Printability and Line Edge Roughness of Optical Proximity Correction Features

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Abstract— **Optical Proximity Correction (OPC) has been used for many years now in the semiconductor industry to provide through-pitch focus and dose matching across an entire mask field. By adding sub-resolution features, lines with large duty ratios can be made to have similar imaging properties as dense line patterns, reducing CD variation and increasing the flexibility of the design space. The sub-resolution features subtract zero-order diffraction energy which is the dominating determinate of how features are imaged in the resist.**

A binary chrome photomask with sub-resolution OPC features was designed at the Rochester Institute of Technology and fabricated by Photronics Inc. Austin, TX. The main features of mask are 1200nm (240nm on the wafer) with OPC features ranging from 300nm to 1200nm. Different scatter bar (parallel to main feature) configurations were implemented to gain a better understanding of when sub-resolution features start to print. Ladder bar (perpendicular to main feature) size and pitch was varied to observe the effect that the proximity of OPC features perpendicular to main features has on line edge roughness.

The mask was printed on 6" wafers using a 248nm exposure tool (NA=0.5, σ=0.5). Shipley UVIII photoresist was coated to a thickness of 5000Å and developed with CD26 developer. Printability data was collected through observation under a light microscope. To evaluate the effect of OPC features on minimizing CD variation, feature CDs were measured using a CDSEM. The CDSEM was also utilized to quantify the line edge roughness associated with ladder bars.

Index Terms—**Resolution enhancement techniques, Scatter bars, Ladder bars, Line edge roughness, OPC**

I. Introduction

Modern IC devices are being imaged using optical lithography at sub-half wavelength dimensions. Certain roadblocks for the implementation of next generation lithography technologies are calling for the extension of 248nm and 193nm lithography. This will require more aggressive application of a number of different resolution enhancement techniques, one being optical proximity correction (OPC).

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The focus of this paper is the application of OPC features to equalize the isofocal intensity for line space patterns of varying pitch value, specifically over a range of 1:1 to 1:4. The isofocal intensity for large pitch features is higher than that for dense features because of more relative transmission through the space area. This difference in isofocal intensity can cause features to print differently or in some cases cease to print, due to photoresist being targeted at the isofocal intensity level associated with the dense features. Figure 1 displays the aerial image from varying pitch sizes through varying levels of defocus.[1] The mask function used to generate the aerial images is shown above it.

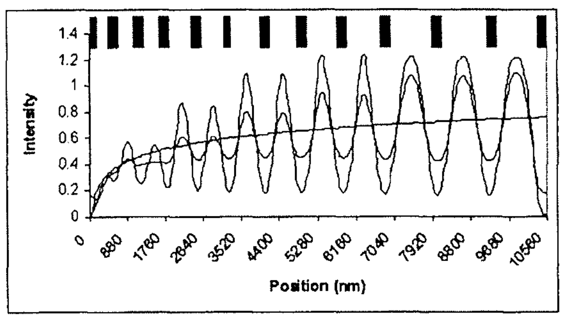


Figure 1-Aerial image through defocus from a mask function containing through pitch 240nm features.

Clearly there is a need to reduce the isofocal intensity of the larger pitch features. To do so requires reducing the transmission through the space on the mask. One method of doing so involves placing features in the space region that are beyond the resolution limit of the imaging system. Scatter bars are sub resolution assist features that run parallel to the main feature whose presence reduces the intensity as a function of the bar width (b) and bar pitch (p_b):[2]

$$\text{Space intensity reduction} = \left(\frac{p_b - b}{p_b}\right)^2 \quad (1)$$

Scatter bars essentially mimic an equivalent reduction in transmission through the space. In modern lithography systems, the 0^{th} and $\pm 1^{st}$ orders are the only diffraction orders captured by the imaging system. Sub resolution assist features, such as scatter bars and ladder

bars only have an influence on the zero order as shown in Figure 1.

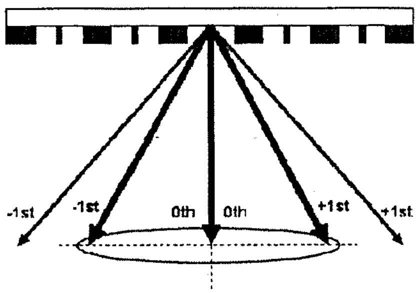


Figure 2-Diffraction diagram for OPC features.

