Resolution and DOF improvement through the use of square-shaped illumination

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ABSTRACT

As optical lithography is pushed to smaller dimensions, methods of resolution enhancement are considered necessary. Illumination modification is getting a good deal of attention, through strong and weak off-axis methods. The shape of an illumination profile does not need to be circular, especially if X/Y feature orientation is considered. This paper describes the improvements in imaging that are possible through use of source shapes that have various degrees of square character. Applications are discussed and interaction with optical proximity correction (OPC), aberration, and other imaging factors are addressed.

1. INTRODUCTION

In most situations, imaging systems make use of circular pupils. This is true for optical lithography tools where both the objective lens pupil and the condenser lens pupil are circular, defined by their numerical apertures and related by a partial coherence factor, σ. This situation is not necessary and variations may lead to potential imaging improvements. It would be difficult to expect, and impractical to suggest, that a non-circular objective lens would be fashioned for lithographic application, where achieving near aberration-free performance is required. Minimum and balanced aberration performance is desired over the full objective lens and maximum radial symmetry is targeted. The situation for the condenser lens is different, however, where the lens pupil is chosen to for optimal illumination of mask geometry and distribution of diffraction information. Partial coherence is generally limited to σ values of 0.8 or below, though values to 1.0 are possible. The situation suggests that there may be flexibility in the choice of the condenser lens pupil shape as well as size if the ultimate goal is to maximize the efficiency of diffraction order collection. It might be expected that since IC device geometry is often constrained to X/Y orientations, there may be a similar preferred X/Y character to the illumination system via the condenser lens pupil. Prospects will be addressed in this paper.

The frequency and spatial representations of square and circular pupils are often assumed to be equivalent. This is a convenient method of understanding the behavior of an optical imaging system, where a one-dimensional representation of a circular pupil is evaluated as a square function. Since only a circular pupil is radially symmetric, these functions, as well as their Fourier Transforms, are not equivalent. The two-dimensional fourier transform of a circularly symmetric function may be better evaluated by using the Hankel transform, which can be expressed as

$$H(\rho;\upsilon) = 2\pi\int_0^{\infty} h(r)J_{\upsilon}(2\pi\rho r)r\,dr$$

where J_ν is the *nth* order Bessel function, and r and ρ are radial coordinates in space and frequency domains. Properties of this transform are similar to the Fourier Transform. It is unique though in that it is also self-reciprocal. The Hankel transform of a circular pupil gives rise to what is commonly referred to as Besinc function, which when squared is also known as the Airy function:

$$\text{Airy functon} = \left| \text{Besinc}(u) = \frac{2J_1(u)}{u} \right|^2$$

Since circular and square pupil functions are not equivalent, an important goal should be to determine whether there is room for improvement over circular pupils in a lithographic illumination system. Köhler illumination images a condenser lens pupil into the frequency plane of an objective lens. Circular and square shaped functions act to spread the frequency of diffraction orders in this plane. Such pupil shapes and their Fourier (or Hankel) transforms are shown in Figure 1. The Optical Transfer Function (OTF) is a convolution of condenser lens and objective lens pupils. This translates in the image plane to the product of the Fourier Transform of the two pupils. When squared, this becomes the Point Spread Function (PSF), which is an indication of the “blur” a point image experiences in an otherwise perfect system. A system that utilizes circular pupils has a PSF character with a Sinc^2 character while the PSF for a system with a circular objective pupil and a square illuminator pupil is proportional to the product of Besinc and Sinc functions. The potential improvement of using a square pupil are suggested here. As seen from Figure 1, more of the total area of a Besinc function is contained in the region bounded by the first minima compared to that for a Sinc function. The impact on the PSF is an increased confinement, leading to potential improvements in imaging. Evaluation of the OTF for circular and for square pupils will also indicate improvement. Figure 2 shows modulation versus spatial frequency comparisons for square and circular illumination pupils combined with circular objective lens pupils. In one case, a circular illumination pupil with a corresponding σ value of value of 0.707 [or 1/sqrt.(2)] is compared to a square pupil measured with the same σ value half-width. This corresponds to the largest square shape that can fit into an illuminator pupil with maximum σ value of 1.0. The performance of the square pupil dominates at all frequencies. A comparison is also made for full σ = 1 pupils. The performance of this circular pupil also appears inferior to the square pupil.

Figure 3 demonstrates the situation from a spatial frequency perspective. Here, the objective lens pupil is filled by diffraction orders from a mask with features corresponding to a k_1 factor near 0.35. Circular and square shapes are compared. For both situations, the objective lens collects all of the zero diffraction order and part of the first orders. The spread of the first orders is determined by the illuminator pupil size and shape. Although the collection of the first diffraction order on the spatial frequency axis is equivalent in both cases, the total “area” of the first order collected for the square pupil case is larger than for the circular shape for X/Y oriented features. This improvement can be lithographically significant.

