OPC and image optimization using localized frequency analysis

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ABSTRACT

A method of assist feature OPC layout is introduced using a frequency model-based approach. Through low-pass spatial frequency filtering of a mask function, the local influence of zero diffraction energy can be determined. By determining isofocal intensity threshold requirements of an imaging process, a mask equalizing function can be designed. This provides the basis for frequency model-based assist feature layout. By choosing assist bar parameters that meet the requirements of the equalizing function, through-pitch focus and dose matching is possible for large two dimensional mask fields. The concepts introduced also lead to additional assist feature options and design flexibility .

1. INTRODUCTION

Optical proximity effect reduction methods using sub-resolution assist features have been in use for several years. Reduction methods are referred to as Optical Proximity Correction (OPC) and specific approaches include the use of scatter bars [1] and sub-resolution assist features (SRAFs) [2]. Assist feature OPC has been shown to improve across pitch imaging performance of low k_1 features. Assist feature OPC has been described using various treatments but it can be most useful to consider the diffraction field effects introduced. Description and analysis has been carried out for a variety of RET combinations with assist feature OPC. [3,4] For multiple assist features, bars are evenly spaced within a space opening between main features. Bars are sub-resolution and the bar frequency 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. As an example, consider an imaging situation for 150nm main features with a 1:5 duty ratio using 248nm wavelength and a 0.70NA objective lens. A typical bar size may be 60nm and three evenly spaced bars can be inserted between features with a bar pitch of 187.5nm. The resulting k_1 for the bars is 0.27, effectively eliminating lens capture of first diffraction orders using σ 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):

$$\text{Space intensity reduction} = \left(\frac{p_b - b}{p_b}\right)^2 = (0.68)^2 = 0.46 \qquad (1)$$

The result is exactly that which would be expected if the space transmission was equivalently reduced. It has been suggested that the effect of the adding multiple assist bars corresponds to the introduction of frequency terms 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 the depth of focus of the bars themselves.

Current methods used for OPC layout are based on sets of rules for best pattern performance (known as rules-based OPC) or the extraction of models based on the parameters that result in best pattern performance (known as model-based OPC). With rules-based approaches, adjustments are applied to feature edges, bar sizes, and spacing based on pattern width and edge location. Model-based approaches are based on the convolution of predefined kernel functions with a mask function. [5] Kernel functions may incorporate specific optical, resist, and etch behavior. Both methods are concerned with the spatial (X-Y) fidelity between the structure layout, the mask function, the intensity images, and the images formed in photoresist. It is difficult to optimize lithographic imaging parameters such as OPC

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strictly from the traditional standpoint of dimensional analysis. Furthermore, it is difficult to perform optimum OPC layout using models or rules based on spatial (or X-Y) information and performance. Such approaches usually lead to sets of rules that are only valid around a small factor sample space.

2. ASSIST FEATURE OPC LAYOUT

Several approaches have been developed for OPC layout. Hybrid methods using sequential application of traditional rules-based and model-based have been employed to reduce the complexity of model-based algorithms alone. This is a consequence of operation in the spatial domain. If the complexity of model-based approaches can be reduced in the frequency domain, such methods would be preferred. Though spatial frequency analysis does not necessarily lead to reduced complexity, it could do so if a limited amount of frequency detail were needed for such a model-based approach. Since the main consequence of assist feature OPC is the reduction zero order frequency, analysis may be inherently simplified. When we consider the frequency content of low k_1 images and the impact of OPC, it becomes evident that this is indeed the situation. [3]

2.1 Low frequency impact on dense and semi-isolated features

Figure 1 is used to demonstrate the impact of the zero diffraction order on dense and semi-isolated images. Dense lines (1:1) and semi-isolated lines (1:3) are shown, where various OPC assist structures are inserted between the semi-isolated features. In each case, aerial images are plotted for incoherent illumination over a distance equivalent to twice the pitch. The value of the zero diffraction order bias is shown for each condition. Primary diffraction order magnitude (zero, first, and second orders) contributes to low k_1 imaging and can be calculated from the following equations:

$$|\mathrm{Mag.}|_{\text{zero order}} = [1-(\frac{b}{s})(1-\sqrt{I_b})]\cdot(\frac{s}{p}) \tag{2}$$

$$|\mathrm{Mag.}|_{\text{first order}} = \left|(\frac{s}{p})\mathrm{sinc}(\frac{s}{p})-(1-\sqrt{I_b})(\frac{b}{p})\mathrm{sinc}(\frac{b}{p})\right| \tag{3}$$

$$|\mathrm{Mag.}|_{\text{second order}} = \left|(\frac{s}{p})\mathrm{sinc}(\frac{2s}{p})-(1-\sqrt{I_b})(\frac{b}{p})\mathrm{sinc}(\frac{2b}{p})\right| \tag{4}$$

