Actual Measurement Data Obtained On New 65nm Generation Mask Metrology Tool Set

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Abstract

For 65nm photo mask lithography, metrology becomes significantly more important. Especially the requirements of the photo mask users versus critical dimension (CD) control, CD homogeneity and CD mean to target, give strong headaches to lithography and process control engineers. Despite the fact that optical CD metrology has limitations versus resolution it still provides valuable information since measurement takes place in transmission similar to the application of the mask during printing to the wafer. The optical resolution should at least support to measure minimum features of 250nm on the masks in the linear regime.
In order to qualify structure fidelity and width of assist structures and small contact holes as well as certain OPC pattern which are usually smaller than the limits of optical measurement capability, actually CD SEM systems are recognized as the tool of choice to qualify the reticles. No matter which kind of CD metrology tool is used, long-term repeatability over several days must be below 1nm (3 sigma). This paper will show measurement performance data on two types of reticle CD measurement systems targeting the 65nm node reticles.
Another issue of high importance is pattern placement or registration metrology on reticles. Roadmaps of leading edge mask users request a maximum placement error of less than 13nm for the 65nm technology node. This strong requirement challenges the control of the mask lithography tool and the long-term repeatability of the registration metrology system must not exceed 2.5nm.
This paper summarizes the actual performance of Leica's mask metrology tool set and the improvements on the individual systems leading to the respective performance.

Keywords: Mask metrology, critical dimension measurement, registration metrology, charging free CD SEM, transmitted light CD measurement

1 Introduction

The development of reticles for the 65nm technology node is already ongoing at the leading edge mask shops. The requirements for these reticles regarding CD homogeneity, CD mean to target and overlay are dramatically enhanced over previous generation reticles and require new metrology systems with significantly improved measurement performance compared to current systems.
Leica's tool set for mask metrology includes the registration measurement system and two CD measurement systems based on two different edge detection methods. The edge detection of the LWM500 WI is based on the image obtained in transmitted light illumination. The LWM9000 SEM is using scanning electron microscope (SEM) technology for edge detection. Both technologies have individual significant advantages and therefore are considered as complementary measurement technologies (Tab.1).

	Optical CD	SEM CD
Lateral resolution		++
CD linearity for < 0.25 µm		++
Small contact measurement capability		++
Measurement in transmission	++	
Phase sensitive (PSM's)	++	
Cost of ownership	+	
Contamination	o	o
Charging	+	
Tool-to-tool matching	o	o
Ease of operation		+
MAM time / Throughput		+

Tab. 1 **Comparison table of individual merits of optical edge detection and SEM based edge detection for reticle CD metrology.**

The optical CD measurement system developed in close cooperation between MueTec and Leica Microsystems is based on DUV illumination in transmission at 248nm, taking advantage of water immersion to achieve significant resolution enhancement over previous generations. Water immersion leads to a N.A. of 1.2.
The new SEM based reticle CD measurement system is a joint development between Advantest Corp. and Leica Microsystems. It achieves its outstanding measurement stability through extremely reduced sample charging and contamination.
Measurement performance data obtained on both complementary reticle CD measurement systems provide a short-term repeatability on COG and PSM reticles required for the 65nm reticle generation.
The next generation placement metrology system LMS IPRO3 is under development at Leica Microsystems. Beside the improved optics it incorporates a new strategy for temperature control in the chamber.

2 System Improvements to Enable 65nm Node Reticle Metrology

2.1 Optical CD Measurement System

Leica's optical mask CD measurement systems are developed since many years in cooperation between Leica and MueTec. The newest (fifth) generation of the optical mask CD measurement systems has been significantly improved with respect to optical resolution, mechanical stability, stage performance, and software algorithms. Details are discussed in a separate paper on the same conference [1]. First time, water immersion is used for a metrology system in order to increase the optical resolution significantly. The numerical aperture of the measurement lens was increased from 0.9 of the previous generation (dry objective) to 1.2 for the actual DUV illumination based metrology system. This leads to a resolution improvement exceeding 30%. In consequence, the linear domain of CD measurement could be extended from approximately 320nm for the dry lens to 220nm when using the water immersion type lens (Fig.1).