When placing scatter bars, the printability of the bar has to be considered. The scatter bars have to be placed far enough from the actual feature to avoid being printed as part of it, as well as far enough from each other, to prevent printing in between the isolated lines.

Figure 3 is the aerial image for a series of 1:1 lines and Figure 4 is the aerial image for 1:4 pitch density. Figure 5 displays the effect that scatter bars have on the isofocal intensity. The isofocal point for the 1:4 features is reduced from approximately 0.75 to approximately 0.45 which is much closer to that of the dense line space pattern. Note that the scatter bars are in close proximity to the isofocal point and there is a possibility of them printing if off axis illumination is used.

Ladder bars[3] are another method of reducing the zero order intensity in the space region of large pitch features. Ladder bars are sub resolution features that are perpendicular to the main feature. Ladder bars offer more flexibility because they have more attributes that can be varied to meet the necessary imaging requirements. The width of the ladder bar, the pitch, and its separation from the main feature can all be varied. Figure 6 is an aerial image through defocus of 1:4 pitch line space patterns with ladder bars. Notice that the printability concerns of the assist feature that were present with the scatter bar are no longer there. Ladder bars do introduce the possibility of inducing line edge roughness in the resist pattern because they are parallel to the main feature as shown in the two dimensional aerial image shown in Figure 7.

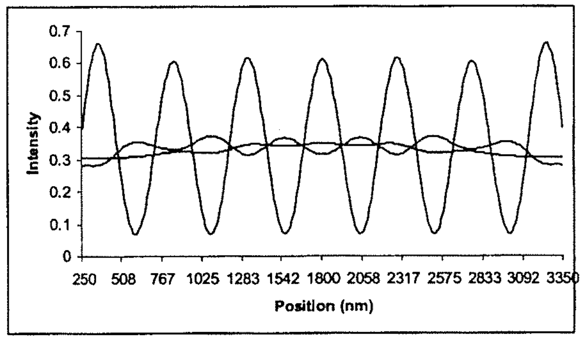


Figure 3-1:1 Line space pattern.

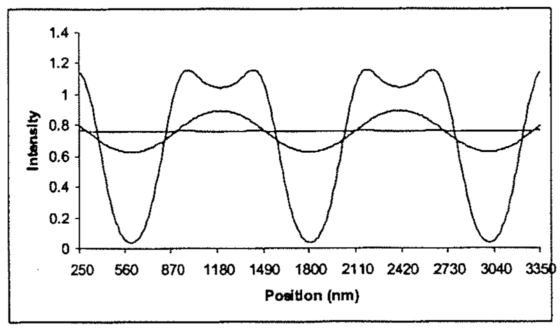


Figure 4-1:4 Line space pattern without scatter bars.

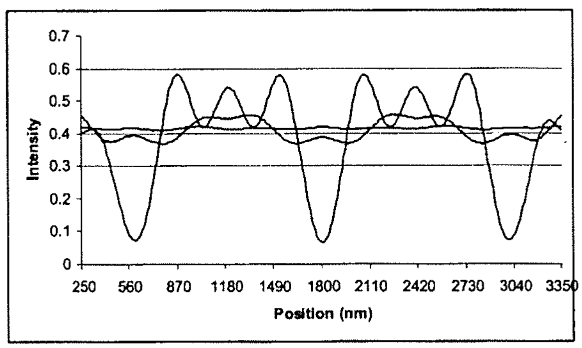


Figure 5-1:4 Line space pattern with scatter bars.

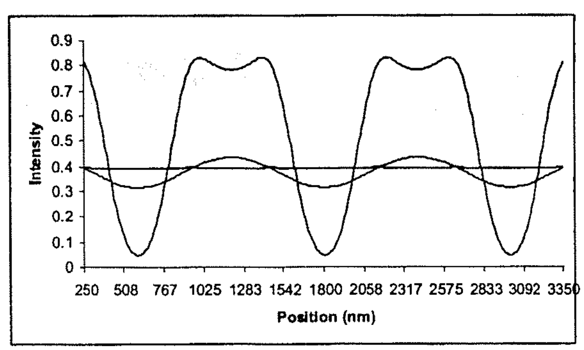


Figure 6-1:4 Line space pattern with ladder bars.

