[1]How to match without copying – An approach for APSM mask process matching using aerial imaging

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ABSTRACT

For mask signature matching in the case of alternating phase-shifting mask it is shown that it is can be achieved using matching of aerial imaging. This is in contrast to the traditional approach of manufacturing an identical copy of the reference mask. Beside description of the method AIMS and wafer data are shown that proof its successful application on a product mask.

Keywords: alternating phase shifting mask, mask process matching, aerial image, AIMS

INTRODUCTION

For merchant mask makers the reproduction of a customer-provided mask process signature is a core competency as it allows qualification without forcing the customer to adjust their OPC model. This reproduction or matching of a mask process signature typically focuses on systematic CD variations driven by feature geometry, two examples are: the CD linearity (i.e. CD variation as function of feature size) or proximity behaviour (i.e. CD variations due to change of local density or distance to neighbouring structures). These signatures are driven by many aspects of mask making ranging from blank material properties, hardware set-up to unit process conditions. Therefore the task is to find a suitable combination of materials, hardware and processing that results the desired signature.

In case of an alternating phase-shifting mask (APSM) another level of complexity is present: the phase balancing. Whereas the above mentioned CD errors are only driven by the absorber structures remaining on the mask after etching, the phase balancing is determined by the quartz profiles. It is well known that resulting transmission and phase of an APSM mask beside etch depths also strongly depend on fine details of the quartz profiles, e.g. sidewall angles and micro-trenching [1], [2]. When setting up an OPC model all of these effects can be taken care of by relative sizing of zero and pi structures (maybe also depending on CD target), overall bias etc., the only remaining constraint is the overall etch depths as it determines the effective phase shift and so the CD behaviour as function of defocus [3], [4].

For a mask maker to match a given APSM mask without adjustment of customer OPC goes beyond mere characterization of the signature by CD-SEM measurements. Due to above described relation between phase balancing and quartz etching this is extended into full analysis of quartz geometries, i.e. determination of etch depths, sidewall angle and micro-trenching as function of feature type and feature size. As this can only be achieved by cross-sections it is very time and resource consuming. The next step would be a fine tuning of the quartz etch process to exactly provide the same profiles. In case of experimental etch process tuning the described characterization of the quartz profiles would be required for etch set of process conditions. In sum this results in a huge amount of work and time required.

An alternative approach is to not copy the mask but to match its imaging properties [5]. In this paper it is described how this can be done successfully: In a first step a customer-provided testmask was characterized using AIMS™ measurements. This mask provides the full range of feature types and sizes as later on used for productive designs. Duplicates of this design were manufactured to set up a quartz etch process and to determine required etch depths for phase balancing using this process. On each mask only non-destructive AIMS™ and SNP-measurements were carried out to assess matching quality with the reference mask. At the end a mask process was found that yields a mask differing from the reference mask in many parameters but nevertheless mimicking their aerial images.

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This duplicate was then printed in the wafer fab side-by-side with the reference mask to check the matching which was confirmed. After this confirmation a mask containing a productive design was manufactured using the same mask process. Also here a perfect match between duplicate and reference was obtained based on customer relevant wafer data.

REFERENCE MASK CHARACTERIZATION

For the purpose of setting up the mask manufacturing process the customer supplied us with a reference mask. This mask was designed to set up the OPC model, i.e. it consists of typical designs later on used on the product with varying sizes of features, different pitches etc. This kind of mask is well suited for the task of process matching as it allows to assess the robustness of the new process to design variations and also highlights design situations that match less well than others. The task of process matching consisted in the manufacturing of a duplicate of this mask that was later printed side-by-side with the reference mask at the wafer fab to check for matching at wafer level.
The productive mask targeted for the new process is a contact layer. The variety of designs ranges from contact fields, chains of contacts to isolated contacts, in all cases surrounded by SRAFs. Some examples are shown in Figure 1. Note: drawn in blue is the data for the Chrome level whereas all structures drawn in red are those that later get etched into Quartz.

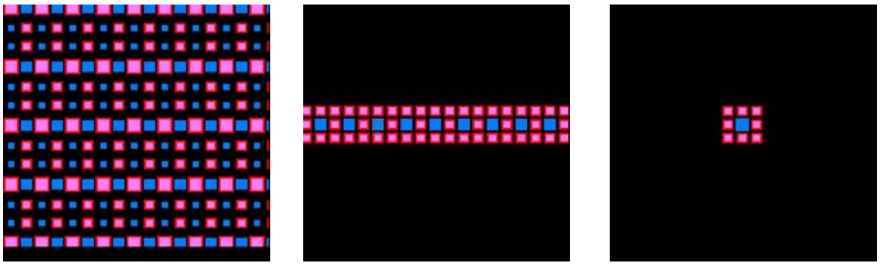


Fig1: Examples of test designs on reference mask.