Additional measures, such as removing polarization-inducing mirrors and designing a completely new optical head avoiding the objective nosepiece, guarantee optical performance and mechanical stability to support extremely reliable measurements on the reticle.
New software algorithms for the edge detection on contacts were developed which take advantage of the improved hardware platform and enable an improvement in measurement performance especially on contact holes.

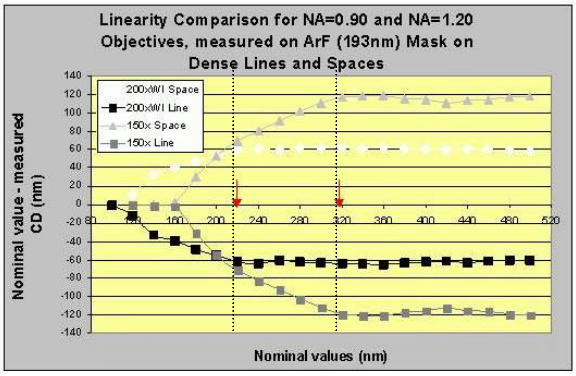

Fig. 1: The lower limit of the linear measurement range was improved from 320nm for the dry objective to 220nm for the water immersion objective.

The tight demand of the airspace technology based optics versus temperature stability requires to put the measurement system into a temperature-controlled mini-environment. The complete system is shown in Fig2.

Fig. 2: The optical based LWM500 WI in the new temperature- controlled mini-environment.

2.2 SEM Based CD Measurement System

Leica's new electron beam based CD measurement system LWM9000 SEM (fig.3) was developed in cooperation of Leica Microsystems and Advantest Corp of Japan. The first three systems have been installed recently at different locations world wide, two of them equipped with a new SMIF handling system (fig.4).
One of the most critical issues for achieving stable measurement performance is to overcome the electron charging. As a result of research in the field of electron beam testing, Advantest developed a technology to effectively reduce charging effects on photomasks to negligible levels. The basic idea is to control the primary electron beam and the emitted secondary and backscattered electrons in a way that the ratio of injected and emitted electrons remains constant at 1:1.

The realization of this principally simple idea is complicated because of locally varying conditions due to different substrate material types and varying pattern densities.

