

Gray Assist Bar OPC

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ABSTRACT

Assist bar Optical Proximity Correction (OPC) has been demonstrated to increase across pitch performance and depth-of-focus of semi-dense to isolated lines¹. As the sub-resolution assist feature (SRAF) or assist bar's size increases, so does its desired lithographic effect, as well as its undesired printability. In other words, when large assist features are required at isolated pitches, the assist features may print. A frequency-preserving assist bar solution is the most preferred one, but difficult to realize for opaque assist features due to printability. The concept of frequency-preserving Gray Assist Bar OPC has been introduced as a method to extend imaging performance for small features across a wide range of duty ratios³. In this paper, we will present the experimental validation of this concept.

The Gray Assist Bar mask was manufactured using a two-level lithography process, and the optical properties have been characterized using a Woollam VUV VASE system. Additional metrology was performed using an AFM (SNP9000) and CD SEM (KLA8250XR).

Exposures on a 0.75NA 193nm scanner clearly show the expected effects. The use of the Gray Assist Bar features reduces the through pitch critical dimension (CD) variations significantly and can hence be regarded as an 'Optical Proximity Correction'. The isofocal inflection point of aerial images is shifted in cases with Gray Assist Bars, resulting in flatter bossung curves and a larger depth of focus (DOF) for the various features through pitch at their target size. This results in larger overlapping process windows. The Gray Assist Bars has also shown a very low printability, even with aggressive off-axis illumination (OAI) settings.

Keywords: Optical Proximity Correction, Gray Assist Bars, SRAF, Printability, Depth of Focus, Process Window

INTRODUCTION

The need for sub-resolution assist features (SRAFs) becomes apparent when trying to image features with the same CD that occur at multiple pitches. When considering a binary case using no assist features, there is considerable difficulty achieving a common process window when multiple duty ratios exist. In order to understand the imaging difficulties and provide a solution, it is helpful to think of the problem from the perspective of the lens pupil.

1. Diffraction of 1-D Gratings

1.1. Binary 1-D Grating (BIM)

In order to illustrate the need for assist features, as well as demonstrate how they work, consider a 1-D grating as a simplified representation of a real photomask. When illuminated with coherent light, discrete diffraction orders are produced. Depending on the size and pitch of the features, the angle and the magnitude of the diffraction orders will change. Figure 1 shows a 1-D grating, along with the matching formulae for calculating the magnitude of the resulting diffraction orders. It is helpful in this case to describe the grating in terms of fractional space width, instead of CD and pitch. The 0th order term is only related to the fractional space width: the larger the fractional space, the larger the 0th order. This term only contains intensity information; there is no information in this term relating to the pitch or the lines. The 1st and 2nd diffraction orders contain the information about the lines, and the partial capture of this information allows the aerial image to approximate the mask function and reproduce the mask pattern in the resist.

Since the half angles of the discrete diffraction orders are functions of pitch and wavelength, at small pitches the diffraction orders are distributed relatively far apart. The discrete diffraction orders resulting from a **coherently** illuminated infinite grating are described by $\sin \theta = n\lambda/p$, where n is the diffraction order in question, λ is the wavelength

$$|Mag|_{0^{th} \text{ order}} = \left(\frac{s}{p} \right)$$

$$|Mag|_{1^{st} \text{ order}} = \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{s}{p} \right) \right|$$

$$|Mag|_{2^{nd} \text{ order}} = \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{2s}{p} \right) \right|$$

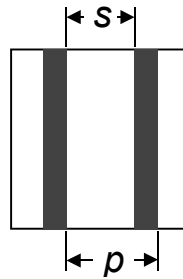


Figure 1: Magnitude of the diffraction orders resulting from an infinite 1-D binary grating.

of the coherent source, and p is the pitch of the grating features considered. It therefore follows that at minimum resolution conditions, the pitch is such that only the $\pm 1^{st}$ orders lie within $\sin\theta=NA$. At small pitches and using modified illumination, the distribution of the diffraction orders is such that only part of the 1^{st} diffraction order and none of the 2^{nd} diffraction order is collected by the stepper or scanner's objective lens. The resulting aerial image has low contrast because of limited capture of the 1^{st} diffraction orders, but the 0^{th} order term is also small. Since the 0^{th} order term is directly related to the offset of the isofocal inflection point of the aerial images for this binary case, the isofocal inflection point is also located at a low relative intensity compared to a more isolated case. The isofocal inflection point of an aerial image is the point where an aerial image has the same relative intensity at all defocus values. By engineering a resist to threshold at this point, the CD of the printed resist image will be maintained through focus.

When considering more isolated binary gratings of duty ratios larger than 1:2 (100nm CD), the diffraction orders are spaced closer together, allowing the objective lens of the scanner or stepper to capture all of the 1^{st} and part of the 2^{nd} diffraction orders. This results in an aerial image with better contrast than a more dense case, but also a larger offset of the isofocal inflection point. With this scheme, it is impossible to print both features to size unless some form of OPC is involved. Figure 2 shows that at a reasonable constant threshold point for a resist, the CD swing associated with focus changes is much more pronounced for the isolated features, and relatively low for dense features.

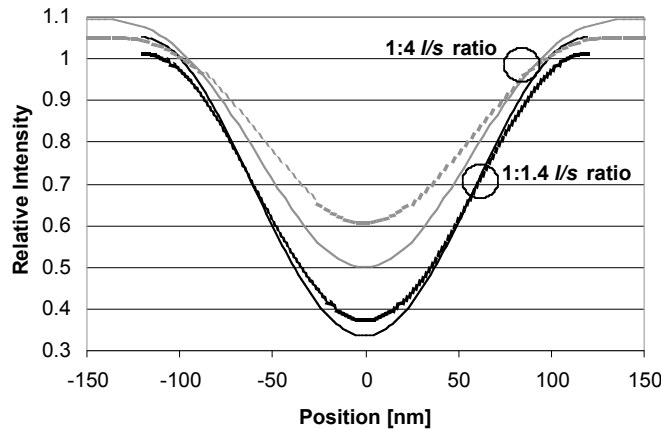


Figure 2: Aerial images of 100nm lines at duty ratios of 1:1.4 and 1:4. Each duty ratio is shown at best focus and at 0.2 μ m defocus.