One finds that contacts are present as main structures as well as being used as SRAFs. Also those SRAFs can appear as zero- and pi-phase structures. This point raises the demands to have a good linearity matching of the contacts in Chrome and also to match the imaging of large and small pi-phase contacts.
After design review, the reference mask was characterized with respect to CD linearity, etch depth and imaging properties. However, before dealing with imaging properties one has to match the linearity of the contacts to ensure that the relative sizes of main feature contacts and assist contacts is preserved. This is required to yield similar process window improvement by the assists as on the reference mask without risking the creation of printing assists.
A combination of lithography and Chrome etch settings was chosen such that the linearity on a duplicate matches the measurements of the reference mask. The result is shown in Figure 2:

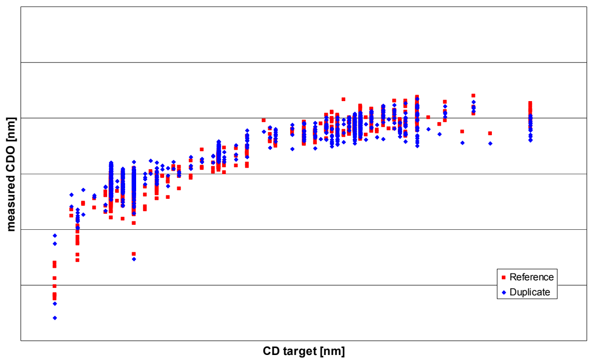


Fig.2: CD Linearity in Chrome as measured on reference mask and duplicate.

One can see that the linearity on the duplicate matches well the reference mask.
After having matched the CD linearity now the task was to match the imaging properties of the reference mask. For this purpose SNP and AIMS™ measurements were done on selected structures. The SNP measurements provided the phase etch depths as applied on the reference mask. The AIMS™ measurements were used to assess the overall transmission of the mask, the phase balancing and also process windows. The illumination conditions were chosen to be the same as later on used for the wafer printing.

AIMS MATCHING STRATEGY

As described in the introduction the approach for manufacturing a duplicate that matches the reference mask in wafer prints was to match the aerial image of the masks instead of trying to copy all physical parameters of the reference mask. This also allowed the usage of a different blank type. Two main parameters were chosen to assess the quality of the match of the aerial image: the peak intensity of the structures and the through-focus AIMS™ CD at a fixed threshold. For alternating main features additionally the quality of the phase balancing was controlled.
The question arose of what threshold should be used for the extraction of CD values from the aerial images. To find an answer to this a comparison was done using wafer CD results of the reference mask and AIMS™ data of the same structures. Various different structure types were selected for this. For all of these structures the through-focus AIMS™ CD at various thresholds was compared with the respective through-focus wafer CDs to find a threshold that for all structures provide a good matching of AIMS™ and wafer CD. As an example results are shown for an isolated zero-phase contact in Figure 3.

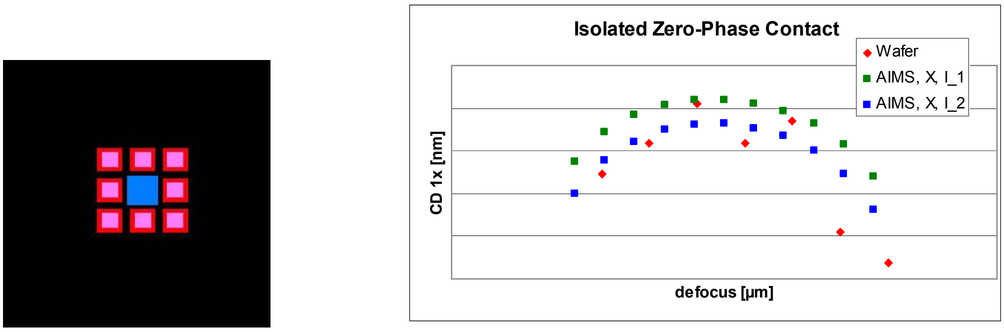


Figure 3: Structure type used for wafer-AIMS™ CD calibration (left) and comparison of wafer CD to AIMS™ CD at two different intensity thresholds.

The graph in Fig. 3 shows that an intensity threshold in a band of the chosen thresholds yields a good match between AIMS™ and wafer data for all structure types. Therefore those two thresholds were used to assess the AIMS™ CD matching between reference and duplicate mask.

