# Mutually Optimizing Resolution Enhancement Techniques: Illumination, APSM, Assist Feature OPC, and Gray Bars

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## ABSTRACT

As sub-half wavelength optical lithography is pursued, the variety of imaging requirements increases. This can result in complex combinations of various resolution enhancement techniques. Optimization based on simple standards or rules is not possible. Although the goal is to design processes so that enhancement approaches work cooperatively as manufacturable solutions, it is often an overwhelming task. Problems often arise as analysis is carried out in a spatial domain, where mask and image properties are evaluated using sizing or dimensional evaluation. A more appropriate perspective for image optimization is that of the lens pupil, in a spatial frequency domain. In this paper, we describe the common characteristics of resolution enhancement, beyond the historical comparisons of alternating PSM and strong OAI. Enhancement techniques including assist feature OPC, custom illumination, attenuated PSM, and pupil filtering are described from a spatial frequency standpoint where each can be utilized to take advantage of strengths and avoid weaknesses. As a result of this type of analysis, we will also describe an alternative OPC method where assist features of varying tone, referred to as Gray Bars, provide for significant image improvement.

Keywords: Resolution enhancement techniques, spatial frequency, OPC, OAI, PSM, gray bars

## 1. INTRODUCTION

A comparison of current lithographic requirements to those of just a few years ago indicates the acceptance of the employment of some form of resolution enhancement technique (RET) for many lithography masking levels. This may amount to optimization of NA and partial coherence for some instances to aggressive use of OPC, modified illumination, or PSM for more critical levels. The lithographer has developed an understanding of these RETs based on a viewpoint of the spatial domain of the mask/image or of the spatial frequency domain of the objective lens pupil. Very often, either is adequate. As combinations of RETs are employed however, a spatial frequency perspective is required. The challenge then becomes one of developing such a perspective that is as intuitive as that of the mask and image.

Figure 1 shows an example of the simulated aerial images confronted by current optical lithography [1]. Although the situation is not the most aggressive imaging attempted today, it does indicate the difficulties involved with imaging small features across a range of duty ratios. The images in the figure are those from 150nm lines using a 248nm wavelength, 0.70NA, and a partial coherence value of 0.85. Both 1:1 dense aerial images and 1:3.5 semi-isolated images are shown at best focus and with 300nm of defocus. These images indicate the problems associated with imaging geometry of varying duty ratio. Small dense features generally suffer from poor contrast yet may be less affected by defocus because of the location of the image's isofocal inflection point. This inflection point results as an image is driven through focus and it will fall dimensionally close to the position of the mask edge for the 1:1 features. This is a consequence of the magnitude of the zero diffraction order. By comparison, more isolated features can exhibit higher contrast but suffer from defocus and aberration effects. This results from large positional differences between the location of the isofocal inflection point and the mask edge, a consequence of the increase in the zero order [2]. Additionally, isofocal intensity values are generally large with respect to the requirements of the intensity thresholding of a resist process. When considered together, the difficulties involved with obtaining process overlap between dense and semi-isolated features becomes evident.

It is useful to track the image isofocal points of features with various duty ratio as an indication of process potential. Figure 2 is a plot of small slices of images from 150nm lines with duty ratios from 1:1 to 1:3.5. These slices contain only portions of the images at best focus and with defocus near their isofocal inflection points (for the right half of the aerial image). As image isolation increases (from 1:1), the corresponding isofocal slices move progressively farther from the mask edge and farther from the resist intensity thresholding position. The goals of resolution enhancement can be tied to these image plots.

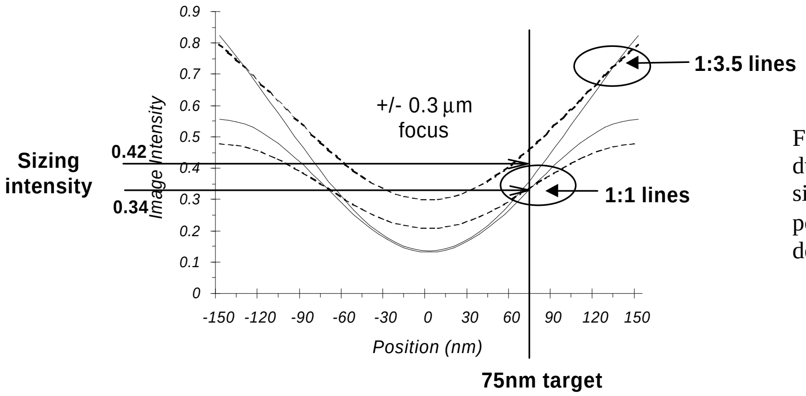

Figure 1. Aerial image plots for 150nm lines at duty ratios of 1:1 and 1:3.5, showing differences in sizing intensity, defocus effects, and isofocal positions. Images are using 0.70NA, 0.85σ, and defocus 0, +/- 300nm.

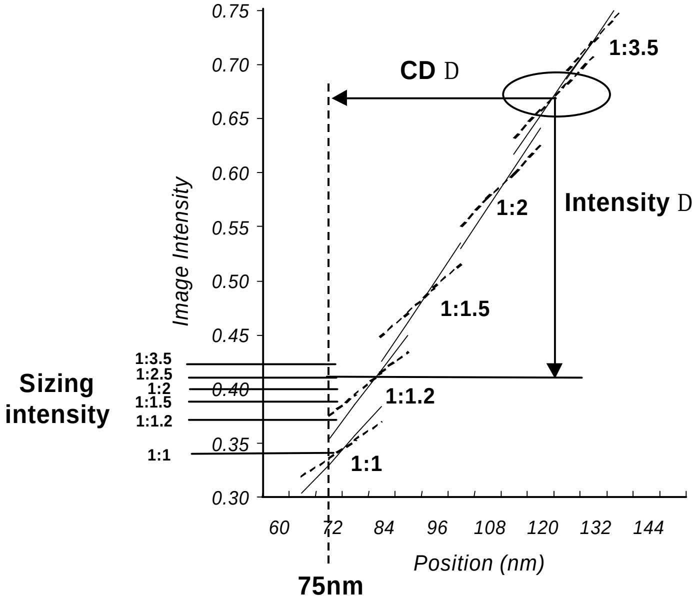

Figure 2. Plots of isofocal slices of 150nm aerial images with duty ratios between 1:1 and 1:3.5. These slices are the right side only of aerial images near the isofocal point for best focus and for 300nm of defocus. Large across pitch process windows are difficult because of these differences. Image slope is lowest with increasing density.

With regards to dense geometry, the goal is to increase image contrast and slope. Dense geometry can be considered as that which results from pitch values below ~λ/NA, or between 1:1 and 1:1.5 duty ratio in this case. For more isolated features, the goal is to drive the intensity and position of the isofocal inflection point closer to those for the dense features and closer to the resist thresholding point. Improvements in dense feature resolution and across pitch performance could then be expected.

## 2. MASK CONTRIBUTION TO IMAGING PERFORMANCE

Phase shift masking and OPC have been described using various treatments. Since it is generally the contribution of the primary diffraction orders that determine the character of an intensity image, representation of a mask diffraction field can be simplified. For example, the magnitude of the zero, first, and second diffraction orders for a real/even binary mask can be calculated as:

$$|\text{Mag.}|_{\text{zero order}} = (s/p)$$

$$|\text{Mag.}|_{\text{first order}} = \left|\left(\frac{s}{p}\right)\text{sinc}\left(\frac{s}{p}\right)\right|$$

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

where *s* is space width and *p* is pitch. As the feature duty ratio increases, the zero order increases proportionately. This leads to the larger isofocal intensity of the aerial image. The location of the isofocal point is driven away from the mask edge as fewer diffraction orders are collected. Modifications to the mask which reduce these disparities could lead to imaging improvement.