Consider the cases of 100nm chrome features at a duty ratio of 1:1.4 l/s and 100nm chrome features at a duty ratio of 1:4 l/s. Figure 2 shows an aerial image simulation done at $0\mu\text{m}$ and $0.2\mu\text{m}$ defocus with a 193nm 0.75NA scanner, annular illumination, $\sigma_0=0.89$, $\sigma_1=0.65$. Compared to the more dense 1:1.4 features, the intensity and position of the isofocal inflection point for the 1:4 l/s features is shifted. Suppose the resist used in this process thresholds at 0.6. As focus changes, the dense features will experience very little CD change. When considering the larger 1:4 features the CD will swing a significant amount. Moreover, with this threshold, lines at 1:4 duty ratio will not be imaged by the resist when in a $0.2\mu\text{m}$ defocus condition.

1.2. Binary 1-D Grating with Single Opaque Bars

Through-pitch imaging performance can be improved by adding opaque assist bars to large pitch cases¹. These assist features effectively make the large pitch cases behave like dense cases by reducing the 0th order present and therefore reduce the observed shift in isofocal inflection point of the aerial image. Modified 1-D grating equations are presented in figure 3 below.

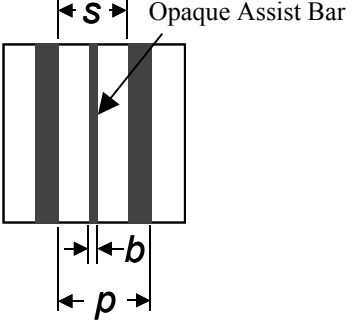
$$\begin{aligned}
 |Mag. |_{0^{th} \text{ order}} &= \left[1 - \left(\frac{b}{s} \right) \right] \cdot \left(\frac{s}{p} \right) \\
 |Mag. |_{1^{st} \text{ order}} &= \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{s}{p} \right) - \left(\frac{b}{p} \right) \text{sinc} \left(\frac{b}{p} \right) \right| \\
 |Mag. |_{2^{nd} \text{ order}} &= \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{2s}{p} \right) - \left(\frac{b}{p} \right) \text{sinc} \left(\frac{2b}{p} \right) \right|
 \end{aligned}$$


Figure 3: Magnitude of the diffraction orders resulting from an infinite 1-D grating with opaque assist bars.

Each term of the grating equation presented in figure 1 has been modified by a term representing the assist bars. By placing the assist bar in the center of the two main features, it will give the assist feature the same pitch as the main feature and have maximum OPC effect. With the assist feature placed with the same pitch, the diffraction orders produced by the assist features will be harmonic to the diffraction orders produced by the main features. This is critical because it ensures that as the assist bars are added, the spacing of the diffraction orders in the lens pupil will not change. The superposition of the diffraction orders of the main features and assist features will therefore allow tuning of the magnitudes of the diffraction orders. By adjusting assist bar size, the 0th diffraction order magnitude for a given pitch can be adjusted. If large pitches are matched to the 0th order magnitude for a smaller pitch, this will result in improved process window overlap and more consistent CD performance through focus.

When using opaque assist features with isolated lines (duty ratios > 1:5), the level of OPC required may be quite high. If the bars are made larger to allow for the high correction, they may begin to print easily, especially when used with strong off-axis illumination conditions. This is an undesirable effect of the opaque assist features, and one that limits their use and size for isolated cases. If more dense pitches are considered, the level of OPC may be much lower. This will result in the need for small assist bars. However, as the assist bar size becomes small, it becomes more difficult for the reticle manufacturer to make.

1.3. Binary 1-D Grating with Single Partially-Transmitting (Gray) Bars

By modifying the transmission of the assist bars, printability can be reduced and manufacturing ease can be improved. If the transmission of the assist bars is increased, the size of bar needed at semi-dense cases become larger, since it will need to cover more area to have a similar effect to the opaque assist bar case. At isolated cases, the Gray assist bar will also need to be quite large, however we have shown that even with off axis illumination the assist feature will not print under normal focus and dose conditions.

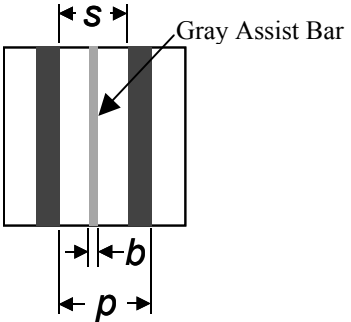
$$\begin{aligned}
 |Mag. |_{0^{th} \text{ order}} &= \left[1 - \left(\frac{b}{s} \right) (1 - \sqrt{I_b}) \right] \cdot \left(\frac{s}{p} \right) \\
 |Mag. |_{1^{st} \text{ order}} &= \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{s}{p} \right) - (1 - \sqrt{I_b}) \left(\frac{b}{p} \right) \text{sinc} \left(\frac{b}{p} \right) \right| \\
 |Mag. |_{2^{nd} \text{ order}} &= \left| \left(\frac{s}{p} \right) \text{sinc} \left(\frac{2s}{p} \right) - (1 - \sqrt{I_b}) \left(\frac{b}{p} \right) \text{sinc} \left(\frac{2b}{p} \right) \right|
 \end{aligned}$$


Figure 4: Magnitude of the diffraction orders resulting from an infinite 1-D grating with Gray assist bars.

The equations for the magnitude of the diffraction orders resulting from the grating with opaque assist bars is further modified with the term considering the attenuation of the Gray assist bars (figure 4). I_b represents the intensity of the bar in the mask function, and is related to the transmission of the bar by a square root relationship.

By adding properly sized Gray assist bars to a design featuring same CD lines printed in at different pitches, the aerial image proximity effects shown in figure 2 can be greatly reduced. Figure 5 shows an aerial image plot for the same 100nm lines at 1:1.4 and 1:4 duty ratios, printed on the same tool, but with the addition of optimized gray assist bars to the 1:4 duty ratio case.

