent maskshop we have to make sure, that our grid matches as good as possible to the ideal Euclidean grid, since there is no high precision two-dimensional grid standard available which could be used for this purpose. Thus, we have to include the isotropy error into the total error. This error gives the best possible estimation of the difference to the ideal Euclidean grid. Only in the case of relative measurements, e.g. the overlay error between two reticles, one can neglect the isotropy error, if both measurements are performed on the same tool.

The errors are evaluated along a scheme, which is described in Ref. 5. Here, we just want to review the calculation of the short term error: An 8x8 grid is measured 10 times, resulting in a total of 640 measurements. Then the deviation from the mean is calculated for each site. Out of these deviations a 3 s.d. is obtained per site (stats per point in the Vistec software). The short term error along our ANOVA methodology is the average of these standard deviations.

With respect to the measurement performance of small features we expect an influence only to the short term error. From a certain critical dimension (CD) on downwards, the edge detection could become more uncertain, since the contrast decreases, resulting in an increased σ_{short}. Long term error and isotropy error are expected to be independent from the structure size.

3. PERFORMANCE OF IPRO3 AND IPRO4

The performance of the IPROs is measured on the Vistec acceptance reticle. This is a CoG mask with a 29 by 29 grid of 1 μm wide registration crosses, which have a pitch of 2.5 mm, resulting in an area of 140x140 mm^2. The results obtained using the ANOVA methodology are summarized in Tab. 1. The first column shows the results for IPRO3 in 2006 (see Ref. 5). The values of the newly installed IPRO4 and the improvement compared to IPRO3 are stated in the next two columns (compare also Ref. 6).

The total uncertainty of the IPRO has been improved by a large amount of 25%, which gives us the possibility to fulfill our customers requests of registration performance for the next node. An enormous improvement of 55% has been made with respect to the longterm stability. This is of crucial importance for double patterning, where extremely tight SPECs are expected for relative measurements between two masks of a double patterning set.

	IPRO3	IPRO4	
Measurement uncertainty type	Performance in 2006	Performance after installation	Improvement over IPRO3
short term	0.66	0.54	$\sim 20\%$
long term	0.58	0.27	$\sim 55\%$
isotropy	1.52	1.2	$\sim 20\%$
total uncertainty	1.76	1.3	$\sim 25\%$

Table 1. Overview of the performance of IPRO3 in 2006 and of IPRO4 after installation at the AMTC, evaluated using the ANOVA methodology. Values are given in nm 3 s.d. The last column shows the improvement of IPRO4 compared to the previous tool generation.

	IPRO3		
Measurement uncertainty type	Performance in 2006	Performance in 2008	Improvement over 2006
short term	0.66	0.60	$\sim 10\%$
long term	0.58	0.47	$\sim 20\%$
isotropy	1.52	-	$\sim 15\%$
matching	-	1.07	
grid	-	0.7	
total uncertainty	1.76	1.48	$\sim 15\%$

Table 2. Overview of the performance of IPRO3, first in 2006, second in 2008. The values are given in nm 3 s.d. and are obtained using the ANOVA methodology. The last column shows the improvement over the years and due to the difference of IPRO3 as a *golden tool* and as a *matched tool* (see text).

Table 2 compares the performance of IPRO3 in 2006 as the *golden tool* (first column) with the performance in 2008 as a *matched tool* (second column). The total measurement uncertainty has improved about 15%, mainly driven by the change of the error components: matching and grid error instead of isotropy error. In that way, the good performance of IPRO4 (especially for σ_{iso}) also improves the matched IPRO3. Nevertheless, also short and long term errors have become smaller over time.

4. MEASUREMENT CAPABILITY ON SMALL FEATURES

4.1 Experiment Setup

Due to the lack of small features on acceptance masks, we have designed and manufactured an in-die test reticle with many different test patterns related to open question of in-die measurements. We used a halftone material, where the Chrome was only removed from some regions in order to have different contrast types on one mask. This enables to measure chrome against quartz or MoSi against quartz, both in clear or dark characteristic.