### 2.1 Attenuated Phase Shift Masking

By introducing a phase shift in a partially transmitting mask absorber, the primary diffraction orders for the mask field are modified. The influence on the orders is a function of the differences in amplitude between dark and clear regions. For an attenuated phase shift mask (APSM) with non-attenuated clear openings, this corresponds to a $\sqrt{T}$ factor, where $T$ is the transmission of the absorbing phase shifters:

$$
\begin{aligned}
|\text{Mag.}|_{\text{zero order}} &= [1+\sqrt{\text{T}}]\,(s/p) - \sqrt{\text{T}} \\
|\text{Mag.}|_{\text{first order}} &= [1+\sqrt{\text{T}}]\,\left|(\frac{s}{p})\text{sinc}(\frac{s}{p})\right| \\
|\text{Mag.}|_{\text{second order}} &= [1+\sqrt{\text{T}}]\,\left|(\frac{s}{p})\text{sinc}(\frac{2s}{p})\right|
\end{aligned}
$$

Figure 3 shows how zero, first, and second diffraction orders are influenced when an APSM is employed. Plots are for APSM transmission between 0% (binary) and 20% with varying fractional space width. These plots are not specific for any particular geometry size but instead show how results are influenced by the mask duty ratio. A fractional space width of 0.5 correlates to 1:1 dense geometry. A smaller fractional space width corresponds to smaller spaces and a larger fractional space width implies smaller lines. The plots contain APSM transmission values at 2% increments. The greatest impact from APSM is realized for small semi-isolated space features where the reduction in the zero order is greatest and the increase in the first order is low. This situation is also true for semi-isolated contact features. As the fractional space size increases, the influence on the zero order is reduced and increases in the first order result. This becomes problematic when considering the printability of side lobe artifacts that result from a large first diffraction order magnitude combined with a low zero order value. Without sufficient zero diffraction order to bias the primary harmonic resulting from the first order, the squared magnitude of both lobes of the amplitude image may have sufficient intensity to influence resist exposure. This can be estimated from the difference between the values of the zero and first orders, or where side lobe magnitude is defined below and is influenced by the resist process:

$$(2 \times |\text{Mag}|_{\text{first}} - |\text{Mag}|_{\text{zero}}) < \text{Resist amplitude threshold}$$

Problems arise if the side lobe magnitude rises above the resist threshold. A resist intensity threshold of 0.3 corresponds to an amplitude threshold of 0.55. Figure 4 shows how APSM parameters can lead to side lobe susceptibility. The plot indicates that APSM values above 6% could be problematic, especially at a critical fractional space width near 0.3. This corresponds to a 1:2.33 duty ratio for maximum sensitivity to side lobe artifacts. For contacts designed on a square array, the diagonal contact frequency or duty ratio becomes a concern. Contacts with a 1:1.36 duty ratio on X/Y axes will provide the greatest opportunity for diagonal side lobe printing of contacts. As fractional space increases or decreases from this point, opportunities for higher transmitting APSM increase. These issues bring a “forbidden pitch” concept into attenuated phase shift masking that can be made worse with illumination that is designed without taking this into consideration.

### 2.2 Assist Feature OPC

Assist bar OPC, also known as scatter bar (SB) OPC, has been demonstrated to increase resolution and across pitch performance of isolated and semi-isolated features [3-6]. One limitation to assist feature OPC is the printability of the bar: the desired lithographic effect may be compromised if the OPC feature itself is resolved. Assist feature OPC has also been described using various treatments but it can be most useful to consider the diffraction field effects introduced [2]. It would be beneficial to place assist bars at frequencies that coincide with harmonics of the frequency of the primary mask features. This implies that bars should be placed at integer multiples of the main feature frequency. For a single bar solution, the bar is placed midway between main features. This often results in problems for dense features when a bar cannot be made small enough to avoid printing. For low feature density, the impact of a single bar is insufficient and multiple bars are placed

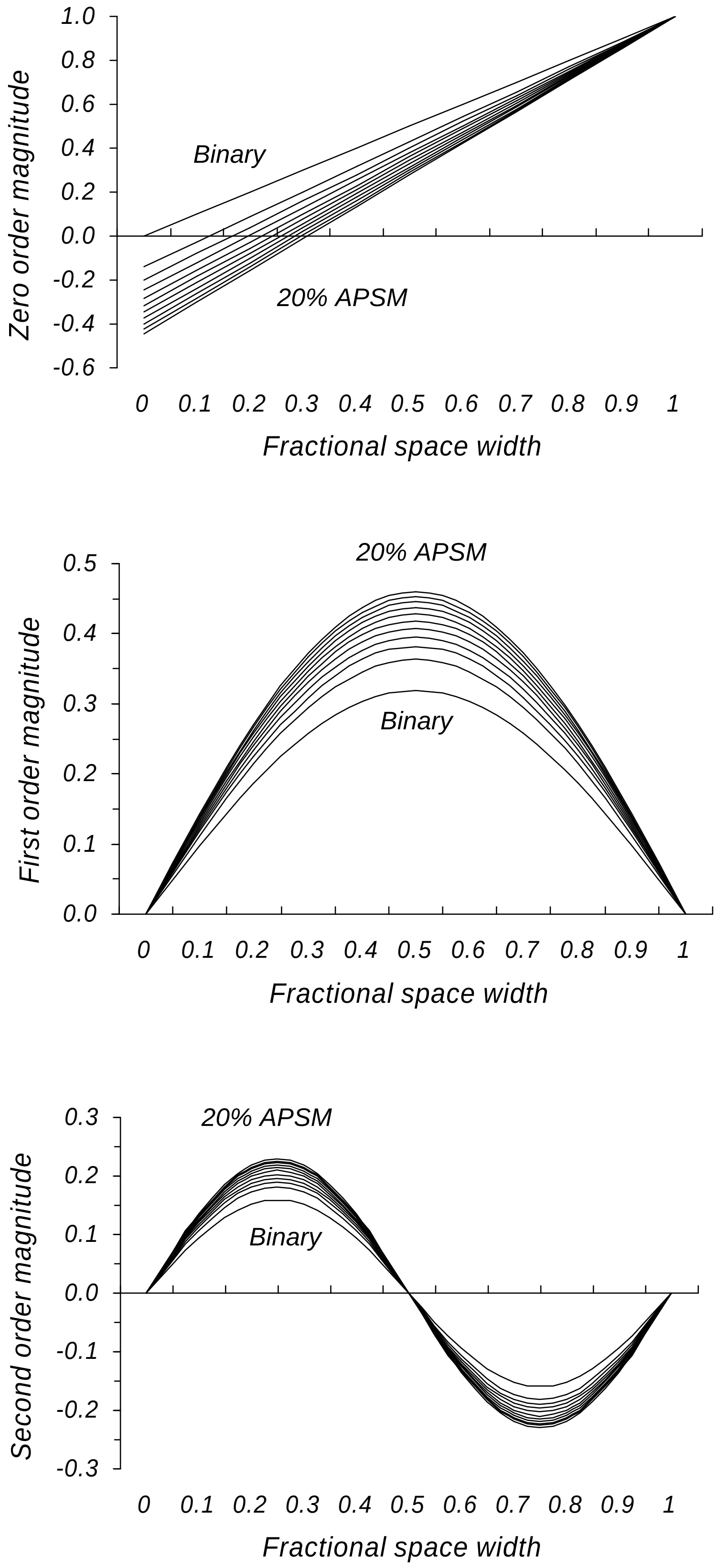

Figure 3. Plots of the zero, first, and second diffraction order values for attenuated phase shift mask (APSM) transmission between 0% (binary) and 20% with 2% increments. The fractional space width is the portion of the pitch value that consists of a space, where a small value represents a small space and a large value represents a small line. A fractional space width of 0.5 corresponds to equal line/space features. As APSM transmission increases, the value of the zero diffraction order decreases while first and second orders increase. Side lobe artifacts arise as the zero diffraction order fails to sufficiently bias the first diffraction order image, as shown in Figure 4.