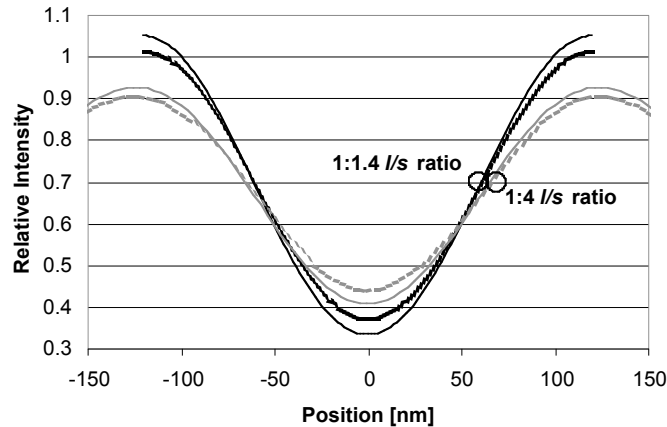


Figure 5: Aerial images of 100nm lines at duty ratios of 1:1.4 and 1:4. Gray Assist Bars have been added. Each duty ratio is shown at best focus and at 0.2 μ m defocus. Note the proximity of isofocal inflection points.

By adding the Gray Assist bars to the isolated case, its 0th order term has been directly affected by the fractional bar width occupying the space, and its magnitude has been reduced. By matching the 0th order magnitude of the 1:4 duty ratio case to the 0th order magnitude of the 1:1.4 duty ratio case, the offset between the two inflection points is reduced, and the main features will print to the same CD. Reconsidering the resist thresholding at 0.6, the CD swing through focus has been greatly reduced for the 1:4 duty ratio case.

2. Gray Assist Bar OPC

As mentioned in section 1.3, by adding Gray Assist features, the magnitude of a feature's diffraction orders can be adjusted. Since we are comparing relatively small features in all cases, it is reasonable to assume that higher order terms will not be collected by the scanner's objective lens. Therefore, although higher order terms are influenced by the addition of the Gray Assist features, analysis in this paper will focus on 0th, 1st, and 2nd diffraction orders. As shown in figure 6, the main advantage of a frequency-preserving assist feature is that there is a non-uniform diffraction order response to the assist features. As Gray Bars are added and sizing is changed, the amount and direction of the response to the bars depends on the diffraction order considered. Figure 6 shows the simulated changes in diffraction order magnitude for a 70nm CD/240nm pitch case, and a 70nm CD/500nm pitch case on a 193nm 0.75NA exposure tool where a Gray Assist Bars with a 0.5 transmission have been added.

Indicated on each plot, is the numerical aperture of the exposure tool's objective lens. In the case shown below, at a duty ratio of 1:1.4 the angle of the diffraction orders is too great to allow capture of the second order, while at the 1:4 case, the diffraction orders have a less extreme angle allowing part of the second diffraction order to be captured.

This is key to the effectiveness of assist feature OPC, since only part of the benefit of the assist feature comes from attenuation of the 0th diffraction order. As the width of the Gray Assist feature is increased from zero, the magnitude of the 0th order decreases with respect to b/s , where b is the bar width, and s is the space width between two main CrON features. The 1st and 2nd diffraction orders are adjusted as well, but only offset by the value of $(b/p)\text{sinc}(nb/p)$, where n is the diffraction order in consideration, and p is the assist feature pitch and the main feature pitch. By scaling the 0th diffraction order and subtracting from the 1st and 2nd orders, the 0th order can be matched between two separate pitches, without a significant impact on NILS or pattern fidelity. In the 1:1.4 duty ratio case below, as Gray Assist feature is added, the 0th and 1st orders are attenuated, and the 2nd order is increased until the fractional bar width becomes 0.6.

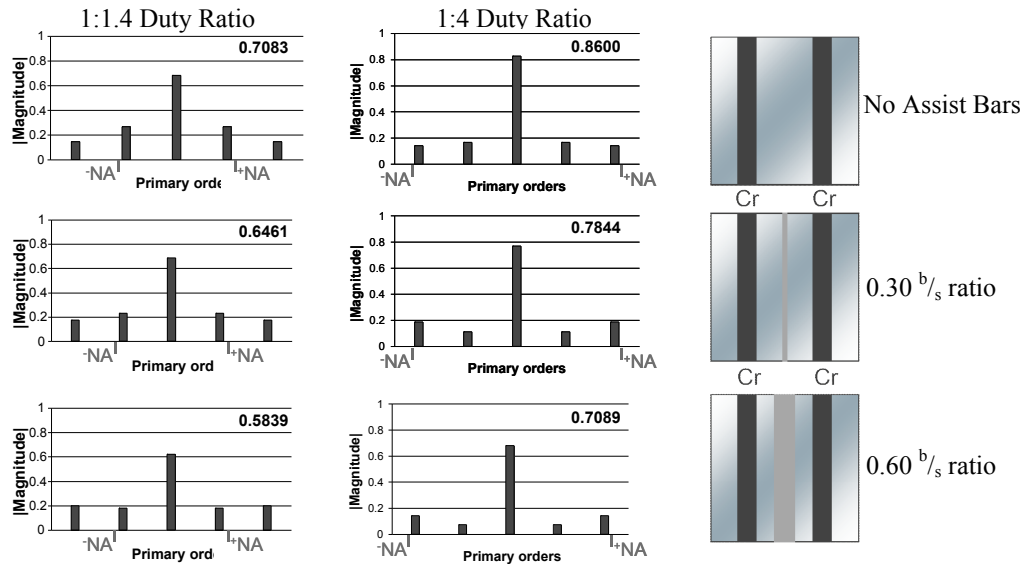


Figure 6: Dense and Isolated Cases with no bars, 0.3 fractional bar width, and 0.6 fractional bar width. 0th order magnitude is indicated in each plot.

In this dense case however, the assist feature gives no advantage, since the 2nd order is not captured by the lens pupil. The assist feature in this case is a disadvantage because the magnitudes of the 1st diffraction orders are reduced, resulting in a loss of NILS and worse exposure latitude and process window.

In the 1:4 case however, the assist features become beneficial. As assist bars are added until 0.6 fractional bar width, the large 0th order magnitude is reduced until it very close to the 0th order magnitude of the 1:1.4 case. By tuning the 0th diffraction orders, the two pitches are made to perform similarly and increased common process window, as well as DOF improvement result. In addition, the 2nd diffraction order in this case reaches a maximum near 0.3 fractional bar width, and then decreases back to near its original value at 0.6 fractional bar width, allowing the process to be tuned to dense pitches without sacrificing aerial image quality.