Clear chrome crosses with a arm length of $4\,\mu m$ are placed on this reticle in regular grid, with the following nominal CDs: 80, 90, 100, 125, 150, 175, 200, 225, 250, 275, 300, 350, 400, 450, 500 (nm). We compared these

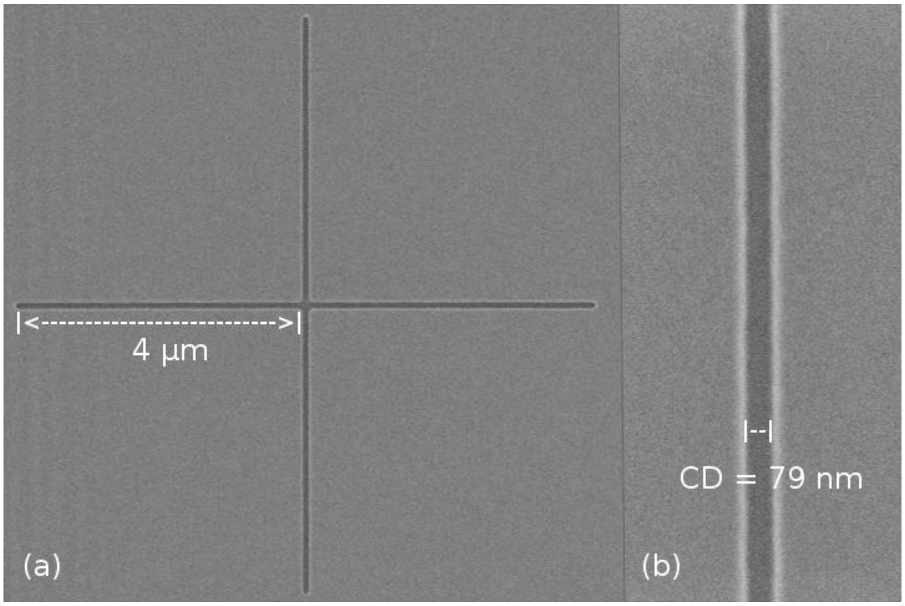

Figure 1. (a) Electron micrograph image of a registration cross with a nominal CD of 80 nm. The length of the cross arms are $4\,\mu m$. (b) shows a magnification of one arm. A CD measurement with the SEM results in a value of 79 nm.

nominal values with measurements on a CD-SEM*. For the first five crosses we obtained: 79, 93, 103, 130, 155 (nm). An electron micrograph of the smallest registration cross is shown in Fig. 1. Dark chrome crosses, as well as MoSi to quartz contrast in clear and dark are available with the following nominal CDs: 110, 140, 250, 500 (nm). The sizes of the smallest ones have again been verified by CD-SEM measurements: dark Chrome 106 nm, clear MoSi 113 nm, and dark MoSi 104 nm. Since the deviations from the nominal CD values are very small, we will use only the nominal ones in the following. Clear Chrome crosses where measured on a regular 8x8 grid on IPRO4 with a pitch of 20 mm. On IPRO3 they have been measured on a 5x5 grid with a pitch of 35 mm. All other structures are also measured on a 5x5 grid with a pitch of 25 mm.

All measurement jobs have the same region of interest of $1.5\,\mu m$ width and $4\,\mu m$ length. For the remaining parameters we used the standard values proposed by Vistec. Maybe it would be possible to increase the capability of the tool by job optimizing, e.g., changing the slope for the edge detection, or other parameters. To keep the results as comparable as possible, we abandoned this option. Secondly, setting up an automated recipe creation process, where these parameters are changed in dependence of the pattern to measure, is a difficult task.