TRANSMISSION MATCHING

The task of matching the aerial imaging of the reference mask consisted in finding Quartz etch depths (for zero- and pi-phase shifter) such that phase balancing as well as overall transmission matches the reference. For this purpose a first duplicate was manufactured to perform experiments to determine these depths. On one side phase balancing is controlled by a relative depth differences between neighboring structures. In contrast the peak intensity is determined by a global etch depth applied to all structures. This means that one cannot independently tune one parameter as any change of the other has impact on it. Also the peak intensity at best focus of individual structures on an alternating phase shifting mask depends on the balancing quality, i.e. it varies at the presence of phase errors. By the nature of the phase balancing error the peak intensity of two neighboring features will change, as the phase depth varies. However, the average of the peak intensities of these features will not be affected that strongly in the presence of a phase error.
Therefore a set of curves were measured that for a fixed overall depth shows the impact of various phase depths on the average peak intensity of two neighboring features. This was also done for isolated main contact with assist features of opposite phase assignment. An example of such curves is shown in Figure 4.

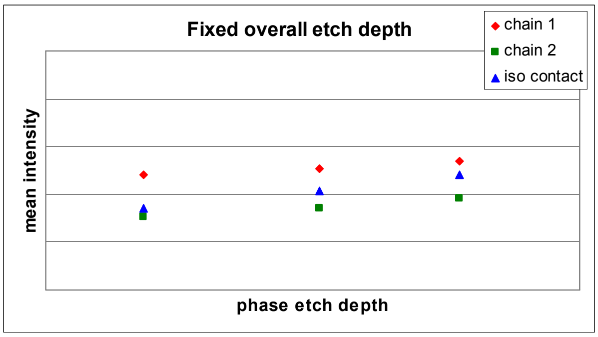


Fig.4: Mean intensity of two different types of alternating contact chains and an isolated pi-phase main contact at a fixed overall etch depth for various phase depths.

For the same structures the mean and the peak intensities were determined on the reference mask. A comparison allowed the adjustment of the overall etch depths based on the selected phase etch depth.

PHASE BALANCING

To determine the optimal phase depth a standard technique in phase balancing for APSM was applied (see e.g. [5]). This means: for a selection of design situations the through-focus CD of neighboring zero- and pi-phase features was compared. The optimal etch depth is achieved when the CDs of these features is identical for all focus settings. However, it might be possible that the CD difference is not zero but a constant. In this case a transmission error remains which can be corrected by different sizing for the zero- and the pi-phase features.
However, one has the bear in mind the above mentioned relation between overall transmission adjustment by global etching and the selection of the optimal phase depth. By the method outlined one can for each global etch depth approximate a phase etch depth so that both criteria are satisfied simultaneously.
The following figures show examples of data collected for the determination of the phase etch depth at a fixed overall etch depth. First of all the CD differences for various focus levels was determined for multiple etch depths. One can see in Figure 5 that the slope of these curves changes when crossing the optimal etch depth which is given by a flat curve. A good estimate of this depth can be achieved when plotting the slopes of the curves at best focus vs. the etch depth and determine its zero.

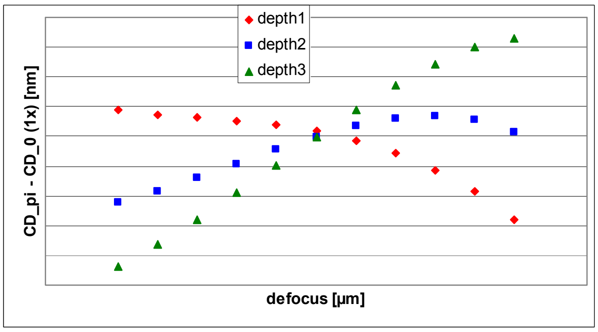


Fig. 5: Through-focus CD difference of zero- and pi-phase features for various etch depths.

An alternative way to determine the optimal phase depth based on aerial image data is provided by an analysis of the Bossung curves of a selected feature. A phase error results in a tilt of the Bossung curves around best focus. Again an analysis of the slope for various etch depths provides a good estimation of the optimal phase etch depth.

Obviously for phase errors the matching always means to perfectly balance the mask regardless of the reference mask as only then an optimal performance of an APSM can be achieved.
Beside the phase error another important property of APSMs can be assessed by the methodology just outlined: the transmission error. This is not to be mixed-up with the transmission matching as already discussed earlier. Whereas then the task was to match average mean intensity of zero- and pi-phase features the topic now is the relative intensity of these features. Due to scattering in the quartz trenches of the pi-phase features there might be less light being transmitted through them. This causes the effect that at a fixed threshold in the aerial image the CD measured at for zero-phase feature is larger than for a pi-phase feature. This can be separated from a phase error by the fact that this offset is constant for all focus levels. In the light of the balancing methodology as outlined above a transmission error is present if the curves in the picture of Fig. 5 do not intersect at zero at best focus. Also it can be seen that the intersection point (i.e. transmission error) is independent of the phase depth, i.e. the phase error.
Typically this error is taken care of when the OPC model for the mask is set up as it can be corrected by increasing the size of the pi-phase features. When matching a given mask process without adjusting the OPC model this task is to be done by mask manufacturer. This means, first of all the required bias needs to be determined and in a second step it needs to be applied during the data preparation for the mask making. For this purpose the first level data need to be separated into two sets: the one containing all zero-phase features and the one containing all pi-phase features. Then the zero-pi bias is applied to the second set and data are merged again for the first level exposure.
The determination of the zero-pi bias can be done as part of the phase balancing by analyzing features with constant size of zero-phase features but varying size of the pi-phase structures. Then the transmission error is determined as function of the difference in the sizing of these features and this bias is selected that matches the reference mask. Figure 6 shows the through-focus CD differences of zero- and pi-phase features for various zero-pi biases compared to the measurements on the reference mask. Based on this kind of data one can select an appropriate bias.

