第29卷 第5期
2008年5月

半 导 体 学 报
JOURNAL OF SEMICONDUCTORS

Vol.29 No.5
May,2008

A Systematic Study of the Forbidden Pitch in the CD Through-Pitch Curve for Beyond 130nm*

Zhao Yuhang, Zhu Jun†, and Cao Yongfeng

(*Shanghai IC R&D Center*, *Shanghai* 201206, *China*)

Abstract: The forbidden pitch "dip" in the critical dimension (CD) through the pitch curve is a well-known optical proximity effect. The CD and CD process window near the "dip", usually found near a pitch range of 1.1 to 1.4 wavelength/NA (numerical aperture), is smaller when compared with other pitches. This is caused by inadequate imaging contrast for an unequal line and space grating. Although this effect is relatively well-known, its relationship with typical process condition parameters, such as the effective image blur caused by the photo-acid diffusion during the post exposure bake or the aberration in the imaging lens, has not been systematically studied. In this paper, we will examine the correlation between the image blur and the effect on the CD, including the decrease in the CD value (the depth of the "dip") and the CD process window. We find that both the decrease in the CD value and the focus latitude near the forbidden pitch correlate very well with the effective Gaussian image blur. Longer effective diffusion length correlates well with a smaller process window and a deeper CD "dip". We conclude that the dip depth is very sensitive to the change in image contrast.

Key words: forbidden pitch; effective resist diffusion length; OPC; OAI; deep-UV

EEACC: 2550G

CLC number: TN305.7 **Document code**: A **Article ID**: 0253-4177(2008)05-0889-04

1 Introduction

For deep-UV (DUV) photo processes, as the pitch becomes wider than the minimum pitch, the linewidth will first become narrower and then quickly reach a minimum value at an intermediate pitch, which is around 1.1 to 1.4 wavelength/NA (numerical aperture). The process window around this pitch range is smaller when compared with that of the denser lines and spaces. Under certain conditions, e.g., when the k_1 factor is small, the process window can be critically small such that no reliable process can be built. Therefore, the "dip" is also called the "forbidden pitch". This optical proximity effect can strongly affect the overall health of a photolithographic process and is extremely undesirable for layout designers. However, the use of a good resist and exposure tool can improve the process window in this pitch range.

In this paper, we will study the effect of resist resolution and scanner lens performance on the process window and CD in the intermediate pitch range. We will show the CD and CD process window data obtained from three resists with varying effective image blur and the data from two scanners, one of them having some residue spherical aberration. In the analysis, we use the mask enhancement error factor (MEEF)[1~6] to define the overall quality of the imaging capability of the exposure system.

2 Simulation methodology

The mask error enhancement factor (MEEF)[1~6] quantifies the impact of reticle CD errors on the CD of the corresponding printed feature:

$$\mathrm{MEEF} = \frac{\partial \mathrm{CD}_{\mathrm{wafer}}}{\partial\left(\dfrac{\mathrm{CD}_{\mathrm{mask}}}{M}\right)} \qquad (1)$$

where M is the image reduction ratio. For non-ideal MEEF (MEEF$\neq 1$), the deviation of the CD of the printed feature from the nominal value is magnified beyond the error in the CD of the corresponding feature on the reticle. The equation for the MEEF can be analytically solved for narrow pitches (When the pitch p is narrower than wavelength/NA). When the mask line width and the mask space width are equal, the MEEF for dense features can be simplified as described by Eqs.(2) and (3).

$$\mathrm{MEEF}(\mathrm{Annular}\quad \sigma_{\mathrm{out}}/\sigma_{\mathrm{in}}) =$$

$$\frac{\displaystyle\int_{\sigma_{\mathrm{in}}}^{\sigma_{\mathrm{out}}} \sigma \mathrm{d}\sigma \frac{1}{\sin\dfrac{\pi \mathrm{CD}}{p}}\left[\frac{\pi \mathrm{e}^{2\pi^2 a^2/p^2}}{2\phi\left(1-\sin^2\dfrac{\lambda}{2np}\right)} \mp \frac{2(1+\alpha)}{\pi(1-\alpha)}\cos\frac{\pi \mathrm{CD}}{p}\right]}{\displaystyle\int_{\sigma_{\mathrm{in}}}^{\sigma_{\mathrm{out}}} \sigma \mathrm{d}\sigma} \qquad (2)$$