If the aerial image isofocal slices of unassisted features through pitch are compared, a significant offset exists between the dense 1:1.4 duty ratio cases and 1:8 duty ratio cases.

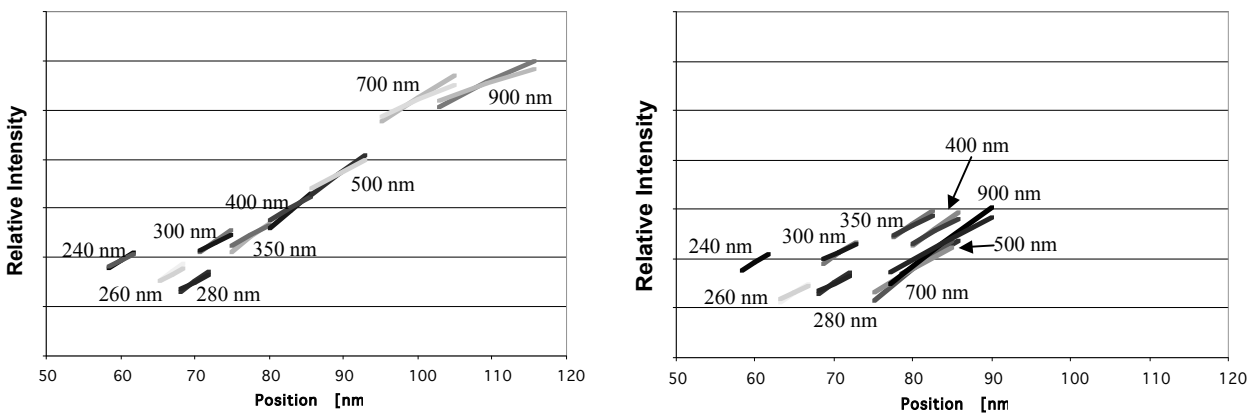


Figure 7: Left – Isofocal slices of 70nm features through pitch, indicated by label. Right – Isofocal slices of 70nm features with optimized Gray Assist features, pitch indicated by labels.

Figure 7 above shows an overlay plot of isofocal slices for 70nm lines of different pitch, indicated by the text labels. These simulations were performed for a 0.75NA 193nm tool with annular illumination ($\sigma_o=0.89$, $\sigma_i=0.65$). The offset between the slices represents the 0th order offset between the dense and isolated cases, and is primarily why the lines of different pitch print to different CD when imaged at the same dose and focus conditions.

Gray Assist features were added and optimized for features pitch 350nm and above, due to the requirement that 2nd order diffraction information should be present in the lens pupil to avoid worsening the process window and exposure latitude. The 0th orders for the more isolated pitches were matched to the 0th order magnitude of the so-called forbidden pitch, for this case 300nm. For all cases using the assist features, a visible shift in the isofocal slices is observed.

MANUFACTURING OF THE GRAY ASSIST BAR RETICLE

The Gray Assist Bar reticle was manufactured successfully by Photronics. A fused silica substrate suitable for use with 193nm was first ion-beam sputtered with a thin layer of partially transmitting ‘gray’ material. Thickness control of this thin film layer is extremely important, since it defines the amount of transmission the Gray Assist features will have. Next, a second layer of CrON was sputter deposited at a standard thickness of 90nm over the gray material.

The reticle then undergoes the first lithography step, using a 50keV electron-beam, which defines the primary features and Gray Bar features in one self-aligned process. The pattern is then etched down to the fused silica substrate. A second lithography step is performed using a laser mask writer and protects all of the chrome binary features and exposes the chrome above the Gray Bar features. The chrome is removed using a wet etch that is highly selective to the chrome, and leaves the Gray Bar intact and the mask complete. Figure 8 is an illustration of the manufacturing process used to create the prototype reticle. A major key to the successful fabrication of the reticle is the wet etch to uncover the Gray Assist Bars. By being highly selective, it assures that the bars will have the same thickness, and therefore a uniform transmission across the chip.

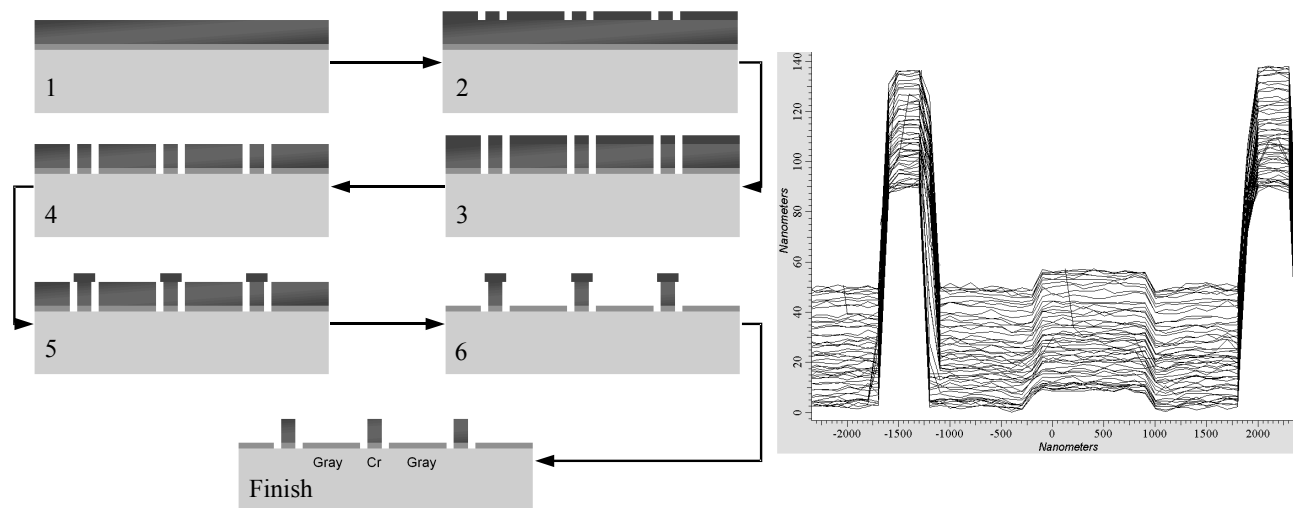


Figure 8: Illustration of the manufacturing process used for the prototype Gray Assist Bar Reticle and AFM scan of the reticle.

