Analysis of illumination pupil filling ellipticity for critical dimensions control in photolithography

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Received October 9, 2005

Shrinking of critical dimensions (CDs) in semiconductor circuits has been pushing optical lithography to print features smaller than the wavelength of light source. The demand for CD control is ever-increasing. In this paper, the study is conducted to reveal the impact of illumination pupil filling ellipticity on CD uniformity. As main parameters of CD uniformity, horizontal-vertical feature bias (H-V bias) and isolated-dense feature bias (I-D bias) caused by pupil filling ellipticity are calculated using the PROLITH software under four different illumination settings. Simulation shows that H-V bias and I-D bias are proportional to the pupil filling ellipticity. The slopes of the fitting lines of the H-V bias versus pupil filling ellipticity are calculated.

OCIS codes: 220.0220, 220.3740.

The characteristic feature size of integrated circuits has been shrinking for more than two decades. Indeed, 25 years ago, few believed that the minimum feature size would go below 0.5 μm. But now, feature sizes have reached 65 nm and continue to shrink. Therefore, the control of critical dimensions (CDs) becomes increasingly important for highly integrated microprocessor chips with large die size and for high speed devices. The demands for the CD uniformity also become tighter in chip manufacturing. The accepted tolerance for CD is roughly $\pm 10\%$. For example, 100-nm features must be controlled to within 100 ± 10 nm.

CD uniformity is one of the most appropriate parameters by which one can evaluate the total performance of the lithography tools. Errors introduced by each unit of the exposure tool will surely worsen CD uniformity. The main contributors to CD error are the reticle and wafer stages, the projection lens, and the illumination system[1−3]. As CD shrinking, the effect of illumination pupil filling distribution must be considered, especially when the off-axis illumination is used. Various illumination pupil filling measurement techniques have been developed. According to the measurement of pupil filling, the design and adjustment of the illumination system can be evaluated[4−9]. Besides, analysis of the effect of imperfect illumination pupil filling on CD uniformity is necessary for improving the capability of the illumination system and for exploiting the existing exposure tools.

Horizontal-vertical feature (H-V) bias and isolated-dense feature (I-D) bias are significant parameters that influence the CD uniformity. H-V bias is the maximum deviation of a horizontal CD to a vertical CD. I-D bias is the maximum deviation of an isolated CD to a dense CD. In this paper, illumination pupil filling ellipticity (IPFE) is used to describe the imperfect illumination pupil filling. H-V bias and I-D bias caused by IPFE and their effect on CD uniformity are calculated by using PROLITH, which is a commercially available advanced lithography process optimization tool from KLA-Tencor and widely used in lithography process to study the lithographic performance.

Off-axis illumination, which is one of the important resolution enhancement techniques, can improve the imaging performance for some types of patterns. The pupil filling distributions of annular and quadrupole illuminations, as two types of off-axis illumination, are described in Fig. 1. For annular illumination, the intensity is assumed to be a certain value in the region of circular ring (between two values of partial coherence factor), and zero outside. For quadrupole illumination, the pupil filling is assumed to be a certain value in the four round areas at the symmetric poles. The partial coherence of the illumination light is characterized by the ratio $\sigma = \frac{\sin\theta_i}{\sin\theta_0}$, which is a measure of the filled entrance pupil of the optical system[11], $\sin\theta_0$ is the numerical aperture (NA) of the exposure lens, θ_i is the incident angle of the off-axis illumination. In Fig. 1, the x-y coordinates are normalized on their maxima. For perfectly coherence light, $\sigma = 0$, while $\sigma = \infty$ for completely incoherent light. The light used in lithography tools is partially coherent.

Implementation of off-axis illumination can lead to deterioration in illumination uniformity. IPFE, as one of

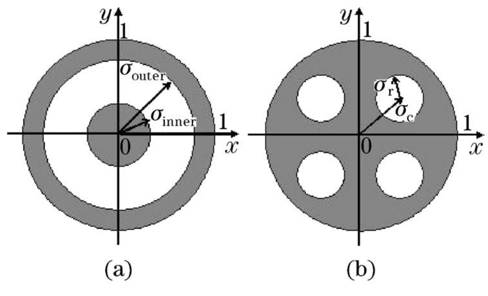

Fig. 1. Light distributions in the lens pupil plane under ideal annular illumination (a) and ideal quadrupole illumination (b) conditions.

