Quadrupole Illumination Design for a 193nm Hyper-NA Exitech Immersion Stepper

Derek J. Summers

Abstract — **As device sizes reduce in size and processes become more complex, enhancement techniques for optical lithography are essential. Several ways to enhance the current lithographic systems include immersion lithography, phase-shifting masks, optical proximity correction and OAI (off-axis illumination). Depending on the process, these RETs (resolution enhancement techniques) may be used individually or in combination to compensate for image degradation caused by optical diffraction and resist behavior.**

The purpose of this project is to design and test a quadrupole off-axis illumination aperture for the 193 nm Immersion stepper at RIT. Process window simulations, using Prolith, were used to determine theoretical effectiveness and benefits for off-axis illumination conditions. The targeted features of 100 nm and 80 nm respectively, each with a duty ratio of (1:1), were processed and compared to simulations. Improvements in terms of (DOF) Depth of Focus and resolution, have been demonstrated for 100 nm and 80 nm features. Off-Axis Illumination and Liquid Immersion are cost effective techniques to extend the lifetime of optical lithography.

Index Terms— Resolution Enhancement Techniques; Off-Axis Illumination; quadrupole; immersion; aperture design

I. INTRODUCTION

When exploring the theory behind lithographic imaging systems it is important to understand the factors that influence them including the illumination wavelength (?), numerical aperture (NA), coherence factor (s) and method of illumination. These factors will be defined by presenting the components of the lithographic system that will be used for this research, the Exitech 193nm Immersion system. This will be followed by a theoretical discussion on the implementation of a quadrupole aperture into the system as a resolution enhancement technique. The quadrupole aperture can be inserted into the optical column between the radiation source and the condenser lens.

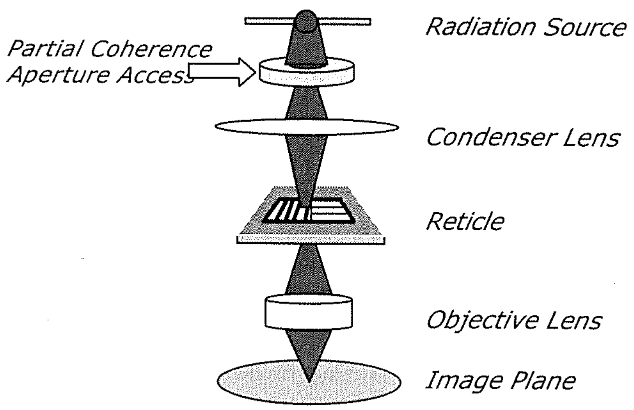

Figure. 1 Illustration of lithographic system depicting main components of the EXITECH 193nm system.

The source for the EXITECH system is an Argon Fluoride (ArF) laser designed to a wavelength of 193nm. Following the source, a condenser lens sufficiently distributes the energy to illuminate the reticle.

The reticle is the next component in this optical system following the condenser lens. The reticle is the optical tool, which provides the pattern or "information" that is to be recreated on the wafer in the resist. After the light passes through the lines and spaces on the mask the resulting "patterned" light is to be collected by the objective lens. Then the "patterned" light is often reduced by four to five times the original size by the specific combination of lenses in the optical column. The Exitech Immersion stepper has a 90X reduction factor. This means that a 100nm feature on the wafer was printed with a 9000nm or 9μm feature on the reticle. In order to ensure that the latent image captured by the resist is sufficiently close to the intended design on the reticle, the objective lens must be able to capture a sufficient amount of information namely the 0th and some of the ± 1st diffraction orders. A more thorough understanding of this will be presented later in this paper when discussing the benefits of off-axis illumination on the basis of diffraction theory.

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This optical system is based upon the theory of Köhler illumination. This theory demonstrates a system by which an image of the source is created at the entrance pupil of the objective lens by the means of the condenser lens. [2] In this system the resulting image is then projected through the reduction optics to a focal plane near the level of the resist. The theory of diffraction must be discussed in order to understand how this system is used in conjunction with a reticle to produce a latent image in the resist.

