Simulation study of the NA/σ's dependence of DOF for 193-nm immersion lithography at 65-nm node

Guosheng Huang (黄国胜)[1,2] and Yanqiu Li (李艳秋)[1]

[1] *The Institute of Electrical Engineering of Chinese Academy of Sciences, Beijing 100080*

[2] *Graduate School of Chinese Academy of Sciences, Beijing 100039*

Received October 10, 2004

Recently, ArF immersion lithography has been considered as a promising method after ArF dry lithography by a factor of refractive index n of the liquid filled into the space between the bottom lens and wafer, in the case of 193-nm exposure tools, water (n = 1.44) has been found as the best liquid. We explore the NA/σ's dependence of depth of focus (DOF) under 3/4 annular and 3/4 quasar illumination by resist imaging simulation. Line/space pairs of line-to-space ratios 1:1, 1:2, 1:4 on binary mask are considered. Finally, we explored the high NA's dependency of DOF and gave the explanation for the peak value of DOF through three-beam imaging process, MicroCruiser 2.0, Prolith version 8.0.2 and k_2 factor based on the Rayleigh equation.

OCIS codes: 110.5220, 070.2580, 220.4830, 230.0230.

There are three ways to improve the resolution of optical projection imaging, namely, increasing numerical aperture (NA), reducing wavelength, and implementing resolution enhancement techniques (RETs), such as phase-shift mask, modified illumination, optical proximity correction, and pupil filtering, to reduce the k_1 requirement of a given NA-wavelength combination.

While the choice of reducing wavelength for next-generation lithography is always difficult. This difficulty is caused not only by the availability of the technology itself but also by the complex infrastructure and costs involved. From an optical point of view, a short wavelength is preferred for the ease of resolving fine structures. However, the process of photolithography deals not only with the aerial image formation but also with the three-dimensional (3D) developed resist image. Unfortunately, materials, even air, become more absorptive when the next available wavelength below 193 nm is encountered.

Currently, immersion lithography has been proposed as a method of extending the feasibility of optical lithography beyond the 65-nm node. The premise behind this technique is to increase the index of refraction of the space between the lens and wafer through the insertion of a high-index liquid in place of the low-index air that currently fills the space. This technique enables the NA to approach 1.4 in water (n = 1.44). The Rayleigh equation has to be changed as[1,2]

$$R = k_1 \frac{\lambda/n}{\sin\theta}, \tag{1}$$

$$\mathrm{DOF} = k_2 \frac{n\lambda}{\mathrm{NA}^2}, \tag{2}$$

where R is the resolution, λ is the wavelength of the light source of the exposure system, n is the refractive index of the medium (liquid, gas, or vacuum) of the focal region, θ is the maximum incidence angle, and the parameters k_1 and k_2 depend on the imaging technology.

This paper researches the NA/σ's dependence of DOF for 65-nm line/space pattern under annular and quasar illumination. Line/space pairs of line-to-space ratios 1:1, 1:2, 1:4 on binary mask are considered. We tune the NA/σ setting for 65-nm line/space pattern under 3/4 annular and 3/4 quasar illumination to get the DOF distribution at different conditions. High NA dependence of DOF is explained due to three beam imaging process through MicroCruiser 2.0, Prolith version 8.0.2, and Eq. (2). In addition, since photoresist chemistries are still under consideration for immersion lithography, we choose Prolith's lumped parameter model (LPM) as our resist model to demonstrate current ArF resist by including a liquid between the last lens surface and the photoresist. LPM is based on a model for development rate and a phenomenological description of the development process. The major advantage of LPM is its extreme ease of application to a lithography process and computational simplicity.

Prolith version 8.0.2 is employed in this simulation research with its vector model which is the most accurate model for large NA. In addition to support the research, we have developed an in-house software, MicroCruiser, which can call Prolith to run the aerial image simulation automatically with a large range and flexible setting of NA and σ, at the same time, save the simulation result to an EXCEL sheet in the form user desired. In order to pursue the NA/σ's exact dependence of the DOF, Prolith's LPM[3] is applied to our simulation research with such papameters, resist contrast = 17, effective resist thickness = 300 nm, dose to clear = 15 mJ/cm^2, effective resist absorption coefficient = 0.7/μm, and aerial image diffusion length = 4.0 nm. We set exposure latitude (EL) as 5%, ΔCD $\leq$ +/−10% CD, side wall angle $>$ 80°, and resist loss $<$ 10%. All results assume unpolarized incident light and an aberration-free lens system is considered to research the suitable NA/σ setting.