where b is the assist bar size, s is the space width, p is pitch, and I_b is the bar intensity. Figure 1 gives insight into the problems associated with determining a common process window over a variety of duty ratios. The zero diffraction order is primarily responsible for the isofocal intensity value for a given mask pitch. As the duty ratio is increased, the zero order (or DC signal) increases, leading to larger isofocal intensity. A resist process baseline operates in a small isofocal intensity range, most generally close to that for dense features. For semi-isolated features, the insertion of an assist feature leads to a decrease in the zero order, matching more closely to the behaviour of the dense geometry. An increase in the second order energy also results, which is a consequence of the placement of the bar mid-way between main features (producing a frequency harmonic). As the bar width increases, the zero order is further reduced but second order increases sufficiently so that the bar may begin to print. By reducing the transmission of the bar (making it a gray bar), a larger bar width is tolerable, while limiting its printability through more moderate increases in second order.

2.2 Separation of low frequency (DC signal) through convolution

The impact of assist feature OPC on the local mask DC signal leads to the improvements in process latitude and common process overlap demonstrated by their use. The convolution methods used in traditional model-base OPC attempt to describe a large array of imaging effects. The convolution kernel for assist feature OPC is not concerned with high frequency detail but instead the lowest frequency information on a local scale. Low-pass kernels of the form shown in Figure 2 are utilized for the separation of local DC signal. Rather than performing a convolution or sampling operation in the spatial domain however, we operate on a mask function in the frequency domain with a filter function that is represented by the Fourier Transform these kernels.

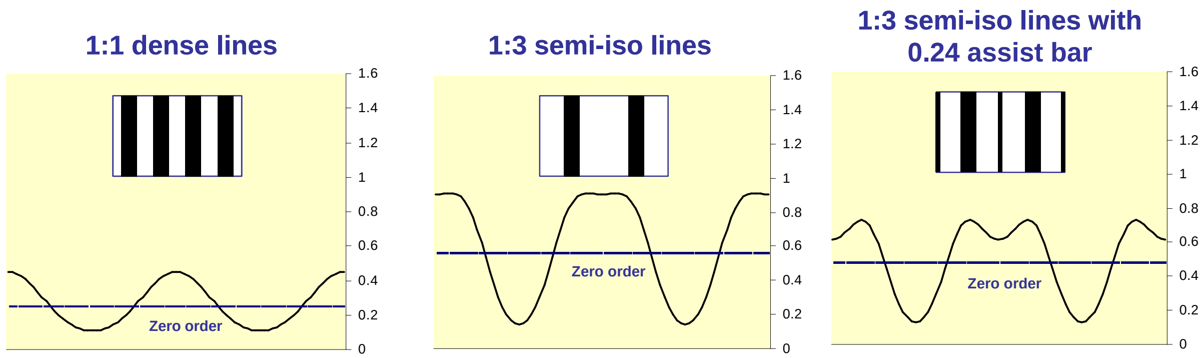
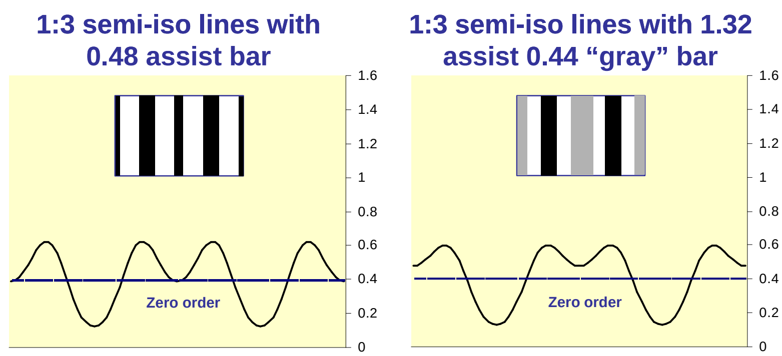


Figure 1. Incoherent aerial image plots for dense and semi-isolated lines and the impact of assist bar OPC on zero order isofocal intensity.



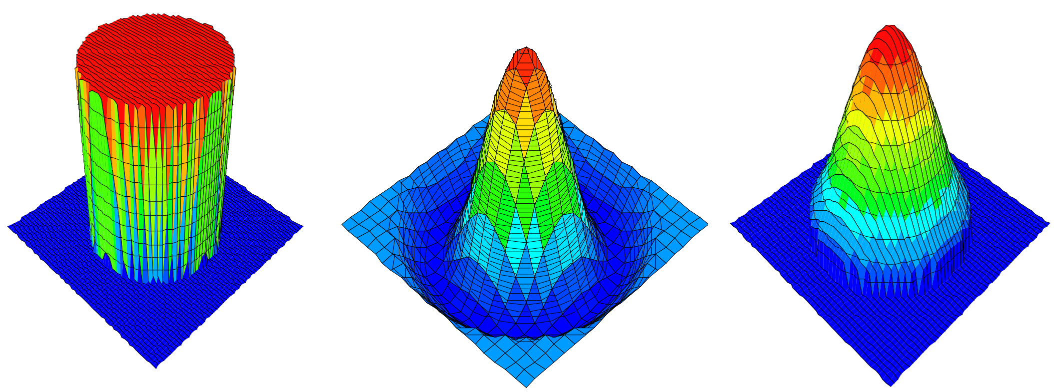


Figure 2. Kernel types h(x,y) for localized low frequency convolution.