Most of the measurements have been performed in reflected mode. For small dark features, the ratio of the structure which reflects the light onto the CCD chip to the non-reflecting surrounding becomes very small. Therefore, the following measurements have been performed in transmitted mode: 110 nm dark MoSi crosses on IPRO4 and on IPRO3 all dark structures with 140 nm and 250 nm. These transmittance measurements have been marked by gray boxes in the figures. 8x8 grid measurements have been repeated at least 10 times, 5x5 grid measurements at least 20 times.

4.2 Evaluation & Results

For evaluation of the measurements, we calculated the 3 s.d. of the distribution for each site (stats per point). The distribution of these standard deviations are illustrated by box plots. The thick black line of such a box represents the median of the distribution, the boxes above and below indicate the 75% and 25% quantile, respectively. Thus, the whole box represents the interquartil range, where 50% of the samples are located. Values, which are more than 1.5 times the interquartile range away from the box are marked as outliers, depicted as open circles in the plots. The whiskers range from the smallest to the largest value not marked as an outlier. To compare two experiments, it is helpful to look at the notches. If the notches of two plots do not overlap this is a "strong

*CD values are correlated to NIST standard

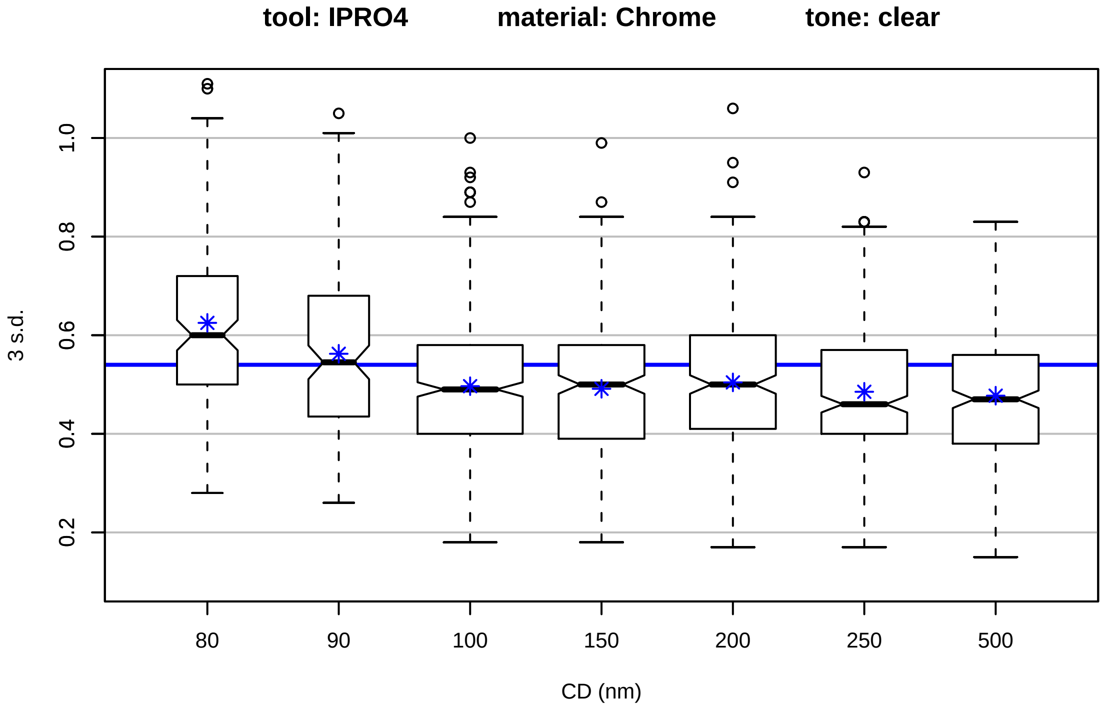

Figure 2. Distribution of 3 s.d. over CD as explained in the text. The structures are clear Chrome crosses on a 8x8 grid. The thick blue line indicates the short term error of the IPRO4. Down to a CD of 100 nm the capability remains unchanged. Only for structures of 90 nm and smaller the short term error gets larger. Keep in mind, that the short-term SPEC by Vistec for that tool is 1.3 nm max. 3 s.d., which is fullfilled for all CDs.

evidence" that the two medians differ (e.g., in Fig. 2 there is no statistically significant difference between the medians for CDs between 100 nm and 200 nm). The width of the boxes are proportional to the square-root of the number of observations in the groups, in our case the total number of measurement sites.