In our study, we set the NA from 0.8 to 1.4 with its step of 0.01, σ_o (sigma-out) from 0.6 to 0.96 with its step of 0.02. The opening angle for quasar illumination is 30°. This NA/σ range is consistent in the following simulation of line/space pattern line-to-space ratios of 1:1, 1:2, 1:4 under both 3/4 annular and 3/4 quasar illumination. The simulation result is illustrated in Figs. 1 and 2. According to our simulation, NA/σ's dependence of the DOF behaves dissimilarly due to different line-to-space ratios for line/space pattern.

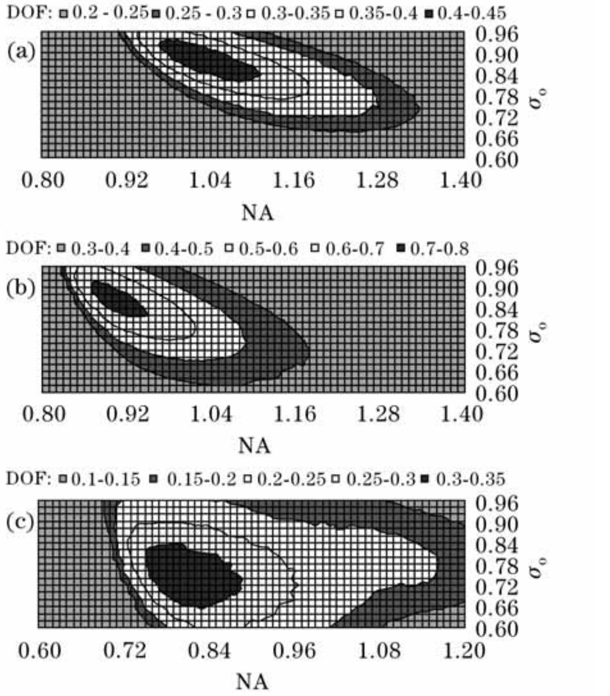

Fig. 1. DOF matrix under various NA/σ with annular illumination for different line-to-space ratios of (a) 1:1, (b) 1:2, (c) 1:4, when EL = 5%.

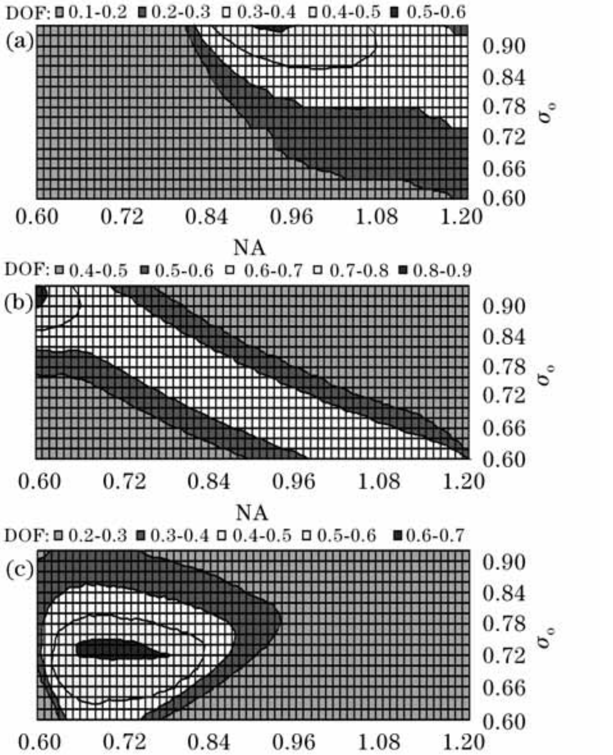

Fig. 2. DOF matrix under various NA/σ with quasar illumination for different line-to-space ratios of (a) 1:1, (b) 1:2, (c) 1:4, when EL = 5%.

Under 3/4 annular illumination, NA from 0.91 to 1.2 and σ_o from 0.84 to 0.88 are eligible to yield larger DOF for line-space pairs of line-to-space ratio 1:1. However, for line/space pattern of line-to-space ratio of 1:2, the suitable NA/σ setting for larger DOF is NA from 0.74 to 0.86 and σ_o from 0.72 to 0.78. As for the line-to-space ratio of 1:4 case, the eligible area is NA from 0.74 to 0.92 and σ_o from 0.76 to 0.82.

