

Image enhancement through square illumination shaping

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ABSTRACT

Optical imaging is traditionally carried out using circular pupils, assuring the absence of orientation dependency. In the case of IC microlithography however, such dependency exists and is generally limited to orthogonal axes. We have previously reported the potential improvement to lithographic imaging through the use of a square character to an illumination pupil using fully open pupils, square rings, and slot shapes. In this paper we show lithographic results for this shaping at 193nm using a full field (ASML) imaging tool. Results show improvement in both DOF and exposure latitude over conventional circular shaping, leading to the consideration of this approach as a manufacturable method of resolution enhancement.

1. INTRODUCTION

The use of square shaped optical illumination systems can take advantage of IC geometry oriented on X/Y directions. In an earlier report, we have shown that square illumination approaches can offer improvement potential over circular shapes at relatively low cost¹. In many optical instances, square and circular pupil shapes 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:

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

where J_n is the nth order Bessel function, and r and \mathbf{r} 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:

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

A system that utilizes circular pupils has a PSF with a Sinc² 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 improvements of using a square pupil are suggested here as 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 also indicates improvement. Figure 1 shows a comparison of a circular pupil and a square pupil, in spatial and frequency domains.

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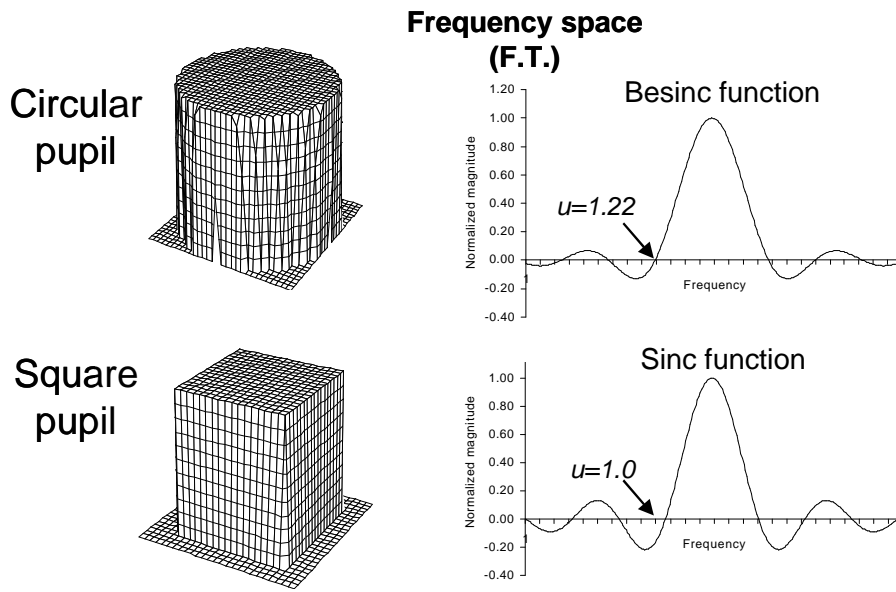


Figure 1. Circular and square pupil shapes and their corresponding frequency distribution.

2. OFF-AXIS ILLUMINATION USING SQUARE SHAPES

Since square or rectangular shaped illumination can lead to improvement over circular illumination for conventional illumination, it might be expected that gains are possible with off axis illumination. With annular illumination, optimization is achieved through the 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, a 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 2. 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.

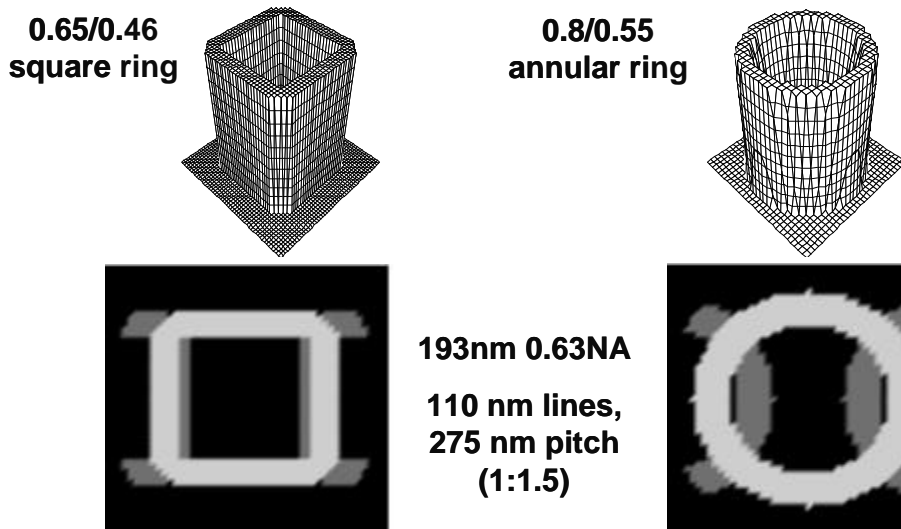


Figure 2. Square annular off-axis illumination vs. Circular annulus.

As partial coherence values are increased toward 1.0, it is preferable to increase the outer ring dimension of the square annulus to include the largest illumination angles. Illumination would be defined with a square center but with an circular source field, as shown in Figure 3.