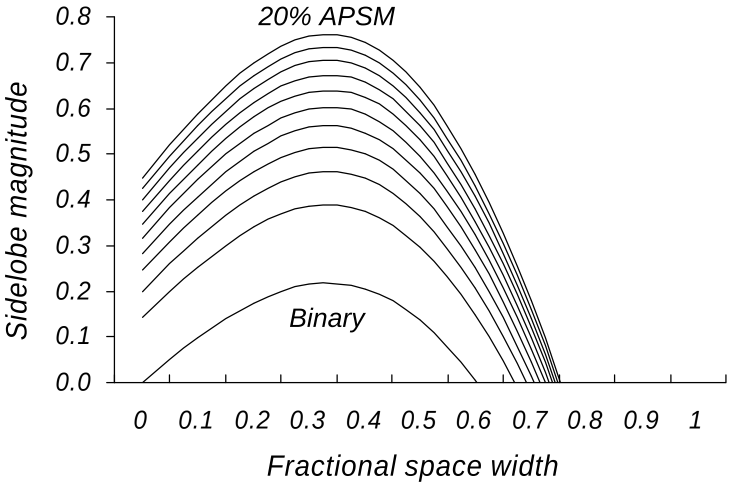

Figure 4. The coherent side lobe magnitude for APSM with transmission values between 0% (binary) and 20% for fractional space width values from zero to one. The maximum sensitivity to side lobe printing with APSM occurs at a 0.30 fractional space width. This corresponds to 1:2.33 duty ratio space or contact features. The maximum sensitivity to contact side lobe printing across the diagonal occurs when contacts are spaced 1:1.36 duty ratio along an X/Y axis. The likelihood that side lobe artifacts will print decreases for line features and is of little concern for fractional space values above 0.7. This corresponds to 1:2.33 duty ratio line features.

within space regions. A desirable frequency solution however is generally not practical as the separation between outer bars and a main feature can be small. The solution is generally to place multiple bars spaced equally within a space opening, as shown in Figure 5. Placement of assist bars often relies on rules based on specific process and print performance [5,6].

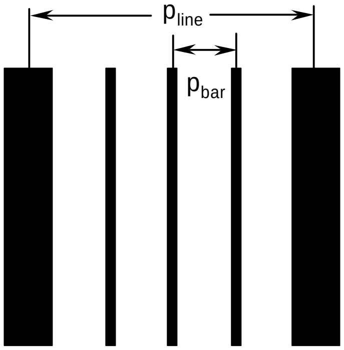

Figure 5. Layout of multiple assist bars for use with semi-isolated line features. Line pitch and bar pitch are indicated. The bar pitch here is a function of the line spacing rather than the line pitch.

### 2.2.1 Analysis of Multiple Assist Bars

In practice, multiple bars are evenly spaced within a space opening between main features. As a result, the frequency of the bars is a function of the main feature space width rather than of the pitch, as seen from Figure 5. Although it first appears that this assist bar placement may not lead to a desired bar frequency solution, it turns out that it is of little consequence for small closely spaced bars. Although the bar frequency does not coincide with that of the main features, it is generally beyond the diffraction limits of the imaging system. Because of this, no first order diffraction energy is collected from the bars making the bar frequency inconsequential. Consider for example Figure 5 consisting of 150nm main features with a 1:5 duty ratio using 248nm wavelength and a 0.70NA objective lens. A typical bar size of 60nm placed on a 187.5nm pitch will result in three evenly spaced bars between the main features. The resulting $k_1$ for these bars is 0.27, effectively eliminating lens capture of first diffraction orders using $\sigma$ values of 0.95 and below. With only zero diffraction order collection, the entire space between the main features experiences a reduction in intensity as a function of the bar width ($b$) and bar pitch ($p_b$):

$$\text{Space Intensity Reduction} = \left(\frac{p_b - b}{p_b}\right)^2 = (0.68)^2 = 0.46$$

The result is exactly that which would be expected if the space transmission was equivalently reduced. Such half-toning or gray scaling solutions can be limited because of the overall adverse impact on image modulation. While the zero diffraction order of the main features is reduced, so too are the higher diffraction orders where their magnitude becomes:

$$|\mathrm{Mag.}|_{\text{zero order}} = \left(\frac{p_b - b}{p_b}\right)(s/p)$$

$$|\mathrm{Mag.}|_{\text{first order}} = \left(\frac{p_b - b}{p_b}\right)\left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{s}{p}\right)\right|$$

$$|\mathrm{Mag.}|_{\text{second order}} = \left(\frac{p_b - b}{p_b}\right)\left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{2s}{p}\right)\right|$$

Figure 6 for example shows aerial image isofocal slices for 1:2.5 duty ratio 150nm features with various amounts of half-toning or gray scaling, filling the entire space between main line features, as is accomplished with multiple scatter bars. Image isofocal inflection points are reduced at the cost of image modulation. No isofocal positional shift is possible and performance of the features is generally reduced.

It has been suggested that the effect of the adding multiple assist bars corresponds to the introduction of a frequency character to isolated features so as to resemble that of the dense features. This analysis is problematic on two accounts. First, as shown above, the frequency of the bars is often beyond imaging limits, eliminating all but their zero diffraction order influence. Second, if the bars are placed at a frequency that matches that of the dense main features, the likelihood that the bars will print increases when using modified illumination. The frequency of the bars would be such that off-axis distribution of diffraction energy will increase the modulation and increase the depth of focus of the bars themselves. This is not a desirable effect.

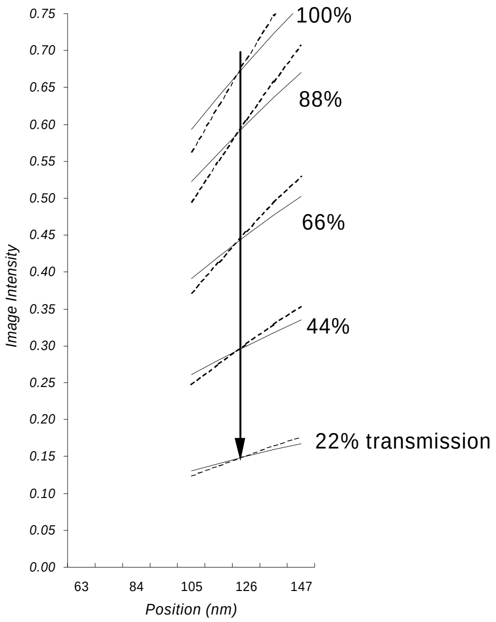

Figure 6. Plots of isofocal slices of 150nm aerial images with at 1:2.5 duty ratio with various amounts of half-toning or gray scaling between main line features. The result of the reduction in the magnitude of all diffraction orders is a decrease in image modulation and focal depth.