Similarly, under 3/4 quasar illumination, different line-to-space ratios also bring the distinct distribution of NA and σ for a large DOF. The expected NA/σ areas to yield larger DOF for line/space pattern of line-to-space ratios of 1:1, 1:2, 1:4 are NA from 1.05 to 1.27 and σ_o from 0.84 to 0.88, NA from 0.8 to 1.05 and σ_o from 0.84 to 0.88, NA from 0.85 to 1.0 and σ_o from 0.64 to 0.78, respectively.

It is interesting that we find such relationship between DOF and NA either for line-to-space ratio of 1:1 under 3/4 annular illumination or for line-to-space ratio of 1:1 under 3/4 quasar illumination, as shown in Figs. 3 and 4. It may be thought that DOF should decrease all the while as NA increases, according to Eq. (2). However, we should note that k_2 also changes as NA varies, so DOF will not always fall as NA increases. Our simulation result shows that DOF first increases as NA increases, then DOF begins to fall as NA continues to increase after DOF peaks out. To understand why DOF performs like this, let us turn to three-beam theory[4]. The three-beam imaging process is illustrated in Fig. 5. It is well known that at least 2 diffraction orders of light are necessary for an image to form. Now, let us turn to the Prolith's graphic interface which is easy to be understood.

Taking line/space pattern of line-to-space ratio of 1:1 under 3/4 annular illumination as an example, we choose three points from Fig. 3, corresponding to the following situations. 1) σ_o = 0.86, σ_i = 0.65, NA = 0.88.

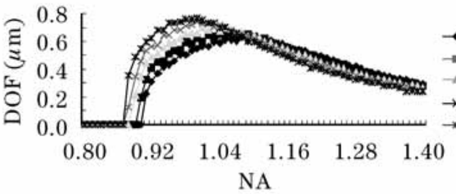

Fig. 3. DOF versus NA under 3/4 annular illumination and line-to-space ratio of 1:1.

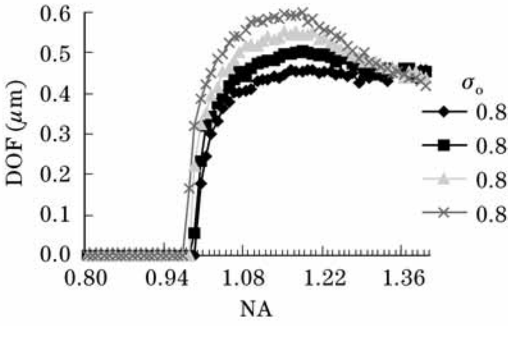

Fig. 4. DOF versus NA under 3/4 quasar illumination and line-to-space ratio of 1:1.

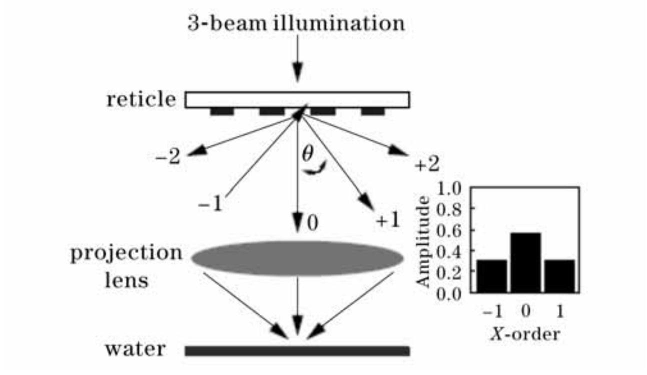

Fig. 5. Three-beam imaging process.

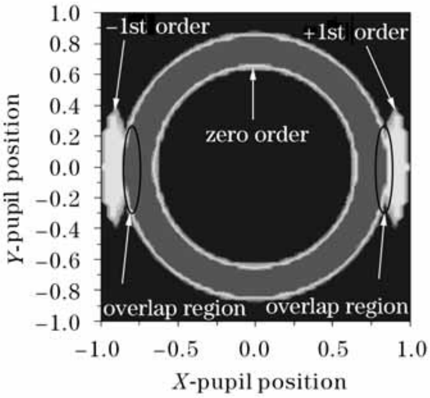

Fig. 6. Diffraction pattern at σ_o = 0.86, σ_i = 0.65, NA = 0.88, 3/4 annular illumination, and line-to-space ratio of 1:1.