In some instances, illumination modification could lead to problems with overfilling of the objective lens pupil. For example, Figure 2 suggested that a square pupil with a half-width σ value of 1.0 could lead to improvements over a circular pupil. Although this appears true from a PSF or OTF standpoint, there is an over-filling of the objective lens that occurs which is actually detrimental. Figure 4 shows such how problems can arise. The extend of overfill for a square pupil using a half-width σ value of 1.0 is evaluated. Here, only the difference between unity σ

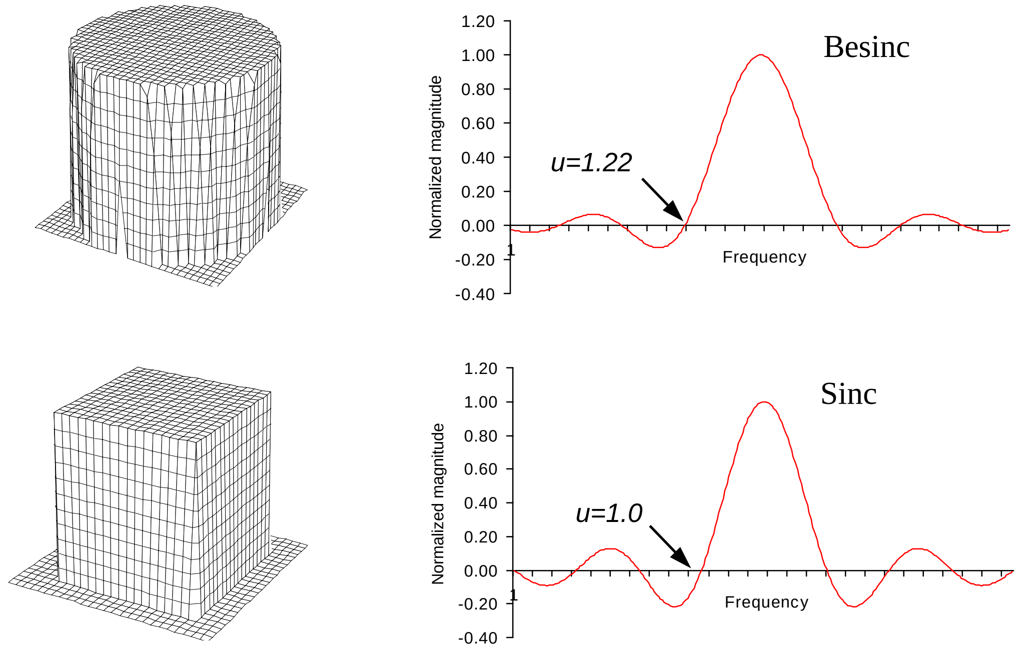

Figure 1 Circular and square shaped pupils and their corresponding transforms.

square and circular shapes is considered, representing the full extent of the overfill. (This illuminator pupil is referred to here as a "difference pupil".) The frequency plane for mask features corresponding to k_1 ~0.35 is plotted in the objective lens, consisting only of first diffraction orders. The zero order does not exist since the difference pupil has no circular σ value less than 1.0. Since the zero order is removed, the original frequencies of the diffraction orders is aliased to lower frequencies. This gives rise to undesirable lower frequency image content, leading to degradation when combined with the image that would result without the overfill. This analysis suggests that the largest square illumination pupil that should be considered is one with a half-width σ value of 0.707. Alternatively, a square aperture with round corners is used for values larger than 0.707, which will continue to outperform a full circular pupil.

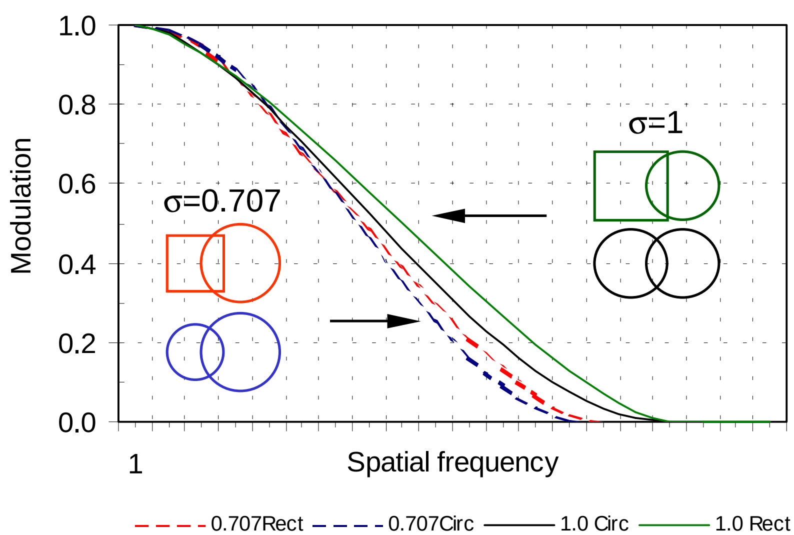

Figure 2. OTF for square and circular pupils illuminating a circular objective lens pupil. Geometry is oriented along X/Y directions and σ=1 corresponds to equivalent size condenser and objective lens NA values.