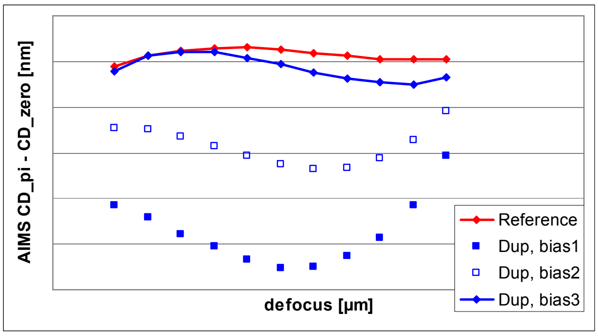


Fig.6: Through-focus CD difference of zero- and pi-phase features for various zero-pi biases.

However, a re-sizing of parts of the layout also impacts other kind of structures which are not represented by this kind of design. As mentioned earlier, parts of the customer design consisted of isolated contacts with assisting contacts of the opposite phase assignment. How a resizing of all pi-phase structures affects these kinds of structures is not represented by graphs as shown in Figure 6. An example to be discussed a bit more in detail is a chain of zero-phase main contacts surrounded by pi-phase assists.
This design suffers from the fact that the feature affected by the re-bias does not print and so no AIMS^{TM} CD at the fixed thresholds can be extracted. However, there are several aspects that can be assessed to investigate the impact of a re-biasing of the pi-phase features. The first point to check is the peak intensity of the assist contacts. This is to ensure that by an enlargement of the assists these do not start to print on the wafer. Figure 7 shows the assist intensities as a function of the pitch of the main contacts of the chain to additionally assess the robustness of the matching to design variations.

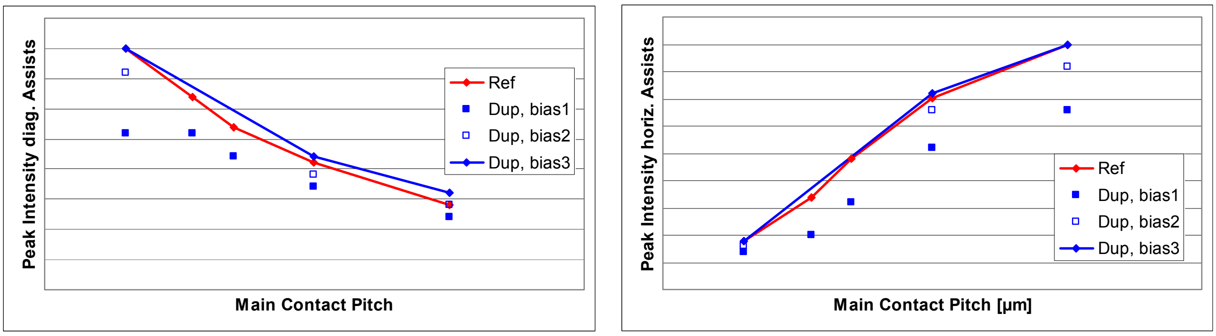


Fig.7: Peak intensity of the assists at the corners of the main contacts (left) and between main contacts (right).

One finds that at the same zero-pi bias that yields good phase balancing without transmission error also the peak intensity of the assist contacts of this structure type is matched.

Beside the intensity one can also assess the impact of the assist re-sizing by the effect that these assists are supposed to have: an enlargement of the process window. For this purpose the maximum process window around the wafer targets of the main contact CD was determined. Figure 8 shows the exposure dose latitudes (EDL) and the depth-of-focus (DoF) as representatives of this process window for various zero-pi biases.