### 2.2.2 Frequency-Preserving, Single Assist Bar OPC

Improvements in the imaging performance of assist bar OPC can be realized if the frequency content of the bars is preserved. This is achieved when using a single bar because of the 2X multiple of the bar frequency with respect to that of the main features. The use of a single opaque scatter bar can be limited as the required bar size becomes large enough to image. When a single opaque bar is replaced with multiple bars, the frequency content can be eliminated, giving rise to significant modulation loss. To evaluate the full potential of frequency-preserved bars, we will confine bars so that they are forced into desirable frequency locations. Simply put, we consider single bars that are placed midway between main masking features. To allow for the greatest control of the impact of these bars, the width of the bars is allowed to vary from values of zero width up to the entire space width between the main mask features. The transmission of the bars is allowed to vary from 0% to 100% where 0% corresponds to the conventional binary bar.

The influence that assist bars have on the magnitude of the zero, first, and second diffraction orders can be calculated for a mask such as that shown in Figure 7. By introducing an assist feature within the space between main mask features, the primary diffraction orders for the mask field are modified. For opaque main features and non-attenuating clear openings, the magnitude of the orders become:

$$|\mathrm{Mag.}|_{\text{zero order}} = \left[1-\left(\frac{b}{s}\right)\left(1-\sqrt{I_b}\right)\right]\cdot\left(\frac{s}{p}\right)$$

$$|\mathrm{Mag.}|_{\text{first order}} = \left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{s}{p}\right)-\left(1-\sqrt{I_b}\right)\left(\frac{b}{p}\right)\mathrm{sinc}\left(\frac{b}{p}\right)\right|$$

$$|\mathrm{Mag.}|_{\text{second order}} = \left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{2s}{p}\right)-\left(1-\sqrt{I_b}\right)\left(\frac{b}{p}\right)\mathrm{sinc}\left(\frac{2b}{p}\right)\right|$$

where $s$ is main feature space width, $p$ is main feature pitch, $b$ is bar width, and $I_b$ is bar intensity.

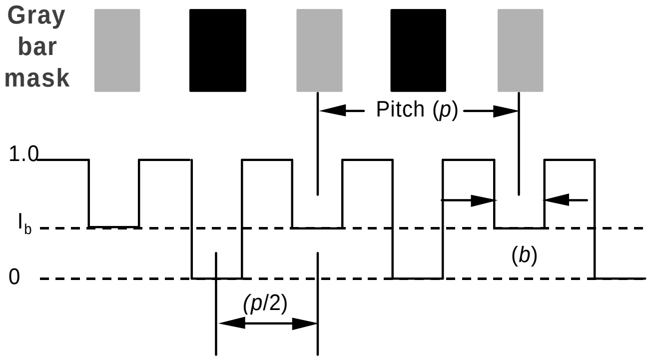

Figure 7. A mask electric field diagram for a gray bar OPC mask. Assist features are placed between main features with variable width and transmission.

Unlike the half-toning or gray scaling effect of the multiple sub-resolution opaque bars, the modulation of the diffraction orders is unique and a function of the bar parameters. Figure 8 shows how the primary diffraction orders are influenced by the assist features. Zero order magnitude values are plotted along with the first and second order magnitude values normalized to the resulting value of the zero order. This gives an indication of how higher orders are modified with respect to the zero order. These plots are for 1:1 and 1:2.5 duty ratio features with gray bar assist features ranging from zero width to the entire space opening in the mask. A fractional bar width of zero implies no bar and a width of 1 implies a full space width bar. The transmission of the bars is allowed to vary from 0% (binary) to 100% (no bar). The half-toning solution is the right side of the plots, where the effective fractional bar width is 1.0. Here, the normalized first and second order values remain unchanged, as described in Section 2.2.1. The single scatter bar solution is the 0% transmission bar. Inspection of the 1:2.5 duty ratio plots show how the zero order magnitude can be reduced with the SB to a value approaching that of the 1:1 features. This would have the effect of reducing the isofocal point of the 1:2.5 duty ratio features closer to that for the 1:1 features. A fractional bar width of 0.3 would produce an equivalent zero order. The impact on higher orders is also shown, where a decrease in first orders result along with an increase in second orders. Problems arise when the second order magnitude rises to the point where the bar itself prints. Experience shows that a 0.3 width SB will print in resist, making this solution impractical. A more practical limit to SB width may be a 0.15 to 0.2 fractional width.

If a gray bar is chosen as the assist feature, the printability issues resulting from large second order effects can be reduced. Figure 9 shows three gray bar solutions for 1:2.5 duty ratio features that result in equivalent zero order reduction. Specifically, these are a binary scatter bar with a 0.17 fractional width, a 25% transmitting gray bar with a 0.33 fractional width, and a 44% transmitting gray bar with a 0.50 fractional width. The second order values are reduced with increasing bar width and decreasing transmission. Images in Figure 9 are of 150nm lines with a duty ratio of 1:2.5 through 300nm of defocus. The corresponding bar widths are indicated. The intensity of the bar region for the 44% transmitting 0.5 width bar is 16% larger that that for the 0.17 width binary bar at best focus. The likelihood that the gray bar will print is significantly