As light is passed through the lines and spaces on the reticle, diffraction occurs spreading the light into orders of magnitude in reference to an optical axis (OA). These different orders of magnitude correspond to an electric field distribution modeled in increments of ± ?/p, which is defined as the wavelength of the source divided by the pitch of the feature (nominal critical dimension of a line plus a space). As previously mentioned, enough information must be collected by the objective lens to propagate the image to the resist.

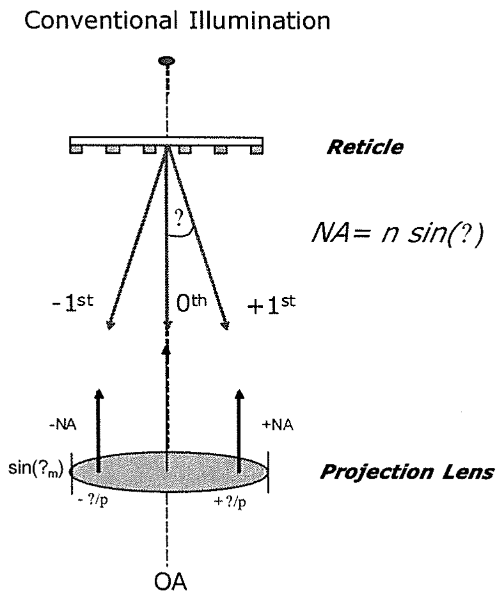


Figure 2. Conventional point source illumination illustrating diffraction.

The 0th diffraction order supplies intensity, whereas the ±1st diffraction orders provide the feature and pitch information to transfer to the resist. Typically, the 0th and at least some of the ±1st diffraction orders must be collected by the objective lens to propagate an image of acceptable quality. The following image illustrates the diffraction orders and the electric field distribution quantified in relation to the numerical aperture of the objective lens.

The amount of possible information that can be collected by the objected lens is a function of its numerical aperture. The NA is derived from the usable diameter of the objective lens, the distance from the reticle to the objective lens, and the refractive index of the media in which the light travels in that distance. The following is the resulting theoretical equation for numerical aperture.

$$NA = n \sin(?) \qquad (1)$$

The NA for the EXITECH system is 1.05. Numerical apertures that now have the capability of NA greater than 1 are so called "Hyper-NA". Though it is true that building a larger usable objective lens increases NA, benefits must outweigh the cost and feasibility.

The theoretical resolution and DOF is limited by the NA and wavelength of the system.

$$R = \frac{0.5\lambda}{NA} \qquad (2)$$

$$DOF = \pm k_2 \frac{\lambda}{NA^2} \qquad (3)$$

A problem arises from this theoretical equation, due to a theory of diffraction limitation. The ability to propagate a "patterned" image to the objective lens is diminished as feature sizes on the reticle shrink. As feature sizes on the reticle shrink, the diffraction orders spread out to the extent where the objective lens only captures the 0th diffraction order. Again, at least some of the ±1st diffraction orders must be captured to propagate the image as intended per the design. Therefore, there has been much research into Resolution Enhancement Techniques to reduce the diffraction effects and effectively allow a "sufficient" amount of energy for capture by the objective lens. Off-axis illumination is a well known RET used to adjust the diffraction pattern produced by the reticle. The following image illustrates the shift of diffraction orders.