---

* Project supposed by the Foundation of Shanghai Science & Technology Committee (No.075007033)

† Corresponding author. Email: zhujun_sh@163.com

Received 29 October 2007, revised manuscript received 5 December 2007

$$\phi = \cos^{-1}\left\{\frac{\dfrac{\lambda}{p\mathrm{NA}} - \dfrac{p\mathrm{NA}}{\lambda}}{2\sigma} + \frac{p\mathrm{NA}}{2\lambda}\sigma\right\} \tag{3}$$

where α represents the amplitude attenuation, σ represents the partial coherence (from 0 to 1), a represents the effective diffusion length, λ represents the wavelength of light, n represents the refractive index of the resist, p represents pitch, and CD represents the printed feature critical dimension. When the mask linewidth and mask space width are not equal, the mask error factor has a more complicated form, which we will not show in this paper. For the MEEF of isolated lines, under incoherent illumination, the following equation is a good approximation:

$$\mathrm{MEEF} = \frac{\delta\mathrm{WCD}}{\delta\mathrm{MCD}} = \frac{\mathrm{PSF_D}\left(\dfrac{\mathrm{WCD}-\mathrm{MCD}}{2}\right)^2 + \mathrm{PSF_D}\left(\dfrac{\mathrm{WCD}+\mathrm{MCD}}{2}\right)^2}{\mathrm{PSF_D}\left(\dfrac{\mathrm{WCD}-\mathrm{MCD}}{2}\right)^2 - \mathrm{PSF_D}\left(\dfrac{\mathrm{WCD}+\mathrm{MCD}}{2}\right)^2} \tag{4}$$

where $\mathrm{PSF_D}$ is the diffused point spread function of the imaging system, WCD represents the CD on the wafer, and MCD represents the CD on the mask.

3 MEEF and the process performance

In this paper, we will present our study on the exposure tool variation, and resist diffusion to the CD and process window at the intermediate pitch range around 1.1 to 1.4 wavelength/NA (numerical aperture). We use off-axis illumination (OAI) (0.68NA/0.75−0.375 annular), which is widely used in 130nm generation node. The tolerance setting on lens aberration will be analyzed from the experimental comparison between two scanners (Scanner 1 and Scanner 2). The study of the effect of the effective resist diffusion length will be based on the data taken from three typical resists (Resists A, B, and C), which are standard resists from Shin Etsu, Fuji film, and Rohm Haas.

Table 1 MEEF summary for resists A, B, and C under 0.68 NA/0.75−0.375 annular illumination condition

Resist	Scanner 1		Scanner 2	
	Dense	ISO	Dense	ISO
A	1.31	1.13	1.44	1.22
B	1.43	1.37		
C	2.08	1.67	2.16	1.82

The reduction of MEEF is critical to maximize the across field CD uniformity, especially for the smaller features printed near the resolution limit of a low K1 process[4]. In this paper, we use the MEEF, which is sensitive to lens performance, to help characterize exposure tools. The summary of these MEEF data are shown in Table 1. The three resists have different MEEF numbers and the resist diffusion length and lens aberration can significantly influence the MEEF performance. Through the scanners data comparison, the MEEF number can differ for the two scanners, even for the same resist.

Next, we use the analytical theory described in previous sections to analyze the MEEF data and extract the diffusion length. The diffusion length from the dense features can be exactly extracted from MEEF numbers while that of the isolated features can only be approximated since the illumination we use is partially coherent while Eq. (3) requires incoherent illumination. The results of our analysis are listed in Table 2.