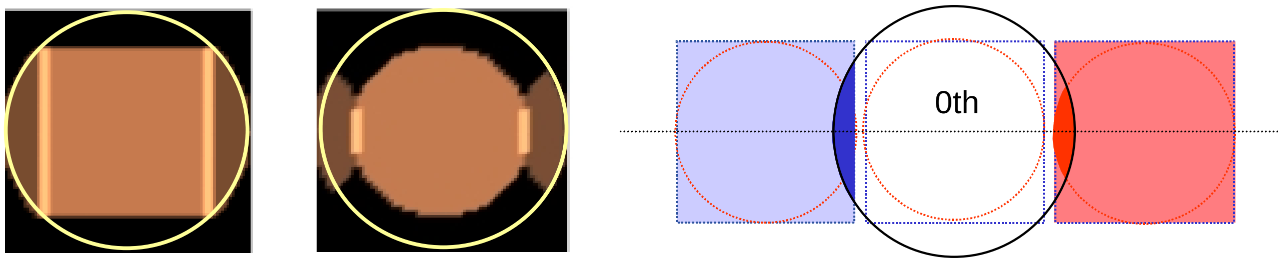

Figure 3 Frequency distribution of diffraction orders in the objective lens pupil for square and circular shaped illumination. Collection of first order is increased for square illumination.

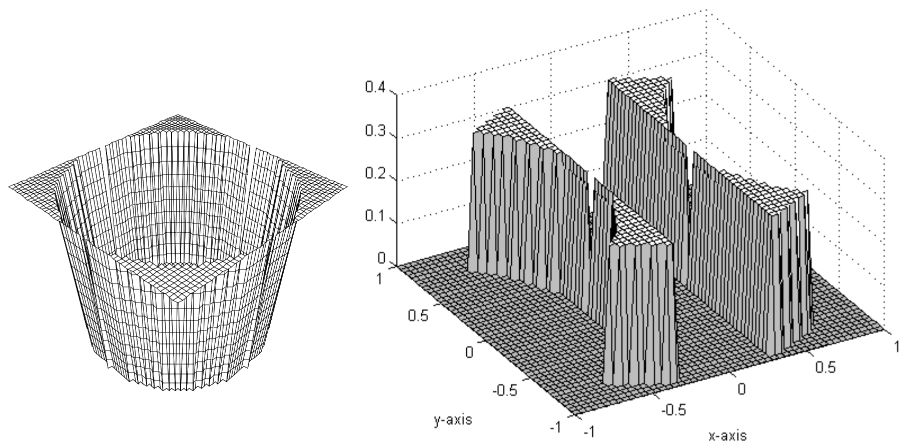

Figure 4. The effects of overfilling the objective lens with a "difference" pupil and $\sigma > 1.0$

2. IMAGE EVALUATION

To evaluate the performance potential of square shaped illumination, aerial image simulation has been performed using a high NA scalar model [Prolith v6.04]. A three bar elbow pattern was evaluated, as is shown in Figure 5. The imaging situation studied utilized a 248nm wavelength, a 0.60NA objective lens, and 160 nm line features using various illumination conditions. Comparisons of circular and square illumination shapes were made through measurement of aerial images, using aerial image intensity and normalized image log slope (NILS). Image orientations along X/Y and 45 degree directions were included. Figure 6 shows a comparison of aerial images along horizontal cut lines of the mask for circular and square illuminator shapes with σ values of 0.70. Images were generated through 0.5 micron of defocus. It is seen from these results that the use of the square shaped illumination pupil leads not only to improved performance for features at best focus but also as defocus is considered. The impact is greatest for central grouped features, as would be expected by considering the distribution of the diffraction field. A concern about diagonal orientations follows naturally, and is evaluated in Figure 7. Here, a cut line along a 45 degree angle is considered, as depicted in Figure 5. Results

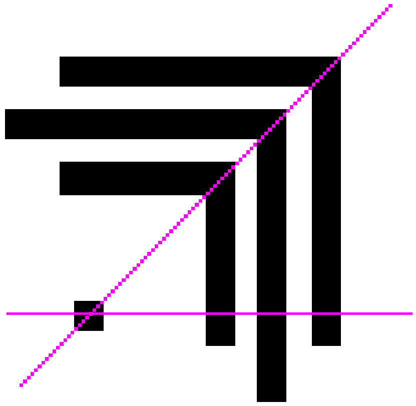

Figure 5. Two dimensional mask image used for simulation and evaluation of illuminator effects. Mask geometry corresponds to 160 nm and a wavelength of 248 nm was studied with a 0.60 NA objective lens. Cut lines along horizontal and diagonal directions were explored.

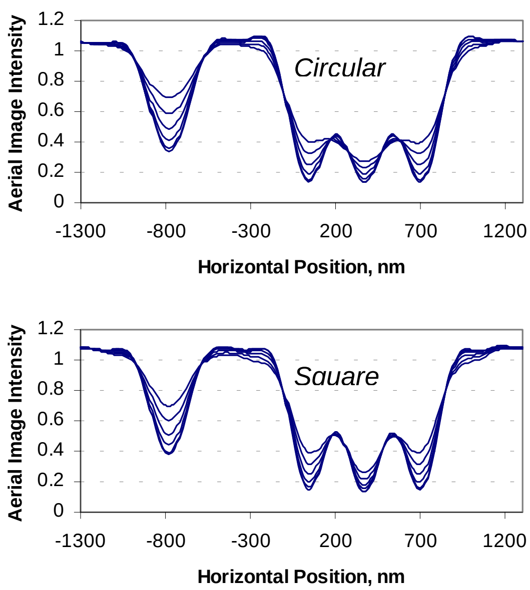

Figure 6. 2D image comparisons for a horizontal cut-line through elbow pattern for circular and square source shapes.