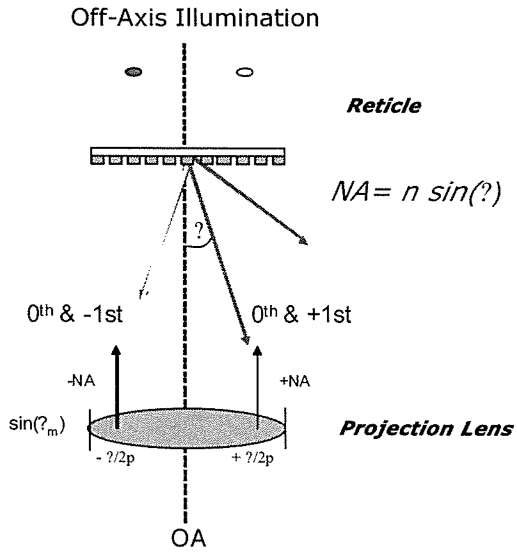


Fig. 3. Illustration demonstrating Off-axis illumination

By the means of changing the single point source illumination to two or several point sources "off-axis" in theory can provide enough of the 1st diffraction orders to the objective lens to sufficiently propagate the intended reticle design. The 1st diffraction orders overlap with the 0th diffraction order as illustrated in Figure 3. Note that the ±1st diffraction orders fall well within the limits of the objective lens at ±?/2p instead of ±?/p for on–axis illumination. When there are more than two point sources used in OAI, each of the resulting diffraction orders will be spread according to their orientation with the optical axis. What will be discussed further on is that depending on the targeted feature orientation may need to be taken into account when considering OAI. Once OAI is implemented the light is no longer coherent, but is partially coherent. The following equation relies upon on the numerical aperture of the condenser lens (NAc) and the numerical aperture of the objective lens (NAo).

$$\sigma = \frac{NAc}{NAo} \qquad (4)$$

With standard illumination conditions the partial coherence for the EXITECH system can be adjusted from 0.3 to 0.7. The conventional standard condition is a partial coherence value of 0.7. The system achieves this by blocking off specific amount of radiation with the specified aperture. Each aperture corresponds to a specified coherence value based upon the set NA of the EXITECH system.

Based on the previously mentioned EXITECH system parameters and theories of OAI, the following will be a discussion of combining partial coherence and OAI to increase resolution capabilities. As previously mentioned, OAI orientation design will depend on targeted feature include critical dimension and pitch. Previous work has been completed on the design of slot pole apertures for the ASML 248nm system. However, there are known limitations to the design most important are isolated feature degradation and the ability to optimize imaging only in one direction. The investigation of this research will evaluate the efficiency of an OAI orientation design, which is capable of resolution enhancement, and depth of focus improvements regardless of x/y orientation of features. Depth of Focus can be defined as the distance along focal plane that still produces an image of acceptable quality. The OAI technique that is capable of such results is quadrupole illumination.

II. Quadrupole Illumination Design

In order to determine the correct sigma values for the quadrupole illumination, the system parameters and governing equations for OAI will be utilized. The requirements for quadrupole illumination can be further realized by understanding the governing relationships to improve the imaging of a feature with several duty ratios. The duty ratio of a feature is defined as the ratio of line critical dimension to space critical dimension. For example, a duty ratio of (1:1) corresponds to a feature with an equal line and space critical dimension. Furthermore, an 80 nm feature with a duty ratio of (1:3) has a pitch of 320 nm, where pitch is defined as the sum of a line and accompanying space critical dimension. The following illustration depicts the frequency plane of the objective lens and demonstrates the relationship that the pole positions have with a specific pitch, numerical aperture, and exposing wavelength.

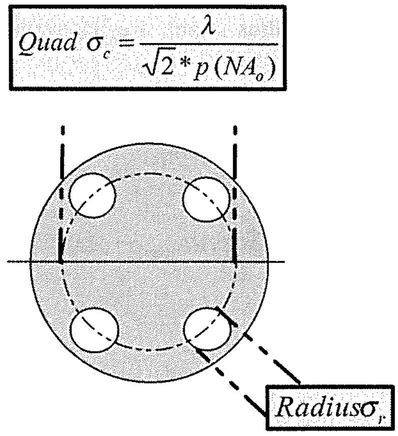


Fig. 4. Quadrupole Illumination theoretical sigma values

This illustration specifically points out the definition of the quad center sigma value and the pole or radius sigma value again in relation to the frequency plane of the objective lens. Each sigma value is relative to the grey area which is a full σ = 1. The following equations govern the placement of the poles based on the pitch, numerical aperture and exposing wavelength.