Here, the diffusion length covers the PIS (process induce shift) and TIS (tool induce shift) performance. This value is an important guideline for the evaluation of the process. As shown in the table, from scanner 1, resists A, B, and C have diffusion lengths of 5, 22, and 48nm, respectively. For the MEEF data from scanner 2, the MEEF numbers for all resists also increase. The diffusion lengths from scanner 2 for resists A and C are 22 and 50nm. The extracted data from the isolated MEEF is very close

Table 2 Experimental MEEF data and simulated effective Gaussian diffusion lengths for resists A, B, and C The Gaussian blur introduced by scanner 2 relative to scanner 1 is listed in the last column. All diffusion length numbers are in nanometers (nm).

	Dense MEEF	Diffusion length	Dense MEEF	Diffusion length	Machine Blur
Resist	0.68/0.75−0.375, Scanner 1		0.68/0.75−0.375, Scanner 2		
A	1.3	5	1.44	22	22
C	2.07	48	2.16	50	14
B	1.43	22			
	Isolated MEEF		Isolated MEEF		
	0.68/0.75−0.375, Scanner 1		0.68/0.75−0.375, Scanner 2		
A	1.13	0	1.22	15	15
C	1.67	48	1.82	55	26.9
B	1.37	25			

Table 3　Depth of focus summary for resists A, B, and C under 0.68 NA/ 0.75 − 0.375 annular illumination condition (unit: μm)

Resist	Dense	Forbidden Pitch	ISO
A	0.7	0.5	0.4
B	0.6	0.4	0.3
C	0.5	0.35	0.3

to those obtained from the dense MEEF, indicating that the annular illumination is very close to the incoherent condition. The lens contribution to the total image blur can be obtained by subtracting the diffusion lengths from scanner 2 from the corresponding numbers from scanner 1, following the error propagating rule (quadratic rule). The numbers we obtain are 14～22nm. Also, the diffusion length of resist A is very small.

4　Process window performance comparison

We have collected the focus-exposure matrix for resists A, B, and C from 130nm line in the dense pitch (320nm), forbidden pitch (527nm), and isolated situation, and the results are summarized in Table 3.

In Table 3, the depth of focus for resist C is the smallest of the three. The effective resist diffusion length for resists A, B, and C are 0, 22, 48nm, respectively. Resist C has the longest diffusion length and the smallest depth of the focus process window. This is understandable since random diffusion will degrade aerial image quality, especially at the forbidden pitch region, where the image contrast is very low. Any diffusion, or blurring, can cause significant image contrast change, which reduces the process window. The data also indicates that resist A has the largest process window at the dense pitch, the forbidden (intermediate) pitch, and the isolated lines.

5　CD through pitch performance comparison

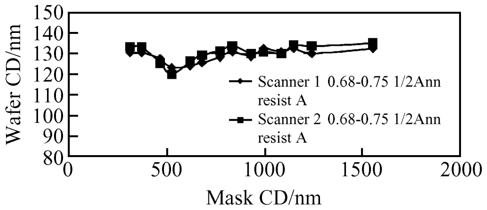

Fig. 1　CD through pitch curves for scanner 1 and scanner 2 with resist A, respectively, under 0.68 NA/ 0.75 − 0.375 annular illumination condition

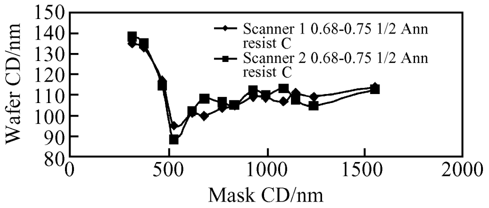

Fig. 2　CD through pitch curves with scanner 1 and scanner 2 for resist C, respectively, under 0.68NA/0.75 − 0.375 annular illumination condition

In order to find the relationship between the diffusion length and the CD "dip", we measured the CD through pitch performance for resists A, B, and C. The dip depth (measured from the dense CD to the minimum CD) seems to increase as the diffusion length increases. Figures 1 and 2 show the comparison between scanner 1 and scanner 2. The data (summarized in Table 4) indicates that the dip depth for scanner 1 is shallower than that of scanner 2 for both resist A (5nm shallower) and C (10.1nm shallower) at the intermediate pitch of 527nm. Compared with the results from previous sections, this difference correlates well with the lens performance of the two scanners. The lens from scanner 1 is nearly perfect, while the imaging blur from scanner 2 is around 14～22nm. To control the dip, we need to control the scanner aberration.