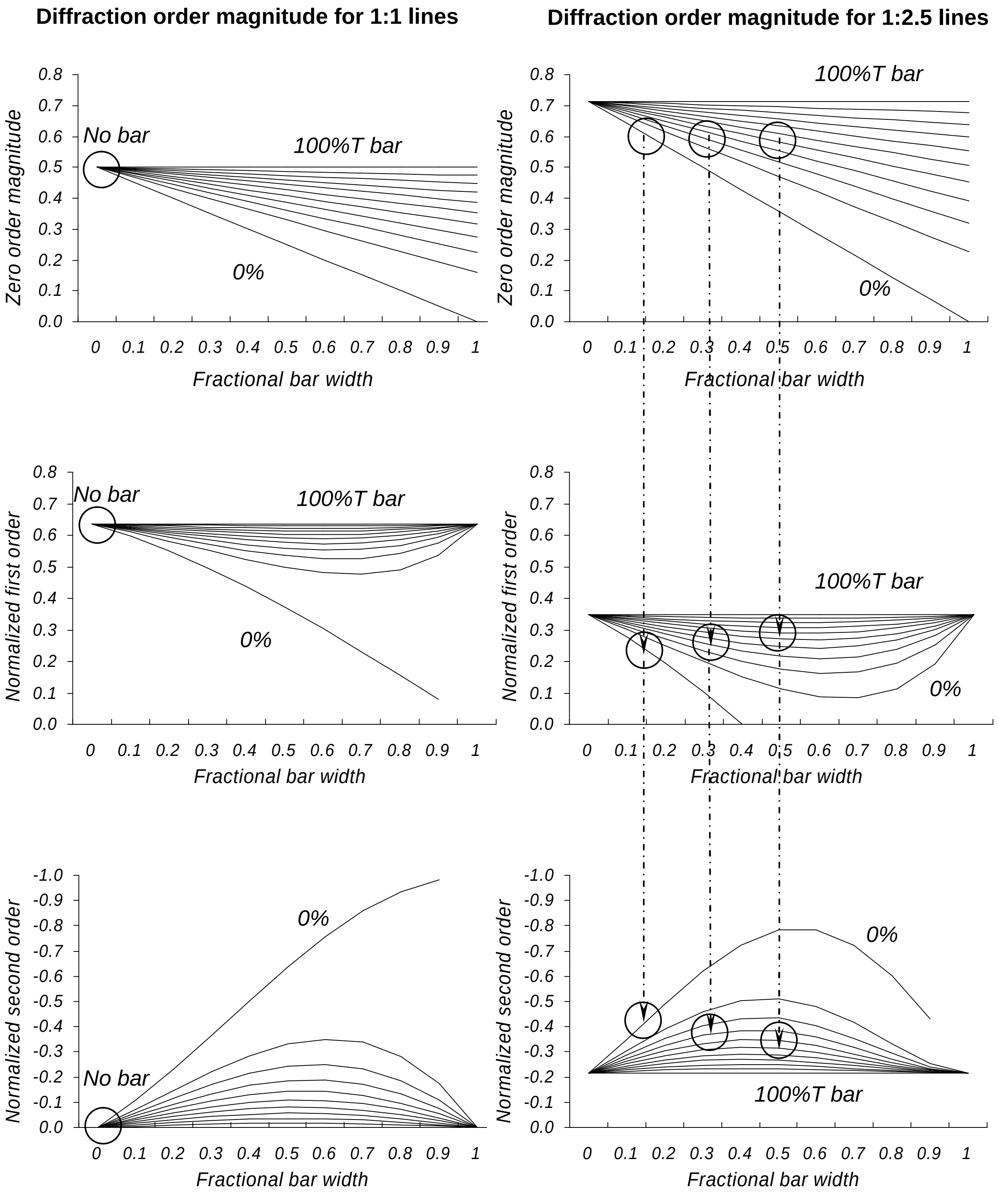

Figure 8. Plots of the zero, normalized first and normalized second diffraction order values for 1:1 and 1:2.5 duty ratio lines using various bar width and bar transmission values. The example shows equivalent zero order reduction solutions for 0.17, 0.33, and 0.50 fractional bar width and the impact on first and second diffraction orders.

reduced. More aggressive assist feature OPC can be carried out using a gray bar and Figure 10 shows how the isofocal point of these features can be reduced further by using a 30% transmitting 0.5 width bar. The isofocal inflection point is reduced an additional 13% and the printability of the bar is still quite low. The significance of gray assist bars will become more pronounced when modified or off axis illumination is considered.

A plot of isofocal slices for 1:2.5 duty ratio 150nm features is shown in Figure 11. The binary case with no OPC is compared to four assist bar cases. By allowing for some transmission within the assist bars and by preserving spatial frequency by using a single bar, more adjustment of the image isofocal inflection points is possible. Matching of the performance of more isolated features to more dense features becomes possible.

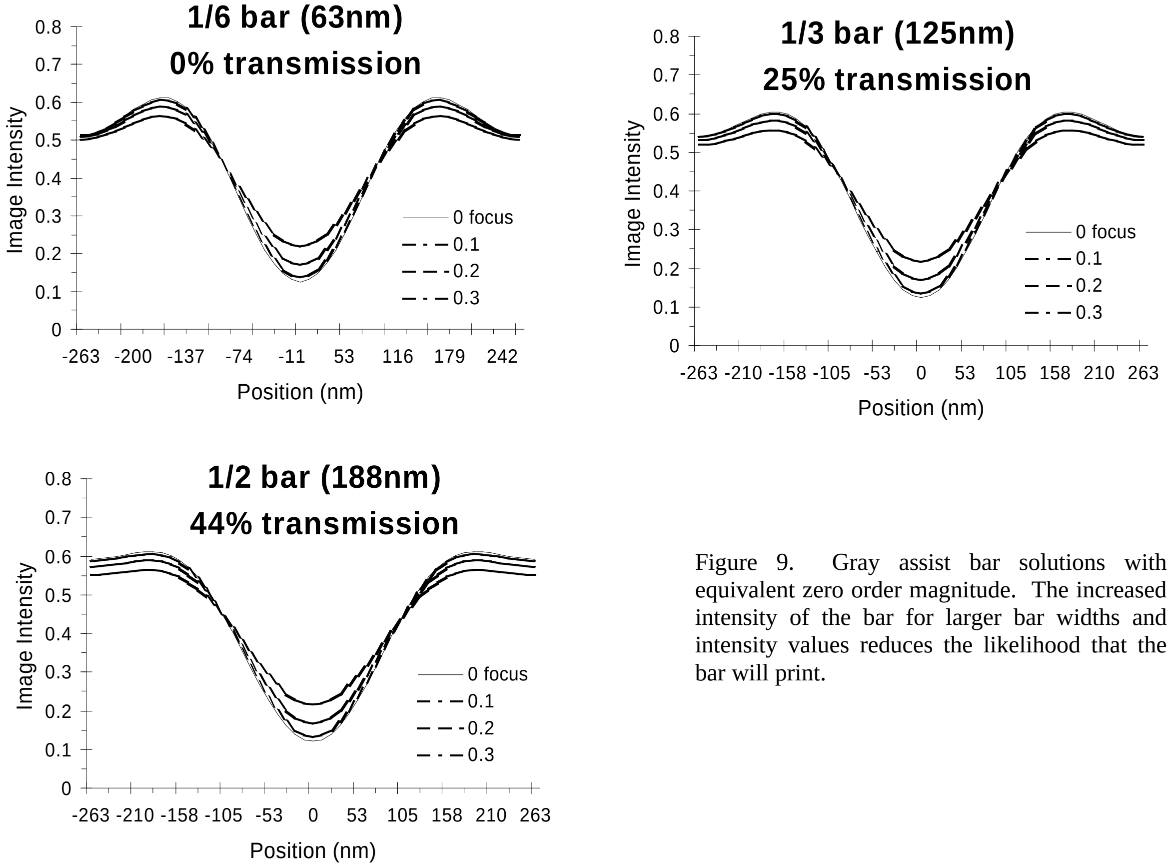

Figure 9. Gray assist bar solutions with equivalent zero order magnitude. The increased intensity of the bar for larger bar widths and intensity values reduces the likelihood that the bar will print.

## 2.3 Combining APSM and Assist Bars

It has been shown that APSM has the effect of reducing zero order contribution to imaging while increasing first order effects. This can lead to image improvement but can also lead to artifacts as the first order becomes too large. The use of frequency-preserved gray bars reduces the zero order contribution to imaging with an increase in the second order. As the second order increases, the bar is more likely to print. The combination of APSM with gray bar OPC seems like a logical progression to reach optimum imaging potential and off-set problem areas. The resulting primary diffraction orders as influenced by APSM and assist bars become:

$$|\mathrm{Mag.}|_{\text{zero order}} = \left[\,[1+\sqrt{T}]\,(s/p) - \sqrt{T}\right] \times \left[1-\left(\frac{b}{s}\right)\left(1-\sqrt{I_b}\right)\right]$$

$$|\mathrm{Mag.}|_{\text{first order}} = [1+\sqrt{T}]\left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{s}{p}\right)\right| - \left|\left(1-\sqrt{I_b}\right)\left(\frac{b}{p}\right)\mathrm{sinc}\left(\frac{b}{p}\right)\right|$$

$$|\mathrm{Mag.}|_{\text{second order}} = [1+\sqrt{T}]\left|\left(\frac{s}{p}\right)\mathrm{sinc}\left(\frac{2s}{p}\right)\right| - \left|\left(1-\sqrt{I_b}\right)\left(\frac{b}{p}\right)\mathrm{sinc}\left(\frac{2b}{p}\right)\right|$$

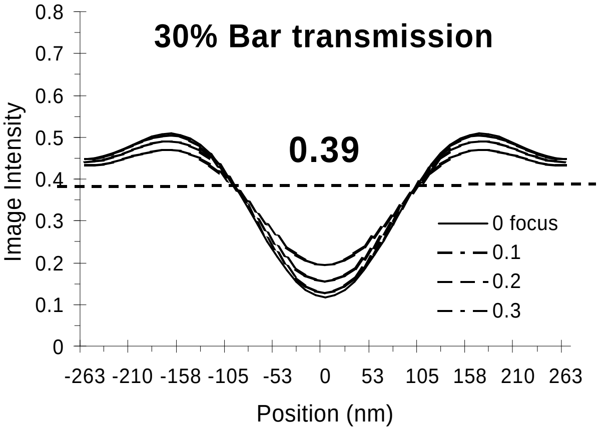

Figure 10. A 0.50 width gray bar (188nm) solution for further reduction in the isofocal inflection point.