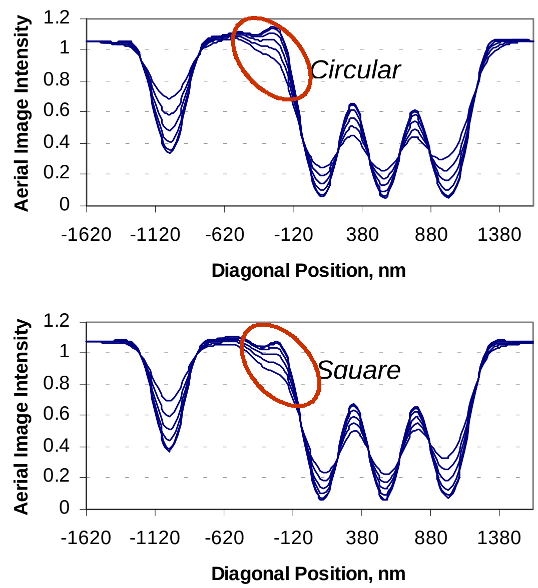

Figure 7. 2D image comparisons for a diagonal cut-line through elbow pattern for circular and square source shapes.

show improvement for features at this orientation as well, though for different reasons than those for the X/Y orientation. In this case, the size of features is larger by a factor of sqrt. (2) as is the effective partial coherence value for the square pupil. This decrease in coherence can accommodate higher frequency, leading to increased performance.

Image matching with OPC

To further evaluate the X/Y verses diagonal performance of square shaped illumination, through-focus image integrity was evaluated for X/Y and diagonal feature orientations, as shown in Figure 8. Here, the metric chosen was the increase in NILS for a square shaped pupil compared to a circular pupil. Results show how an X/Y orientation is impacted differently than

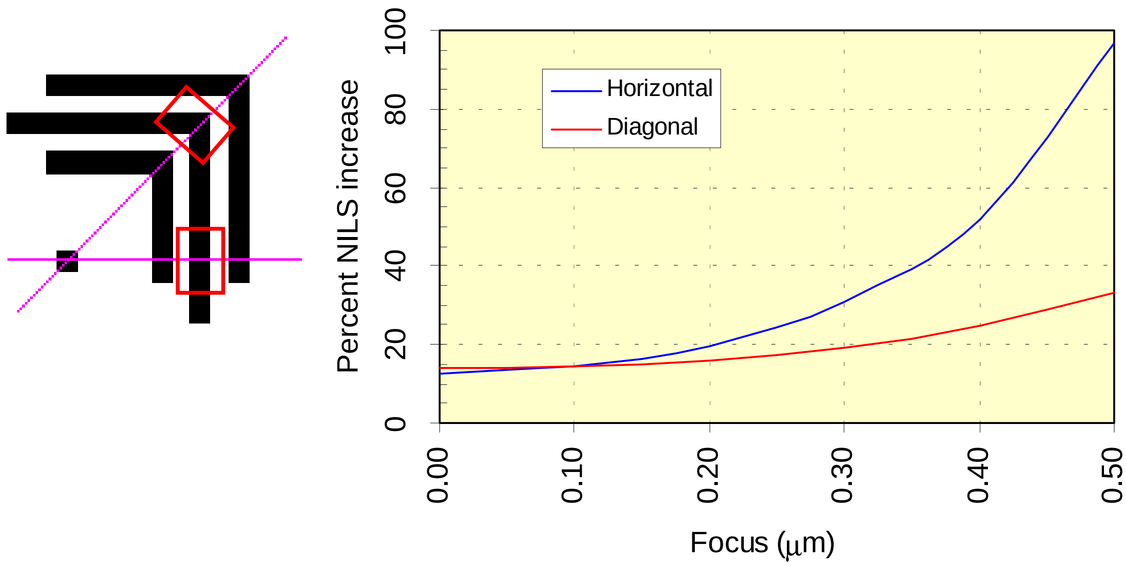

Figure 8. The improvement with square shape over circular, measured in terms of NILS increase, for horizontal and diagonal orientations.

diagonal orientations. In both cases, there is an improvement in imaging performance. The improvement across the X/Y direction, however, is greater than that across the diagonal, especially with large amounts of defocus. Although the square illumination is shown to be preferred overall for both cases, these difference lead to an increase in the bias over what would be expected for circular illumination. The situation appears to be an ideal candidate for optical proximity correction (OPC) using serif type structures. Through the use of corner serif features, improvement could be expected at corners and along diagonal positions to match performance along X and Y directions. Figure 9 shows the results from such mask correction. A comparison is made of aerial images resulting from 0.7 circular s illumination of the elbow mask patterns and 0.7 square HW s illumination with 50 nm mask serif OPC features. The impact on image performance is immediately obvious. X/Y feature performance is improved via the square illumination and corner performance is improved via square illumination and OPC. This situation represents the potential offered through use of square shaped illumination.