Localized low frequency kernels are defined using lithography requirements, where sizing should discriminate between dense and isolated geometry. Figure 3 describes the method for choosing kernel width values, where the region of interest of the function h(x,y) should fall between dense pitch and isolated pitch values. If a limiting dense pitch value of $\lambda/(\sigma+1)\mathrm{NA}$ is considered, width values between $2\lambda/\mathrm{NA}$ and $4\lambda/\mathrm{NA}$ are practical.

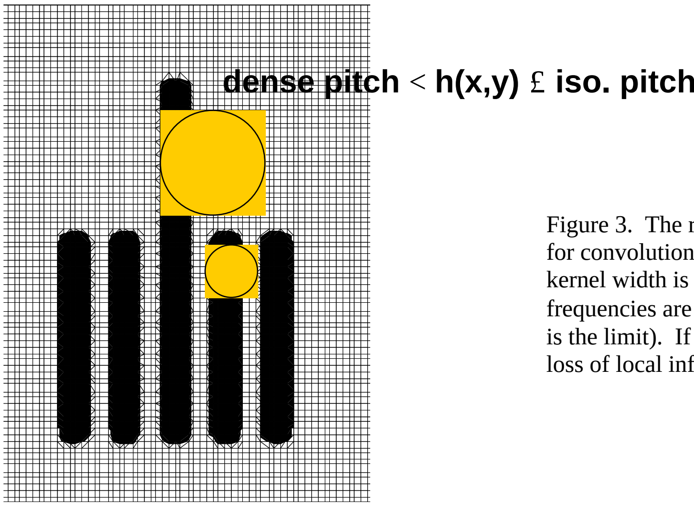


Figure 3. The region of interest for convolution kernels. If a kernel width is too small, high frequencies are included ($\delta(x,y)$ is the limit). If it is too large, loss of local information results.

2.3 Frequency filtering using image models

Frequency based filters that correspond to the kernels of Figure 2 are shown in Figure 4. These functions are defined in frequency domain with a corresponding width H(u,v) between NA/2λ and NA/4λ. The advantage of operating on a mask function in the frequency domain is the ability to insert the functions as pupil filters in a lithography image model. If such a frequency filter is inserted into a lithography model as a pupil plane filter, the entire parametric description of a lithography process is possible. The full kernel becomes the aberrated, partially coherent imaging system. The process is depicted in Figure 5 using a full lithography model.[6] A mask function is illuminated with an arbitrary source shape, leading to a partially coherent frequency plane distribution, which is filtered through the low frequency pupil function. The resulting image is an indication of the local DC signal across the mask field.

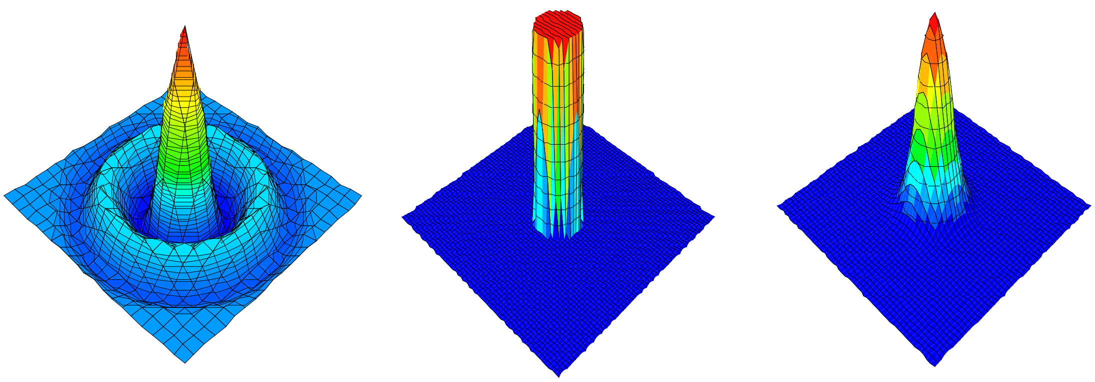


Figure 4. Frequency filters H(u,v) based on low frequency kernels. Width values vary between NA/2λ and NA/4λ.

