PHOTOMASK

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Second Place Best Poster Award

Mask Inspection Placement Maps for Improving Overlay

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ABSTRACT

With each successive technology node the overlay specifications of the immersion lithography scanner have become increasingly more stringent. One of the challenges is high order distortions introduced by the mask. These distortions may contribute significantly to the product overlay budget raising it above the specification requirements and are not easy to correct.

The higher order distortions, originating from pellicle and mask process imperfections, have been shown to result in errors in the range of several nanometers to the overall overlay budget.[1,2] Correction markers and the actual product features cannot occupy the same space on the mask. As a result they might be exposed to differing local distortions which could result in non-optimal systematic distortion corrections.[3] Therefore high precision placement measurements of features across the mask are required for placement control and correction.

The Applied Materials Aera2™ aerial imaging mask inspection system is capable of generating high precision global and local feature placement maps with a high measurement density. These maps can be used to monitor feature placement. Furthermore, the maps

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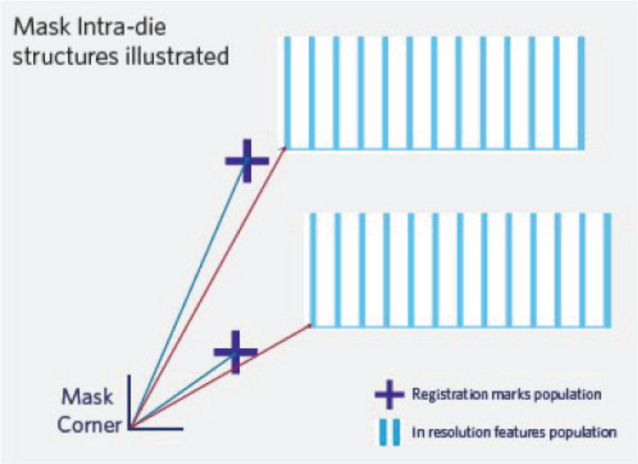

Figure 1. Systematic placement errors can vary between correction marks and in-resolution features since they occupy different locations on the mask.

EDITORIAL

"What is a Mask Really Worth?"

Frank E. Abboud, Intel Mask Operation, Santa Clara Ca

The phrase "a picture is worth a thousand words" has origins going back to the 18th Century when Napoleon Bonaparte, said "Un bon croquis vaut mieux qu'un long discours," or "A good sketch is better than a long speech". Although this statement seems intuitive and self-explanatory, it has been the basis for numerous advancements in technology ranging from the early days of Leonardo Da Vinci with his revolutionary methods for mechanical and engineering structures to today's visual communication that we take for granted, including computer displays and other consumer electronics products. As a matter of fact, the scientific field of Visualization has the primary goal to transmit and convey the largest amount of data in the smallest amount of time. Bringing this closer to our industry, I was compelled to think of the Mask and the role it plays in conveying information.

A quick back of the envelope calculation, taking as an example a 32 nm critical layer containing two billion transistors and 4 die on a mask would result in about 8 billion transistors. Assume 10% additional logic and that the average cell can be described by 16 polygons. Also assume each polygon has 16 vertices (medium OPC), and that each vertex or edge can be described by 16 bits, thus the amount of information the mask layer contains is about one Terabyte. This is a modest amount of data but not horrifically out of line for data files sizes. Now let's look at how this information is getting transferred. Assuming a 150 wafer per hour scanner and a 250 die per wafer, then we are transferring about two Terabyte per second; with zero replication error. Now that is something to stop and notice! It is truly amazing how faithfully and accurately such a large amount of information can be transferred in such a small amount of time. The speed rivals today's best computers, networks and storage devices. The latest information tells me that a really good hard drive can transfer about 250 Mbyte/sec making it the limitation and weakest link in the data path including memory, and network speeds. In comparison the mask does an invaluable job of faithful and speedy transfer of data.

Without favoring a particular type of mask, binary, PSM, APSM, Imprint or even EUV, I am simply trying to bring perspective to the value the mask plays in our industry and how much of an enabler the mask has been to the semiconductor industry for years. Unfortunately, I cannot think of a time when the mask was loved! Almost every conference has a section on Maskless, Cost of Ownership, Mask Equipment and Infrastructure Cost, characterizing the mask as a burden to our industry! I say enough of the whining and let's turn the table around! The mask is invaluable and the industry needs to value it appropriately and embrace future needs to get ahead of the curve and push the envelope on mask capability before we get asked to do so. We do it anyway, maybe kicking and screaming, but when the Fab wants tighter CD's and registration, we do it. When the Fab wants exotic APSM in production, we do it. When they ask for a pixilated mask, EUV, imprint, we do it. You name it, it's been done. Our mask industry always finds ways to deliver, from equipment, material to innovative mask making know-how. I would say: "let's be proactive" and, "let's embrace being enablers and promote the value the mask provides. It is a critical optical enabler in the image transfer process". The mask cost relative to wafer fabrication cost on average is less than 2%, but the value it brings is a whole lot greater.

