An investigation on capabilities of polarization control for immersion lithography through simulation

Guobin Yu (余国彬)[1,2], Tingwen Xing (邢廷文)[1], and Hanmin Yao (姚汉民)[1]

[1] *State Key Laboratory of Optical Technology for Microfabrication, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209*

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

The fundamental resolution limit and depth of focus of immersion lithography are described. The image contrasts for TE polarization, TM polarization, and unpolarized condition are explored in detail. There are complications associated with diffraction orders incident on the resist at large incident angles. Image contrast can be improved or degraded depending on the choice of polarization states. The influence of polarization on processing windows for 65 and 45 nm 1 : 1 line/space patterns is studied by simulation. It shows the use of vector image lithography simulator to quantify exposure-focus processing window improvements for TE polarization as compared with TM polarization. The results show that the full resolution capabilities of immersion lithography systems can only be realized when the polarization control is used.

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The relentless demands of Moore's law on lithography are well known. The current industry roadmap[1] calls for initial volume manufacturing of the 65-nm half-pitch node in the 2005 to 2007 time frame, which demands a decision on the manufacturing technology in the near future. It now appears that next generation lithography techniques will be hard pressed to meet this time line, and attention has turned to extensions of optical lithography. Immersion lithography has recently risen to a promising candidate position for the nanolithography technology roadmap for critical dimensions (CDs) down to perhaps 65 nm. In the last few years, some articles[2−4] have been written on various aspects of immersion lithography. Clearly, numerous factors need to be investigated to evaluate the viability of this potential lithography technology. One thing we have seen recently is that polarization problems are more severe in immersion lithography system. The obliquity of the waves required to form the target image cause the TM polarization to detrimental to the image quality. So for immersion lithography, polarization control is a big thing.

Immersion lithography uses some kind of liquid filled into the space between the bottom lens and wafer. Generally speaking, the resolution limit R and depth of focus (DOF) of the immersion lithography system are given by

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

$$\mathrm{DOF} = k_2 \frac{\lambda/n}{2(1-\cos 2\theta)} \approx k_2 \frac{\lambda/n}{\sin^2\theta} = k_2 \frac{n\lambda}{\mathrm{NA}^2}, \tag{2}$$

where n is the refractive index of the liquid, θ is the maximum incidence angle, k_1 and k_2 are constants.

By these formulas, we can understand the resolution is enhanced by factor n compared with dry lithography at the same incidence angle θ and also understand the DOF is increased by factor n compared with dry optics of the same numerical aperture (NA).

Imaging at very high NA values in immersion lithography will require polarization effects to be taken into account. A fundamental loss in image contrast for TM polarization component that occurs at large oblique angles is explored. To understand this effect, let us consider the image created by the interference of two coherent beams of light. Figure 1 shows the image contrast $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ versus NA for three polarization conditions: TE polarization, TM polarization, and the unpolarized condition. The contrast is calculated inside a photoresist of index 1.75 as function of NA. As can be seen, the TE polarization case has maximum interference resulting in a contrast of 100% for all NA, as shown by the open squares in Fig. 1. The TM polarization case has a contrast that decreases by the cosine of the angle between the beams because the TM polarization component cannot fully interfere since the electric field vectors are not parallel. The image contrast, shown by the open circles in Fig. 1, will drop to 0 at NA = 1.2 where the two electric field vectors are perpendicular, and cannot interfere at all. Increasing the NA further results in image reversal for TM polarization case. Since the unpolarized condition is the average of the TE and TM polarization, the unpolarized case will also suffer from an image degradation that increases with NA, as shown by the open triangles in Fig. 1. The low image contrast of TM polarization and the proximity to the phase reversal region imply that immersion lithography

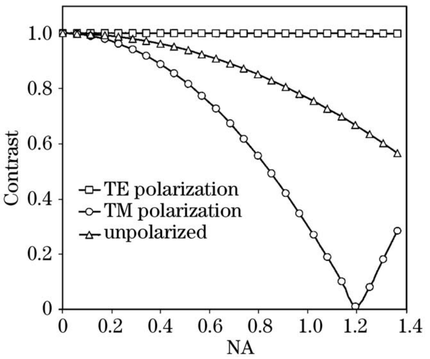

Fig. 1. Image contrast versus NA for TE polarization, TM polarization, and unpolarized case. The image contrast of TE polarization case is highest in immersion lithography.

technique will be required to use TE polarization exclusively for the highest spatial frequencies in the image.