3. APPLICATION TO ONE-DIMENSIONAL MASK PATTERNS

The mask function depicted in Figure 6 is used to demonstrate the analysis method used to determine assist feature application. In this example, 100nm lines are considered with duty ratios ranging from 1:1 through 1:4. A wavelength of 193nm is used with an objective lens NA of 0.8 and a partial coherence value of 0.8. Image results with defocus values from 0 to 1 μm are shown below the mask layout. The isofocal intensity varies through pitch from a value near 0.4 for 1:1 dense features to 0.8 for 1:4 features. This ~2X variation is at the heart of the problems associated

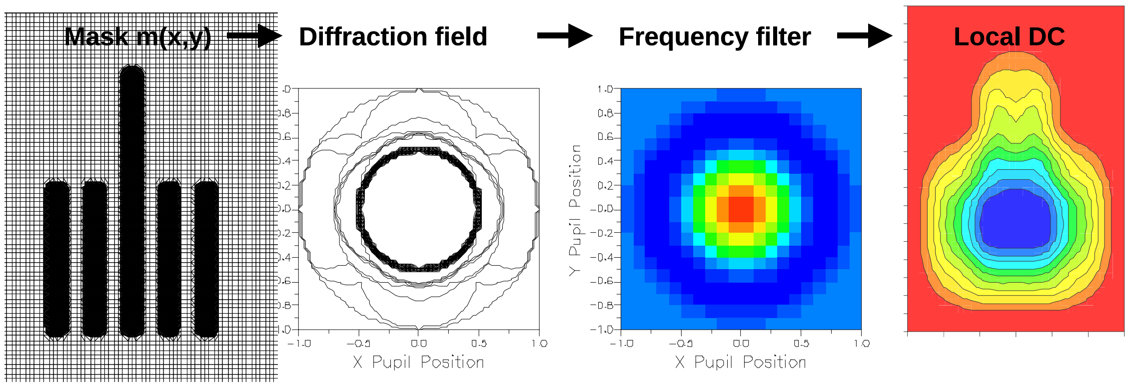


Figure 5. Frequency filtering approach using an image model to determine local DC signal.

with focus and dose matching across a large duty ratio range. The goal for assist feature OPC is to produce a better match in the isofocal intensity through this pitch variation.

Frequency plane filtering was carried out for the mask function using the method depicted in Figure 5 with a NA/4λ filtering function. The result is a local DC threshold function that is indicative of the isofocal behavior of the mask through focus. Figure 7 shows this result, with excellent agreement to the through-focus isofocal behavior, increasing from a value near 0.4 for 1:1 duty ratio to 0.8 for 1:4. Since this result is calculated using a lithography image model, it is possible to make variations in the imaging situation to arrive at unique solutions for specific image conditions. Figure 8 shows the through-focus behavior of the mask function imaged as before but illuminated with an annular source using an outer σ of 0.8 and an inner σ of 0.6. The isofocal behavior is shown along with the local DC threshold function, generated through frequency filtering. The solution is unique compared to that for partially coherent illumination. Note also the slight reduction in intensity in the space regions starting at a duty ratio of 1:2.5. This is an aliasing artifact, a result of higher frequency harmonics introduced with oblique illumination. Figure 9 shows the results using a quadrupole illumination with a center σ of 0.8 and a radius of 0.3. The local DC threshold function is also plotted.

The result from low frequency filtering can be used to generate mask corrections to equalize the isofocal behavior across the mask. An equalized mask transmission function is generated from the local DC threshold function, such as that seen in Figure 7. The result is shown in Figure 10, where a baseline intensity of 0.42 was chosen to match all duty values to dense lines. The resulting threshold leveling mask is shown in Figure 11, where the intensity of the space regions between lines is reduced according to Figure 10. Imaging results from this gray level mask are shown in Figure 12 through 1 µm of defocus. The isofocal intensity across pitch is reduced to values

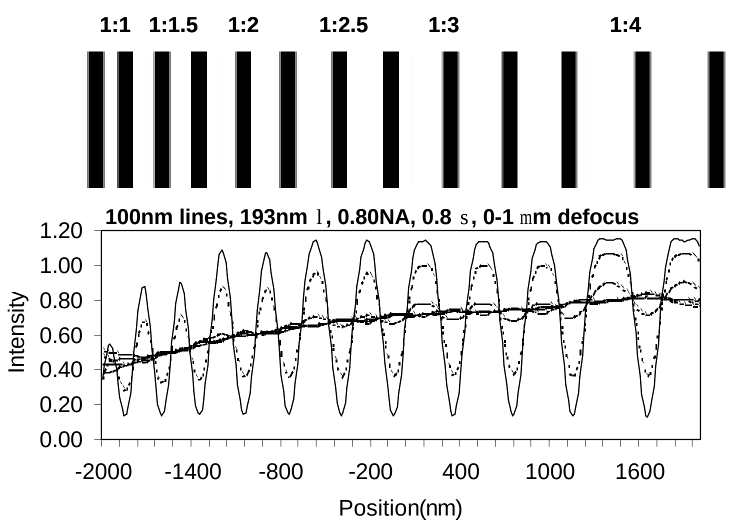


Figure 6. The mask function consisting of 100nm through pitch and the resulting aerial image behaviour through 1 µm defocus

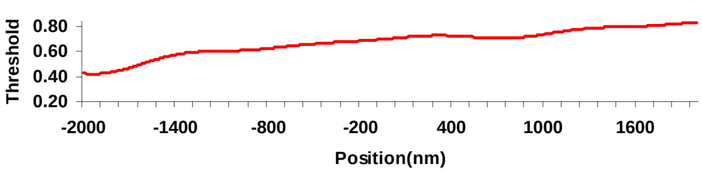


Figure 7. The local DC threshold function for 100nm features with 0.8 σ partial coherence.