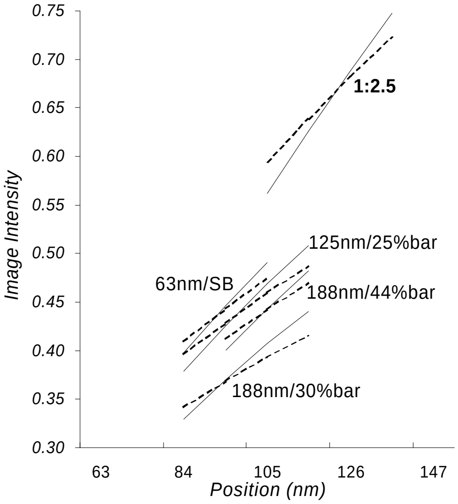

Figure 11. Plots of isofocal slices of 150nm 1:2.5 aerial images with various gray assist bar OPC. Reduction of the intensity and position of the isofocal inflection points will lead to increased across pitch process overlap

Figure 12 is a plot of the primary diffraction orders resulting from a combination of an opaque assist bar with APSM for 1:2.5 features. APSM values are varied from 0% (binary) to 20%. SB widths are varied from zero to the full space width. As described earlier, a practical limit for a single scatter bar may be 0.15 to 0.20 of the space width opening. The results suggest that by combining opaque assist bars with APSM, increased APSM transmission could be used. For example, a 10% APSM using a 0.17 width SB results in side lobes equivalent to those for a 6% APSM without assist bars. Figure 13 shows two APSM examples combined with gray assist bars. Plots are of the zero, normalized first and normalized second diffraction order values for 1:2.5 duty ratio lines with 6% and 18% APSM using various gray bar width and gray bar transmission values. The example shows how APSM reduces zero order while increasing first order and impacting second order to a lesser degree. At a zero gray bar width, the increase in first order can be large enough for high transmission APSM that side-lobe artifacts result. The use of gray bars can further reduce the zero order as well as first order, decreasing the likelihood of side lobe effects. Frequency-preserving gray bars are required to achieve this additional control.

## 3. GRAY BAR MASK FABRICATION METHODS

Several opportunities for gray bar mask fabrication exist. One solution is the use of half-tone features as small sub-resolution masking elements placed so that first diffraction orders of the elements are not collected with the imaging tool. These elements can consist of small islands or holes, such as those shown in Figure 14. The sizing and pitch of these features are adjusted to achieve the desired transmission values within a gray bar. For example, using a 248nm wavelength and 0.70 NA with a partial coherence value of 0.85, 60 nm islands placed on 80, 100, 120, and 140nm grids results in transmission values of 21%, 45%, 62%, and 74% respectively. Alternatively, a half-tone gray bar can be fabricated using sub-π or super-π phase shifted elements on a sub-resolution grid. Phase islands of 40, 60, 80, and 100° result in transmission of 12%, 25%, 42%, and 60% respectively.

A multilayer mask structure could also be employed to achieve the desired halftoning. As an example, an amorphous Si or a Si-rich silicon nitride layer could be used below a conventional Ar-Chrome masking layer to allow for dual tone masking. In the case of gray bars combined with APSM, the Ar-Chrome layer would be replaced with an absorbing phase shifting layer. Methods of imaging main features and assist features can be carried out using several self-aligned strategies introduced for multiple level mask fabrication. Fabrication methods are currently being explored and will be addressed in future disclosures.

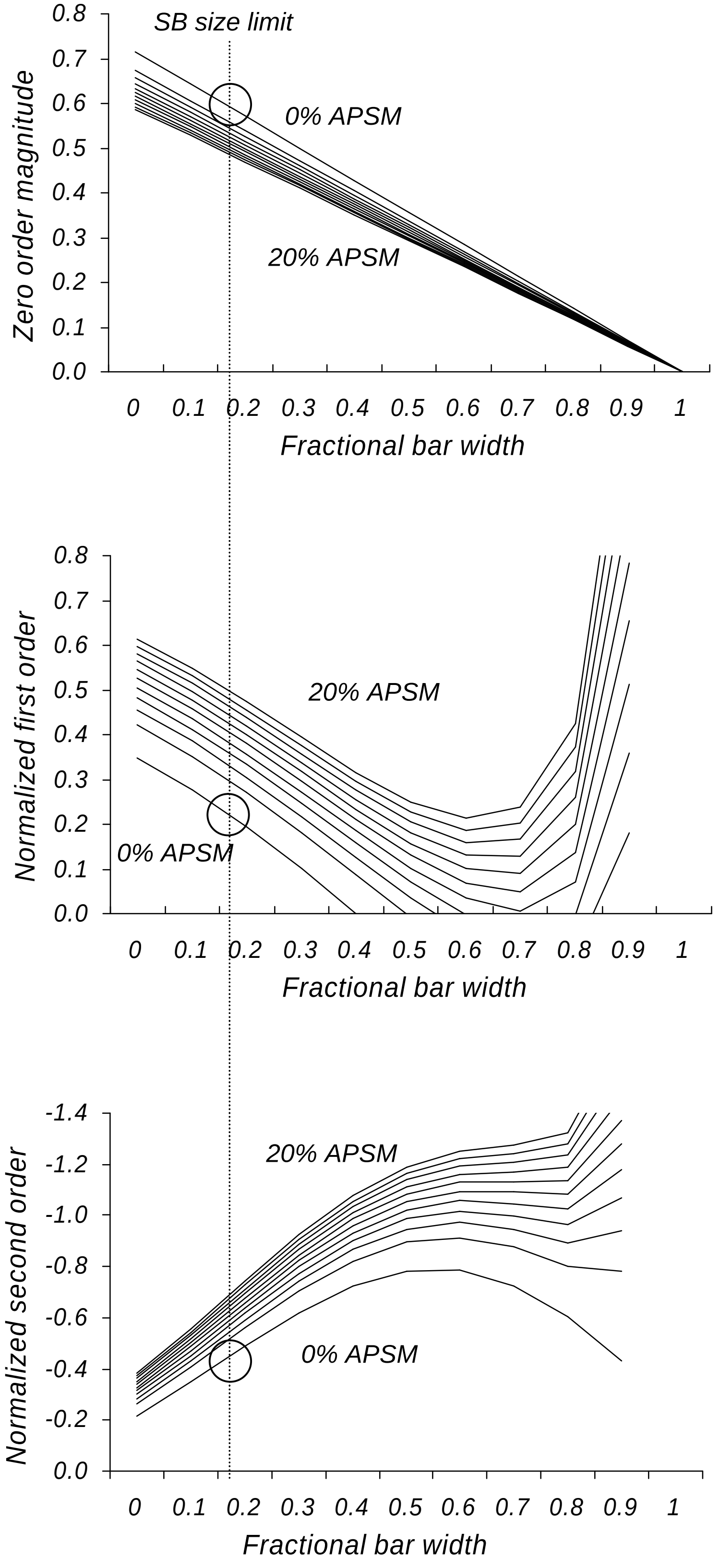

Figure 12. Plots of the zero, normalized first, and normalized second diffraction order values using an attenuated phase shift mask (APSM) combined with scatter bar (SB) OPC for 1:2.5 duty ratio lines. The fractional SB width is plotted with APSM transmission values between 0% (binary) and 20% . For 150nm primary features, the limiting SB size may be 60nm. This corresponds to a 0.16 fractional bar width for 1:2.5 duty ratio. APSM combined with SB can reduce zero order contribution with small increases in first and second order. The impact of the combination is reduced as with increasing duty ratio.