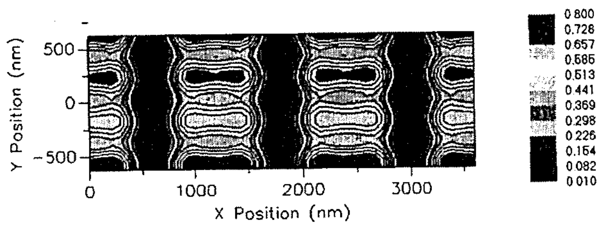


Figure 7-Ladder bar two dimensional aerial image showing possible line edge roughness.

Besides the possibility of inducing line edge roughness, ladder bars also increases the complexity associated with designing and fabricating the mask due to the significantly increased polygon count.

II. Mask Design

The photomask was designed using Mentor Graphics IC Station. The main features were printed on the mask at 1200nm resulting in printed resist features of 240nm (5X stepper). The photomask is a 6" binary chrome mask that was exposed on an Alta 3500 pattern generator at Photronics in Austin, TX and etched using a dry etch plasma tool.

The mask consisted of five main sections, where the pitch of the main feature, as well as different characteristics of the assist features were varied. Figure 8 is a picture of the mask layout.

A. Single Scatter Bar

The single scatter bar, is the simplest of sub resolution assist features implemented on this mask. The scatter bar was placed evenly in the middle of the main features and varied in width from 300nm to 1200nm, in steps of 50nm (B), on the mask. The main feature pitch varied from 1:1.5 to 1:4 in steps of 0.5 (A). Figure 9 shows all four of the scatter bar configurations used on this mask.

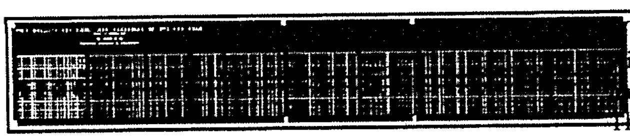


Figure 8-Mask layout.

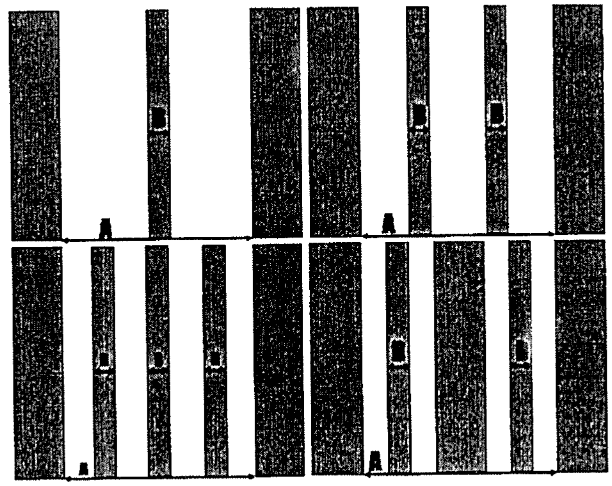


Figure 9-Different scatter bar configurations implemented on the mask.

B. Double Scatter Bar

The double scatter bar is used to increase the OPC feature density between main features when increasing the width of the single bar would result in it printing. The scatter bars are evenly spaced. The scatter bar width varied from 300nm to 1200nm, in steps of 50nm (B), on the mask. The main feature pitch varied from 1:2 to 1:4 in steps of 0.5 (A).

C. Triple Scatter Bar

Again, another scatter bar was added to increased to increase the OPC feature density between main features when increasing the width of the single bar would result in it printing. The scatter bars are evenly spaced. The scatter bar width varied from 300nm to 1200nm, in steps of 50nm (B), on the mask. The main feature pitch varied from 1:2.5 to 1:4 in steps of 0.5 (A).

D. Triple Scatter Bar with Wide Center Bar

The center bar for these triple bars, was set to a fixed dth of 700nm to see what possible effect it would ve on printability. The scatter bars are evenly spaced. e outer scatter bar width varied from 300nm to 1200nm, in steps of 50nm (B), on the mask. The main feature pitch varied from 1:2.5 to 1:4 in steps of 0.5 (A).