Fig. 3: The LWM9000 SEM with the manual (non-SMIF) loading system

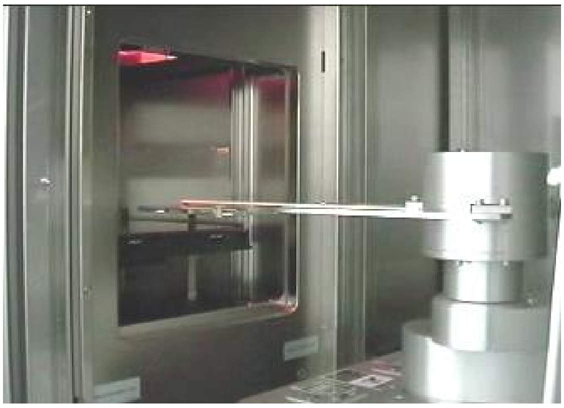

Fig. 4: LWM9000 SEM robot unloading the reticle into the (optional) SMIF pod

CD measurement performance is also significantly influenced by carbon contamination. The interaction of the electron beam with any organic residuals on the photomask leads to contamination. The organic molecules are cracked, leaving a thin carbon layer on the sample where the electron beam was scanning the surface. In the SEM image this area shows up darkened because the electron emission coefficient for low atomic number material is low. A substantial contribution to contamination likely comes from resist-coated reticles when After Develop Inspection (ADI) or After Etch Inspection (AEI) is performed. The electron beam interacts with the resist on the photomasks leading to out-gassing contamination of the chamber components, and to contamination of masks loaded subsequently. This contamination contribution cannot completely be eliminated if resist coated reticles are evaluated on a regular basis. In the new Leica LWM9000 SEM this problem is effectively reduced by applying ozone at a very low pressure into the vacuum chamber of the SEM when evaluating masks while still maintaining a high-vacuum level. The aggressive ozone reacts with the contaminants in the chamber. The high-vacuum pumps then transport the reaction products out of the SEM chamber providing a continuous cleaning process. During measurements on ADI and AEI plates the ozone injection is interrupted to avoid the interaction of the aggressive ozone with the resist on the mask. Low voltage operation further contributes in keeping the contamination effects at a low level.

A contamination test was performed utilizing a Molybdenum Silicide (MoSi) mask by imaging a feature at a magnification of 150 kx. After 32 seconds of continuous scanning the magnification was reduced to 50 kx to image a larger field of view and to check for any residual contamination effects. The result in Fig. 5 demonstrates the very low contamination rate of the LWM9000 SEM. Normal measurement scan times are about one to two seconds.

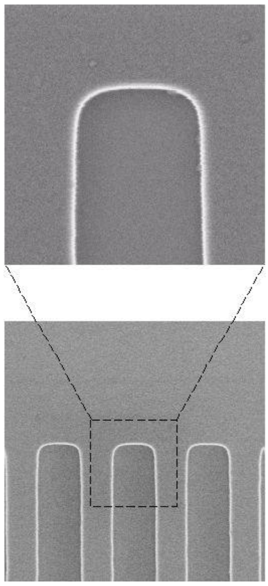

Fig. 5: MoSi mask imaged at 150 kx (top) and verified at 50 kx (bottom) for contamination test

CD measurements on state of the art reticles often require measurement capability on one specific feature, e.g. on a specific contact within a dense array of contacts. In these cases, there are no unique patterns available on the reticle close to the measurement structure to perform any fine alignment using pattern recognition. Therefore, a very precise and accurate sample stage is mandatory in order to enable fully automatic measurements. The Leica LWM9000 SEM uses a laser-interferometer controlled stage with a digital resolution of 0.6 nm. High precision stage guides, control electronics, and software contribute to an accurate stage positioning. Any temperature inhomogeneities at the stage area obviously have also a significant impact on stage performance in the submicron range. Therefore, avoiding any cold trap for the purpose of contamination reduction (but using the ozonizer instead) minimizes temperature gradients close to the sample stage. All these measures enable a typical stage performance of the Leica LWM9000 SEM in the range of less than +/- 100nm.

Further technical details were already discussed [2].

2.3 Registration Measurement System

The LMS IPRO2 is the actual generation of Leica's registration metrology system family. The development of the successor system is under way and the first beta-site system is scheduled for installation in summer 2005. Table 2 shows the actual registration measurement performance of the LMS IPRO2 and the performance targets for the next generation LMS IPRO3.

	Performance LMS IPRO2	Performance Target LMS IPRO3
Short term repeatability	2.0nm	1.3nm
Long term repeatability	3.0nm	2.2nm
Nominal accuracy	4.0nm	2.7nm

Tab. 2: Comparison of actual registration measurement performance of the LMS IPRO2 and the performance targets for the successor LMS IPRO3 Repeatability data are given in 3σ units and the nominal accuracy is given as 99.7% confidence level.

As it can be derived from tab. 2, a significant performance improvement of about 30% for each registration measurement specification is expected for the next generation system LMS IPRO3. Obviously, this kind of improvement requires major and substantial R&D tasks, especially when considering how close the performance of the LMS IPRO2 already is versus the physical limits.