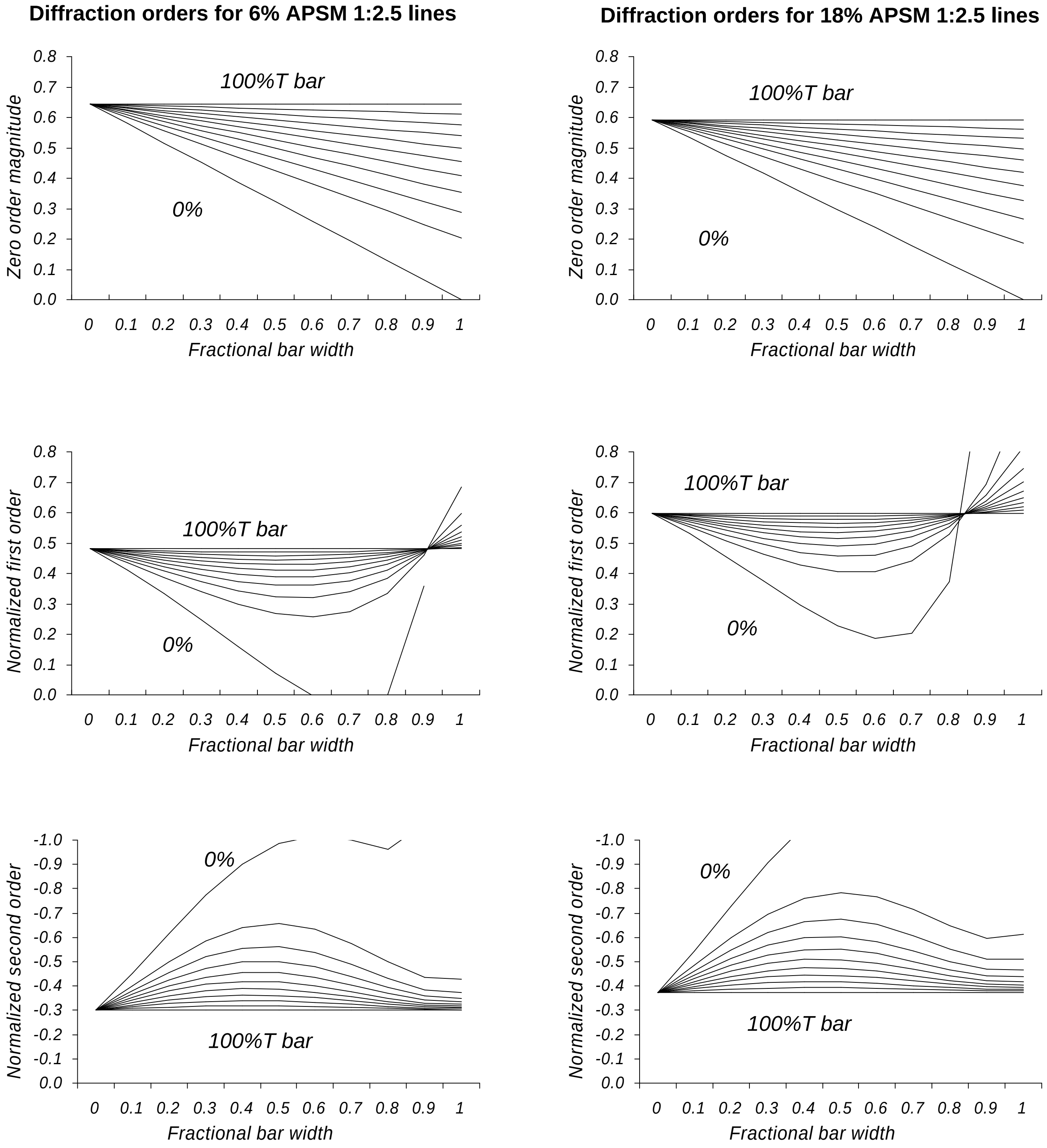

Figure 13. Plots of the zero, normalized first and normalized second diffraction order values for 1:2.5 duty ratio lines with 6% and 18% APSM using various bar width and bar transmission values. The example shows how APSM reduces zero order while increasing first order and impacting second order to a lesser degree. At zero bar width, the increase in first order can be large enough for high transmission APSM that side-lobe artifacts result. The use of frequency-preserving assist bars can lead to improvements in imaging.

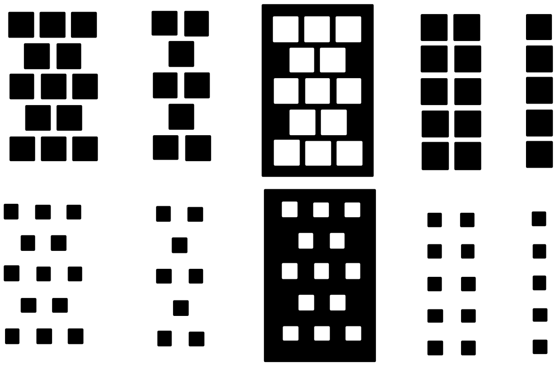

Figure 14. Various element half-toning designs to create a gray bar and to control transmission of the bar.

## 4. OPTIMIZING ILLUMINATION

The analysis carried out above for APSM and assist bar OPC considered the primary diffraction orders resulting from a single illumination point, or coherent illumination. The expansion of these concepts to cases of partial coherence or customized illumination leads to insight into appropriate illumination choices for use with mask RET. The use of conventional circular illumination is generally not optimal for imaging of small pitch features because of the large amount of non-imaging background zero order collected by a lens. By reducing the zero order component for these small features, two beam imaging is allowed and image modulation is increased. As pitch values increase, the zero order contribution is combined with corresponding first diffraction order energy eliminating its non-imaging impact and also increasing modulation. The consequence is that illumination can be customized for small pitch values while conventional circular illumination is best for large pitch values. The goal when combining mask RET with illumination RET is to target small pitch feature improvement with custom illumination and address through-pitch image matching with mask RET.

The zero order and first order contribution for small pitch images can be determined based on feature pitch, wavelength, NA, and the maximum allowable partial coherence value. Figure 15 shows how it would be desirable to remove the center portion of an illumination pupil for X-oriented 150nm 1:1 features when imaged with a 248nm wavelength and 0.70NA. When considering X and Y feature orientations, a good solution for illumination is at the intersection of the first order contribution for the two feature orientations. As pitch values increase, these intersections move closer to the optical axis. By placing weighting functions on various pitch values, a composite illumination shape can result, as shown in Figure 16. The illumination at the edge of the source is best for small pitch features while the illumination in the center is for more isolated features. Figure 17 shows how use of this source for imaging 150nm lines will lead to modulation and focal depth improvement of 1:1 to 1:1.5 duty ratios but have little or adverse impact on the more isolated features. To enhance these features, mask RET is needed.