So, in simple terms, if a picture is worth a thousand words, I would say: "a Mask is worth a trillion!"

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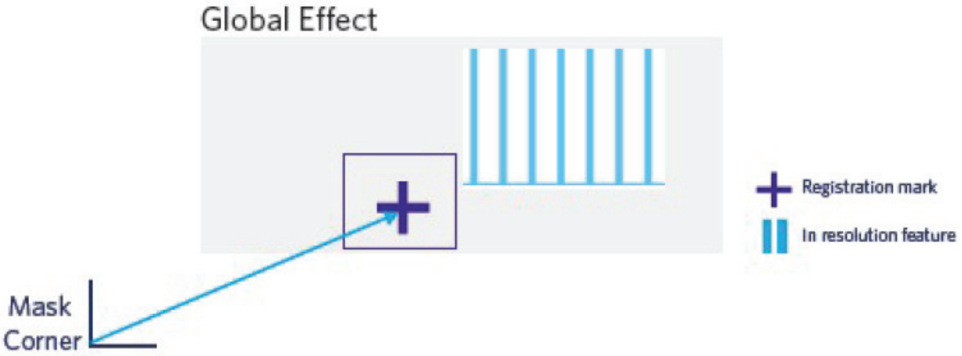

Figure 2. Global placement defined as a vector between an origin of the measurement grid (for example the mask corner) and a known registration feature.

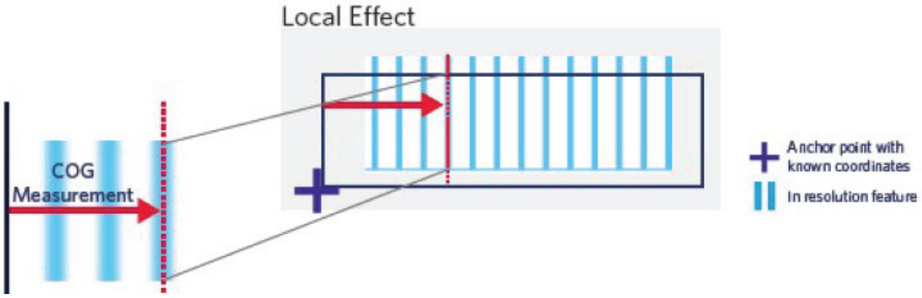

Figure 3. Local placement defined as vector between a reference points with a known coordinates and a nearby in-resolution feature.

can be used in a feed forward APC system such as ASML's GridMapper Intrafield™.[4] This feed forward system helps to reduce the overall overlay error of feature processes and to meet the stringent overlay budget requirements.

In this paper we present for the first time mask registration results obtained with the Aera2 and show that this tool is able to meet the 1 [nm], 3σ ITRS requirement[5] for the 22nm node.

1. Introduction

Multiple factors contribute to feature placement errors in a single layer on the wafer. Wafer process variations and positioning, illumination conditions, type of feature and its direct environment (such as low k1 imaging of adjacent multiple pitch ratio features),[3] mask positioning and, the subject of this paper, feature placement errors on the mask are few of these factors. On the mask we can distinguish between temporary placement errors and permanent placement errors.

Temporary placement errors occur when the mask is placed on and distorted by the chuck of a metrology or exposure tool. These errors can be local, for example due to reticle mounting pins on the chuck, intermediate range due to reticle heating or polarization effects originating from the pellicle, or long range resulting from gravitational sag, mechanical distortion by the pellicle and environmental conditions such as temperature.

The permanent placement errors are errors that have been written in the absorber layer of the mask. They can be divided into three categories: long range, intermediate range and local errors. These errors can result from issues occurring during the feature creation process such as chucking of the mask writer (support pins, gravitational sag, etc.), electrostatic charging on the writing tool and chemical loading during etching. In addition, the long-range variations on the mask (also known as global placement effects) can also originate from thermal or mechanical stress e.g. a pellicle attachment. Permanent physical local variations are mostly due to shortcomings in local pattern creation. Intermediate variation can originate from some combination of both pattern creation and external effects. In this paper we will focus on the permanent placement errors. Both global and local placement measurements will be discussed in more detail.

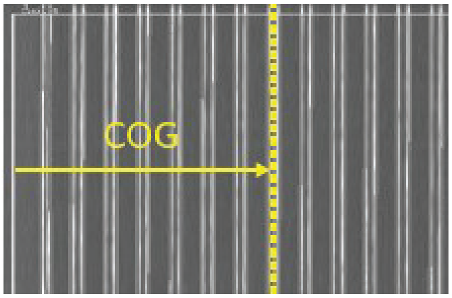

Figure 4. COG measurement with Verity2 CDSEM bench mark study.[7] The actual COG measurement is illustrated with an arrow.