In case of pattern placement metrology, temperature stability is recognized as a major contributor to the residual error budget. The temperature control chamber of the actual LMS IPRO2 has a temperature stability of better than +/-0.01K and temperature homogeneity in the chamber of better than +/- 0.02K, which was at the technical limits at the time of LMS IPRO2 development. In the mean time a new concept is available to further improve the homogeneity of the temperature distribution in the chamber. This concept takes care of the fact that there are temperature sources in the chamber that are not evenly distributed. These temperature sources create a slightly inhomogeneous temperature distribution within the above specifications in the actual chamber of the LMS IPRO2. The new concept called zone-control was developed from Leica's supplier M&W Zander. It is designed to improve the temperature homogeneity. Actual measurements proving the advantages of the new air flow design versus long-term repeatability and nominal accuracy are ongoing.

Leica's R&D group has taken further investigations on the LMS IPRO2 hardware design and searched out the autofocus system and the measurement algorithms as potential error sources for further improvements towards measurement repeatability performance. The stiffness of the autofocus mechanics will be improved for the LMS IPRO3 and thus the straightness of z-movement of the measurement objective further optimised.

A new design of the etalon wavelength tracking system will be integrated into the LMS IPRO3 and is expected to contribute as well to improve the measurement repeatability.

These significant hardware and software improvements altogether are expected to let the LMS IPRO3 achieve the repeatability performance as shown in table 2.

Of course, all above improvements contribute also to the enhanced accuracy performance of the LMS IPRO3. In addition, major parts of the optical path including the illumination optics and the tube lens are redesigned in order to reduce screen linearity error as well as system accuracy.

Further significant contributors to the enhanced accuracy performance will be software related. The algorithms of internal system correction as well as the mask bending correction are to be improved in order to achieve the performance goal regarding nominal accuracy.

3 Actual Measurement Performance Data

3.1 Optical CD Measurement System

Various samples from customers have been measured for the evaluation of the reproducibility (or long term repeatability) performance on the LWM500 WI, including chrome on quartz (binary) and halftone phase shift masks for 248nm lithography (KrF-HT) as well as halftone phase shift masks for 193nm lithography (ArF-HT). The evaluations were including line/space pattern in the range of 0.2µm to 1.0µm as well as arrays of small dots and holes in the range between 0.3µm and 0.5µm. A picture of 200nm dense line/space pattern as obtained in transmitted light on the LWM500 WI is shown in fig.6 and an array of dense contacts is shown in fig.7.

Tab. 3 shows typical performance data obtained on these samples, measured on three consecutive days, 20 loops each day.

Fig. 6: 200nm dense lines/space pattern (400nm pitch) obtained in transmitted light at 248nm using water immersion for resolution enhancement

Fig. 7: Dense array of 300nm contacts on binary mask obtained in transmitted light on the LWM500 WI

Plate	Pattern	Feature size [µm]	3 sigma [nm]
Binary	Line/Space	0.2 -1.0	0.5
KrF-HT	Line/Space	0.2 -1.0	0.5
ArF-HT	Line/Space	0.2 -1.0	0.9
Binary	Hole/Dots	0.3 - 0.5	1.0
KrF-HT	Hole/Dots	0.3 - 0.5	0.8
ArF-HT	Hole/Dots	0.3 - 0.5	1.4

Tab. 3: Typical reproducibility (long term repeatability) performance data obtained on the LWM500 WI on various kinds of binary and phase shift masks.

3.2 Measurement Performance on SEM Based CD Measurement System

The measurement reproducibility performance of any SEM based CD measurement system depends on various factors, including edge detection algorithms, system stability, stage performance, the amount of residual electron charging and sample contamination. As described above in chapter 2.2., residual charging and contamination are reduced to a minimum and the stage performance is in the +/-100nm range.

During the past months three systems have been shipped and various sample evaluations for customers have been performed. In addition to the basic performance data as described in a previous paper [2] we would like to provide recent measurement data on critical structures on samples like contacts on ArF phase shift masks or small assist bars on COG samples.