Additionally the blue star marks the average of all 3 s.d. (no outliers excluded), which is the AMTC definition of the short term error (see Section 2 and Ref. 5). The thick blue lines in the plots show the short term error of the corresponding tool, as given in Table 1. All box-plot figures have the same y-scale, and no outliers are outside this range, i.e. no 3 s.d. is above 1.1 nm.

Fig. 2 shows the results for 10 times repeated measurements of the 8x8 grid of clear Chrome crosses on IPRO4. For all CDs down to 100 nm the average 3 s.d. (blue star) is below the short-term error of the tool (thick blue line) obtained on $1\mu m$ structures. Only for a width of 90 nm and smaller the capability decreases slightly. The maximum of the standard deviations is for all structures smaller than 1.3 nm, which is the tool SPEC. The average is always very close to the median, which indicates that the distribution is not too asymmetric.

The values for IPRO3 on clear Chrome structures are depicted in Fig. 3. The tool shows a very similar behaviour compared to IPRO4, just the limit, where capability starts to decrease, is shifted to 125 nm. Comparing the range of the distributions shows an unexpected result on the first look. The range of the measurements on IPRO4 is larger compared to the ones on IPRO3. This is related to the smaller grid (only 5x5 and smaller area) measured on IPRO3. Performing the same measurements on IPRO4 gives very similar 3 s.d.-ranges (not shown). The differences between both tools result from different lenses and smaller pixel size of the IPRO4 CCD chip compared to IPRO3.

For the remaining structures, we put the results from both tools together in one graph. Dark Chrome features are presented in Fig. 4, clear and dark halftone material in Fig. 5 and Fig. 6, respectively. Measurements in transmitted mode are shown as gray boxes. Table 3 summarizes the results obtained from the various figures. The CDs listed in the graph still lead to standard measurement performance. However, in some cases we could not determine the limits of the IPRO3 and IPRO4 tools versus resolution because either we had no smaller