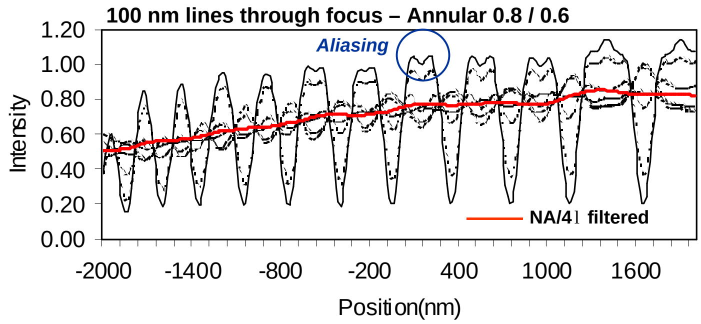


Figure 8. Isofocal performance and local DC threshold function for annular illumination.

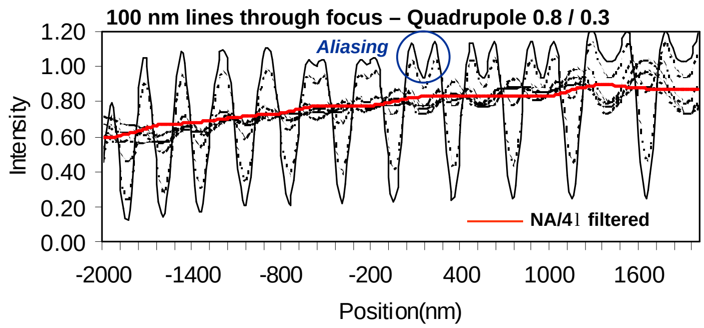


Figure 9. Isofocal performance and local DC threshold function for quadrupole illumination.

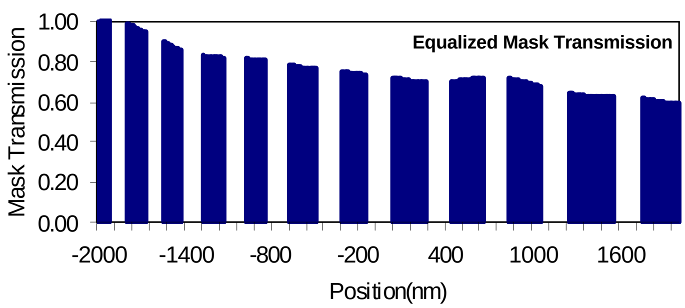


Figure 10. Equalized mask transmission function for partially coherent illumination.

between 0.40 and 0.48 by equalizing the dose in the space regions in the mask. Figures 13 and 14 show the unique results for annular and quadrupole illumination. The use of a gray level mask would have practical limitations, requiring translation into a binary representation to be compatible with lithographic imaging. This is accomplished through the use of assist features.

2.4 Assist feature layout through threshold equalizing

The solutions of Figures 12-14 are a result of a gray level mask function. The reduction of the intensity within space regions results in an equalization of the isofocal behavior. Equivalent solutions are possible by using sub-resolution assist features, designed so that their width and spacing consumes an equivalent amplitude (and resulting intensity). Rules are developed to define the limits of wavelength, NA, and partial coherence. An example is shown in Figure 15, where 25nm and 50nm bars are employed and equally spaced between main features as solutions to the equalized mask transmission, such as that from Figure 10. The equalization of isofocal intensity using bars for a partial coherence factor of 0.8 is shown in Figure 16. There are regions where bar printing becomes evident, especially at the 1:2.5 duty ratio. This is an artifact of the layout and mask constraints. Figures 17 and 18 show through focus imaging with annular and quadrupole illumination. Equalization is also achieved through the entire pitch range. Bar printing can be compounded with the high frequency aliasing effects from the oblique illumination used. This effect is problematic and often leads to the avoidance of certain pitch values.