$$Axis\sigma_c = \frac{\lambda}{2p(NA)} \qquad (5)$$

$$Quad\sigma_c = \frac{\lambda}{\sqrt{2}p(NA)} \qquad (6)$$

For this research, 100 nm and 80 nm features were targeted for imaging with an objective lens numerical aperture of 1.05 and an exposing wavelength of 193 nm. The following table is a summary of the design results for 80 nm features ranging in duty ratios from 1:1 to 1:6. It should be noted that that the pole positions with respect to the optical axis spread out as the duty ratio approaches 1:1.

Duty	Pitch (nm)	Axis Sigma	Quad Sigma
1:1	160	0.57	0.812
1:1.5	200	0.46	0.650
1:2	240	0.38	0.542
1:2.5	280	0.33	0.464
1:3	320	0.29	0.406
1:3.5	360	0.26	0.361
1:4	400	0.23	0.325

1:4.5	440	0.21	0.295
1:5	480	0.19	0.271
1:5.5	520	0.18	0.250
1:6	560	0.16	0.232

Table 1. Summary of center sigma values for 80 nm features with a range of duty ratios.

In order to improve the resolution and depth of focus for the entire range of duty ratios there needs to be a certain amount of overlap for duty ratio. To achieve this the quad center sigma and the radius sigma are determined by the following relationships:

$$\sigma_c = \frac{\sqrt{2}(Axis\ Sigma_{\max} - Axis\ Sigma_{\min})}{2} \quad (7)$$

$$\sigma_r \geq \frac{(Axis\ Sigma_{\max} - Axis\ Sigma_{\min})}{2} \quad (8)$$

The summary of the results for 80 nm features for optimized quad center sigma and radius sigma values are included in the following table.

Pitch Range	Quad Sigma	Sigma Radius
1:1 - 1:3	0.61	0.14
1:1 - 1:6	0.52	0.21

Table 2. Summary of center sigma values for 80 nm features for range of duty ratios.

Based on this data the quadrupole illumination design to accommodate 80 nm features with a range of duty ratios from 1:1 to 1:3 would have a corresponding quad center sigma of 0.61 and a radius sigma of 0.15. The radius sigma value must have a minimum value to assure a sufficient overlap of pole position for each duty ratio.

For this research two quadrupole illumination aperture designs are fabricated for experimentation purposes. Each design is optimized for 80 nm and 100 nm features respectively, each with a duty ratio of (1:1). The resulting designs are summarized in the following table.

Target Feature	Quad Sigma	Sigma Radius
80 nm (1:1)	0.812	0.15
100 nm (1:1)	0.65	0.15

Table 3. Summary of center sigma values for 80 nm features for (1:1)

An increase in the radius sigma values for the quadrupole illumination translates to more light to pass resulting in greater intensity at the resist level. When compared to the conventional illumination the intensity of radiation is reduced which then requires a higher dose to clear the image on the resist and could translate to a lower contrast in the final image. Radius sigma values were chosen as to balance the benefits of the off-axis illumination with the loss of intensity.

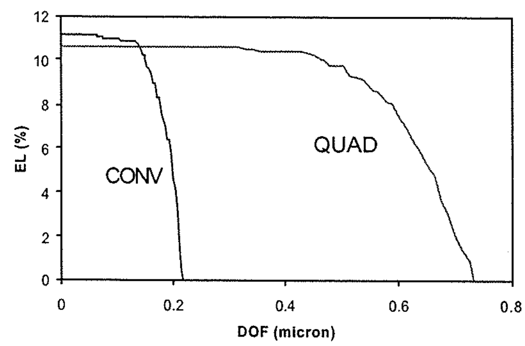


Fig. 5. Prolith process window for 80 nm quadrupole illumination versus conventional illumination

Prolith can modify the illumination of a lithographic system and simulate the theoretical results. Figure 5 is an example of how prolith can be used to simulate the enhancement of off-axis illumination over conventional illumination. Although this is strictly a theoretical plot using ideal resist models and does not take into account aberrations in the lens, there is evidence of an increased depth of focus for quadrupole illumination over conventional on-axis illumination.