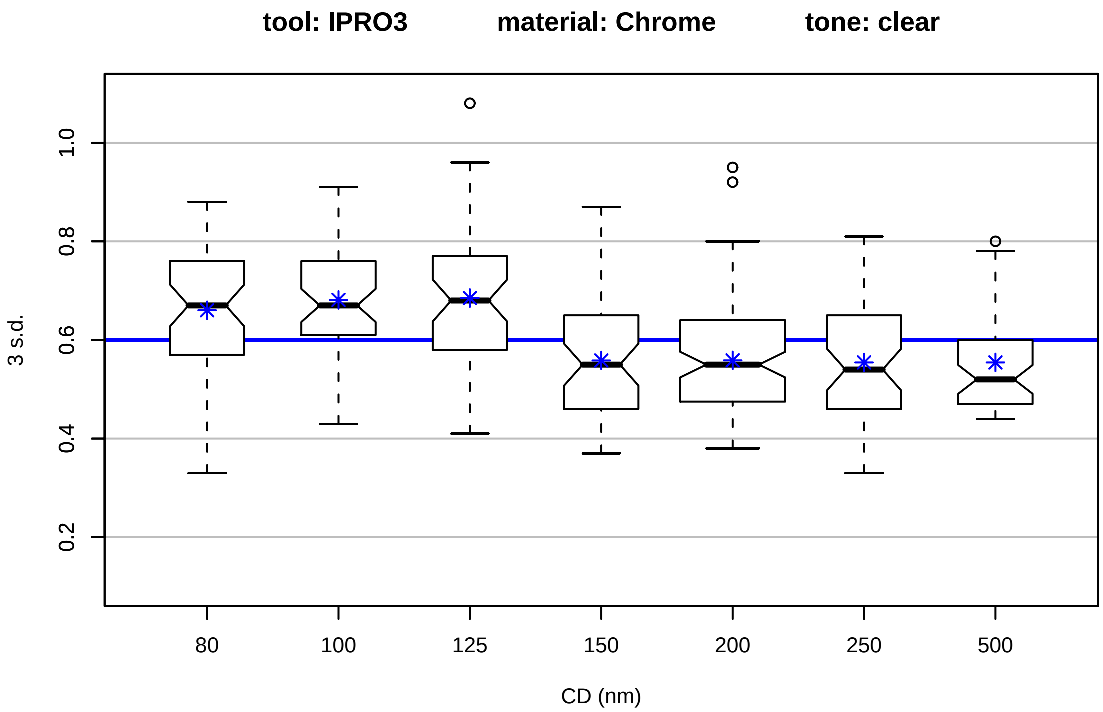

Figure 3. Distribution of the standard deviation over CD for IPRO3. The structures are clear Chrome crosses on a 5x5 grid. There is no change in the short term capability for measurements on registration crosses with a CD down to 150 nm.

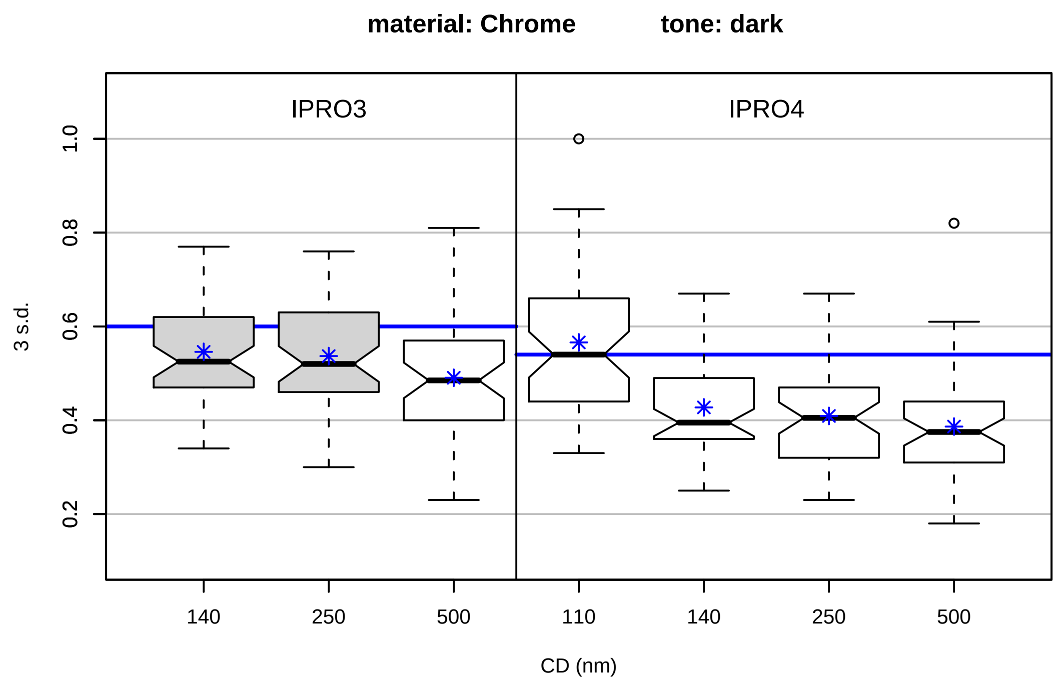

Figure 4. Results of the measurements on dark Chrome crosses over the CD are summarized for both tools. Measurements which have been performed in transmitted mode are marked by gray boxes.