Vector simulations that accurately track the polarization vectors of the electric fields that propagate from the lens to and through the film stack on the wafer allow the high-NAs immersion lithographic systems to be accurately modelled. For the simulation presented below, vector imaging code was used. Figures 2 and 3 show that controlling the polarization direction for imaging light can improve the processing window and depth of focus when printing the same features at the same numerical aperture in immersion lithographic system. In the figures, the processing window of TM has been significantly reduced compared with that of TE, as expected from the TM image contrast loss discussed in Fig. 1. As can be seen, the use of TE polarization improves the processing window and somewhat improves the depth of focus for these 130 and 90 nm pitch line/space patterns.

For more precisely understanding the polarization effects, resolution and DOF in immersion lithography, we have to simulate them by using vector imaging code. Figures 4 and 5 show that controlling the TE polarization direction for imaging light can improve the resolution. As we can see from Figs. 4 and 5, immersion lithography of NA = 1.1 has the capability of 65-nm line and space patterns and immersion lithography of NA = 1.3 has the capability of 45-nm line and space patterns for the TE polarization case.

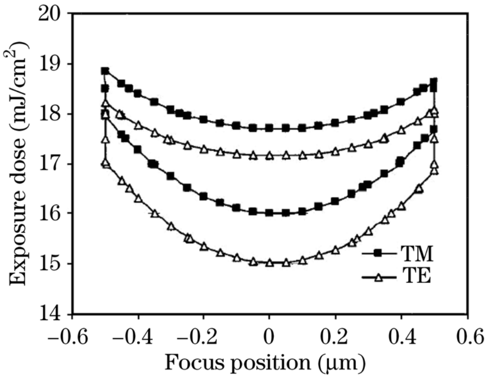

Fig. 2. Polarization affects the size of the processing window (immersion, 193 nm, NA = 1.1, (65 ± 6.5 nm 1 : 1 line and space patterns).

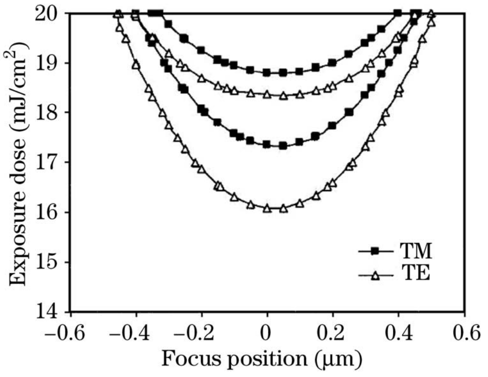

Fig. 3. Polarization affects the size of the processing window (immersion, 193 nm, NA = 1.3, (45 ± 4.5) nm 1 : 1 line and space patterns).

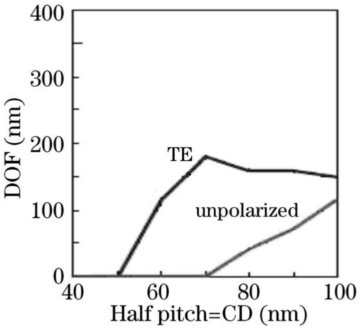

Fig. 4. DOF versus half pitch for 1 : 1 line and space patterns (immersion, 193 nm, NA = 1.1). TE polarization and unpolarized are assumed.

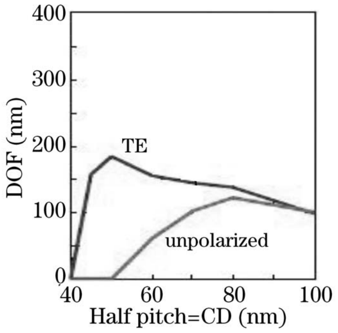

Fig. 5. DOF versus half pitch for 1 : 1 line and space patterns (immersion, 193 nm, NA = 1.3). TE polarization and unpolarized are assumed.

If immersion lithography will be used, we are going to have to control polarization to fulfill the potential of immersion lithographic systems. Polarization control will become a necessary component of a high NA immersion lithographic tool. This requires a major change to illumination optics and impacts exposure strategies and tool cost-of-ownership evaluations. But controlling polarization may not be a giant difficulty. All that is needed is a polarizer somewhere. Three strategies for necessary polarization control are presented. To realize polarized illumination, it is pretty easy to put polarization controlling optical elements in the illuminator. There have been proposals for polarization-controlling materials on the mask. And it might even be possible to arrange polarizing pupil filters in some lens designs.

G. Yu's e-mail address is yu5100902@263.net.

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