E. Ladder Bar

The ladder bar is a sub resolution assist feature that runs perpendicular to the main feature. Ladder bars were implemented for main feature pitches of 1:1.5 and 1:4 (A). Figure 10 is a picture of a ladder bar feature as well as the different characteristics that can be varied.

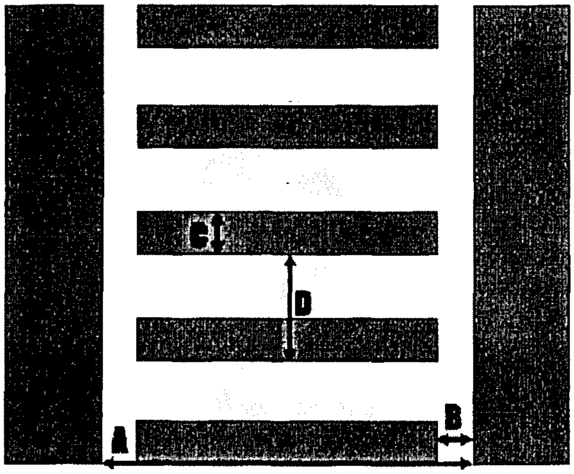


Figure 10-Ladder bars.

The ladder bar separation from the main feature (B), was varied from 0nm to 1200nm in steps of 50nm to observe the effect that ladder bar proximity has on the line edge roughness of the main feature. Whether or not ladder bars with no separation from the main feature would print was also of interest. The width of the ladder bar (C) was varied from 300nm to 1200nm in 50nm steps to see what effect it would have on main feature line edge roughness as well as ladder bar printing. Finally, the pitch of the ladder bars (D) was varied from 1:1 to 1:4 in 0.5 steps to see what effect it would have on printability of the main features as well as line edge roughness.

III. Exposure and Development Process

Exposure were carried out using an ASML 5500/90 248nm DUV stepper with NA=0.5 and σ=0.5. It is outfitted to use 6" wafers.

The photoresist used was Shipley UVIII which is a chemically amplified 248nm resist. It was spun coat to a thickness of approximately 5000Å and then exposed on the ASML 5500/90. Four wafers were exposed under the conditions shown in Table 1. An X slotpole was used to observe how off axis illumination affects the printing of scatter bars.

Table 1-Exposure conditions.

Wafer #	Min mJ/cm^2	Max mJ/cm^2	Step mJ/cm^2	Illumination
1	17	27	0.25	X-slotpole
2	12	32	0.50	X-slotpole
3	17	27	0.25	Conventional
4	12	32	0.50	Conventional

After exposure, the wafers were immediately put into a post exposure bake at 140C for 90 seconds. Following the PEB, they were puddle developed for 45 seconds in CD26 developer, then rinsed and spun dry.

IV. Results And Discussion

The first observation to investigate the printability of the line space patterns with assist features was done in the lower left hand corner of the mask, where the single and double scatter bars are located. Figure 11 is an image capture from a light microscope at 500X magnification.

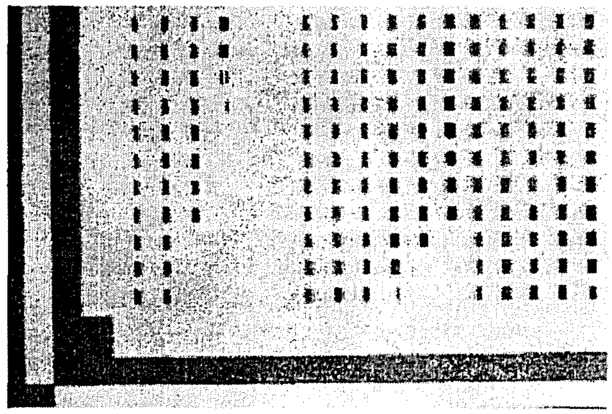


Figure 11-Light microscope image capture of the lower left hand corner of the mask.

This image is a testament to the need for OPC to allow through pitch printing of the 240nm lines on the mask. Main feature pitch increases in the x-direction, while single scatter bar width increases in the y-direction. The 1:2.5 pitch main features do not begin to print until the single scatter bar width reach 450nm. The double scatter bars, with their increased density; start to print the main features, with less individual bar thickness.