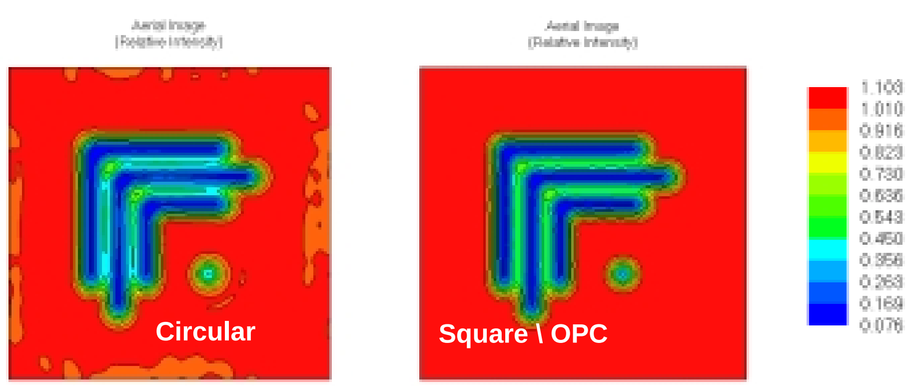

Figure 9. Comparison of 2D aerial images for circular pupil illumination and square pupil illumination with 50 nm serif OPC. Partial coherence for each case is 0.70. Improvements over circular illumination are present in X/Y and diagonal orientations as well as at corners.

Impact with aberration

The influence of aberrations on imaging is becoming an increasingly greater concern as optical imaging is pushed and various resolution enhancement methods are considered [1,2]. The evaluation of the impact that square shaped illumination would have on imaging with lens aberration should therefore be considered. Coma effects are especially critical as image shifting and degradation in modulation can occur. Figure 10 compares the situation of imaging with coma for square illumination and circular illumination pupils. The diffraction field in the objective lens is plotted with the presence of 0.25 waves of primary coma. Feature size corresponds to a k_1 of 0.38 and σ is 0.7, placing first diffraction orders toward the edge of the pupil. Comparison of these diffraction fields shows how square illumination distributes first diffraction order information over more of the objective lens pupil than the circular illumination does. This can lead to an increase in an averaging effect over the lens pupil, which can be beneficial if the result is a lowering of OPD or phase error. The impact on aerial images is shown in Figure 11. NILS vs. focus is plotted for circular and square illumination using an ideal (perfect) objective lens and a lens with 0.25 waves of primary coma. Although this level of coma is exaggerated over what would be expected in a lithographic lens, it allows for consideration of the potential impact. In the presence of coma, square illumination shows improvement over circular illumination. As defocus is considered, the performance with the square shape further dominates. At 0.5 μm of defocus, the square illumination performance with coma aberration approaches that for the circular illumination and perfect lens. Image improvement effects for other aberration types, including spherical and astigmatism, are similar. Figure 12 also shows how coma induced image placement error (IPE) is influence by illumination. In this case, 0.25 waves of coma is also considered. IPE vs. defocus for square illumination is lower at best focus. As defocus is introduced, the increase in IPE remains significantly lower for square illumination. Results from tilt and higher order coma are similar.

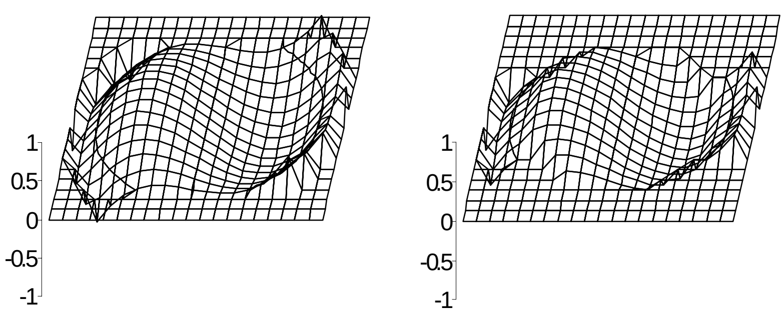

Figure 10 Impact of illumination on coma aberration effects. The diffraction field is plotted for k_1=0.38 with σ = 0.7 and 0.25 waves of primary coma.

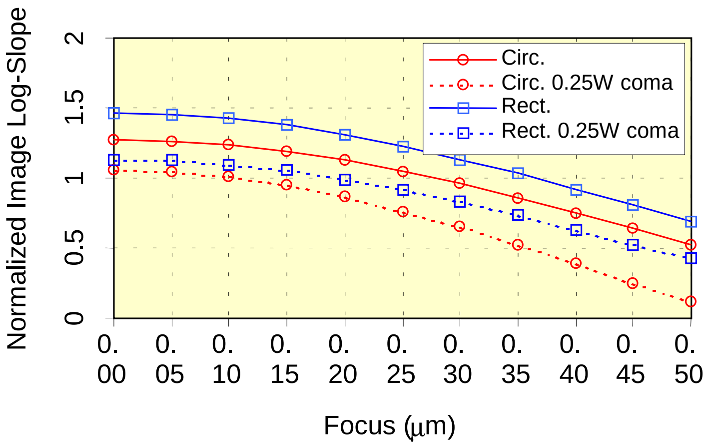

Figure 11. Effects of coma on NILS for circular and square (rectangular) source shapes.