As the in-resolution features scale down with every successive technology nodes, their accurate placement determina-

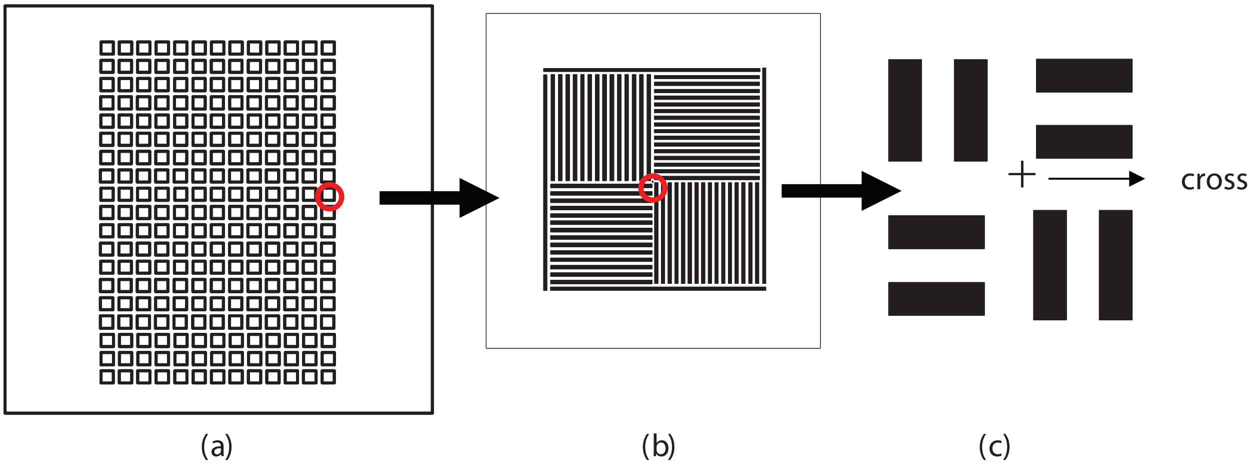

Figure 5. Schematic representation of the (a) reticle, the (b) standard ASML overlay mark (OV-mark) and the (c) cross at the center of the OV-mark.

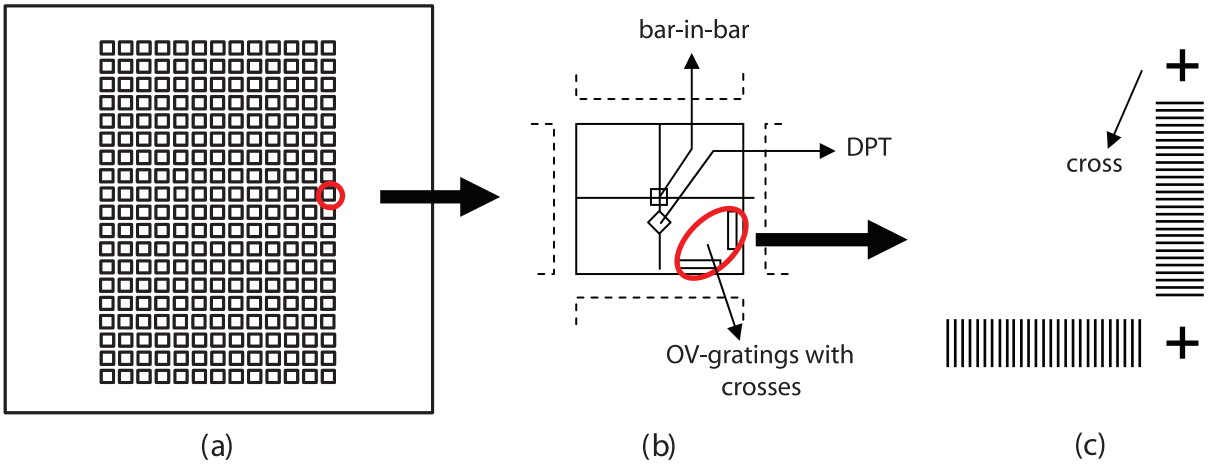

Figure 6. Schematic representation of the (a) reticle, the (b) DPT module the DPT gratings, OV gratings and bar-in-bar features (c) the location of the crosses with respect to the OV-gratings.

tion becomes challenging. During mask writing, it is possible that areas on the mask have different systematic placement errors, originating from local contributors. The issue becomes significant when those systematic errors are not the same for adjacent large and small features e.g.: large features used for optical registration versus the in resolution features[3] as illustrated in Figure 1.