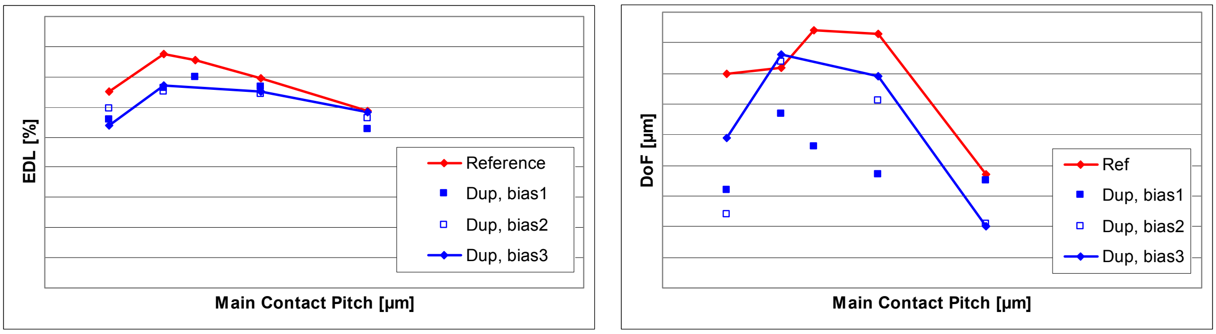


Fig. 8: EDL and DoF of the maximum process window of the main contact for various biases of the assist contacts.

It can be seen that the re-sizing of the assists only affects the depth-of-focus whereas the exposure dose latitude is well matched for all biases. Again the same bias as extracted from previous analyses yields a good match to the reference mask.

AIMS MATCHING RESULTS

Based upon the data shown above a mask process was selected to manufacture a final duplicate to be used later for wafer prints. This duplicate differs from the reference mask in a variety of points: blank material, phase depths, overall etch depth, zero-pi bias etc.
The quality of the manufactured duplicate was assessed using AIMS™ data only. For this purpose a variety of different feature types were selected and AIMS™ measurements of them were taken on the reference and the duplicate mask. For all features the AIMS™ CDs as well as the peak intensities were compared. The following figures show examples of the selected features and the quality of the matching.

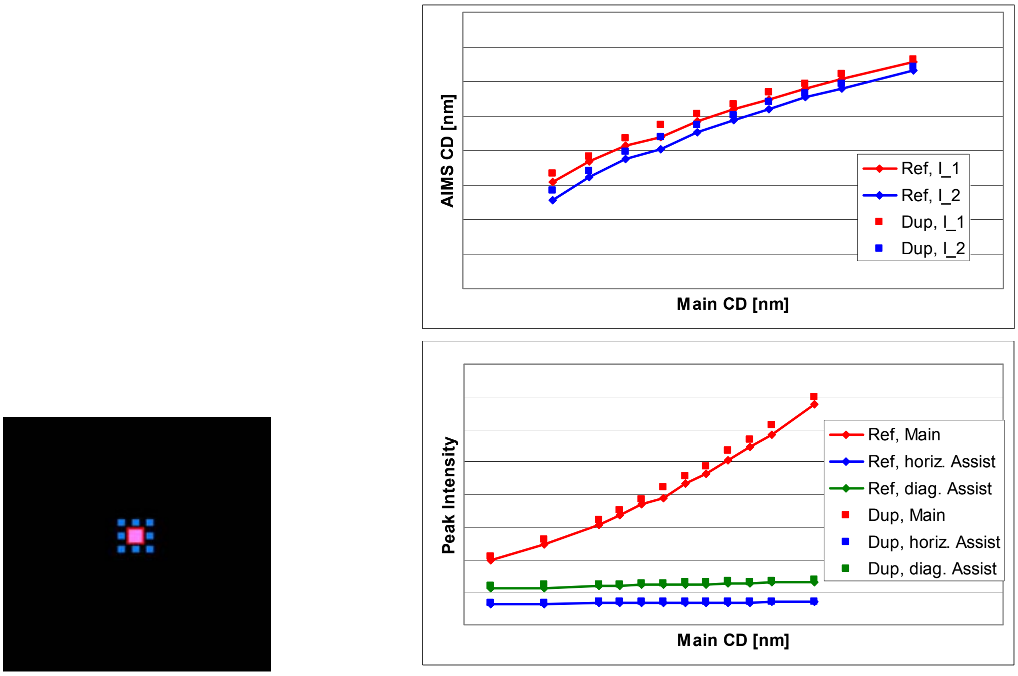


Fig. 9: AIMS™ CD and intensity comparison for an isolated pi-phase main contact vs. size of this contact at fixed assist contact size.