The evaluation of measurement precision was performed on 10 dynamic measurement loops and evaluated for 3 sigma and for total range. Reproducibility performance was evaluated over four or five days, taking 10 dynamic loops each day. Tab.4 shows a summary of the daily precision and the overall reproducibility over 4 days on single and dense lines. The columns „Precision 3 sigma" and „Precision tatal range" provides the minimum and maximum of the four daily precision values per site. Fig.8 illustrates the reproducibility performance on the dense lines over 4 days.

	Precision 3 sigma	Precision total range	Reproducibility 4 days, 3sigma	Reproducibility 4 days, range
Iso opaque 250nm line on ArF PSM	0.24nm - 0.34nm	0.22nm - 0.36nm	0.61nm	0.95nm
Iso clear 250nm space on ArF PSM	0.31nm - 0.51nm	0.28nm - 0.58nm	0.66nm	1.11nm
Dense 200nm line on ARF PSM	0.14nm - 0.44nm	0.12nm - 0.52nm	0.46nm	0.71nm
Dense 200nm space on ARF PSM	0.16nm -0.38nm	0.18nm - 0.50nm	0.55nm	0.81nm

Tab. 4: Summary of actual precision and reproducibility data (for a detailed description see text)

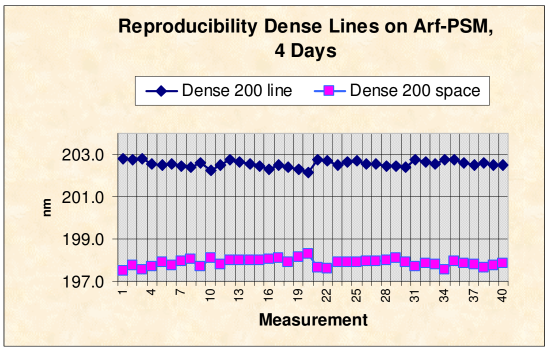

Fig. 8: Reproducibility performance on 200nm dense lines over 4 days

Fig 9 shows typical measurement performance of the LWM9000 SEM on small assist features. The performance on 150nm assist bars is summarized in tab. 5. Assist features are due to their nature very sensitive versus charging and contamination. Therefore, a systematic drift in the long term data of 0.03nm per measurement could be observed. Tab. 5 shows a summary of the raw data (observed without drift correction) as well as drift corrected data.

	Reproducibility 5 days, 3sigma, without slope correction	Reproducibility 5 days, range, without slope correction	Reproducibility 5 days, 3sigma, slope corrected	Reproducibility 5 days, range, slope corrected
Assist 1 (155.3nm)	1.70nm	1.80nm	0.89nm	1.21nm
Assist 2 (154.3nm)	1.51nm	1.86nm	0.85nm	1.26nm

Tab. 5: Performance summary of the LWM9000 SEM on 150nm assist bars: Daily precision and reproducibility over 5 days.

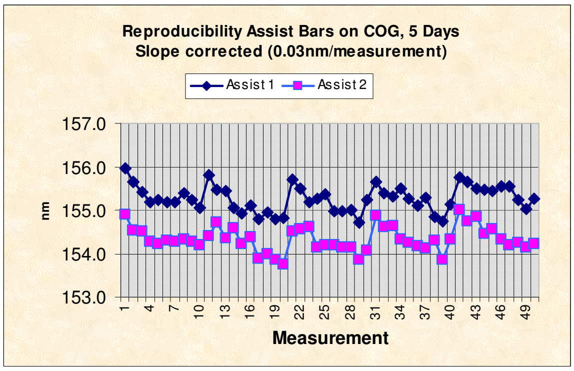

Fig. 9: Measurement reproducibility over 5 days obtained on the LWM9000 SEM on 150nm assist bars. A slope of 0.03nm per measurement due to minor contamination was removed .

The summary of LWM9000 SEM reproducibilty performance on small contacts (300nm and 500nm) on an ArF PSM is given in tab. 6. Data were collected over 4 days. Also in this case a minor slope of less than 0.05nm per measurement was observed and data are listed without slope correction as well as with slope correction. The total range of measurement data was below 2.5nm (slope not removed) and was significantly below 2nm after slope correction.

