HIGH NA DUV PRINTING TOOL WITH COMBINATION
OF OBLIQUE ILLUMINATION SOURCE
FOR 0.25 μm LITHOGRAPHY APPLICATION

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In this paper, the performance of quadrapole illumination source under two types of high numerical aperture (NA) deep-ultra-violet (DUV) printing tools, namely, excimer laser stepper with chromatic lens design and step-and-scan systems without chromatic aberration for the application of 0.25 μm lithography is studied through simulation. The results are based on both aerial image and Shipley XP89131 negative DUV resist model [1] study. Due to the unique characteristics of oblique illumination source imaging, i.e., imaging by using only zero and first diffraction order light, both stepper resolution limit and depth of focus (DOF) of dense lines are extended. As a result, the proximity effect and the chromatic aberration effect in resist printing are also different from that of conventional illumination source. The optical proximity effect increases under the oblique illumination source as compared to that of conventional illumination source, especially when the light incident angle is large. For chromatic lens aberration, unlike the conventional illumination source, aerial image degradation depends not only on the laser spectral profile and amount of the lens aberration, but also on the mask feature sizes and pattern types.

1. Introduction

With today's new advanced imaging techniques such as oblique illumination, frequency filtering at entrance pupil plane, and phase shift masks, etc., the limit of optical lithography is able to be pushed further than what is predicted by the Rayleigh criteria. For feature sizes in the region of 0.25 μm, high NA projection tools with DUV wavelength of 248 nm in combination with oblique illumination source form one of the simplest combinations that could possibly fulfill the lithographic requirement. In this combination, the short wavelength is necessary to provide the critical resolution, and the oblique illumination source is used to further enhance DOF of the periodic features. Due to different characteristics of the oblique illumination sources, the aerial images of the periodic features are formed by using only zero
and first diffraction orders rather than zero plus both +1 and -1 diffraction orders as in the conventional illumination case. As a result, the frequency distributions of the mask pattern in the Fourier transform plane will be different, and somewhat unbalanced as compared to that of conventional illumination case. The proximity effect and the chromatic lens aberration effect in resist printing, etc., also expect to be different from that of conventional illumination source. In this paper, the performance of different high NA (≥0.5) DUV 248 nm printing tools, namely, the excimer laser stepper with chromatic lens design and step-and-scan printing tool without chromatic aberration, in combination with the quadrapole illumination source for the application of 0.25 μm lithography is studied through both aerial image and resist simulations. In section 2, the simulation method will be described. Section 3 discusses the parameter optimization for quadrapole sources and the dependence of DOF, proximity effect, and exposure dose on these parameters. The detailed study of proximity effect and its correction under the quadrapole illumination source is given in section 4. In section 5, the effect of chromatic aberration under the quadrapole illumination source is studied. Section 6 is the conclusion.

2. Simulation Method

The simulation results presented in this paper are obtained using iPHOTO-II, a high NA aerial image and resist profile simulator. The program is designed for efficient computation of large area aerial images with and without lens aberrations. For a simulation domain of 24 μm by 24 μm, the aerial image with partial coherence σ=0.5 (conventional illumination) takes less than 6 minutes on an IBM RS6000-320. The computation is nearly feature independent. Cross comparison of the simulation results with SPLAT program developed by U.C Berkeley showed close agreement.

In the case of chromatic projection lens with finite laser spectral profile (or spectrum) bandwidth, the effect of chromatic aberration is simulated by first dividing the laser spectrum into 16 sub-portions (the choice for the number of sub-portions is balanced between the computation accuracy and computation time). The corresponding wavelength of each portion is represented by the center wavelength of that portion. The aerial image formed by each portion of the spectrum is then calculated based on the lens defocusing rate "r", i.e., the chromatic aberration coefficient. It is defined as the amount of focus shift per unit wavelength shift due to chromatic projection lens. Each of these subsections are subsequently propagated independently through the lithographic system to form images. The final aerial image is obtained by adding the aerial image contributions of each spectral component with weighing factors representing the illumination spectrum shape.
The stepper parameters used in the simulation are the followings: \( \lambda = 248 \) nm, \( \sigma = 0.5 \) (in the case of conventional illumination source). The quadrapole source parameters are optimized for 0.25 \( \mu \)m periodic features (details are given in the next section). In resist process window simulation, 0.5 \( \mu \)m thick Shipley XP89131 negative resist with parameters \( A = -0.65, B = 1.137, \) and \( C = 0.002 \) are used. Bare Si is used as the substrate material.