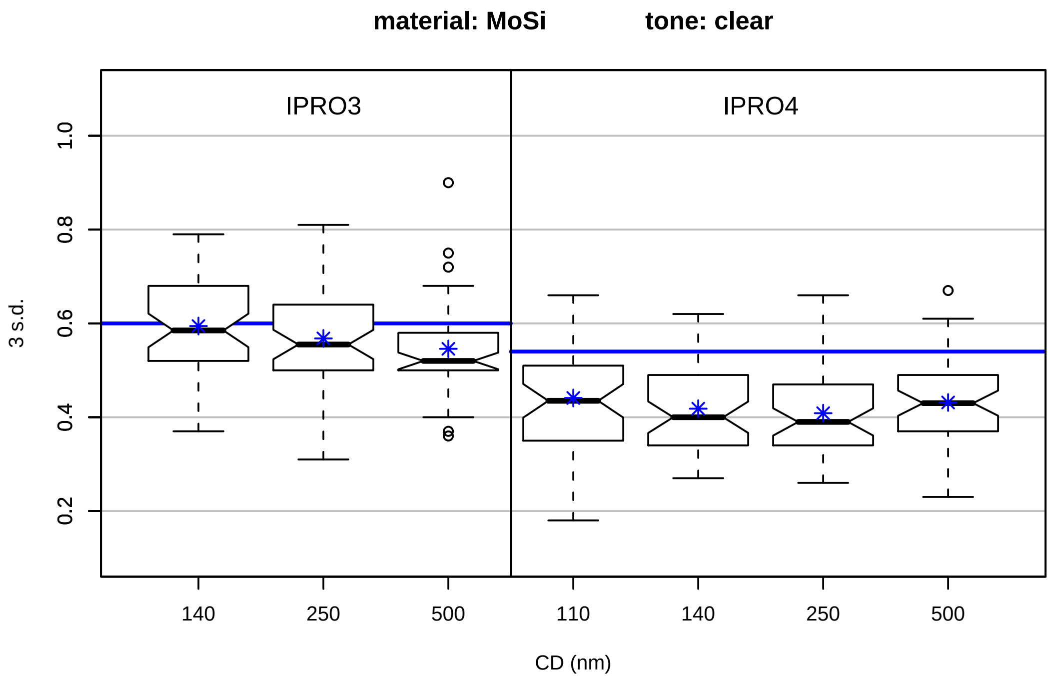

Figure 5. The distribution of the 3 s.d. is shown for clear structures on halftone material for IPRO3 and IPRO4, respectively.