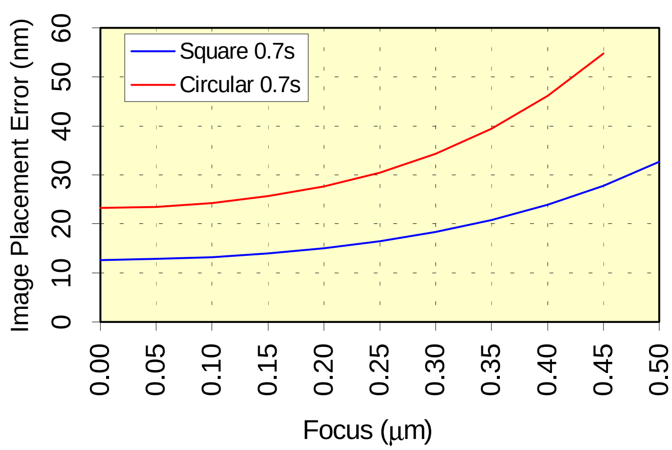

Figure 12. Effects of coma on IPE for circular and square source shapes (0.25 waves of primary coma).

3. APPLICATION TO OFF-AXIS ILLUMINATION

Square annulus OAI

Since square or rectangular shaped illumination can lead to improvement over circular illumination for conventional or on-axis illumination, it might be expected that gains are possible with off axis illumination. Consider, for instance, annular illumination, where optimization is achieved through choice of illumination parameters so that zero and first diffraction orders overlap to some extent in the objective lens. For circular annular shapes, only a small portion of the ring will overlap, determined by the ring width (or inner to outer σ difference). If features oriented along X/Y directions only are considered, maximum overlap can be achieved with square ring shapes, where openings in the ring are chosen to accommodate the range of frequencies targeted, as shown in Figure 13. For horizontally or vertically oriented features, the efficiency of such an off-axis source comes about from the projection of an entire square edge onto frequency axes. Performance comparisons in Figure 14 show how this approach dominates over a circular ring approach. NILS through focus is plotted for square and circular annular rings, for 150 nm features using 248nm wavelength and a 0.63 objective lens NA. Illumination parameters are equivalent for both source types, where corner frequencies for the circular annulus match those for the square annulus (square ring parameters are 0.65 outer σ and 0.46 inner σ, circular parameters are a multiple of sqrt(2) or 0.92 outer σ and 0.65 inner σ). Illumination has been optimized for both cases. The performance for the square ring is superior through focus and across pitch. For the most dense features (375 nm pitch or 1:1.5), resolution is not likely for the circular annulus for a photoresist that would need a NILS value above 1.5. Significant focal depth can be expected for this dense pitch as well as more isolated features (up to 1:5 is plotted here). Across pitch NILS matching through focus also remains, suggesting that any increase in dense to isolated feature bias may be minimal.

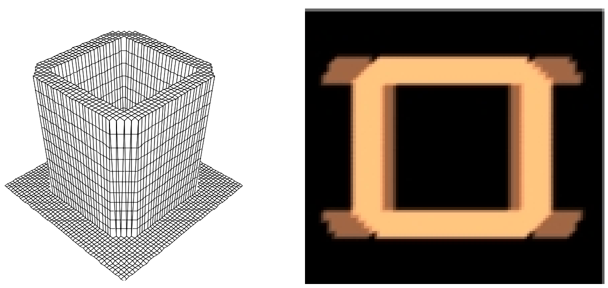

Figure 13. A square-ring annulus shape for off-axis illumination. This source is optimized for k_1 near 0.40. Maximum overlap of diffraction orders is achieved, which is superior to circular-ring annular illumination.

Weak quadrupole OAI

Modified off-axis illumination techniques have been introduced to increase the resolution, focal depth, and through-pitch performance of optical projection lithography [3]. Approaches have included weak gaussian quadrupole and similar designs, which have been implemented into several applications and across many wavelengths. These illumination schemes can also benefit from square shape character, through use of square hard-stops or features similar to the square annulus described above. An example is shown in Figure 15 (a and b). Shown here is an illuminator shape designed for imaging features with duty ratios from 1:1 to isolated. For a 248 nm wavelength and 0.63 NA, this corresponds to 150 nm features on pitch values of 300 nm and above. Design of such a distribution is carried out by considering imaging and feature characteristics. For example, the corner pole position and fill is chosen to accommodate off-axis illumination of more dense features, in this case 1:1 through 1:2.5 duty ratio. The resulting diagonal σ (center) value for this example is 0.78. Since this approach is used for X/Y feature orientation, these corner positions correspond to diffraction order frequencies identical to those projected onto the X and Y axes. A square limiting hard stop therefore leads to further accommodation of these dense features. In this example, the square limiting stop has a half-width value of 0.65. The central fill of the illuminator is chosen to accommodate more isolated features, which are best illuminated with on-axis, lower σ illumination. A comparison of NILS and aerial image contrast is also shown in Figure 15 for the square-character weak quadrupole illumination and a more conventional weak quadrupole using Gaussian poles. The Gaussian illumination profile has also been optimized for this particular imaging situation, resulting in a σ (c) value of 0.70 and a σ (r) value or 0.30. In both cases, a