3. Quadrapole Source Parameter Optimization

The quadrapole source used in the simulation is optimized for 0.25 \( \mu \)m dense lines. In the parameter optimization process, the radius of each circular opening is fixed with value of 0.22, while the distance between the four circular openings is optimized to yield maximum DOF for that given feature. The metrics used in determining the DOF is the aerial image Modulation Transfer Function (MTF) defined as

\[
MTF = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]

where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and minimum intensities of the aerial image. In Fig. 1, a set of MTF's plot with 0.6 NA lens as a function of defocus for quadruple separations of \( d = 0.3, d = 0.4, \) and \( d = 0.5 \) along x-direction (or y-direction) are given. The allowable quadruple separation range is defined by the area of the quadrapole source which should be no larger than a circular area with radius of partial coherence \( \sigma \). In a given printing tool, the maximum allowable quadrapole source (or quadruple separation) will depend on the maximum partial coherence design for that system. Our results in Fig. 1 showed that the optimized quadruple separation for 0.25 \( \mu \)m dense lines with 0.6 NA lens is about 0.4. The optimized quadruple separation depends on both the feature size and NA of the lens. In general, the larger are the feature size and NA, the smaller the quadruple separation is required.

According to the above results, the DOF performance of dense lines depends upon the oblique illumination source parameters. It should be mentioned here that other lithographic performances, such as exposure dose and proximity effect, are also influenced by the source parameter.

![Fig. 1 Modulation Transfer Function versus defocus for quadruple separations of 0.3, 0.4 and 0.5.](image-url)
In Figs. 2 and 3, the responses of resist exposure dose to the two variable parameters, namely, stepper NA and quadruple separation, are given for 0.25 µm dense and isolated resist lines, respectively. The labeled dose values for each line in the plot have the unit of mJ/cm². It is shown in both cases, the larger the quadruple separation is, the more the exposure dose is needed to obtain the nominal 0.25 µm line width. The major contribution to this dose difference is the combination of oblique incident angle on the wafer plane and the reflection of wafer substrate. When a relatively transparent resist and relatively high reflectivity substrate are used, certain amount of the light will be reflected back to the resist and expose additional resist. In the case of normal incident angle (conventional illumination case), all the reflected light will travel back to the resist until it strikes on the resist top surface. However, when the exposure light incident on the wafer with an angle (oblique illumination case), the light will be reflected back with the same angle. As a result, part of the reflected light will travel out of the designed exposure area and enter into the non-exposure area. The less the incident angle, the more the reflected light will expose the designed exposure area, and the less the exposure dose is needed to print a given feature size when compared to that of larger incident angle case. To confirm above argument, we further calculated the dose requirement for obtaining 0.25 µm lines and spaces when the substrate index of refraction matches that of the resist. The result showed that it only requires about 1.5% and 3.0% more dose for quadruple separations of 0.4 and 0.5, respectively, as compared to that of 0.3 separation. The small dose differences in this case for different quadruple separations are attributable to the slight difference in the aerial images at different quadruple separations. While in the case of silicon substrate, according to Fig. 2, 9.9% and 22.2% more dose are needed for quadruple separations of 0.4 and 0.5, respectively, as compared to that of 0.3 separation.
Another problem associated with the larger quadruple separation is the proximity effect. According to Figs. 2 and 3, the exposure dose difference (in percentage) increases as quadruple separation increase. For example, for NA = 0.6 and quadruple separation of 0.35, the dose needed to obtain 0.25 µm isolated line is 7.1% higher than that of 0.25 µm dense lines. While for quadruple separation of 0.5, the dose needed to obtain 0.25 µm isolated line increased to 14.1% as compared to that of 0.25 µm dense lines. This dose difference in printing nominal dense and isolated lines is the proximity effect. The larger the percentage dose difference, the larger the proximity effect is. This dependence can also be seen from the aerial image plot given in Figs. 4 and 5, where aerial images of 0.25 µm dense and isolated lines at zero defocus for three different quadruple separations: 0.3, 0.4, and 0.5 are given, respectively. Lens NA of 0.6 is used in the calculation. It is shown that the aerial images of lines and spaces are almost independent of the quadruple separations at zero defocus (please note that the aerial images of d = 0.4 and d = 0.5 coincide with each other at zero defocus). However, for isolated lines, the aerial images degrade (more sloped) as the quadruple separation increases. The lower image peak intensities at larger quadruple separations indicate that more exposure dose is needed to obtain the same line width as compared to that of small quadruple separation case.