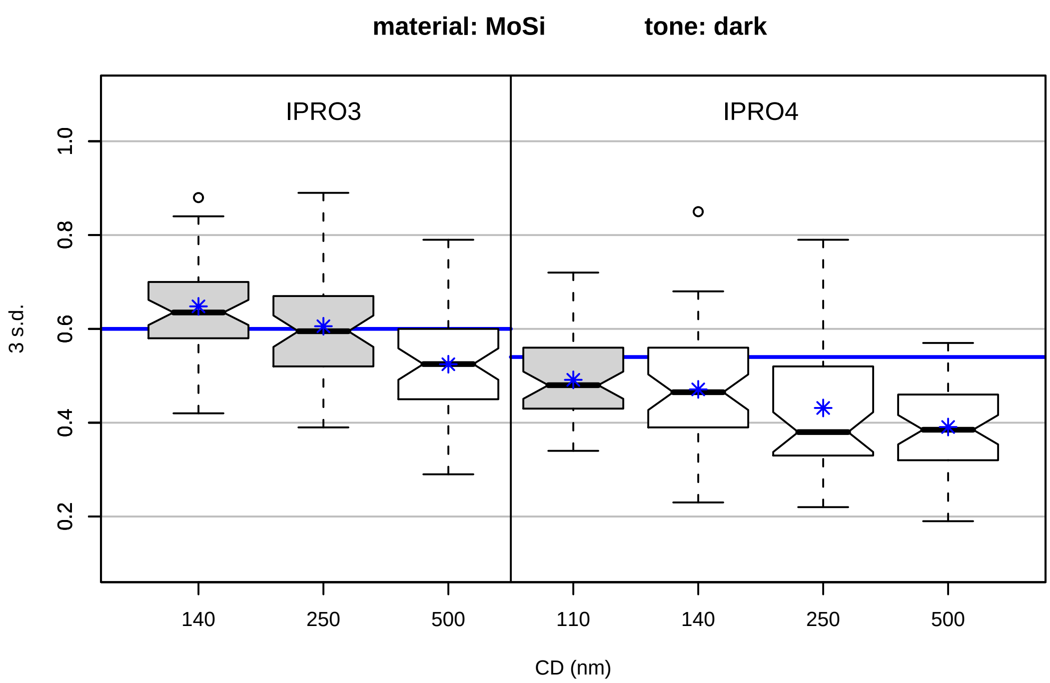

Figure 6. Results for dark MoSi crosses over CD, again for both tools. Measurements which have been performed in transmitted mode are marked by gray boxes.

	IPRO4	IPRO3
clear Chrome	$\sim 100\,nm$	$\sim 150\,nm$
dark Chrome	$\sim 140\,nm$	$\sim 140\,nm$
clear MoSi	$\sim 110\,nm$	$\sim 140\,nm$
dark MoSi	$\sim 110\,nm$	$\sim 250\,nm$

Table 3. Limits of the CD for a registration measurement on the two tools for different tone and material, where no influence on the capability is seen in the experiment. The values might be even smaller, partly they are a result of the coarse discretization on the test mask or just due to the fact, that even smaller ones have not been measured.

structures on the test masks or just have not measured them yet. This is especially valid for dark Chrome on IPRO3 and for dark or clear MoSi on IPRO4. Investigations on even smaller structures are planned for the future.

5. SUMMARY AND OUTLOOK

We could report on two exiting results from AMTC point of view:

First, with the introduction of the IPRO4 into our production, the metrology capability could be improved significantly by 25%! We consider this as a major step and a very important message to our customers. Especially the long term error has been reduced by more than 50%, which is very important for mask to mask overlay measurements for upcoming double patterning requirements. In addition, due to the improved grid error on the *golden tool* and the excellent matching between our IPRO3 and IPRO4 systems, we could also improve the process capability of the previous generation IPRO3 system by 15%, enabling us to utilize that tool now for product reticles with tighter specifications and extend the utilization period of the tool significantly (see Section 3).

Second, we could prove to our customers that the measurement capability does not decrease for measurements on small structures with CDs down to material and tone specific values, which are summarized in Tab. 3 (compare Section 4). For our production environment it is important to understand that the standard parameter settings from Vistec can be used for this purpose without requiring any engineering support to optimize parameter settings during job setup. The only parameter changed was the setting of reflected or transmitted light mode. This is an extremely important and useful information since it was assumed from our customers that due to i-line illumination the resolution would be restricted and accordingly the measurement performance would decrease. Obviously, the capability of the LMS IPRO4 to measure on smaller structures than the common registration marks will enable us to reduce the metrology cell and thus support in-die measurements.

To complete the picture of the tool capability further investigations are planned. First, it is planned to perform further investigations on even smaller features on various materials and feature types in order to determine tool limitations. Second, it is of high interest to reduce the size of the measurement ROI and check any limitations from ROI size as well as the influence of neighbouring structures. Here, numerical simulations could save time, to estimate the optical proximity effect for a pattern placement measurement on an LMS IPRO4. Additional experiments are planned in cooperation with Vistec in order to verify the tool capability of the IPRO4 with regard to structure size limitations of dense structures using 1:3 line/space ratio as it is assumed for DPT in-die measurement applications.

ACKNOWLEDGMENTS

AMTC is a joint venture of AMD, Qimonda and Toppan Photomasks. This work has been partially funded by the German Ministry of Education and Research (BMBF) under Contract No. 01M3154A (Abbildungsmethodiken fuer nanoelektrische Bauelemente).

We would like to thank Jens Rudolph and Sven Knoth (both from the AMTC) for help during the experiments and fruitful discussions.

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