4. PERPENDICULAR ASSIST FEATURES – LADDER BARS

Historically, multiple bars are arranged parallel between main features. The result is that which would be expected if the space transmission was equivalently reduced. Control of the isofocal intensity for certain space values is difficult with the multiple assist bar approach because of the constraints of the bar width and spacing values. An alternative method to achieve the effect of space intensity reduction is to place perpendicular ruled bars (or Ladder Bars, LBs) between main mask features where the bar pitch is beyond the resolution limits of the imaging tool, or below $\lambda/(\sigma+1)NA$. This can allow for finer control of the resulting space intensity reduction and it allows for control of an effective frequency component of the correction bars along the axis of the main feature edges and between the main feature. By placing perpendicular bars between the main features, the primary diffraction orders (that is the zero, first, and second orders) are modified according to Equations 2-4. Parameters are defined as before but the bars are oriented orthogonal to the main features. The presence of the perpendicular bars with pitch values below the diffraction limits of the exposure tool provides for the control of the main feature diffraction energy along the feature edges and at the ends.

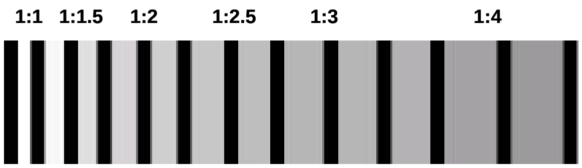


Figure 11. Isofocal equalizing gray level mask.

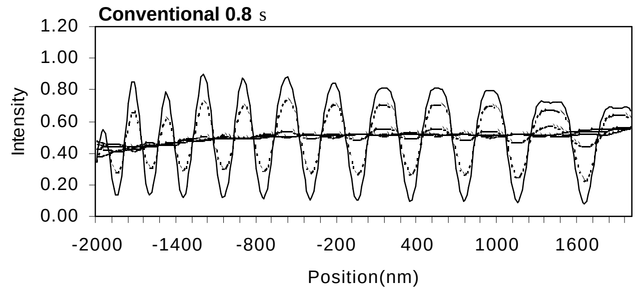


Figure 12. Equalized isofocal performance for partial coherence.

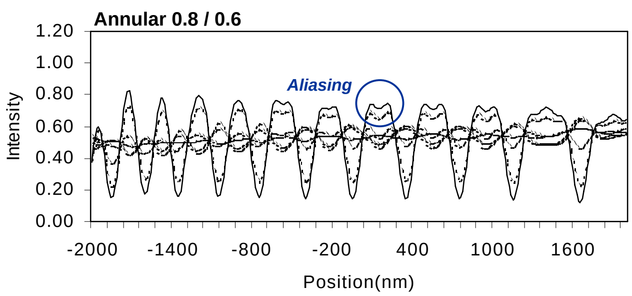


Figure 13. Equalized isofocal performance for annular illumination.

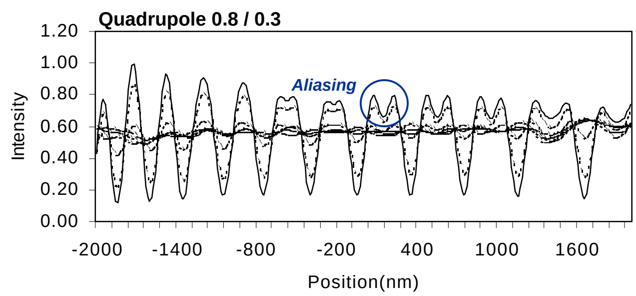


Figure 14. Equalized isofocal performance for quadrupole illumination.

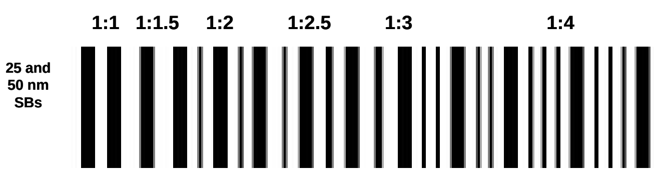


Figure 15. Assist feature OPC solution to isofocal equalizing mask.

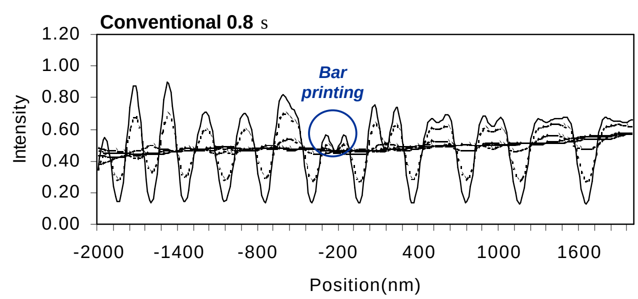


Figure 16. Equalized isofocal performance with assist feature mask for partial coherence.