Reticle metrology was performed using a KLA-Tencor 8250XR CD SEM as well as an SNP9000 AFM. An image from CDSEM is presented below, clearly showing good placement of the bars, and intact CrON main features.

The target for the transmission of the Gray Assist Bar material was 0.50. This value allows for bar solutions to work at all ranges of duty ratio from 1:1.4 through 1:8. An optical analysis of the Gray Assist Bar material was performed using a Woollam VUV VAS ellipsometer and found the transmission of the gray bars to be close to target at 44.2% transmission at 193nm. The transmission of the fused silica substrate was 90.2%, so the relative transmission of the Gray Assist Bar material was 49%. The optical analysis of the gray material is shown in figure 9 below.

The Gray material's transmission drops above 193nm, and the lower transmission at slightly higher wavelengths allows the use of standard mask inspection tools.

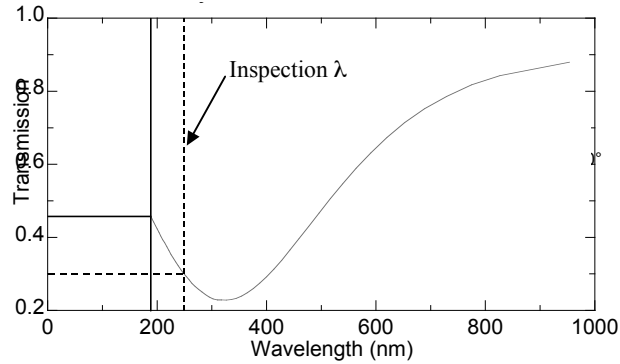


Figure 9: Transmission analysis of the Gray Assist Bar material. The material is less transmissive at inspection wavelengths, allowing the use of standard mask inspection tools.

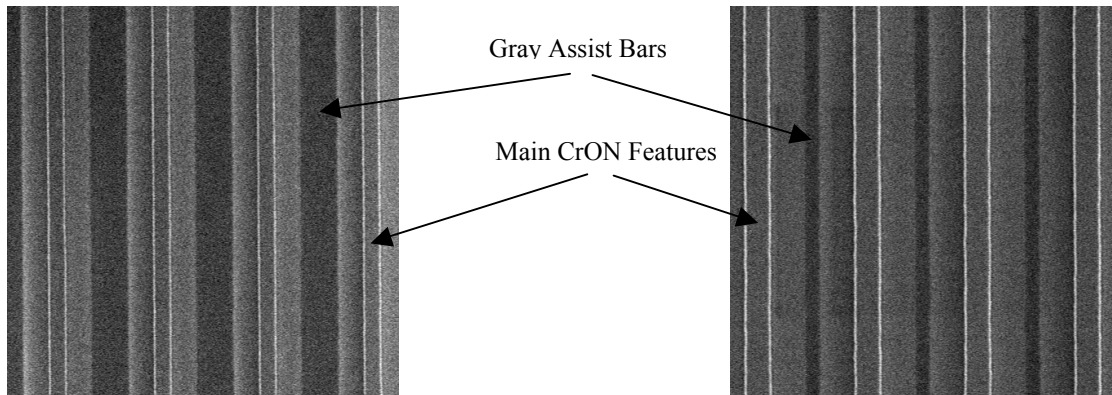


Figure 10: CD-SEM micrographs of the Gray Assist Bar reticle (two different CD cases), showing good agreement with AFM scans.

EXPERIMENT

The Gray Bar reticle consists of several hundred combinations of five-bar test patterns, with Gray Assist bars placed in the central locations between the CrON main mask features. The length of the test pattern is sufficient to neglect end effects, and all measurements are taken at the central location. The CD of the five-bar patterns is set at 70nm, and the bars are varied in pitch from 240nm (1:1.4 duty ratio) to 900nm (1:8 duty ratio). The CD of the chrome features is swept through a range of biases ranging from -20nm to +20nm, and the width of the Gray Assist features is changed from 0 (no assist bars) to 600nm. This full factorial method of design ensures that for each pitch, there will be ample patterns available for fully testing the consequences of the bar.

All experiments were performed with an ASML PAS5500 /1100 193nm scanner, using Quasar™ illumination ($\sigma_o=0.89$, $\sigma_i=0.65$) unless otherwise noted. The film stack for all wafers was 150nm of Sumitomo PAR 817 high contrast photoresist on 77nm of Brewer Science ARC29A. All measurements were obtained on a KLA 8250XR CDSEM, and Klarity ProDATA was used to fit process windows.

There are several main areas investigated in this paper. The Gray Bars were analyzed to determine their effectiveness at reducing optical proximity effects. A comparison of exposure latitudes and DOF of cases through pitch was done, and

finally the through pitch process windows were compared for a case with optimized Gray Bars and bias to a case with no assist features.

1. Proximity Matching

Optical Proximity Correction is, by definition, correction for differences in the printability of features caused by their different surroundings. In order to test the effectiveness of the Gray Assist Bars as OPC, the 70nm CD five-bar patterns were measured through pitch, ranging from 240nm to 500nm. At each pitch, the Gray Assist bar was varied from no bar, to maximum available in the design. In order to be sure that reticle effects were removed from the experiment, the reticle was first measured, and main feature CD for each case used was measured 280nm (4x) on reticle (70nm (1x)). The results of the experiment are summarized below in figure 11.

As expected, the unassisted five bar pattern exhibits slight proximity effects, which can be seen along the y-axis of the plot. As an assist feature is introduced to each pitch, the proximity effects can be compensated for and corrected. The 240nm and 260nm pitch cases are printing larger than design, and in these cases, the addition of a Gray Assist feature is not useful, since the 2nd diffraction order lies at an angle beyond capture for a 0.75NA system. In order to print these two cases to size, the exposure dose must be adjusted, or a negative mask bias must be used to bring the printed CD down to the target value of 70nm. For the 280nm through 500nm pitch, the CD can be controlled by addition of the Gray Assist features, and the different optical proximities of the various five-bar patterns can be normalized, bringing the printed CD to 70nm in all cases.