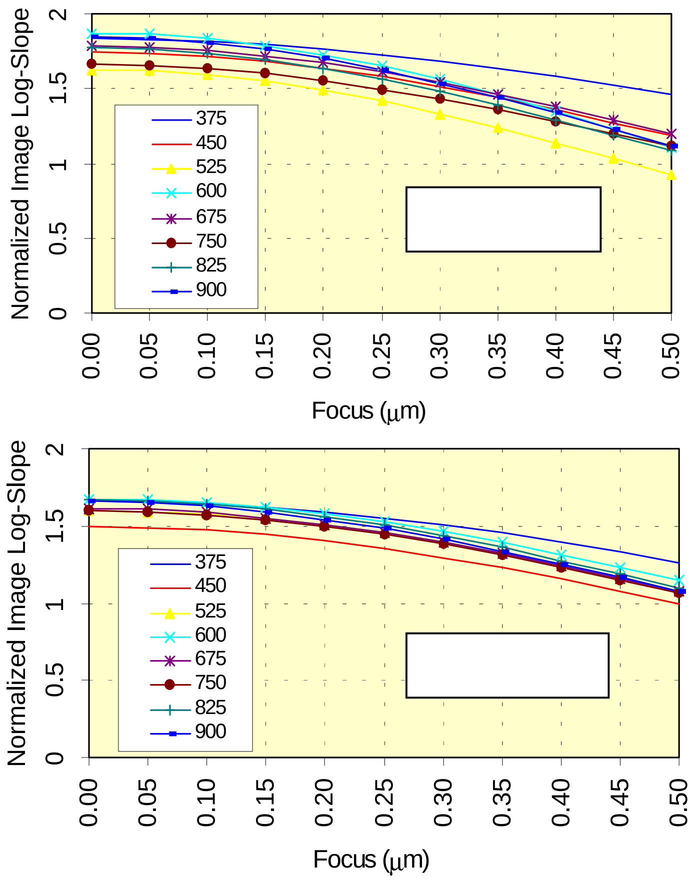

Figure 14 Annular vs. square ring performance measured as NILS through focus and pitch. Wavelength is 248 nm with a 0.63 NA for 150 nm features with duty ratios from 1:1.5 to isolated.

limiting circular σ value of 0.8 has been incorporated, representing exposure tool limits. Optimal imaging performance is achieved with maximum NILS and image contrast through focus and across pitch. As seen from these plots, the optimized square-character source exhibits better through focus performance in terms of both NILS and image contrast. Where imaging of 1:1 features is not likely with the Gaussian approach, there is significant improvement demonstrated with the square-character approach. Furthermore, the square-character source shows better through pitch performance for both NILS and for image contrast. The tradeoff for using square-shaped weak off-axis illumination may be non-existent if the application is considered. Quadrupole approaches to off-axis illumination are utilized with the assumption that feature orientation is along X and Y directions. Optimizing illumination should therefore include minimal circular character. The use of circular limiting stops can only lead to degradation of dense feature geometry: diffraction order frequencies at the outermost on-axis positions are not accommodated at the corners. The maximum square half-width σ value for any quadrupole design should therefor be 0.707 σ (max), where σ (max) is the maximum partial coherence utilized by the illuminator or available on the imaging tool. This suggests, therefore, that in order to accommodate the most challenging geometry, exposure tools need to be built with maximum partial coherence of 1.0, allowing square half-width sigma values of 0.707. Beyond this, any square edge / round corner character will be superior to fully round shapes. This open the potential for attainment of k_1 values to 0.37 across a wide range of duty ratios!