6　Conclusion

We studied the effect of resist diffusion length, lens performance, and illumination condition on the process characteristics around the intermediate pitch, or the "dip". We found that the "dip" is closely related to the acid diffusion length, lens aberrations, and illumination condition. At the intermediate pitch around 1.1 to 1.4 wavelength/NA, shorter diffusion length resists exhibit larger process windows and less CD variation, or shallower "dip," in contrast to the

Table 4　Summary of experimental data for MEEF, depth of focus, and "dip" depth for all split experiments　S1: scanner 1; S2: scanner 2; OAI: 0.68 NA/0.75 − 0.375 annular; Forbidden Pitch: 1.1 to 1.4 wavelength / NA; a: Dip performance at 465nm pitch; b: Dip performance at 527nm pitch

Resist	Process window/μm			Dip depth/nm				MEEF			
	Dense	Forbidden Pitch	ISO	S1 OAI a	S1 OAI b	S2 OAI a	S2 OAI b	S1 Dense	S1 ISO	S2 Dense	S2 ISO
A	0.7	0.5	0.4	3.1	8.2	8.1	13.2	1.31	1.13	1.44	1.22
B	0.6	0.4	0.3	13.5	24.5			1.43	1.37		
C	0.5	0.35	0.3	18.4	39.8	24	49.9	2.08	1.67	2.16	1.82

longer diffusion length resists. We also found that the lens aberration may contribute around 20nm in total Gaussian blur, which relates to a significant CD shift and process window reduction. The grand summary for this study is displayed in Table 4.

References

［1］ Wu Qiang, Halle S, Zhao Zengqin. The effect of effective resist diffusion length to the photolithography at 65 and 45 nm nodes, a study with simple and accurate analytic equations. Proceedings of the SPIE, 2004, 5377: 1510

［2］ Postnikov S, Lucas K, Wimmer K. Impact of optimized illumination upon simple lambda based design rules for low K1 lithography. Proceedings of the SPIE, 2001, 4344: 98

［3］ Granik Y. Generalized MEEF theory. Interface, 2001

［4］ Socha R J, Dusa M V, Capodiei L, et al. Forbidden pitches for 130nm lithography and below. Proceedings of the SPIE, 2000: 4000

［5］ Mack C A, Schellenberg F M. Impact of the mask errors on optical lithography. Interface, 1999

［6］ Conley W, Hankinson M, Socha R J, et al. Improvements in mask error factor reduction through photoresist and process design for 0.13μm imaging. Interface, 1999

130nm 以下光刻禁止光学空间周期的系统性研究[*]

赵宇航　朱　骏[†]　曹永峰

（上海集成电路研发中心，上海　201206）

摘要： 禁止光学空间周期“Forbidden Pitch”是光学临近效应修正（OPC）中必须要面对并解决的问题之一．它主要出现在1.1～1.4倍（曝光波长/数值孔径）的范围内．由于在此范围内空间图像对比度的削弱，这种效应会导致图形的线宽明显小于其他空间周期．目前业界常用的规避手段主要是通过采集大量的数据校正光学临近效应修正模型，但随着半导体进入深亚微米时代，数据的采集量、置信度越发重要和关键．因此，成功地采用光学临近效应修正技术的关键和前提是建立一套成熟的相关工艺．本文着重研究空间光学和光刻工艺技术的相互关系．我们发现在禁止光学空间周期附近的光学表现与有效高斯模糊息息相关．较长的有效光酸扩散长度将显著地消弱光刻表现，进而影响禁止光学空间周期的图形表现．

关键词： 禁止光学空间周期；掩模版误差因子；有效光刻胶扩散长度；光学临近效应修正；离轴照明；深紫外线

EEACC： 2550G

中图分类号： TN305.7　**文献标识码：** A　**文章编号：** 0253-4177(2008)05-0889-04

---

[*] 上海市科委国际合作资助项目（批准号：075007033）

[†] 通信作者．Email：zhujun_sh@163.com

2007-10-29 收到，2007-12-05 定稿