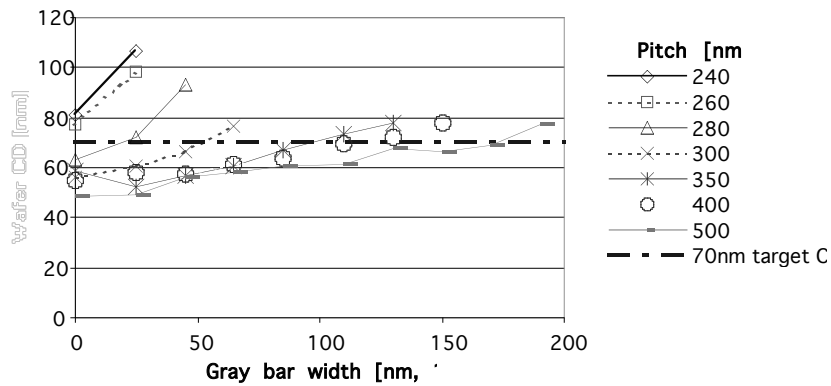


Figure 11: Proximity Correction and Matching Using the Gray Assist Bar features.

2. DOF Improvement

In addition to proximity correction, Gray Assist Bar OPC gives an added depth of focus improvement to cases where the assist features are used. This is in part due to the shift of the isofocal point closer to the resist threshold, and also because of the response the 1st and 2nd orders have to the assist features. The 2nd order magnitude gain is then visible as a NILS improvement and a DOF gain. Figures 12 and 13 show simulation and experimental data obtained from 500nm pitch 70nm CD features with different cases of Gray Assist Bars present.

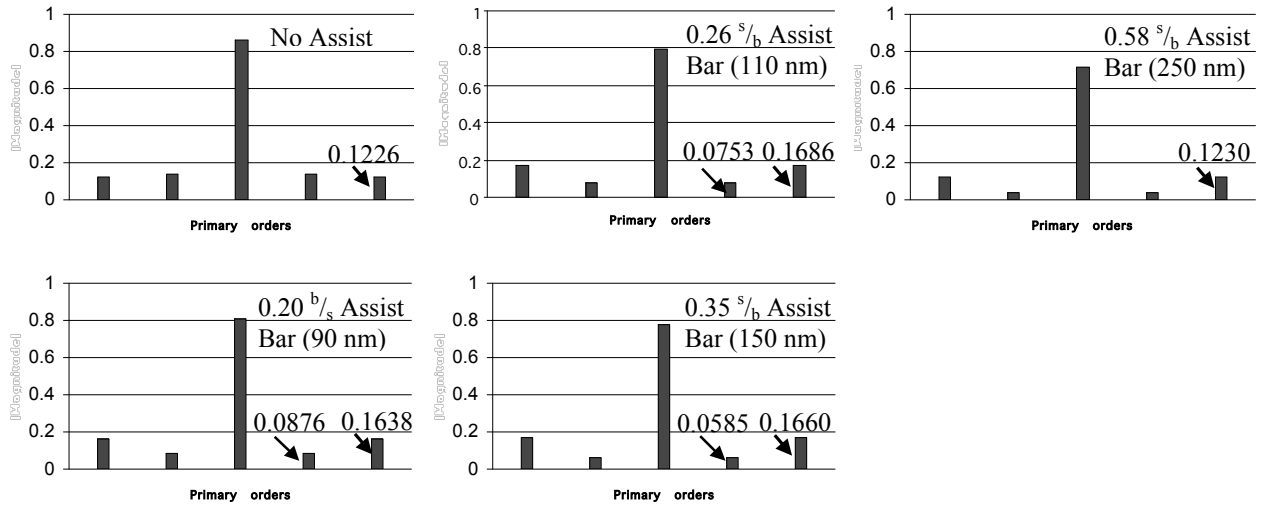


Figure 12: Magnitude of the primary diffraction orders as Gray Assist Bars are added.

As the Gray Assist Feature is introduced, it has an immediate impact on the 2nd diffraction order, raising it by a factor of 1.33 when a 90nm bar is present. As more Gray Assist feature is added to the space, the 2nd diffraction order continues to rise and reaches a maximum of 0.1686 when 110nm of bar is present. When viewing the same cases measured on a wafer, the DOF and exposure latitude gain is visible. When comparing the best case of 70nm features with 110nm Gray assist bars, an increase of 6% exposure latitude was seen at 0.3 μ m DOF.

As the Gray Assist features are increased further to 150nm and 250nm, the exposure latitude decreases from its maximum. If the 1st and 2nd diffraction orders are considered, it can be seen that in the 150nm Assist Bar case, the 1st order magnitude drops by a factor of 0.77, and the 2nd diffraction order decreases by a factor of 0.98. This large loss of 1st and small loss of 2nd diffraction order magnitude contributes to the worsened exposure latitude and DOF. As expected, as the Gray Assist bar width is increased even further, the exposure latitude and DOF decrease even more due to loss of diffraction information.

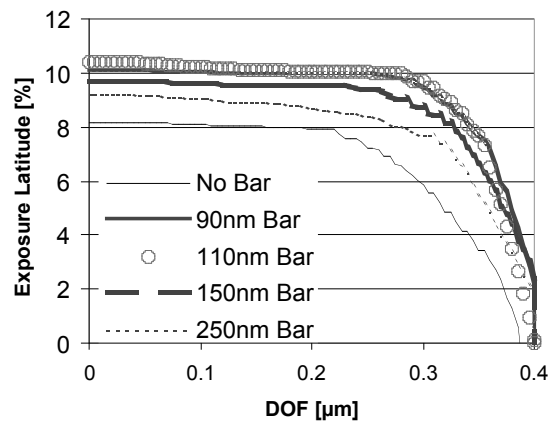


Figure 13: Exposure latitude vs. DOF Plot comparing various widths of Gray Assist Bar. Features are 70nm CD and 500nm pitch.