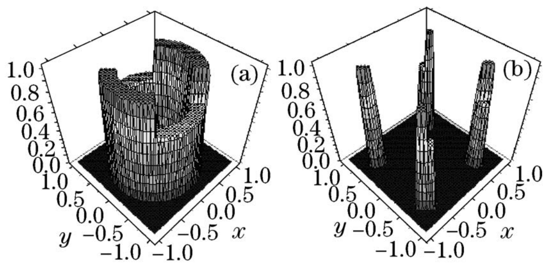

Fig. 2. Light distributions in the lens pupil plane with pupil filling ellipticity under annular illumination (a) and quadrupole illumination (b) conditions.

the parameters to describe the imperfect pupil filling distribution, is defined as[10]

$$\mathrm{IPFE}=\left|\frac{\sum\limits_{|y|<|x|} I-\sum\limits_{|y|>|x|} I}{\sum\limits_{|y|<|x|} I+\sum\limits_{|y|>|x|} I}\right| \times 100\%.$$

To understand the effect of the non-uniformity of illumination on CD uniformity, some imperfect IPFEs are supposed in the simulation, which are shown in Fig. 2. The light intensity in the pupil is normalized. It is assumed that $\sum\limits_{|y|<|x|} I$ is 1, and $\sum\limits_{|y|>|x|} I$ has different values such as 0.7, 0.75, 0.8, 0.85, 0.9, 0.95. The ellipticity values calculated from Eq. (2) are 17.65%, 14.29%, 11.11%, 8.10%, 5.26%, 2.56%, respectively. We will analyze the effect of IPFE on H-V bias and I-D bias in the following.

All calculations were carried out using PROLITH with lumped parameter model (LPM) and full scalar diffraction model. The exposure tool was assumed to be free of aberration, but flare level of 2% was assumed. The simulation parameters are listed in Table 1. All NA-σ settings used in simulations are presented in Table 2. Setting 1 and setting 3 are optimum NA-σ settings under annular and quadrupole illumination conditions, respectively.

Table 1. PROLITH Simulation Parameters with LPM

CD Size (nm)	100
Wavelength (nm)	193
Reticle Type	Binary
Resist Contrast	17
Aerial Image Diffusion Length (nm)	20
Effective Resist Absorption Coefficient	0.2

Table 2. NA-σ Settings under Annular and Quadrupole Illumination Conditions

	NA	Annular		Quadrupole	
		σ_{inner}	σ_{outer}	σ_{r}	σ_{c}
Setting 1	0.82	0.51	0.81	—	—
Setting 2	0.75	0.51	0.81	—	—
Setting 3	0.76	—	—	0.15	0.9
Setting 4	0.70	—	—	0.15	0.9

The pattern with 100-nm horizontal and vertical dense lines was chosen for H-V bias simulation. Image CD H-V bias caused by IPFE was calculated. The relationship between the H-V bias and ellipticity at different defocuses is shown in Fig. 3. From Fig. 3, we can see that H-V bias increases with the increase of ellipticity at certain defocus. The results show a roughly linear relation between H-V bias and ellipticity, and the slope increases with the increase of defocus. The linear slopes were obtained using linear fitting, as presented in Table 3. According to the linear slope, the H-V bias caused by any value of IPFE can be obtained at different defocuses. The calculations also show that H-V bias caused by IPFE under annular illumination is greater than that under quadrupole illumination.