Local and global placement errors affect the overall overlay performance. It is therefore important to map both errors. For this purpose we developed a novel approach which will be discussed in the next chapters.

Applied Materials Aera2™

The Applied Materials Aera2™ aerial imaging mask inspection system has been developed by AMAT to perform leading-edge photomask inspection and qualification tasks at the 45nm node and below, including double patterning.[6] The tool enables its user to monitor and correct mask-based, critical dimension uniformity (CDU) systematic errors in wafer fab volume production. AMAT's IntenCD technology captures mask CD variations in the aerial image regardless of the geometrical or physical aspect of its origin and produces a high-definition CDU map of the reticle. The tool enables accurate prediction of CD variation in the aerial image due to mask phase errors.

The Aera2 emulates a scanner by using actinic light and comparable illumination modes and settings (numerical aperture, partial coherency etc.). The aerial image is captured by a CCD-camera. The camera, lens and light source are at fixed positions. The mask is placed on a chuck and moved through the path of light.

Because of its high precision interferometer based stage motion control and aerial image measurement capabilities, the tool is able to perform accurate local and global mask registration measurements.

Goal

The goal of this paper is to show the capability of the Applied Materials Aera2™ to measure local and global feature placement. In addition, we show that the measurement results of a global placement map are comparable to the measurement results obtained by ASML's reference tool which is a traditional registration tool.

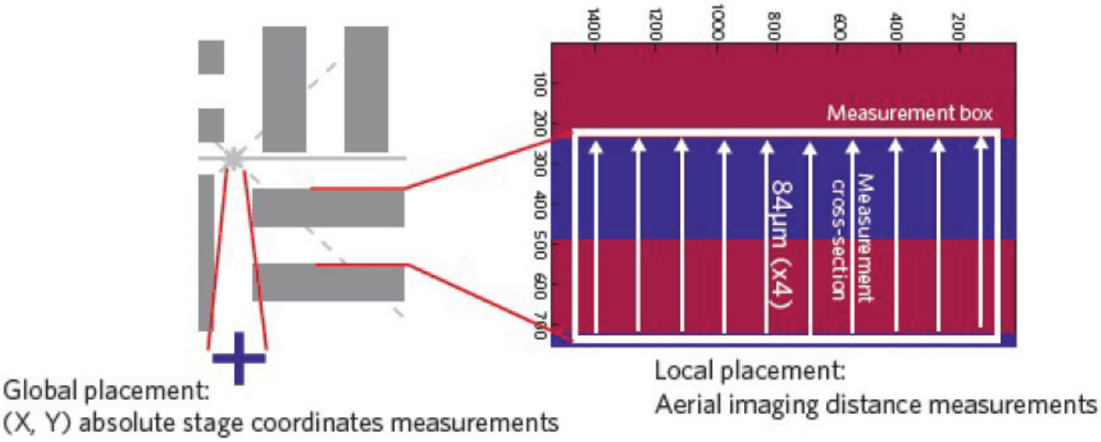

Figure 7. ASML OV-grating with the measurement box for local placement measurements.

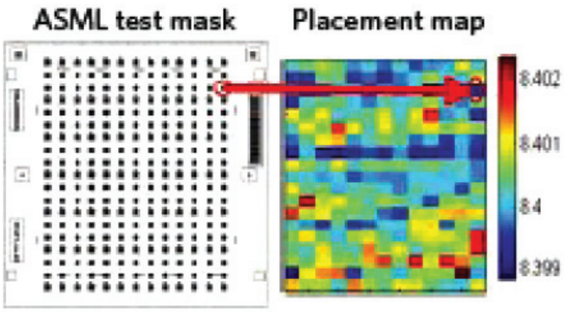

Figure 8. An example of a local Aera2 placement map (left) of a mask (right) showing the distances between the target feature and the reference point.

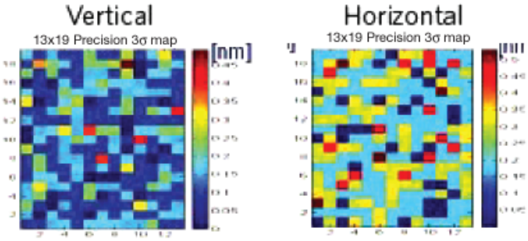

Figure 9. Local placement measurement precision maps (each pixel represents the 3σ over 5 repetitions) for horizontal and vertical distance measurements.

Table 1. Aera2 local placement measurement precision.