To observe the effect of off axis illumination, an x-slotpole was used to illuminate the y-axis orientated features of the mask. In Figure 12, the scatter bar is starting to print between the main features at approximately 180nm due to the influence of the slotpole.

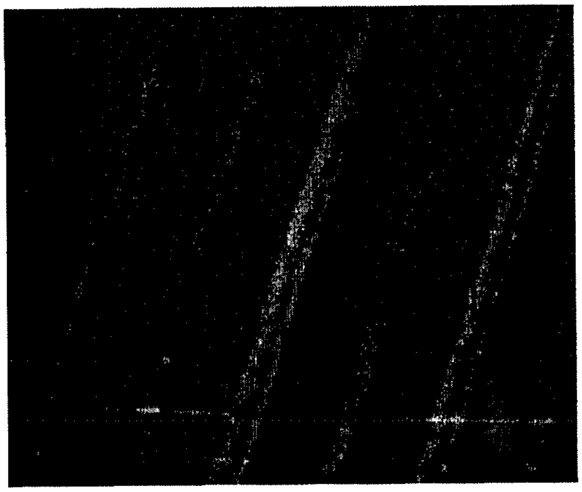


Figure 12-Scatter bar printing due to x-slotpole illumination.

Figure 13 is a side by side comparison of a 1:1 (left hand side) and a 1:4 (right hand side) SEM image of resist lines. The 1:4 pattern had triple scatter bar OPC features which resulted in excellent CD matching.

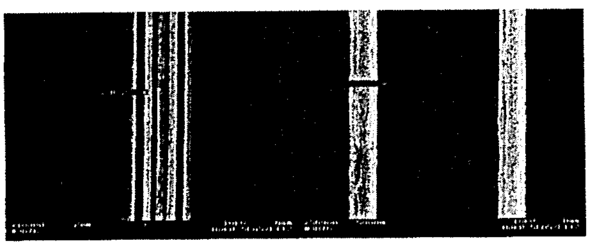


Figure 13-CD matched 1:1 and 1:4 lines.

The ladder bars were the next portion of the mask that was investigated under the SEM. As stated earlier, ladder bars have potential for inducing line edge roughness as shown in the two-dimensional aerial image plot. If the variation is not very large relative to the line width, it will most likely be smoothed out by the PEB. One of the variables changed for the ladder bars was the amount of separation between the bar and the main feature. The following two figures are from main features with a pitch of 1:4 with ladder bar assist features. The ladder bars in each image were the same width and pitch, only the separation from the main feature changed. In Figure 14, there is no ladder bar separation, in Figure 15, it is 300nm.

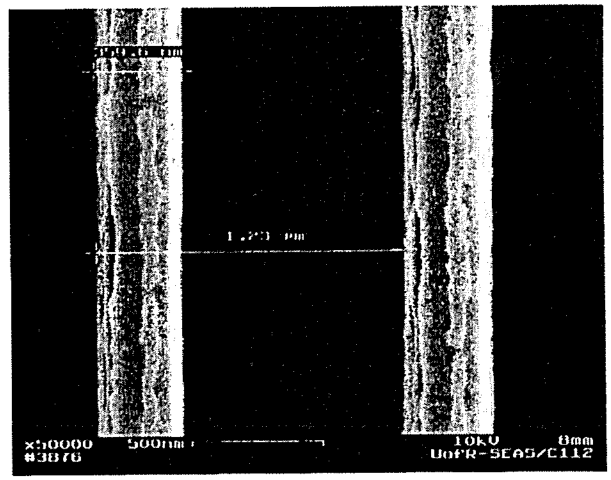


Figure 14-Ladder bars with 0nm separation from the main feature.