According to the above discussion, if the optimized parameter based on the DOF enhancement for desired feature should yield a DOF which is more than what the process
needs, smaller quadruple separation is always preferred to balance the effects between DOF enhancement and the proximity effect.

4. Proximity Effect and Correction

The proximity effect in resist printing is attributable to the image characteristics of the optical exposure tool (optical proximity), resist characteristics, resist process, and wafer substrate characteristics. The proximity effect causes printed feature line widths to vary depending upon the density, size, and locations of nearby features. It greatly reduces the common process window for different types of features on the mask. In the oblique illumination system, this effect is more pronounced as compared to that of conventional illumination sources. In Fig. 6, aerial image estimations of resist CD for 0.25 μm features under both conventional and quadruple illumination sources are given for NA ranging from 0.5 to 0.7. The quadruple separation used in the simulation is 0.4 for all NA's. The solid and dashed lines in the plots correspond to the cases of conventional and quadruple illumination sources, respectively. The line width, or the CD of the feature is obtained at 30% of energy level of the corresponding aerial images. The results showed that the optical proximity effect is larger under the quadruple illumination source than that of conventional illumination source.

When the optical aerial images combine with a given resist, the degree of the proximity effect will vary depending upon the characteristics of resist and wafer substrate. For Shipley XP89131 negative resist and silicon substrate, we calculated the exposure dose difference in percentage (defined as the dose for 0.25 μm isolated lines minus the dose for 0.25 μm L/S and divided by the dose for 0.25 μm L/S) between the dense and isolated 0.25 μm lines under both conventional and quadruple (quadruple separation=0.4) illumination sources for NA ranging from 0.5 to 7.0. The results are given in Fig. 7, where the solid and dashed lines correspond to the conventional and quadruple illumination sources, respectively. It showed a consistent result with the aerial image estimation given in Fig. 6, i.e., proximity effect is larger under the quadruple illumination source than that of conventional illumination source.
As the proximity effect approaches the given CD error budget, there is less process, e.g., focus-exposure, latitude available, even though each type of feature pattern has reasonable larger process latitude when optimized individually. In the case of high NA DUV printing with conventional illumination source, the process latitude of 0.25 µm isolated lines is much larger as compared to that of dense lines. By using oblique illumination source, the process latitude of the dense lines is greatly enhanced. However, as discussed previously, due to larger proximity effect, the common process window of the two types of features can become too small to be applicable when printing simultaneously. In Fig 8, a plot of calculated resist process windows for both dense (solid lines) and isolated (dashed lines) 0.25 µm lines under the quadrapole illumination source are given, respectively. Lens NA used in the calculation is 0.6. In the plot, ±10% allowable CD error budget are used, i.e., the two lines in each plot correspond to CD of 0.225 µm and 0.275 µm, which are the ±10% nominal (0.25 µm) CD's, respectively. The resist angles constraint of ≥87 degrees is also used. This constraint is given by dotted lines for both the cases of dense and isolated lines in Fig. 8. The overlapping region, or the common process window, is given by the shaded area. These results showed that the common process window for the two types of features are reduced to less than half of the individual process window when each process is optimized individually. In other words, the process window gain in dense feature by using the oblique illumination is partially canceled out by the proximity effect when both dense and isolated features are printed simultaneously. Therefore, in order to receive the full benefit from the oblique illumination source, biasing the mask to correct the proximity effect becomes necessary. In Fig. 9, we re-plotted the process windows of 0.25 µm dense and isolated lines with proximity correction for the isolated lines. Our resist simulation showed that about 0.01 µm mask biasing for the isolated lines (i.e., use 0.26 µm in design to print 0.25 µm) will yield maximum common process window. No mask bias for dense lines is used. In Fig. 9, the solid and dashed lines again correspond to the process windows of dense and isolated lines, respectively. The allowable CD budget is again ±10% of the nominal CD, and the resist angles constraint is the same as that in Fig. 8. The results in Fig. 9 showed that with a 0.01 µm mask biasing for the isolated lines, the common process window of dense and isolated lines have been doubled.