Local	Precision, 3 σ [nm]
X	0.7
Y	0.5

2. Placement Metrology

Global mask placement maps

Global placement is defined as a vector with respect to the (x,y) grid of the interferometer control stage between the origin of the grid, which can be placed on for example one of the corners of the mask, and a mask feature as shown in Figure 2. The relatively large mark is used to define the mask grid correction for the scanner and will assist in defining the overlay performance. To determine the global placement, the Aera2 uses an accurate stage. The global (x,y) stage coordinate readings are registered precisely over a feature of interest (i.e. the placement measurement feature). The global placement error is the difference between the designed vector and the actual measured vector.

Local mask placement maps

Local placement is defined within the field of view of the metrology tool as a vector between a local reference point with a known position (e.g. a registration cross) and the in-resolution feature. To determine the local placement the Aera2 uses a distance measurement over the aerial image produced from the target mask location. Instead of using the (x,y) coordinates of the stage as was done for global placement measurements, the Aera2 utilizes a unique image processing algorithm. Figure 3 demonstrates the vector between the in resolution feature and a nearby reference point with known global coordinates. The local placement error is the difference between the designed vector and the actual measured vector.

Center Of Gravity Measurements

One of the main concerns when measuring in-resolution features is their proximity effect sensitivity to various illumination conditions which traditional registration tools are not able to take into account. The Aera2 offers a solution emulating a scanner by using actinic light and comparable illumination modes and settings (numerical aperture, partial coherence and other aspects). For in-resolution placement measurement the actual illumination conditions were used for which the mask has been designed. Proximity effects may cause the in-resolution grating array periphery to be different from the center of the array. The spacing of the feature edge is not constant causing additional errors for conventional distance measurements. Therefore we measure the center of gravity (COG) of the in- resolution feature rather than the edge of the feature.

The COG measurement determines the distance between

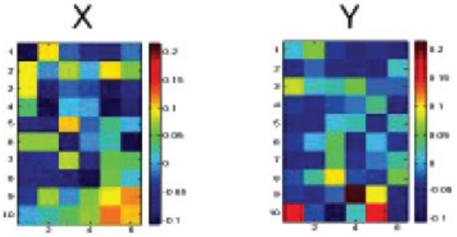

Figure 10. Global placement precision maps (each pixel represents the 3σ over 600 repetitive measurements) for horizontal and vertical absolute stage coordinates measurements.

Table 2. Aera2's global placement measurement precision.

Global	Precision 3 σ [nm]
X	0.3
Y	0.3

a reference point and the symmetry axis of a line or a space in the grating periphery as shown in Figure 4. COG has been successfully demonstrated in a previous work with a CDSEM[7] and is a feasible solution for in-resolution overlay measurements. The same methodology can be used for inresolution mask measurements.

3. Experimental Setup

Mask Design

For our study we used two masks designed by ASML. For the measurement precision study we used a regular ASML overlay mask.[4] The image field measures 104 x 132 [mm] and is covered with an array of 13 x 19 standard ASML overlay gratings. From here on we will refer to these gratings as OV-marks. The marks consist of 32 and 35.2 [µm] bars and a cross (20 [µm] long and 4 [µm] wide bars) that is located at the center of each mark. A schematic of the design of the reticle is shown in Fig. 5.

For the actual mask map measurements we used one of the ASML test reticles that have been used for DPT (Double Patterning) studies.[2] A schematic layout is shown in Figure 6. The image field measures 106 x 134 [mm] and is covered with an array of 13 x 19 modules. A module (Fig. 6b) contains a variety of DPT structures, i.e. complementary parts of split features of the original layout. Furthermore, a number of different metrology targets are included at different locations such as crosses of 20 [µm] long and 4 [µm] wide bars. For our experiments we used the latter test structures (i.e. crosses).

Measurement Set-up

For the global placement measurements the cross that is located at the center of the ASML OV-grating has been used. For the local placement measurements a short distance between two lines within the OV-grating was used. The global and local marks are illustrated in Figure 7.

The resulting placement measurements are represented as color map as illustrated in Figure 8.

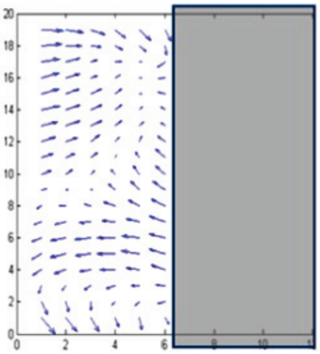

Figure 11. Placement characterization performed for half of ASML mask area.

4. Experimental Data

Local Measurement Precision

The local measurement precision has been determined by repetitive measurement of the distance (84 [µm]) between two lines near the cross in the center of OV-grating as indicated in Figure 5. These measurements have been performed in all 13 x 19 OV-gratings of the mask. The stacked placement maps (3σ per pixel) shown as a colored precision maps in Figure 9. The actual precision is given in Table 1. The origin of the differences between X and Y measurement precision will require further investigation.