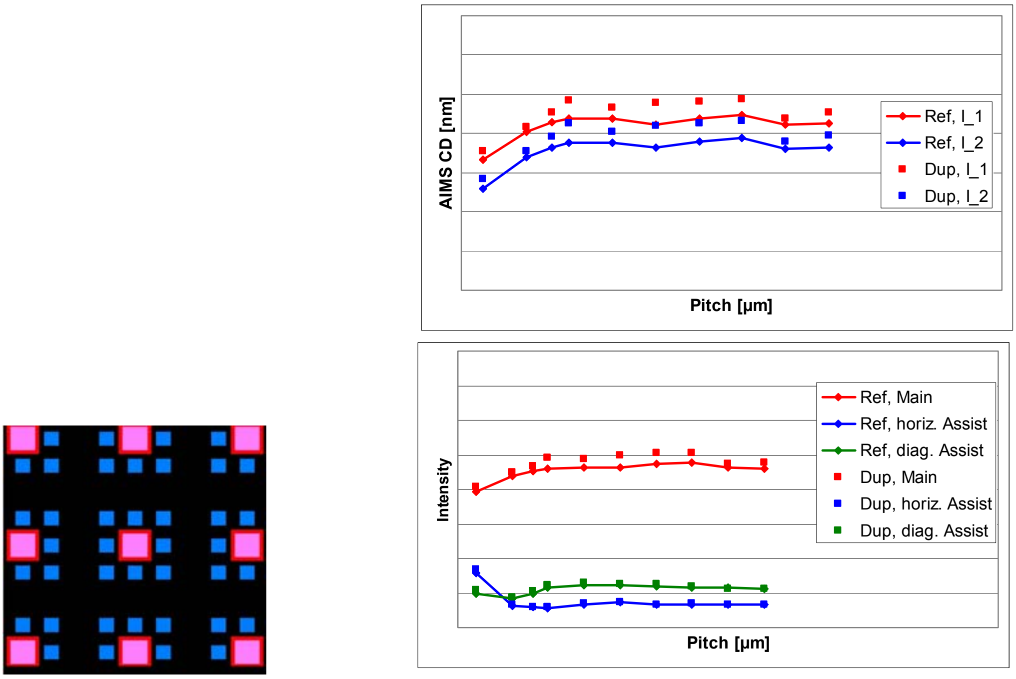


Fig. 10: AIMS™ CD and peak intensity for a pi-phase main contact for various pitches of the main contacts at fixed main and assist contact size.

One finds that the duplicate mask matches the reference up to slight offset in the overall intensity. However, this can be well compensated by a minimal dose offset at the wafer fab. All other OPC relevant characteristics, e.g. AIMS™ CD vs.

contact size, contact pitch, SRAF size etc. were well reproduced. Also the achieved quality of the phase balancing was very good and independent of selected zero- and pi-phase contact sizes. An example is shown in Fig 11.

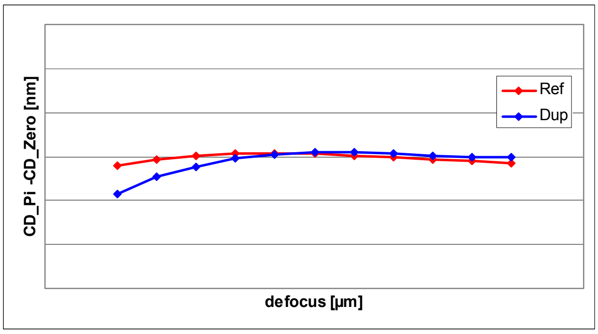
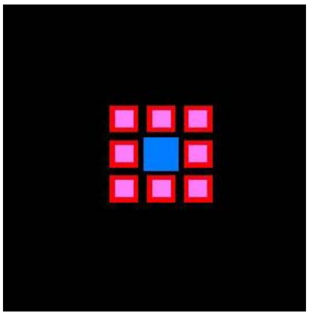


Fig.11: AIMS CD difference of pi- and zero-phase contacts measured on reference mask and duplicate.

WAFER MATCHING RESULTS

As part of the wafer printing tests of the duplicate, CD data of selected structures were collected for comparison with AIMS^{TM} data. The purpose of them was to investigate how well AIMS^{TM} and wafer CD data match. However, for the qualification of the duplicate a good match between wafer and AIMS^{TM} data is not mandatory as it was shown above that they do match in their aerial images. Any deviation in the wafer prints of these two masks is therefore more likely to be due to differences in the wafer process. On the other hand, a good matching of AIMS^{TM} and wafer data would provide the ability to use AIMS^{TM} CD data for further process development, i.e. OPC tuning which is less complex and faster than exclusive usage of wafer prints.

No activities were executed to develop a resist model that predicts the AIMS^{TM} intensity threshold to be used for CD extraction. Therefore, a fixed threshold was chosen for all features and AIMS^{TM} CDs at this threshold was compared to wafer CD at fixed doses. The following figures show examples of the collected data.



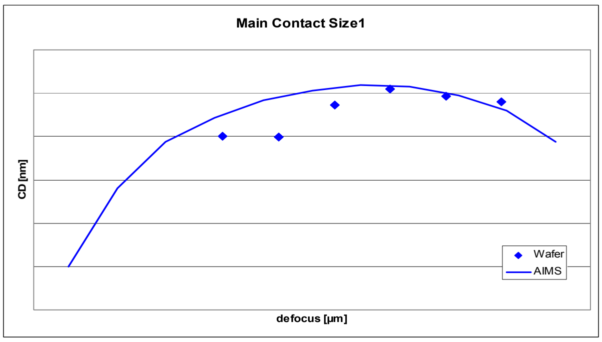
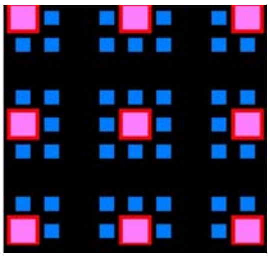


Fig. 12: AIMS^{TM} CD vs. wafer CD comparison for an isolated zero-phase main contact for two different sizes of the main contact and fixed size of the assist contacts.