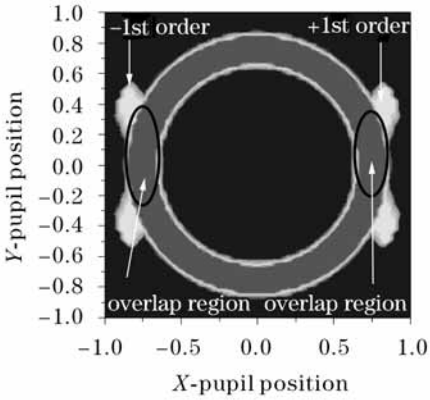

Fig. 7. Diffraction pattern at $\sigma_o = 0.86$, $\sigma_i = 0.65$, NA = 1.0, 3/4 annular illumination, and line-to-space ratio of 1:1.

2) σ_o = 0.86, σ_i = 0.65, NA = 1.0. 3) σ_o = 0.86, σ_i = 0.65, NA = 1.35. Figures 6, 7, and 8 are their corresponding diffraction pattern (amp w/source shape) displayed in Prolith's graphic interface.

In Fig. 6, we can see that the positive and negative 1st order are barely contained in the NA of the lens, and if NA continues to increase, more of the 1st order will appear and more zero, +1 and −1 orders contribute to the image. Thus, image quality is improved and DOF is enlarged. In other words, if the overlapping region becomes larger, that is to say, higher spatial frequencies are captured in the NA and larger DOF is attained. Consequently, DOF has reached its peak because 1st and zero order beams overlap best as shown in Fig. 7. At last, as NA is too large, DOF begins to decrease, for few positive and negative 1st beams are captured in the NA of the lens which is shown in Fig. 8. In fact, the reason why DOF behaves in such way as NA increases is that numerical aperture's change has resulted in the variety of k_2 factor in Eq. (2).

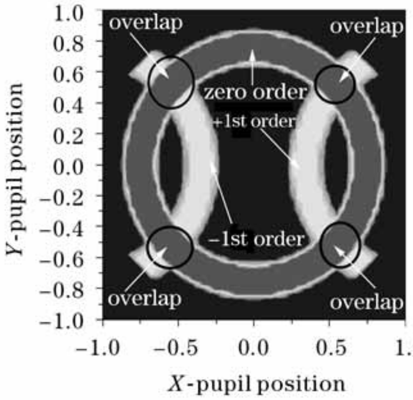

Fig. 8. Diffraction pattern at σ_o = 0.86, σ_i = 0.65, NA = 1.35, 3/4 annular illumination, and line-to-space ratio of 1:1.

NA/σ's dependence of DOF under 3/4 annular and 3/4 quasar illumination is quantitatively evaluated using E-D methodology in an aerial image simulation by a commercial software Prolith and MicroCruiser 2.0, an in-house software we developed. The DOF of line/space of various pitches under annular illumination on binary mask in 193-nm immersion system is plotted as a function of the NA. Finally the research shows the peak value of DOF and gives our explanation through three-beam imaging process and k_2 factor based on Rayleigh equation when liquid immersion lithography is applied.

Great thanks to the invaluable technical support for Prolith from J. S. Petersen and M. J. Maslow of Petersen Advanced Lithography, Inc. US. Besides, this work was supported by the Century Program of China (Hundred Talents Program 2001). Y. Li is the author to whom the correspondence should be addressed, her e-mail address is liyanq@mail.iee.ac.cn.

References

1. S. Owa and H. Nagasaka, Journal of Microlithography, Microfabrication, and Microsystems **3,** 97 (2004).
2. J. Mulkens, D. Flagello, B. Streefkerk, and P. Grapner, Journal of Microlithography, Microfabrication, and Microsystems **3,** 104 (2004).
3. C. A. Mack, *Inside PROLITH^{TM}, A Comprehensive Guide to Optical Lithography Simulation* (FINLE Technologies, Inc., Austin, Texas, USA, 1997).
4. S. D. Hsu, N. Corcoran, M. Eurlings, W. Knose, T. Laidig, K. E. Wampler, S. Roy, X. Shi, M. Hsu, J. Fungchen, J. Finders, R. J. Socha, and M. Dusa, Proc. SPIE **4691,** 476 (2002).