An example of the use of perpendicular bars is shown in Figure 19. Conventional parallel assist bars are inserted in 1:2 regions of the masks. All other regions (excluding 1:1) contain 25nm Ladder Bars spaced to achieve the required intensity reduction for equalized isofocal performance. The use of this bar orientation increases the design flexibility of assist feature OPC. Figures 20 and 21 show imaging results for partial coherence and annular illumination. Note the absence of bar printing except in the 1:2.5 region of the mask, as compared to the conventional assist bar results of Figures 16-18. There are also advantageous polarization effects with perpendicular assist bars, which are described in a companion paper in this publication.[7]

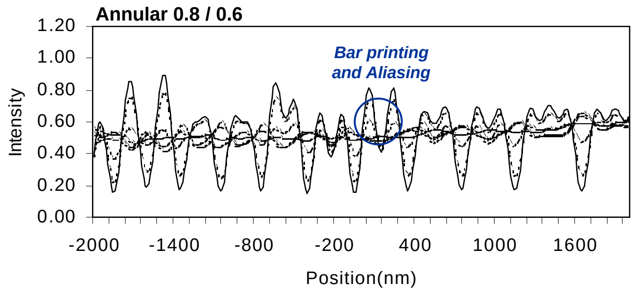


Figure 17. Equalized isofocal performance with assist feature mask for annular illumination.

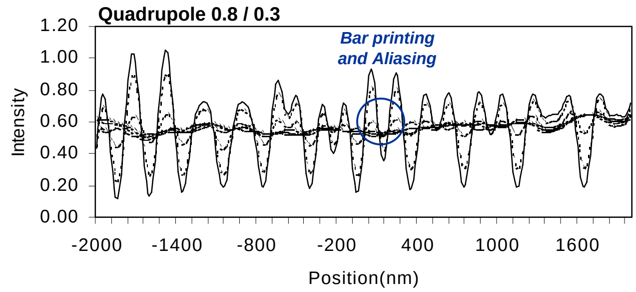


Figure 18. Equalized isofocal performance with assist feature mask for quadrupole illumination.

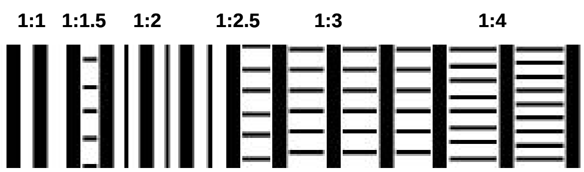


Figure 19. Ladder bar solution for isofocal equalization.

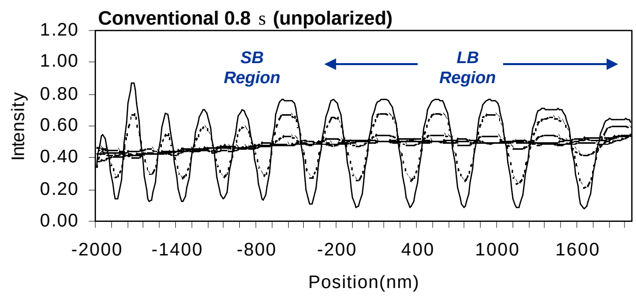


Figure 20. Equalized isofocal performance with ladder bar mask for partial coherence.

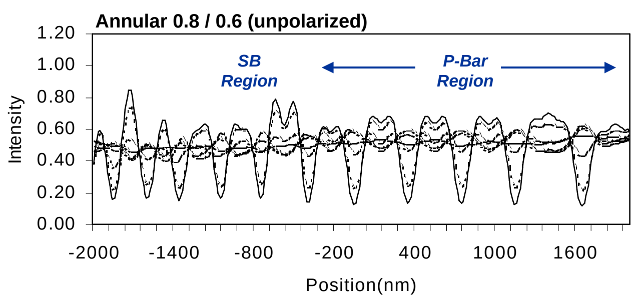


Figure 21. Equalized isofocal performance with ladder bar mask for annular illumination.

5. APPLICATION TO TWO-DIMENSIONAL MASK PATTERNS

The frequency model-based analysis and layout methods described here can be applied to two dimensional mask patterns. As an example, consider the mask pattern in Figure 22, which is a variation of a common layout example used for demonstration of assist feature OPC.[8] This example contains 130nm geometry with a duty ratio of 1:2.5. An exposing wavelength of 248nm is used with 0.75NA and 0.80σ. Local DC frequency analysis was performed on the pattern using the filtering function described previously, resulting in an isofocal intensity distribution shown in Figure 23. There is no 1:1 geometry included in the mask pattern to equalize intensity toward. In this case, resist thresholding was considered, where a common isofocal intensity value was chosen to match resist response. Figures 24 and 25 show two examples. In one case, a 0.32 intensity thresholding resist process was considered. In the second case, 0.42 was used. The flexibility to tune the equalization to a resist process is demonstrated. A binary representation of the 0.32 equalized mask was generated using assist feature rules and 30nm bars. The result is shown in Figure 26. Figure 27 shows the effectiveness of the equalization, where isofocal intensity in the feature region is contained between 0.25 and 0.35. Figures 28 and 29 compare modeled LPM resist images (with contrast of 10, resist thickness of 400nm, absorption of 0.2 μm^{-1}, 10nm diffusion length , and 200nm defocus). The CD control is evident with absence of any image artifacts from assist features.