3. Gray Assist Bar Printability

As mentioned earlier, as the size of an assist feature increases, so does its printability. This is a direct consequence of the assist feature's size and transmission. In order to study the printability of the two types of assist features compared to each other, the 0th diffraction order was again matched between an opaque bar case, and a Gray Assist Bar case. Because of the unavailability of a standard frequency-preserving opaque assist bar reticle, aerial image simulations were used, and compared to on-wafer cases printed with the Gray Assist Bar Reticle. In order to make a fair comparison between the two types of assist bars, first cases were selected on the wafer printed with the Gray Bar Reticle. As a prerequisite, the cases analyzed had to have a large enough pitch to make the addition of assist features beneficial: in other words, to allow for partial 2nd diffraction order collection. Because of this constraint, main features with a CD of 70nm and a pitch of 500nm were selected. To investigate worst-case printability, the largest possible Gray Assist feature was investigated for this pitch and CD case. With this reticle the largest Gray Assist feature CD available was 200nm. At best focus and dose-to-size conditions, the Gray Assist features did not print or show scumming.

This 500nm pitch, 70nm CD with 200nm Gray Assist feature case was then simulated and the 0th diffraction order magnitude obtained. A comparable opaque assist bar reticle was simulated by using the same 70nm CD and 500nm pitch, and by using opaque bar sizing that allowed the simulated 0th order to be matched to the simulated 0th order of the Gray Assist Bar case.

The result was that to gain the equivalent OPC significance offered by the Gray Assist Bar, the opaque bar size was 60nm. From the exposures made with the Gray Assist Bar reticle, and noting that the CD printed to size, an estimate of the resist's threshold can be made. By overlaying the equivalent opaque assist case with the Gray Bar case, and taking into account the resist threshold, the printability of each technique was compared. The results are summarized in figure 14. It is clear that the 60nm opaque bar solution, although producing a resulting 0th diffraction order matching that of the Gray Bar case, will print because the relative intensity minima of the assist bars is below the resist threshold.

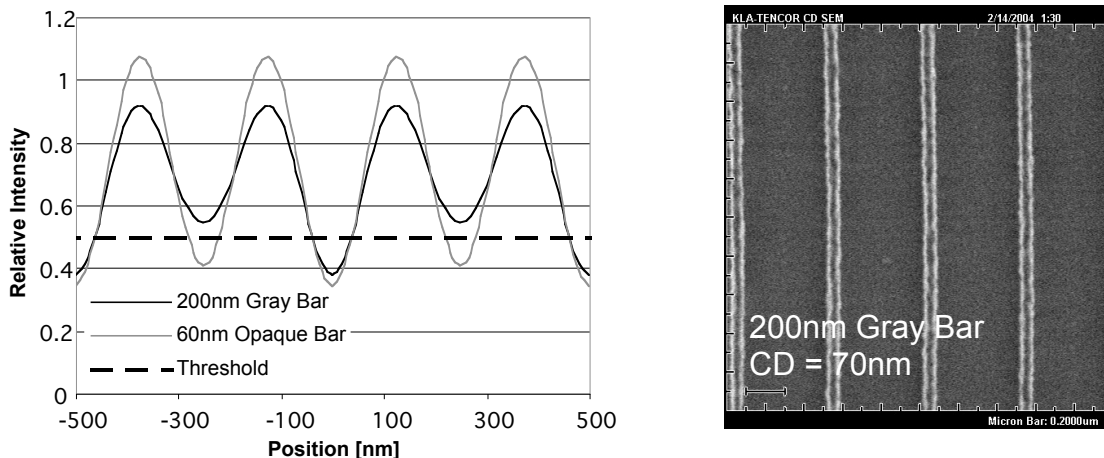


Figure 14: Gray Assist Bar vs. Opaque Bar Printability. Bars are sized to produce equivalent proximity corrections at 500nm pitch with 70nm main features.

4. Through Pitch Process Window Improvement

Combining the capabilities of Gray Assist features to correct for proximity effects, as well as improve the exposure latitude and depth of focus of semi-dense and isolated features, a final solution for improved process window through pitch is available. In this experiment, cases with optimized Gray Assist features were compared to unassisted cases for 70nm CD features at pitches ranging from 240nm to 500nm. The results are summarized in Figure 15 below. The plot on the left is of unassisted features, while the plot on the right contains optimized Gray Assist features in cases where their use is appropriate. The more dense 240nm pitch features maintain their high exposure latitude, and do not need assist features. Similarly, for the problematic pitches of 280nm and 300nm, assist features have not been used, but a bias of 5nm has been applied to the main features in order to compensate for low DOF and small exposure latitude (right plot only)². Above the 300nm pitch, Gray Assist Bars and a 10nm bias have been applied to correct for proximity

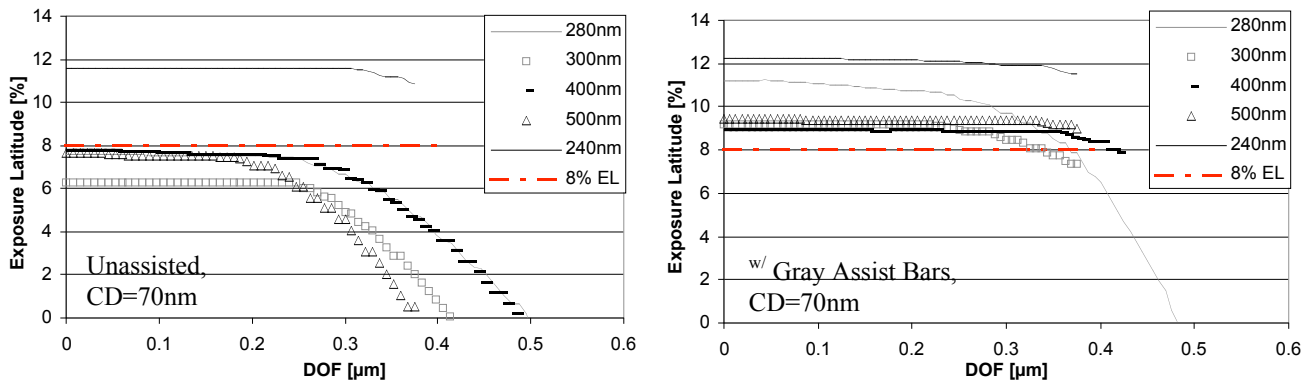


Figure 15: Exposure latitude vs. DOF for unassisted 70nm features through pitch (right), and features with optimized Gray Assist Bars (left).

effects. On both plots, a visual aid marker highlights the 8% exposure latitude point. This 8% exposure latitude represents the point that a process becomes robust enough to be usable under the normal variances of typical process conditions. By comparison, the process in the left plot only has its 240m pitch features above this 8% limit, while the process on the right has adjusted all of its exposure latitudes to be above 8% at 0.35μm DOF.