	Reproducibility 4 days, 3sigma, without slope correction	Reproducibility 4 days, range, without slope correction	Reproducibility 4 days, 3sigma, slope corrected	Reproducibility 4 days, range, slope corrected
300nm hole on ArF PSM	2.1nm	2.3nm	0.88nm	1.4nm
500nm hole on ArF PSM	1.7nm	1.8nm	0.96nm	1.7nm

Tab. 6: Measurement reproducibility performance of the LWM9000 SEM on contact holes on ArF PSM over 4 days.

The dynamic precision of the LWM9000 SEM on these small contact holes on an ArF PSM was determined by measuring ten consecutive loops (Fig.10). The 3σ value and the total range are shown in tab. 7.

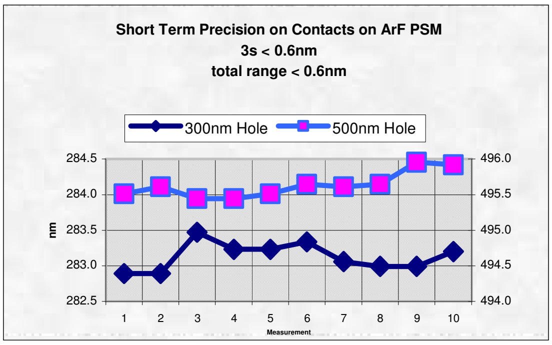

Fig. 10: Short term precision of LWM9000 SEM on small contact holes on ArF PSM.

	Precision 3 sigma	Precision range
300nm hole on ArF PSM	0.58nm	0.60nm
500nm hole on ArF PSM	0.54nm	0.55nm

Tab. 7: Short term precision of LWM9000 SEM

The scan linearity of the LWM9000 SEM was evaluated using the following procedure:
A dense array on a commercial pitch standard was used for the evaluation. 4 pitches were measured and then the stage was moved by one third of the field of view and the 4 pitches were remeasured at the same position on the standard but at a different position in the scan array. In total, the pitches were measured at 9 different locations in the scan array. At each position it was averaged over 10 measurements and the average over the 4 pitches was calculated in order to remove measurement precision from the scan linearity. The result for scan linearity error was below 0.84nm.

The measurement time was recorded for all evaluations and the throughput of the LWM9000 SEM was calculated. The so called MAM time (move - acquire - measure) was in the range between 6sec and 7.5sec, actually depending on the stage movement distance between the measurement sites.

3.3 Measurement Performance on the Registration Measurement System

The LMS IPRO3 is actually under development, as scheduled. The new environmental chamber with enhanced temperature stability control is not yet installed and therefore the R&D system is not yet moved into the new chamber. It is still working in the existing LMS IPRO2 chamber. Therefore, short term repeatability data can be provided, but there are not yet any investigations performed versus long term repeatability or system nominal accuracy including measurements over several days. Fig. 11 provides actual data on short term repeatability of the LMS IPRO3 R&D system evaluated from 20 dynamic loops on a 15x15 array on the Leica testmask, without unloadig/loading of the mask. 3σ is calculated for each measurement site based on the 20 data (Statistics per point evaluation). The new Leica test mask was provided from IMS Chips in Stuttgart/Germany. Finally mean and maximum of all 225 (15x15) measurement sites is calculated and provided as summary in fig.11. The maximum short term repeatability performance is already in the range of 1.5nm (3σ), although the performance target for the LMS IPRO3 of 1.35nm is not yet achieved. The mean of the 225 3σ-values is below 1nm !