In order to use the Shipley BARC AR40 (bottom antireflective coating) to suppress standing waves and a novel Shipley resist 1020C. All processes were developed based upon Shipley recommendations. A VASE or variable angle spectroscopic ellipsometer was used to dial in the correct thicknesses for the BARC and resist accordingly. The BARC AR40 was coated to 80 nm (30 sec @ 1230 rpm) with a Post Applied Bake (PAB) for 60 seconds @ 215°C. The 1020C resist was coated to a thickness of 150 nm (30 sec @ 1190 rpm) and a PAB for 90 seconds @ 120°C. Although contamination can be an issue for this resist no top-coat was used for this experiment and the Post Exposure Bake was for 60 seconds at 120°C.

III. Fabrication of the Aperture

The partial coherence aperture for the EXITECH stepper was accessible and made it possible to fabricate a quadrupole aperture for experimentation purposes. The apertures have been fabricated from aluminum stock in a metal fabrication

facility at the Rochester Institute of Technology. From the theoretical sigma values and given system dimensions a schematic drawing was completed for each aperture design. The metal fabrication tools required to complete the apertures included a band saw, lathe, and drill press.

From the aluminum stock the aperture height was cut to the appropriate sizes. Each face of the aperture was cut and polished using the lathe. The lathe was used to bore out unnecessary material from the aperture. The drill press was used to cut the appropriate sigma values into the aperture. Each aperture was then individually inspected for defects from the fabrication process and fine alignment marks on the apertures for future alignment to the optical column. Each aperture was cleaned with specific cleaning solutions and residual organic materials were removed in preparation of insertion into the Exitech Immersion stepper. The following is and image of a completed quadrupole illumination aperture.

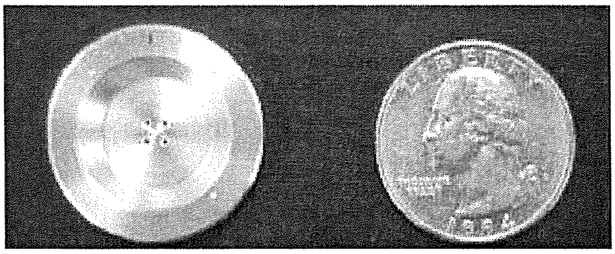


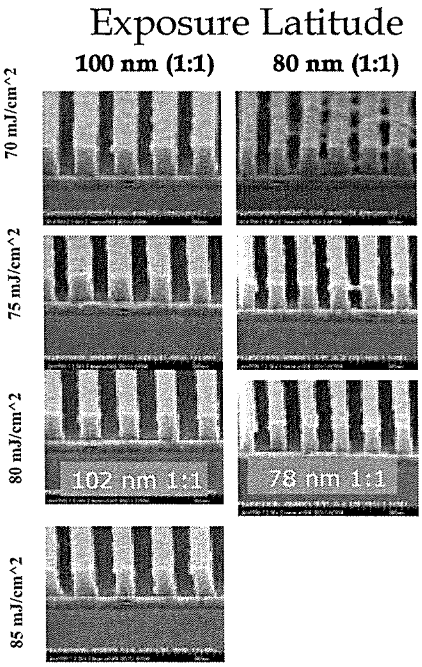
Fig. 6. Finished quadrupole illumination aperture

By utilizing this form of off-axis illumination the resolution limits can be tested for the given imaging system. The benefits of depth of focus and resolution enhancement are realized with the exposure results of the completed quadrupole illumination system. A summary and review of the exposure results with be presented in the following section. According to theory and the following experimental results, DOF and resolution enhancements are be realized for a completed quadrupole illumination system.