The local placement measurement results meet the 1 [nm], 3σ ITRS precision[5] requirement on overlay.

Global Measurement Precision

The global measurement precision has been determined by repetitive measurement of the positions of the crosses at the center of the OV-gratings. From the available array of 13 x 19 crosses every other cross was sampled, ending up with a subset of 6 x 10 crosses.

The positions of the crosses have been determined with respect to the absolute grid of the metrology tool. The absolute grid is formed by the x- and y-axis of the stage coordinate system. From the data a precision map was calculated based on 60 locations. This map is presented in Figure 10. Based on the collected stage coordinate data the stage placement precision has been determined. Repetitive measurement of the crosses showed a stage placement precision of 0.3 [nm], 3σ. The actual precision is given in From these combined local and global placement measurement results it can be concluded that Aera2 meets the 1 [nm], 3σ ITRS precision requirement on overlay.[5] The observed difference between the global and the local measurement precision is due to the number of repetitive measurements and the linearity effects of the CCD camera. In the next chapter we demonstrate the actual global placement mapping capabilities of the Aera2.

Global Placement Map of ASML's Test Mask

Earlier feature placement measurements of various features on the ASML DPT test mask have been shown to yield highly correlated placement data sets.[2] For the pattern placement measurements a traditional registration tool was used. This

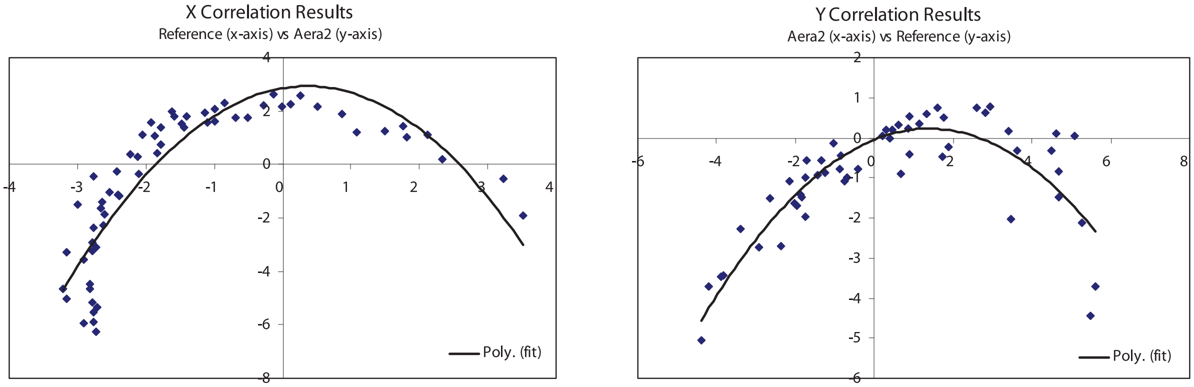

Figure 12. Correlation plots showing the correlation between the raw (as measured) Aera2 placement data of crosses and the reference cross data.

Table 3. Correlation results.

Placement measurements (measurement tool)	Correlation coefficient	
	Rx	Ry
ASML bar-in-bar (reference) vs. DPT, [2] (reference)	0.85 (linear)	0.95 (linear)
Crosses (reference) vs, crosses (Aera2)	0.87 (quadratic)	0.86 (quadratic)