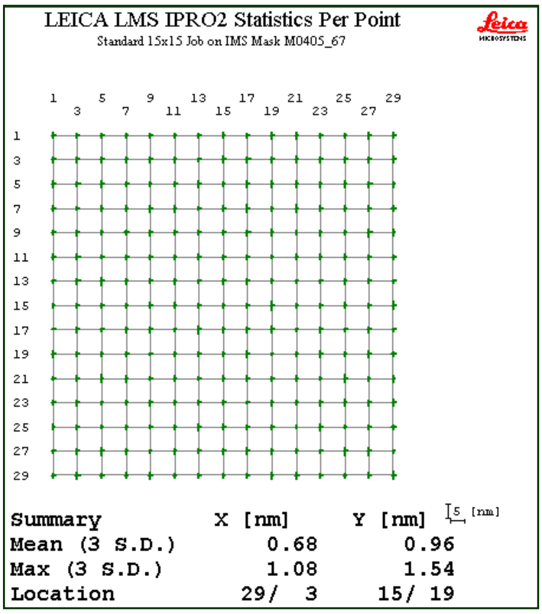

Fig. 11: Short term repeatability obtained on the LMS IPRO3 R&D system. Max 3σ is less than 1.1nm in x-direction and slightly above 1.5nm in y-direction. Measurement procedure is described in text above.

Ideally, any measurement result should be independent from the position of the pattern in the CCD array. In fact, any measurement system has a residual screen linearity error after having removed all systematic error components and contributes to the overall measurement performance of a metrology system. Therefore, the optical path of the LMS IPRO3 has been redesigned and optimised. Fig 12 provides a typical plot of the residual screen linearity error for registration measurements after having removed all systematic components by software. For the evaluation of screen linearity error one single feature on the mask is measured at 49 different positions (7x7 array) in the quality area of the CCD array. The plot (fig.12) gives the residual screen linearity error of the x- measurement in reflected light. The total range is 4nm for the x-measurement and 3nm for the y-measurement in reflected light. The measurement results in transmitted light illumination are 4nm in x-direction and 3nm in y-direction.

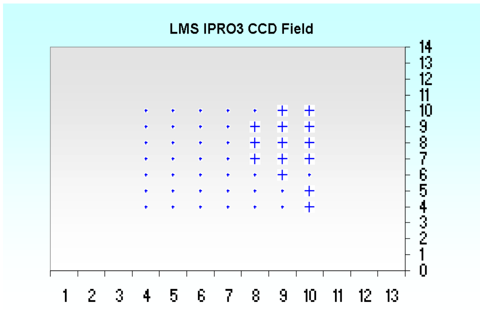

Fig. 12: Screen linearity error plot of the LMS IPRO3. The maximum error is between 3nm and 4 nm, depending on measurement direction (x or y, respectively) and illumination mode (transmitted light or reflected light). The evaluation method is described in text above

The new temperature and humidity control chamber is under development at the supplier. Recently, a site review at the supplier has been conducted. The temperature homogeneity was in the range of 20.968°C to 20.990°C and was almost within specifications of +/-0.01K (see fig.13).

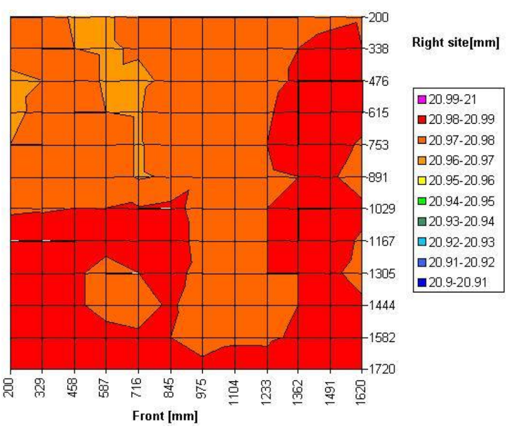

Fig 13: Temperature homogeneity plot inside the new LMS IPRO3 chamber (empty).