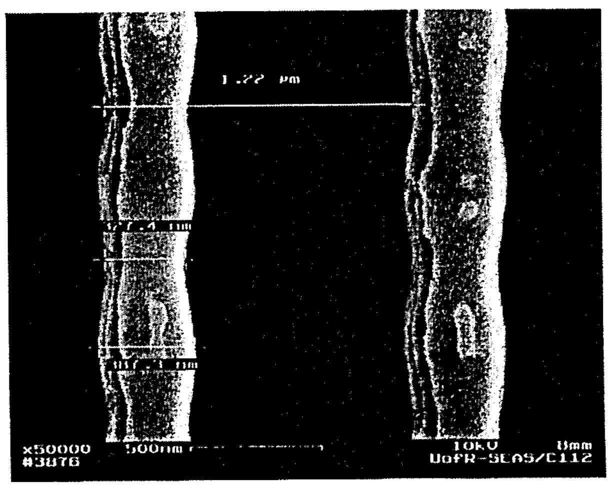


Figure 15-Ladder bars with 300nm separation from the main feature.

There is a positive relationship between the separation of the ladder bars from the main feature and the amount of line edge roughness. With as little as 300nm (on the mask) separation, the ladder bars induced a 50nm difference between points on the roughened line. Prior to this experiment, it was not known whether or not the ladder bars that were attached to the main features on the mask (0nm separation) would print. It was believed that the lack of separation would induce the most amount of line edge roughness, with the line edge roughness smoothing out as separation increases. As seen in the last two figures, it appears to be the opposite. In the more extreme case, as the ladder bars progress further away from the main feature, the line only prints in the areas adjacent to the ladder bar as shown in Figure 16.

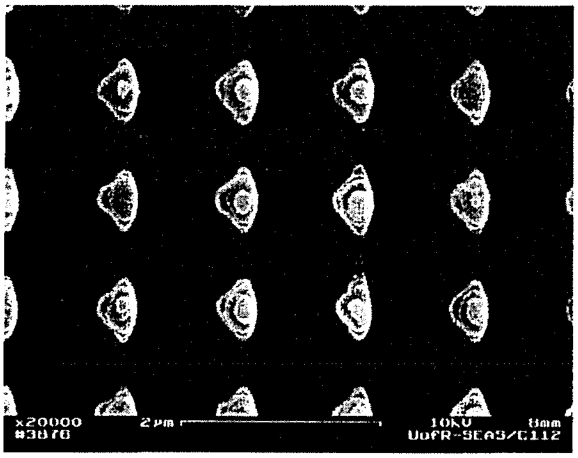


Figure 16-Main features only printing next to ladder bar, when ladder bar separation is large.

V. Conclusion

The need for optical proximity correction features to print a wide range of pitch values has been clearly demonstrated for the Rochester Institute of Technology. Scatter bars behaved as expected, increasing the ability to print lines through pitch and printing earlier than expected when illuminated with slotpoles.

Unexpected results were seen with the ladder bar portion of the mask. The simulated two-dimensional aerial image predicted the possibility of line edge roughness due to the proximity of the ladder bars to the main features. It was not expected that increasing the ladder bar separation would increase the associated main feature line edge roughness. As Figure 13 shows, there is little to no line edge roughness when there is no separation between the ladder bar and main feature on the mask.

There was a fair amount of line width variation present that wasn't accounted for by simple within wafer variation due to PEB temperature gradients, exposure variation, etc. It is believed that a fair amount of it was due to over-exposure of the mask in sections with dense OPC features, due to the Alta 3500 being a laser based tool. To undertake further investigation into the quantitative effect of OPC on line printing a mask written on an e-beam write tool would be highly desirable.

Acknowledgment

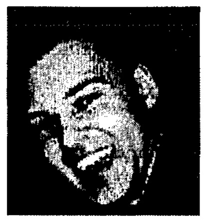
The author would like to acknowledge Dr. Bruce Smith for acting as the advisor for this project, Yongfa Fan for providing examples on how to script IC station to generate OPC features for the mask layout, and Charles Gruener for help with workstation problems and transferring the mask data to Photronics. He would also like to acknowledge Matt Malloy for assistance on operating the ASML 5500/90 stepper and providing a resist process. Finally, the author would like to acknowledge Brian McIntyre from Institute of Optics, University of Rochester for the SEM work.

References

[1] Simulations were carried out using Prolith 7.1.1.

[2] B.W. Smith, D.E. Ewbank, "OPC and image optimization using localized frequency analysis", 2001.

[3] US Patent 2002192570.



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