Fig. 7 Exposure dose difference of 0.25 µm isolated and periodic lines as a function of NA for both conventional and quadrapole illumination sources.

![Dose difference plot](image-url)
as compared to that of no biasing case. This common process window is shown to be reasonably large for 0.25 \( \mu \text{m} \) lithographic application. For example, according to Fig. 9, if we chose total required DOF as 1.0 \( \mu \text{m} \), a total exposure latitude of 13\% can be obtained. The total exposure latitude here is defined as the difference between the total allowable dose variation and the nominal dose divided by the nominal dose. When we reduce the required total DOF to 0.8 \( \mu \text{m} \), the corresponding total exposure latitude increases to 17\%. With new advanced DUV resist available in future, the above estimated process window can further be increased (note that results may be different for positive resist).

5. Chromatic Aberration Effect

In this section, the performance of the DUV printing tool with chromatic lens design, such as excimer laser stepper, under the oblique illumination source is evaluated based on aerial image quality. The origin of the chromatic aberration in excimer laser stepper arises from both single material lens design and finite laser spectral bandwidth. The impact of the chromatic aberration on resolution, DOF, and exposure latitude of the photoresist under the conventional illumination source has been studied in detail previously [2-5]. When oblique illumination source is used, the effect of chromatic aberration in resist printing is expected to be different due to the nature of the aberration: the aerial image is a combination of images with different degrees of defocus. Even at the nominal best focus, the aerial image consists of one in focus sub-image corresponding to the center wavelength and a continuum of out of focus sub-images from other sections of the spectrum. The characteristic degradation of the aerial images, therefore, is a defocus type. To understand better the effect of chromatic
aberration under the oblique illumination source, first, we will focus our discussion on the pattern dependent DOF enhancement of a high NA (NA=0.6) DUV printing tool with achromatic lens design (i.e., no presence of chromatic aberration effect) under the quadrapole illumination source. It will be shown later that this result is related to the performance of the chromatic projection lens when the oblique illumination source is used.

The simulation result of DOF as a function of feature size (periodic lines and spaces) for two different illumination sources, i.e, conventional and quadrapole, for 0.6 NA achromatic lens (no aberration) is given in Fig. 10. The DOF in the plot is determined by 70% aerial image MTF criteria. The solid and dashed lines in the plot correspond to the conventional and quadrapole illumination sources, respectively. It is shown in the plot that the total DOF of 0.25 μm dense lines under the conventional illumination source is only about 0.6 μm, which is too small for any practical application. While under the quadrapole illumination source, the same feature yields a total DOF of 1.7 μm. The two curves in Fig. 10 show that when the quadrapole source is optimized for smaller periodic features, the DOF of those smaller periodic features are extended. However, with the same quadrapole illumination source parameters, the DOF improvement becomes less and finally worse than that of conventional illumination source as the feature size becomes larger. That is, the oblique illumination does not improve the DOF of large features (these results can also be applied to the periodic contacts). This is because when the oblique illumination source is optimized for 0.25 μm periodic lines and spaces, the zero and first diffraction orders are more symmetrically distributed around the optical axis than that of the conventional illumination source. As a result, the optical path difference between the zero and first diffraction orders is minimum at wafer plane when defocus occurs. Therefore, larger DOF can be obtained. By the same argument, the advantage of the oblique illumination will become less as the periodic lines become larger. Since when the periodic lines become larger, the diffraction angle becomes smaller. With the same oblique incident angle, the symmetry of zero and first diffraction orders around the optical axis in the case of quadrapole illumination no longer exists. This situation therefore becomes closer to that of the conventional illumination case.
(that is why the DOF enhancement becomes less when the mask features become larger). Finally, when the diffraction angle becomes small enough (large pitch), the first diffraction order will eventually shift to the same side as that of zero order in the case of oblique illumination source, resulting in more asymmetry in zero and first diffraction orders about the optical axis. As a result, larger optical path difference between zero and first diffraction orders will be obtained when wafer is defocused, resulting in a smaller DOF. Since the DOF enhancement under the oblique illumination source is pattern dependent, the effect of chromatic lens aberration, which illustrates a defocus type of aerial image distortion, will also be dependent on the mask features.