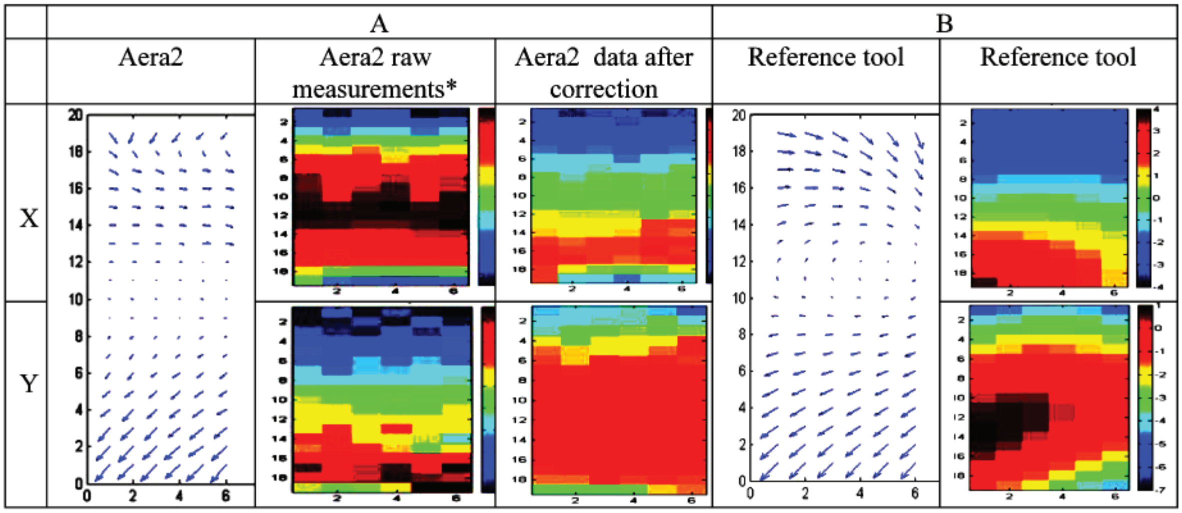

Figure 13. Arrow and contour plots showing (a) raw and corrected Aera2 placement measurements of the crosses and (b) corrected reference results of crosses obtained with the reference tool.[2]

registration tool will be referred to as the reference tool and the resulting data as the reference data. With the tool a good correlation was found between the bar-in-bar and the DPT marks placement data sets, Rx = 0.85 and Ry = 0.95 (Table 3). This tool was also used to determine the position of the crosses (see module layout 6). Aera2 was used to measure the positions of the crosses and data from the reference tool was used for comparison. Due to time restrictions the measurements were limited to one half of the mask (see Figure 11).

We found a non-linear regression between the reticle fingerprint data set obtained with the Aera2 and the reticle fingerprint data set obtained with the reference tool (Figure 12) with correlation coefficient R^2=0.73 or R = 0.86 (see Table 3). The correlation is not linear due to systematic errors (e.g. the reference data is corrected for chucking and gravitational sag).

These systematic errors can be corrected. Based on the non-linear relations as illustrated in Figure 12 feature placement data of the crosses obtained with the Aera2 was corrected.

**Some of the raw Aera2 measurements outliers were omitted from the final results shown in Figure 13 and interpolation has been used for the final map construction.*

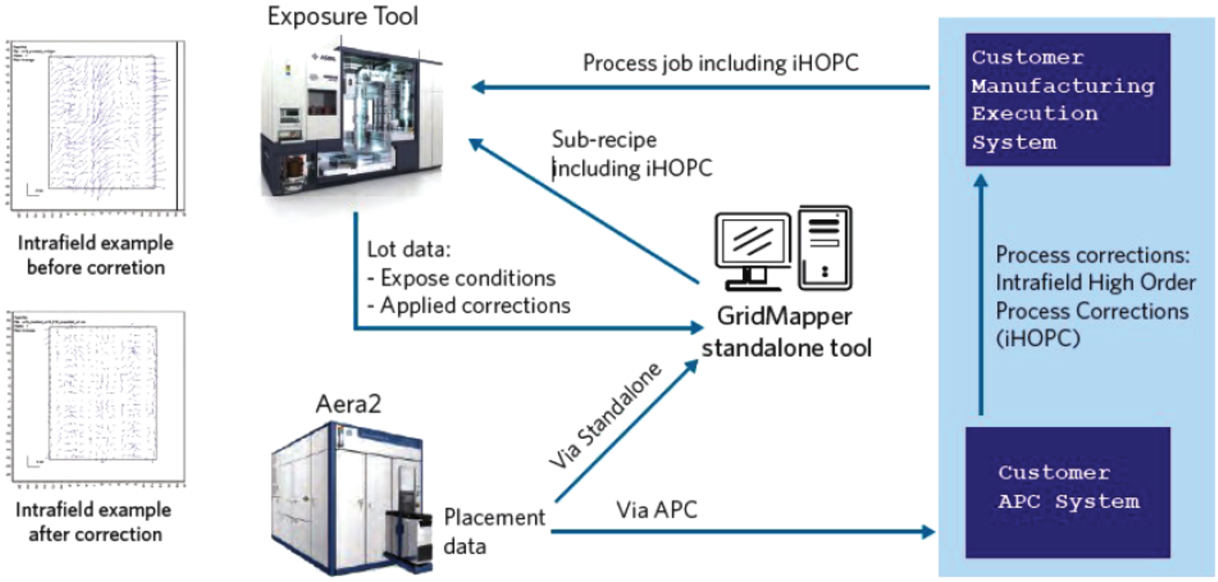

Figure 14. Aera2 connectivity to scanner via GridMapper iHOPC.

The corrected results are presented in Figure 13 and show a good correlation between the obtained reticle fingerprints.

Discussion and Conclusions

In this paper we presented an advanced methodology for pattern placement measurements using the Applied Materials Aera2 mask inspection tool and summarized preliminary results. We distinguish between global and local pattern placement errors. Systematic corrections based on the standard large correction marks might yield different corrections than based on the in-resolution product features. With the Area2 it is possible to map the positions of the correction marks and the deviations between these marks and the in-resolution features which allows for improved correction.