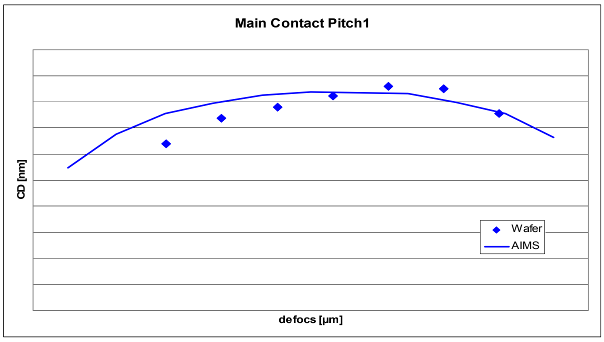
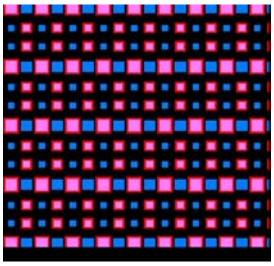


Fig. 13: AIMS^{TM} CD vs. wafer CD comparison for pi-phase main contacts for various pitches of the main contact and fixed size of the assist contacts.



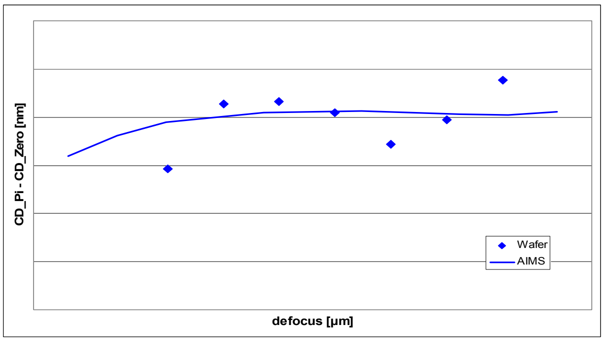


Fig. 14: Difference of CD of pi- and zero-phase contact.

PRODUCT MASK

After successful verification of the mask process matching using a test mask design a product was manufactured using this mask process was produced at both shops. During the mask manufacturing the process control and the assessment of overall transmission and phase balancing was done using AIMS^{TM} measurements only. In the following a summary of the results of the wafer prints of this mask is given.

In Figure 15 the performance for isolated contacts between the product mask and the reference is shown. One finds that less than a 1.5nm difference is observed through dose. This is equivalent to <2% match to target.

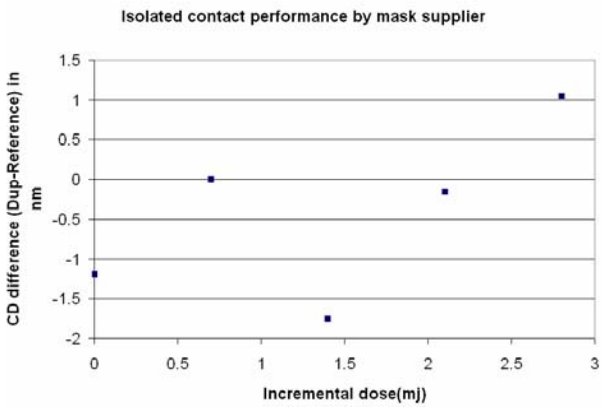


Fig. 15: Wafer CD difference between product mask and reference for isolated contacts.

Figure 16 shows the focus response for the same feature type. Again a decent <5% match is observed.

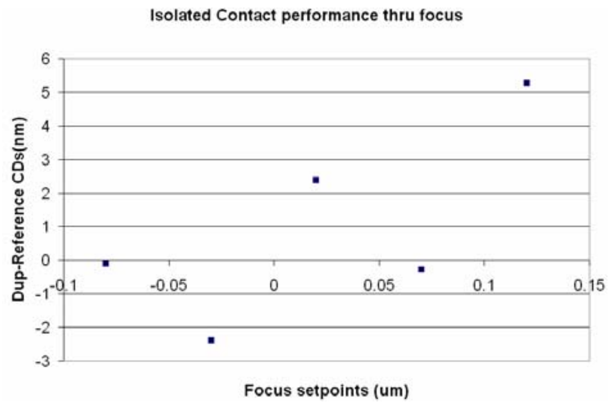


Fig. 16: Difference in focus response between product mask and reference for isolated contacts.