Figure 15. The optimum illumination for 150nm 1:1 features using 248nm wavelength and 0.70 NA through removal of one-beam zero order contribution.

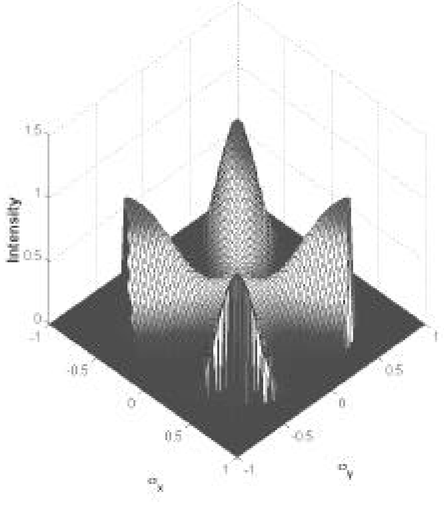

Figure 16. An optimized illumination profile for 150nm geometry with duty ratios from1:1 through 1:1.5

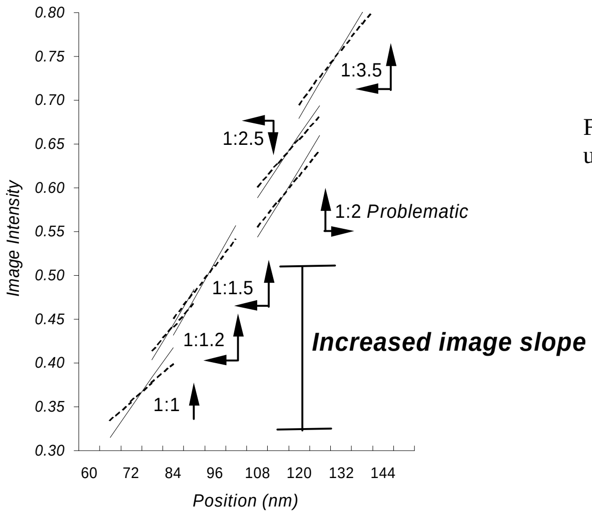

Figure 17. Plots of isofocal slices of 150nm features using the illumination source of Figure 16.

## 5. GRAY BARS AND CUSTOM ILLUMINATION

Improvement of the across pitch performance of 150nm features is targeted using the source described above in combination with frequency preserving gray bar assist features. Gray bar solutions were derived for duty ratio values between 1:1.2 and 1:3.5 using the primary diffraction order evaluation methods described in Section 2.2.2. This approach allows for these solutions prior to any lithographic simulation or imaging. Table 1 summarizes the results including the line bias required for each feature and the gray bar dimensions for a 50% transmitting bar. The bar width is always centered within the space opening and widths vary from 50nm for the 1:1.2 features up to 220 nm for the 1:3.5 features. These represent frequency-preserving solutions that would be difficult for opaque assist features. Figure 18 contains the plots of the resulting aerial image isofocal inflection slices that result from the combination of these gray bar solutions with the custom illumination described in Section 4. The isofocal slices across all duty ratios is brought close to that for the 1:1 features, with respect to both intensity and position. The problem pitch here is the 1:2 duty ratio case, where difficulty is experienced with achieving the improvement seen at other values. This is a consequence of the pitch of these features, which as a multiple of 1.5X of the 1:1 features optimized with the illumination. This illumination condition places the first diffraction order of the 1:2 duty ratio features in the center of the objective lens pupil, resulting in a maximum defocus aberration effect when combined with its corresponding zero order. A second gray bar solution was carried out to compensate for this problematic pitch effect and an improved image isofocal slice plot is shown in Figure 19. This aerial image performance would be difficult without the frequency-preserving character of the gray bars.

| | **1:1** | **1:1.2** | **1:1.5** | **1:2** | **1:2.5** | **1:3** | **1:3.5** |
|---|---|---|---|---|---|---|---|
| **Line bias (nm)** | - | - | - | - | - | 10 | 20 |
| **Bar transmission** | - | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Space design** *[space/bar/space] (nm)* | - | [65/50/65] | [83/60/83] | [80/140/80] | [88/200/88] | [108/225/108] | [143/220/143] |

Table 1. Biasing and gray bar results for application to 150nm features using the custom illumination of Figure 16.

## 6. CONCLUSIONS

By dealing with RET methods in the spatial frequency domain, and by concentrating on the primary diffraction orders for real/even mask structures, a common perspective can be established for evaluation of enhancement methods. We have described the manner by which masking RET influences the diffraction information for single source points as well as for more customized illumination. The concepts of frequency preserving Gray Bars has been introduced as a method to extend imaging performance for small features across a range of pitch or duty ratio values.

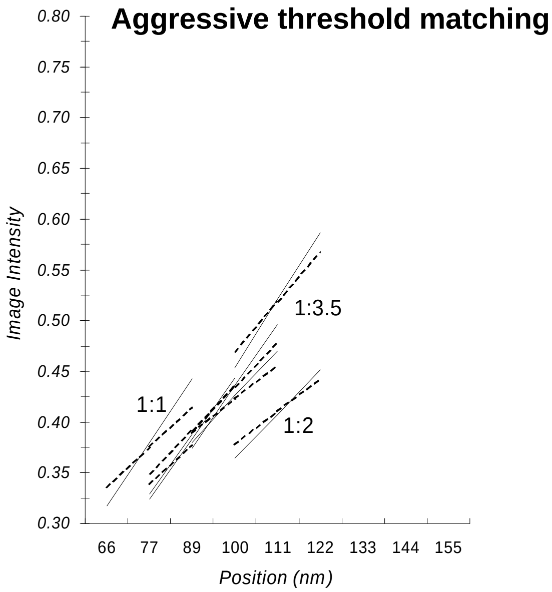

Figure 18. Plots of isofocal slices of 150nm images using the customized source along with the gray bar solutions in Table 1. The isofocal inflection points of all features have been brought closer together. The 1:2 duty ratio features remain problematic because of the distribution of the first diffraction order with the custom illumination.

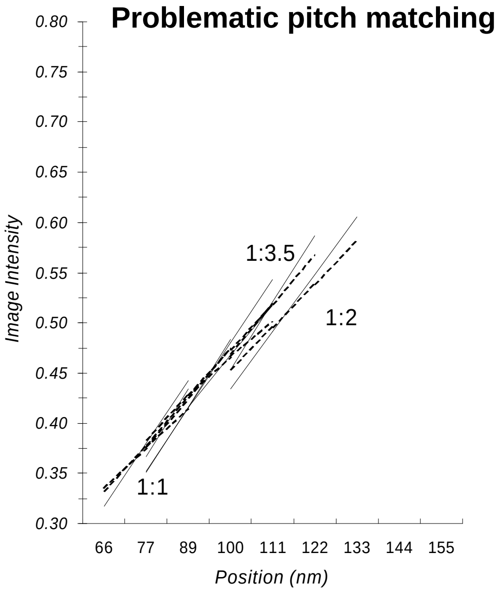

Figure 19. Plots of isofocal slices of 150nm images using the customized source along with the a second set of gray bar solutions to reduce the problems with the 1:2 duty ratio features. The adverse effects that custom illumination may have on unique pitch values can be reduced using frequency preserving gray bars.

## 7. REFERENCES

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