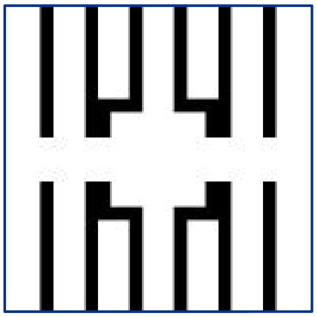


Figure 22. Two dimensional mask layout.

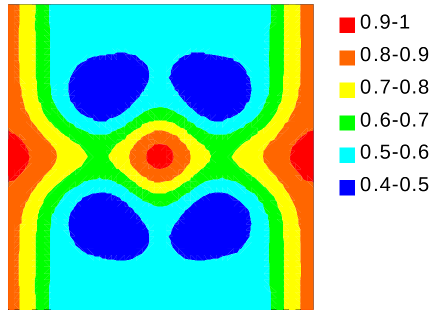
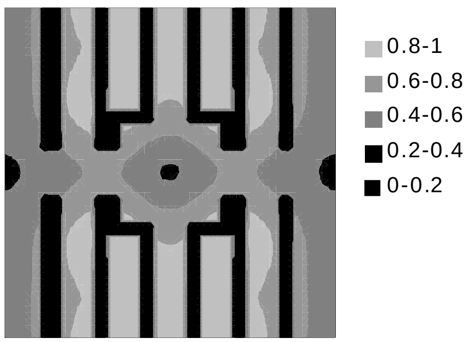
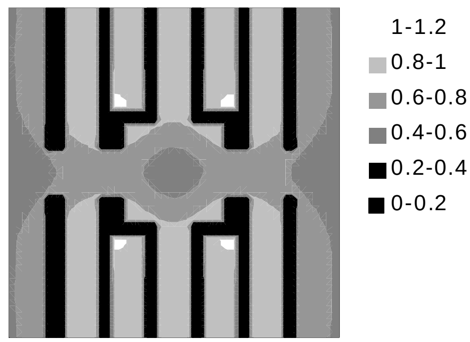


Figure 23. Local DC threshold function.



0.32 Resist Baseline

Figure 24. Equalized gray mask for 0.32 isofocal baseline.



0.42 Resist Baseline

Figure 25. Equalized gray mask for 0.42 isofocal baseline.

Binary Equalized Mask

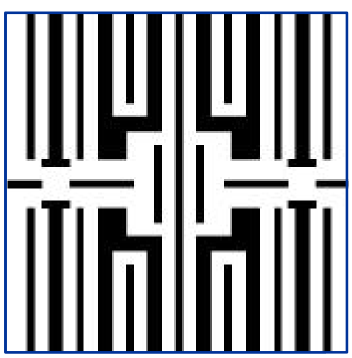


Figure 26. Binary equalized mask with assist features.

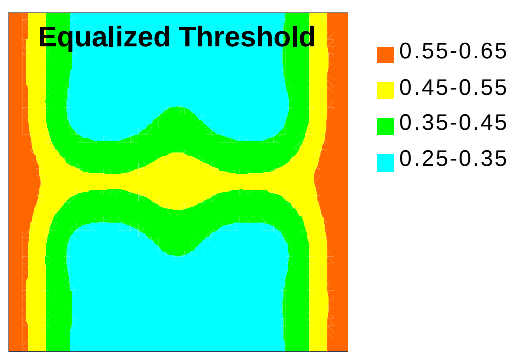


Figure 27. Equalized local DC threshold.

Original

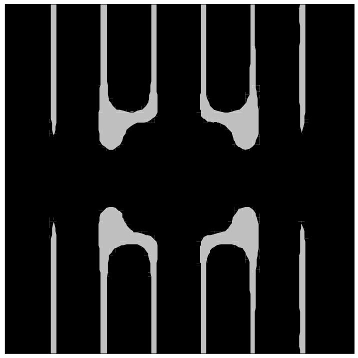


Figure 28. Simulated resist images for original mask.

Corrected

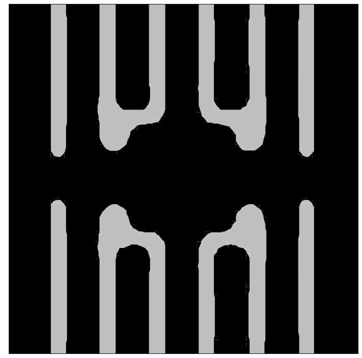


Figure 29. Simulated resist images for equalized mask.

6. CONCLUSIONS

A method for frequency model-based assist feature OPC analysis, optimization, and layout has been introduced using local DC signal analysis. By defining kernel and frequency filtering functions for implementation into a lithography model, imaging specific solutions are possible. The method allows for an increase in the design space of assist feature OPC by considering features that are not necessarily parallel to main features. Examples of one dimensional and two dimensional mask functions have demonstrated the flexibility.

7. REFERENCES

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