The nested structures show a similarly good match.
For optical proximity correction models through pitch performance is a major concern. In Fig 18 the CD difference between the two mask across pitch on wafer is shown. Again matching to within 3% has been achieved. Also shown are SEM images of a wafer structure printed by product mask and reference.

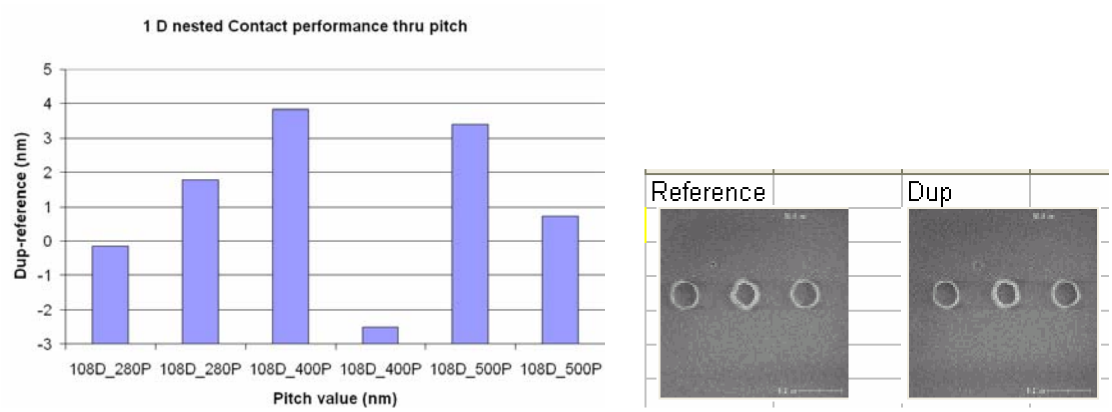
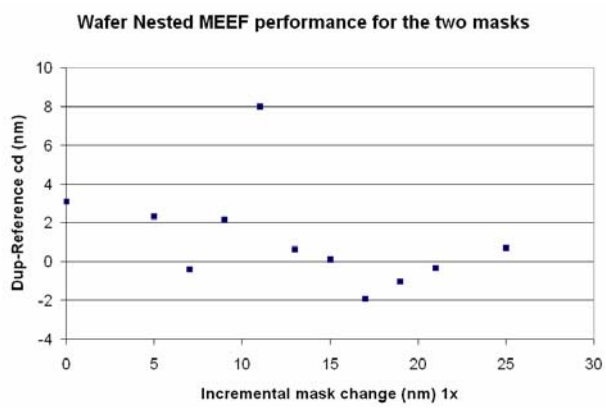


Fig. 17: Wafer CD difference between product mask and reference for fixed contact CD and various contact pitches (left). Right images show wafer SEM pictures of same structure printed by product mask and reference

To ensure adequate process window can be maintained across the mask specification the mask error enhancement factor (MEEF) for numerous feature types was analyzed. The nested and isolated MEEFs on wafer through incremental mask size is constant with a little offset as show in Figure 18. At the 4X mask cd values this corresponds to a 120nm range well within the current specification for mask making



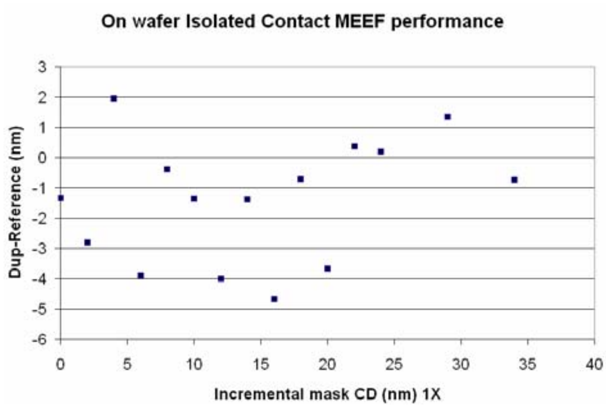


Fig. 18: Differences in MEEF for nested (left) and isolated contacts (right) between product mask and reference.

CONCLUSIONS

In this paper a methodology was presented that allows the matching of customer reference mask without creation of an exact copy of this mask. The main idea deployed here is the matching of the aerial imaging of the mask assessed by AIMS^{TM} data at the mask house. It was shown that using this approach the typical problems of matching an APSM mask (e.g. matching of Quartz profiles) can be prevented but still a very well matching mask can be manufactured. Beside the saving of resources and time at the mask shop by this it also provides the mask manufacturer with increased flexibility during the process set up. Also this technique allows a quality assessment of the mask at a level that really concerns the customer: its printing behavior. Furthermore, the results of the present paper once again illustrate the high potential of aerial image based mask metrology. This is of particular importance of all types of masks that use quartz etch processes as they typically show a strong sensitivity to properties of the quartz etch profiles which are difficult or almost impossible to quantify especially on product masks.

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