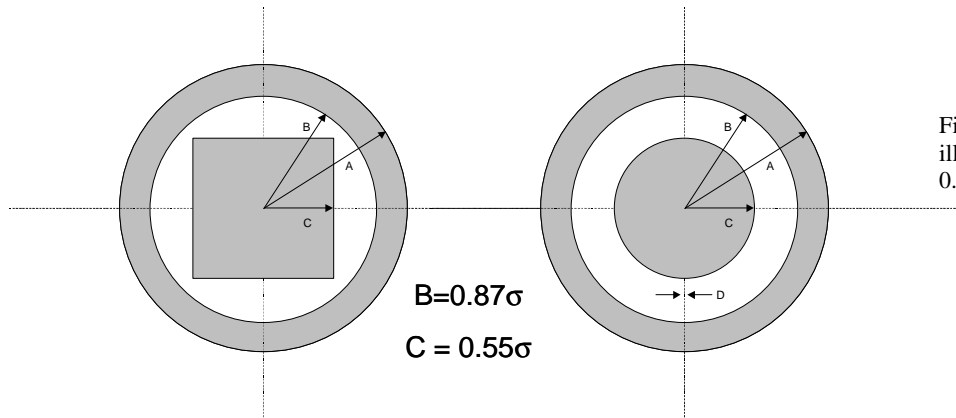


Figure 3. Hybrid square illumination shape for 193nm, 0.63NA, 100nm lithography.

As an example, illumination is designed for lithography at 193nm using a 0.63NA and 0.87 maximum partial coherence (σ). The extent of the outer pupil edge is limited and a full circular shape is chosen. By considering 100nm geometry (on duty ratios between 1:1 and 1:2), an inner annulus dimension of 0.55 is targeted. This value is chosen to accommodate the desired pitch range and calculated as $1/2pNA$ for average pitch p . Diffraction energy in the objective lens pupil is shown in Figure 4 for 1:1.2 features with 100nm defocus. The increased collection of first diffraction order and the decrease in unmatched zero order is demonstrated.

Physical aperture plates were fabricated in metal for insertion into the pupil plane of the exposure tool illuminator. An alternative method to achieve such illumination distribution is through the use of one or more diffractive optical elements (DOEs).

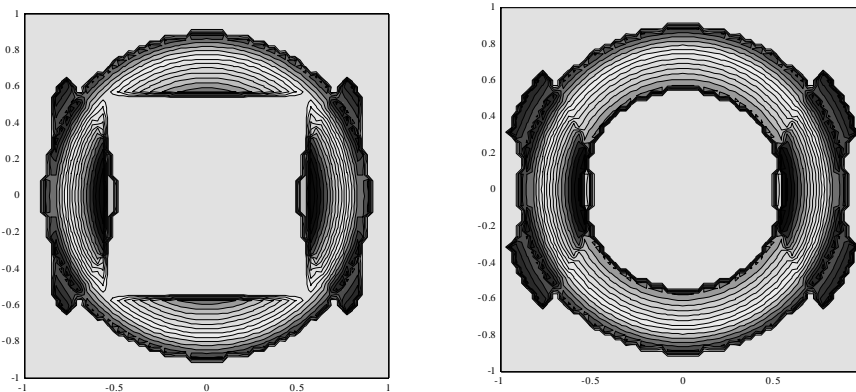
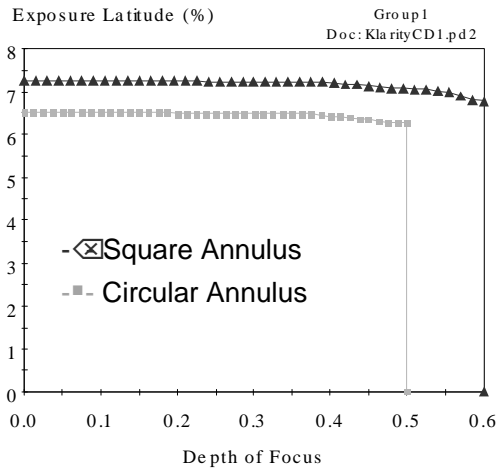


Figure 4. Diffraction energy in the objective lens pupil for hybrid square annular and circular annular illumination.

3. LITHOGRAPHIC RESULTS

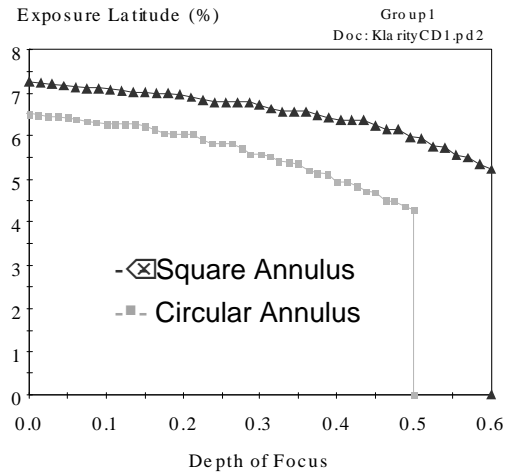
Lithographic exposure tests were carried out in a full field (ASML) system, operating at 193nm and 0.63NA. Images were captured in 3300Å of an AR165J 193nm resist coated over 820Å layer of an AR19 193nm anti-reflective layer. Exposure latitude vs. DOF plots resulting from SEM analysis of 1:1 feature FE matrices are shown in Figure 5. Both elliptical and square process windows were used for the comparison of the square annulus and circular annulus images. In both cases, improvement in exposure latitude measuring between 13% and 22% is achieved.

Exposure Latitude vs. DOF



Elliptical process window

Exposure Latitude vs. DOF



Rectangular process window

Figure 5. Process window comparisons for circular and square annulus illumination

4. CONCLUSIONS

We have demonstrated the improvements possible through the use of square annulus illumination shaping. These effects were predicted in earlier reports¹, which was the basis of this work. Extension of these concepts to larger inner square dimensions leads to variations to cross-quadrupole illumination with square character. Similar improvement over circular shaped poles should be achievable.

¹ B.W. Smith, L. Zavyalova, S. G. Smith, J.S. Petersen, "Resolution and DOF improvement through the use of square-shaped illumination," Proc. SPIE 3679, pp. 408-420, 1999.