Different from the traditional registration tools, the Aera2 is able to take into account the proximity effect sensitivity of in-resolution features to the various illumination conditions by emulating a scanner, using actinic light and illumination settings similar to that of a scanner.

The results show a local pattern placement measurement precision of ≤ 0.7 [nm], 3σ and a global measurement precision of 0.3 [nm]. The overall pattern placement precision of the Aera2 meets the ≤ 1 [nm] requirement of the ITRS roadmap for the 22nm node.

When comparing the Aera2 global measurement results to reference data obtained on a reference tool (traditional registration tool) we find a good correlation with a correlation coefficient of R=0.86. Since the correlation between the measured positions of two different features on the same mask with the reference tool yields a same value ($R=0.86^2$) we can conclude that the correlation between a traditional reference tool and Aera2 is very promising.

This technique can provide a mask shop a better understanding of the final product in-resolution placement quality. The mask shop can also assess in advance the overlay performance of a mask set on wafer level by using Aera2 placement maps for overlay simulations. Fabs can use the maps to actively compensate for high order local variations, using ASML's GridMapper Intrafield applying intrafield High Order Process Corrections (iHOPC) (Figure 14).

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Industry Briefs

BACUS Panel at SPIE Advanced Lithography Symposium Provides some Lighter Moments

The annual BACUS panel at the SPIE Advanced Lithography Symposium was well attended and provided a unique insight to the challenges that remain for the introduction of Extreme Ultraviolet (EUV) lithography. The panel title: "EUV Source $10M. EUV Scanner $100M. Defect Free EUV Mask, Priceless! For some there's NIL, for everyone else, there is EUV." focused primarily on the main challenges for the last major challenge for any lithography solution, the mask infra-structure. While the mask substrate has been defined the key challenge in this area remains the availability of defect free substrates. The current substrate defectivity is approximately 10 times higher than required for masks at the 22nm technology node. Metrology and defect inspection are the two key areas requiring both intense development efforts and funding. The panel members felt that actinic inspection would not be required for the initial introduction of EUV, however it would eventually be required. While recently EUV has been directed at the 22nm node, it appears that the 16nm node has become the most likely target for its introduction in 2015. Additionally, it became very clear during the panel that the overall cost of the mask infrastructure cannot be borne by the photomask industry, particularly the merchant mask industry. In one of the more entertaining moments during the panel Bryan Rice of SEMATECH passed the collection basket for donations and received four Euros to assist in his goal to develop the mask infrastructure. The other entertaining moment came after Tony Yen of TSMC presented a slide that declared EUV lithography more cost effective than other lithography solutions, only to prompt a question for the audience; "Does that include the cost of the mask?" The response was "No" to the laughter of the audience. I guess we can assume for now that the "…Defect Free EUV Mask, Priceless!" part of the title is pretty accurate.

D2S Announces Photomask Pattern Generation Initiative

Aki Fujimura, Chairman and CEO of D2S (design2silicon) announced the introduction of a new approach to mask pattern generation whereby cell projection is used as opposed to the currently used variable shaped spot (VSS) e-beam solution. The activity will be pursued under the umbrella of the E-beam Initiative, a forum of 27 members. The forum will be dedicated to the education and promotion of a new design-to-manufacturing approach known as design for e-beam (DFEB). The E-beam Initiative roadmap incorporates new innovations to e-beam mask making using DFEB in conjunction with e-beam mask writing equipment currently on the market. Six new members have joined the initiative including Global Foundries, JEOL, KLA-TENCOR, NuFlare Technology, Petersen Advanced Lithography and Samsung.. A complete list of members can be found at www.ebeam.org. Aki Fujimura stated "The support from all of the initiative members will enable the cost advantages of DFEB to be brought to bear on one of the fastest cost growth areas in optical lithography-the photomask. We are excited about the new member base given the expertise they bring to mask making, and where DFEB is headed." A new white paper on DFEB mask technology and further details concerning the E-beam Initiative can be found on their website.

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About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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2010

SPIE Photomask Technology

13-17 September
Monterey Marriott and
Monterey Conference Center
Monterey, California, USA
spie.org/pm

Abstract due 15 March 2010. Late submissions will be considered by Chairs.

SPIE Lithography Asia - Korea

13–15 October
Hyatt Regency Incheon
Incheon, South Korea
http://spie.org/la/

Photomask Japan

13-15 April
Yokohama, Japan
http://www.photomask-japan.org/

2011

SPIE Advanced Lithography

27February-4 March
San Jose Marriott and
San Jose Convention Center
San Jose, California, USA

Abstract submissions to open in May 2010.

You are invited to submit events of interest for this calendar. Please send to lindad@spie.org; alternatively, email or fax to SPIE.

SPIE is an international society advancing light-based technologies.

SPIE

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