In addition to improving the exposure latitude and DOF for each pitch individually, there is also an improvement in common process window. In this case, the unassisted features measured had no common process window. By considering cases with optimized Gray Assist features added to the patterns, a common process window of 5.6% exposure latitude at 0.17μm depth of focus was created.

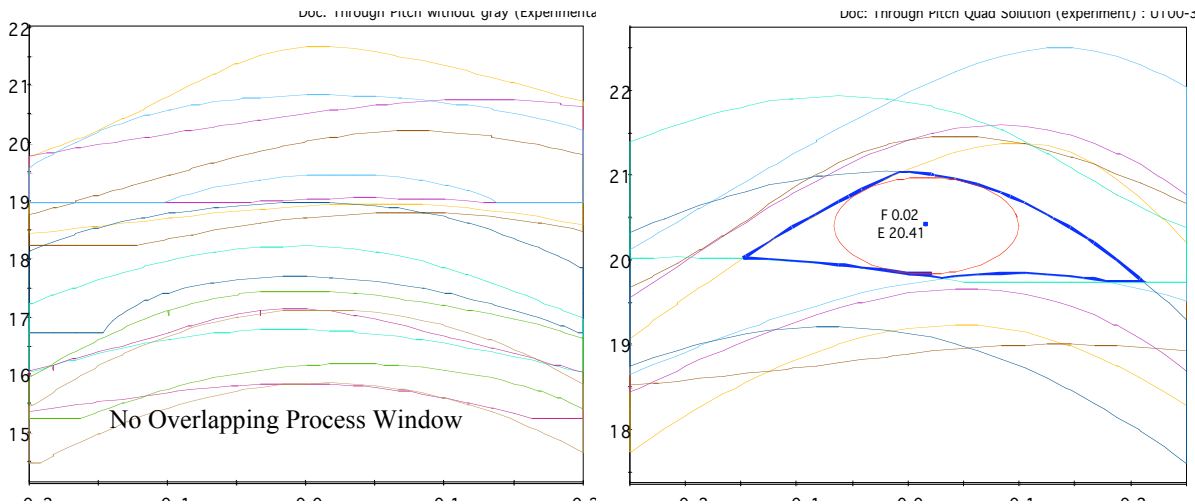


Figure 16: Common process window for 70nm features at pitches from 240nm to 700nm. Left: Unassisted, Right: with Gray Assist Bars

CONCLUSIONS

We have performed simulations and experiments to show the capability of using Gray Assist Bars as a new form of OPC. By using Gray Assist Bars, the 0th diffraction order of a feature's diffraction pattern can be adjusted. This ability to adjust the 0th diffraction order, which is only an intensity offset, is a key benefit to the lithographer who must print

features with the same CD at different pitches across-chip. The advantage of the Gray Assist Bars compared multi-bar solutions is that diffraction orders made by the Gray Assist bars are at harmonics of the diffraction orders caused by the main features. This results on the diffraction pattern being modified only in magnitude of the orders, not in the spacing or angle of the final diffraction pattern. Another advantage to the Gray Assist Bars is that by having a reduced intensity, they can be made larger at semi-dense pitches where only a small adjustment is needed. This increase in bar size makes the mask easier to manufacture for the reticle supplier. At more isolated pitches, the bar must be made larger compared to opaque assist features, but the partial transmission of the bar allows its printability to be much lower than a smaller sized opaque bar. We have shown through experiment that the Gray Bars printability remains low and compared this condition to a standard opaque bar case.

By investigating several cases of 70nm CD patterns spaced at varying pitches, the proximity correction potential for the Gray Assist Bars has been evaluated. Using the CDSEM-verified mask patterns containing varying amounts of Gray Assist feature for each pitch, the correction potential was good. By adding the assist features to a pattern, the optical proximity effects can be compensated for, and CD through pitch can be made to print at a constant designed value.

As the gray bar is introduced, we have seen in simulation that its impact to diffraction order magnitude varies depending on the order considered. The conclusion of this study is that as the Gray Assist features are introduced, exposure latitude and DOF are gained as the 2nd diffraction order is increased to a maximum and the offset caused by the 0th diffraction order is reduced. Increasing the width of the gray feature past the maximum 2nd order magnitude results in a rapid loss of 1st order diffraction information, as well as a subsequent drop in exposure latitude and DOF.

By carefully choosing cases where the Gray Assist features are matching the 0th order magnitude of larger pitch features to semi-dense features, an increased across pitch process window was created. Experiments have shown that optimized Gray Assist features increased the process latitude through-pitch to above 8%. In all cases evaluated, the addition of the optimized Gray Assist Bars has given increased exposure latitude, increased DOF, and a greater overlap of the individual process windows when multiple pitches are considered. In experiments, the Gray Assist features enabled creation of a common process window of 5.6% EL at 0.17 μ m depth of focus, where unassisted cases through-pitch had no common process window.

In addition, the reticle was built using a novel process. By combining dry and wet etching in a self-aligned process, the reticle had no errors between the placement of the bars and the center of the spaced between main CrON features. The innovative wet etch used to reveal the bars after the second lithography step ensures that the thickness and therefore the transmission of the bars remains consistent over the full field.

In conclusion, this novel reticle was fabricated, and simulations and experiments were done for this new type of OPC. The Gray Assist Bars have shown the ability to directly attenuate the magnitude of 0th diffraction order, and the ability to correct for optical proximity effects for features considered through pitch. Gray Assist Bar OPC has also shown the capability to give significant DOF and exposure latitude improvement for assisted cases when compared to unassisted cases, and the ability to improve common process window when features of multiple pitches are considered.

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