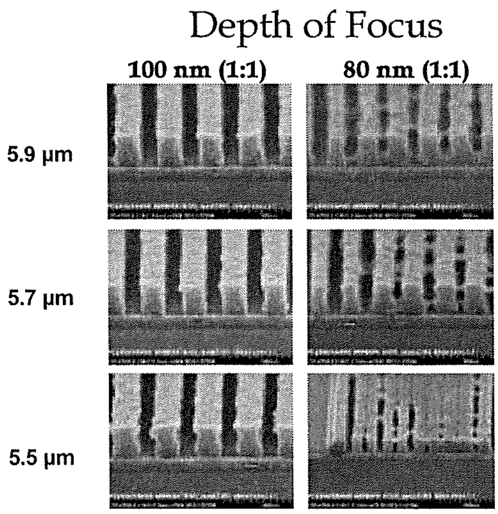
IV. EXPOSURE RESULTS

The exposure results from using the 80 nm quadrupole aperture is presented in this section. There was a significant improvement in the resolution of 80 nm lines and spaces (1:1). Resolution was also improved for the 100 nm line and space (1:1) feature and depth of focus seemed to have been improved for both feature sizes. The following SEM images illustrate the results of the experiment and provide a good representation as to the benefit of off-axis illumination.

The results of the exposure were promising especially considering there was no top-coat used for the experiment. As mentioned earlier a top-coat can be used as a protecting layer to the resist. Resist used at Deep Ultraviolet wavelength such as 248 nm and below can be susceptible to amine contamination. The amine contamination can produce a neutralized layer on the surface of the resist, which can cause the resist to become readily insoluble to the developer. In certain cases a resist feature deformity known as T-topping can occur. Even though no top-coat was used for the this experiment there was no serious contamination issues present.



These cross-sectional SEM images captured by International SEMATECH demonstrate good exposure latitude performance for both 100 nm and 80 nm features with duty ratios of (1:1). The following SEM images also from SEMATECH illustrate a similar performance through focus, demonstrating the DOF for this experiment.



The 80 nm features imaged consistently and clearly with

good aspect ratio the resist thickness was 150 nm therefore the aspect ratio was almost 2:1 (height/width). The results were encouraging with the fact that with conventional illumination of a on-axis partial coherence value of 0.7 the minimum sufficient resolved feature was a 100 nm (1:1). The research project was successful in relation to its given objective to use quadrupole illumination which coupled the benefits of off-axis illumination and immersion lithography to allow sub-100 nm imaging on the 193 nm Hyper-NA Exitech Immersion stepper at the Rochester Institute of Technology.

V. CONCLUSION and Future Research

The efficiency and benefits of off-axis illumination has been successfully demonstrated. Quadrupole apertures were designed based on the off-axis illumination theory discussed. Each design was fabricated at the Rochester Institute of Technology using materials and tools in house. A process was developed to run an experiment with the completed illumination system. The results were illustrated and summarized and the objectives of the research project were met. Sub-100 nm imaging was allowed on the 193 nm Hyper-NA Exitech Immersion stepper at the Rochester Institute of Technology due to a quadrupole illumination system that coupled the benefits of off-axis illumination and immersion lithography.

Further work can be completed including the optimization of further resist processes as well as alternative off-axis illumination systems including dipole. Dipole illumination has the capability to improve resolution beyond quadrupole, however only for features oriented in one direction. In response dipole and annular should both be investigated. The experiments to further assess these illuminations will require more test features on the mask that vary in pitch and orientation. Also, further improvement into the optical column alignment procedure can benefit from future work. Immersion lithography coupled with the correct illumination techniques is promising to extend the lifetime of optical lithography.

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