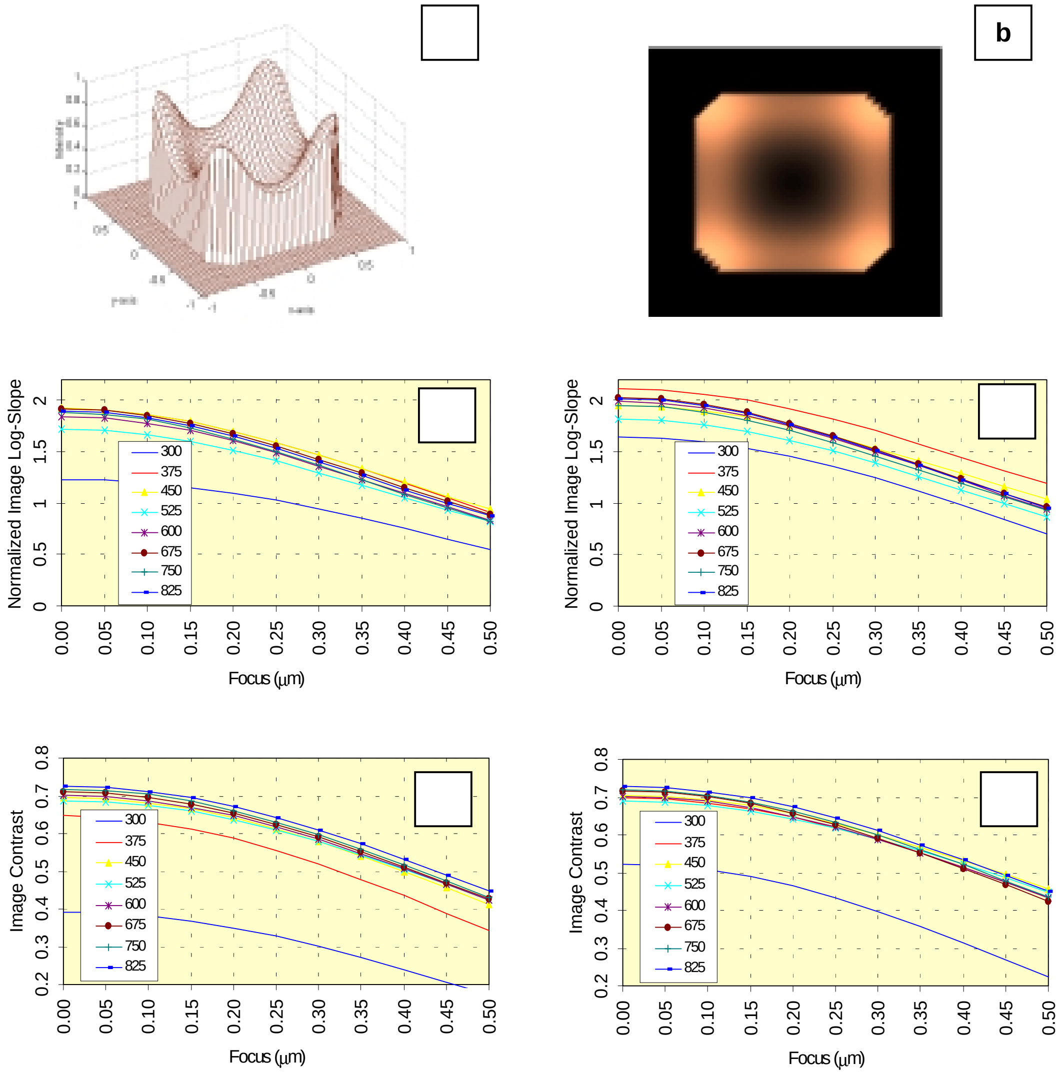

Figure 15. Image performance of a 248 nm, 0.60 NA system for 150 nm lines evaluated using NILS and image contrast. The layout of the source distribution is shown in a and b. Performance of a more conventional Gaussian weak quadrupole source is shown in c and e. Performance of the square-character weak off-axis source is shown in d and f.

4. IMPLEMENTATION

Modification of the mask illumination in a projection exposure system can be carried out through redesign of the optical system or through manipulation at the illuminator pupil plane. The concepts presented here can be incorporated into the design of an illumination system but they are currently better suited for implementation into the lens pupil as specific filtering apertures. A square conventional aperture for instance consists of a square opening in an aperture plate, which can be accommodated on most current exposure tools. The throughput loss is minimal, especially when compared to the potential performance gains. In order to best accommodate square shape pupils with maximum fill of the square profile, an exposure tool needs to be capable of delivering a high maximum partial coherence value. If a tool is limited to a maximum σ value of 0.8 for instance, there is loss of square corners. If a σ value of 0.8 is desired for a given imaging application, this value needs to be allowed on the source axis as 0.8 and on the diagonal as 1.0. Pupil corner rounding does result (since the required corner σ value needs to be 1.13, which would result in overfilling of the objective lens), but this situation is superior to one using a circular σ value of 0.8. An ISI 193nm 0.60NA imaging system has been utilized to evaluate this approach. The tool allows for a maximum partial coherence value of 1.0 and square shaped illumination aperture with half width σ values of 0.7 and 0.8 have been fabricated for testing.

The square ring off-axis approach can also be implemented using a pupil filter in the illuminator. Some loss in throughput can result and this scheme might be better implemented through some modification in the optical system. No attempt has yet been made to carry this out.

Weak off-axis illumination with the square shaping (shown in Figure 15) is under evaluation with a full field 248 nm, high NA system for imaging of 150 nm features. The illumination profile has been translated into a dithered representation of the continuous tone distribution, which has been used to fabricate a 5” chrome on quartz filter adaptable to the tool. The pixilated filter allows throughput of 76% full pupil throughput. The filter is inserted into the accessible pupil plane of the tool using a standard part pupil filter holder. This approach makes specific modification or customization straight forward. Results will be presented in future reports.

5. CONCLUSIONS

To extend the limits of optical lithography, imaging enhancement approaches need to be considered. Flexibility increases as some constraints are allowed. The use of square shaped optical systems takes advantage of IC geometry oriented on X/Y directions. Square illumination approaches have been shown to offer significant improvement potential at relatively low cost. The combination of this concept with off-axis illumination or OPC further strengthens their potential. This paper has provided a fundamental description along with possible applications. As work continues, it is anticipated that lithographic performance will match the predicted results.

Layout and optimization of illumination profiles was performed using SORCERER™ illumination design software and integrated with scalar lithographic simulation. Apertures for insertion into exposure tools were created using SourceMapper™ [4].

6. REFERENCES

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[4] SORCERER™ design software is a product of Lithographic Technology Corp. (LTC) and MicroUnity Systems Engineering. SourceMapper™ is a product of LTC.