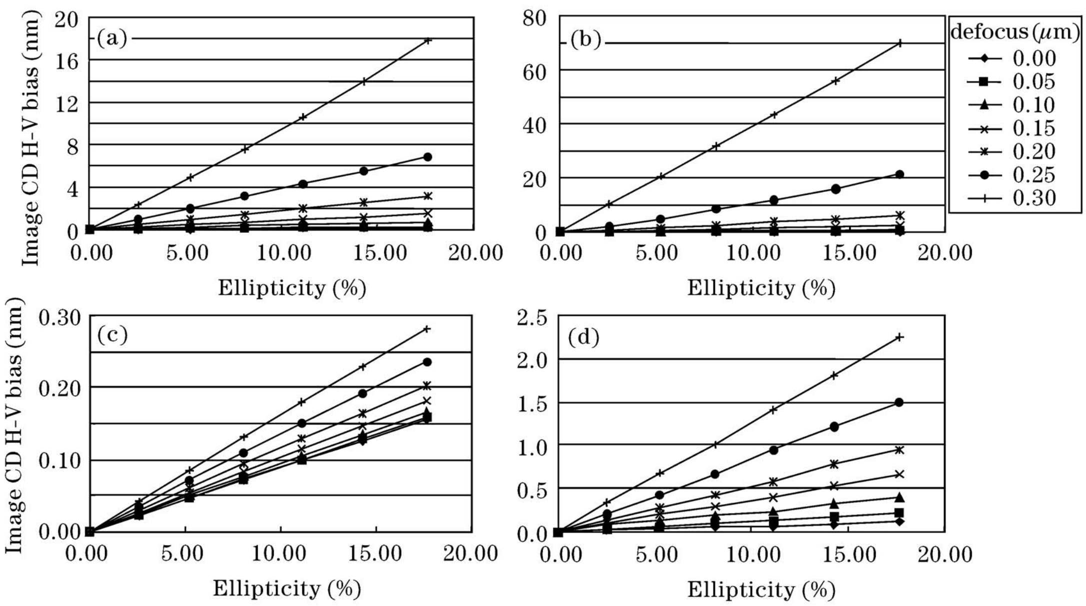

Fig. 3. Image CD H-V bias versus ellipticity at different defocuses for 100-nm dense lines. (a) — (d) correspond to NA-σ settings 1—4 in Table 2, respectively.

Table 3. Slopes of the Fitting Lines of H-V Bias Versus Ellipticity (Unit: nm)

Defocus (μm)	Setting 1	Setting 2	Setting 3	Setting 4
0.00	0.94	0.43	0.88	0.58
0.05	1.59	0.83	0.89	1.28
0.10	3.77	4.94	0.94	2.13
0.15	8.41	13.31	1.02	3.68
0.20	17.95	34.75	1.14	5.42
0.25	38.96	121.98	1.33	8.55
0.30	100.26	393.46	1.59	12.65

We chose the pattern with 100-nm dense lines and isolated lines (with the pitch of 500 nm) for the I-D bias simulation. The I-D biases at different ellipticity values were calculated. As shown in Fig. 4, the existence of IPFE causes the increase of I-D bias and there is a linear relationship between the increase of I-D bias and IPFE. The slopes of the fitting lines are presented in Table 4. Due to the characteristic of off-axis illumination, I-D bias is not zero with the perfect illumination pupil filling. Among settings 1—4, I-D bias under setting 4 gets the highest values compared with the other three settings, it increases from 43.6 nm to the maximum of 47.8 nm when the ellipticity changes from 2.56% to 17.65%.

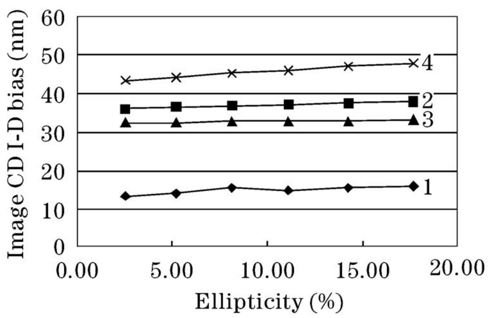

Fig. 4. I-D bais versus ellipticity at best focus for settings 1—4.

Table 4. Slopes of the Fitting Lines of I-D Bias Versus Ellipticity at Best Focus (Unit: nm)

Setting 1	Setting 2	Setting 3	Setting 4
0.4818	0.3362	0.1353	0.8505

In conclusion, we investigated the effect of IPFE on CD uniformity in photolithography. The simulation results indicate that the main effect of IPFE on CD control in lithography involves the H-V bias and I-D bias, both of which are proportional to the IPFE. The slope of the linear relation between the H-V bias and IPFE was calculated. According to the simulation, the effect of illumination pupil filling distribution on CD uniformity can be evaluated, which will help the design, adjustment, and inspection of the exposure tools.

This work was supported by the National "863" Program of China under Grant No. 2002AA4Z3000. L. Guo's e-mail address is guo_liping666@sohu.com.

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