In order to clearly demonstrate the chromatic aberration effect in oblique illumination system, Cymer CX-2LX excimer laser profile with bandwidth of 2.3 pm [6] is used, even though narrower excimer laser spectral profile is also available [7]. The chromatic aberration coefficient "r" of the stepper lens used in the simulation is -0.17 µm/ pm. This number is a typical one for current available excimer laser stepper lenses.

In Figs. 11 and 12, we have plotted the simulation results of MTF of 0.25 µm periodic lines and spaces as a function of defocus for conventional and quadrapole illumination sources with 0.6 NA lens, respectively. The solid and dashed lines in each plot correspond to aberration free lens and aberration coefficient of -0.17 µm/ pm lens, respectively. As we expected, the aerial image degradation due to chromatic lens aberration under the quadrapole illumination source has much smaller effect than that of conventional illumination source. This is because quadrapole illumination source can tolerate more focus spread along the
optical axis than that of conventional illumination source for smaller periodic lines (<0.4 μm). In the case of larger periodic lines (>0.4 μm), the advantage of quadrapole illumination over the conventional illumination sources with chromatic stepper lens disappears as predicted in Fig. 10. To illustrate this point, the aerial images of 0.55 μm periodic lines with 0.6 NA lens are calculated and given in Figs 13, and 14, for the conventional and quadrapole illumination sources, respectively. The solid and dashed lines in each plot correspond to aberration free lens and aberration coefficient of -0.17 μm/pm lens, respectively. This time, the quadrapole illumination source results in larger aerial image degradation than that of conventional illumination source.

It is known that the oblique illumination source does not improve the DOF of isolated lines (or isolated contact) either. It is foreseeable that the effect of chromatic aberration for isolated lines under the oblique illumination should not be better or worse than that of conventional illumination source. In Figs. 15 and 16, the aerial images of 0.25 μm isolated lines at presence of chromatic aberration under the conventional and quadrapole illumination sources with 0.6 NA lens are given, respectively. The solid and dashed lines in each plot again correspond to aberration free lens and aberration coefficient of -0.17 μm/pm lens, respectively. The results showed about same amount of aerial image degradation at presence of chromatic aberration under both illumination sources.

In summary, the oblique illumination source can have more or less chromatic aberration effect than that of conventional illumination source depending upon the mask feature sizes.
and types. The dependency of mask feature sizes follows the DOF trend predicted by Fig. 10. That is, the features whose DOF can be enhanced by oblique illumination suffer less in chromatic lens aberration than that of conventional illumination, while the features whose DOF can not be enhanced or even reduced by oblique illumination suffer equally or more in chromatic lens aberration than that of conventional illumination. However, when only the critical features (e.g., small periodic lines) are concerned, use of oblique illumination in chromatic stepper lens system, especially when the laser spectrum bandwidth is wide, gives more advantages than that of conventional illumination source.

6. Conclusions

Through simulation, we have shown that with the help of oblique illumination source, a reasonable process latitude for 0.25 μm dense and isolated lines can be obtained by using 248 nm wavelength illumination with high NA (>0.5) lens. Due to pattern dependent DOF enhancement of oblique illumination source, the optical proximity effect is larger as compared to that of conventional illumination source. The process window enhancement under the oblique illumination therefore can only be maximized with the proximity correction. The DOF, exposure dose, and proximity effect in oblique illumination system are found all depending upon the source parameters. The optimization of the source parameters, therefore, needs to take into account all these factors. The chromatic aberration effect in excimer laser stepper under the oblique illumination is found to be mask pattern dependent. Use of oblique illumination in chromatic stepper lens system, especially when
the laser spectrum bandwidth is wide, gives more advantages than that of conventional illumination source for critical features.

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References
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