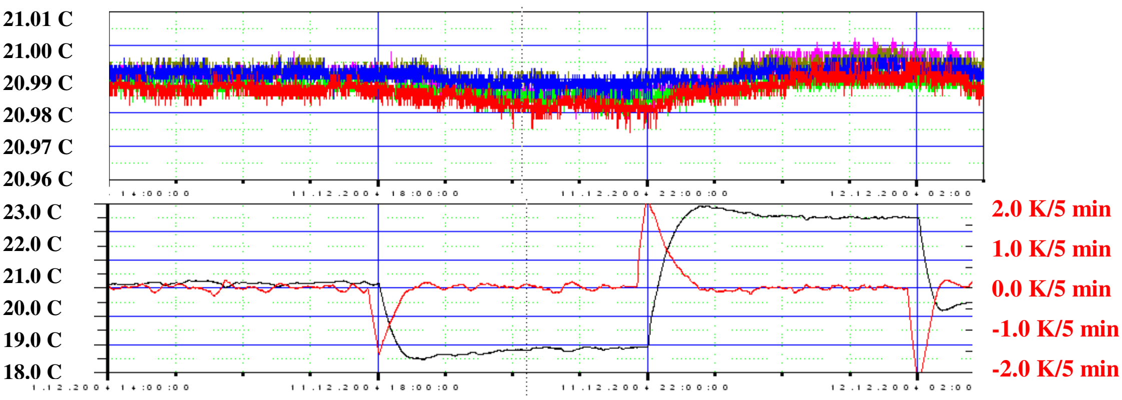

Fig. 14: Temperature stability of the new LMS IPRO3 temperature and humidity control chamber. The temperature inside the chamber and the temperature of the clean room are recorded. The clean room temperture was varied by intension (bottom) within +/- 2 C using a defined gradient and the temperature response inside the control chamber was recorded at five different sensor positions (top).

The temperature stability of the chamber was verified. The temperature of the clean room was changed with a maximum gradient between –0.5K/5min and + 0.75K/5min, respectively. Ideally, the temperature control unit should ensure that there is no temperature variation inside the chamber. The temperature response inside the chamber was recorded at five different locations. It could be observed that the temperature stability performance has already achieved the requested specifications of less than +/- 0.008K (see fig. 14).

4 Conclusion and Outlook

Leica Microsystems provides the Semiconductor industry with a metrology tool set for the qualification of 65nm technology node reticles. Both CD measurement systems, the transmitted light DUV based optical system and the SEM based system, provide measurement reproducibility performance in the sub-1nm regime. The optical system LWM500 WI has field proven the capability of sufficient resolution to measure CDs of line/space pattern and contact holes on 4x reticles for 65nm devices. Thus, this measurement system is available to qualify the reticles in transmission as they are destined for use in transmission.
Leica's new SEM based CD measurement system LWM9000 SEM hasan excellent resolution of an electron beam based microscope in the single digit nanometer range paired with the capability to achieve long term reproducibility performance data even on very small assist structures of below 1nm (3σ). It could be proven on the installed systems that the influence of both effects, electron charging and contamination of the reticle, on the measurement stability can be neglected.
Although previous generation CD SEM systems were limited in throughput, the actual system has a throughput of better than 8s per feature, thus supporting measurements of several hundred or even thousand features per reticle in a reasonable time span.
Improvements of the LWM9000 SEM system as required for the 45nm technology node were already started.
The LMS IPRO3 is under development as scheduled. First measurement performance data could be already obtained and are discussed above. The LMS IPRO3 R&D system, although not yet installed in the new climate chamber, provides already short term repeatability performance of 1.5nm (3σ) and better. The actual performance versus temperature stability and temperature homogeneity of the α-type temperature control chamber is already within the requested specifications. Actually, the optimization of the humidity control is in progress. In parallel, the hardware design of the chamber is under development, still a lot of work to conclude in R&D and manufacturing until the first system can be shipped to the customer in schedule in July 2005.

5 Acknowledgement

The authors would like to thank Dieter Adam and Wolfgang Sulik from Leica Microsystems for their valuable contributions.
The R&D project for the LMS IPRO3 was partly funded by the German BMBF Project 01M3154I.

6 Literature

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