This paper was published in the proceedings of
Optical Microlithography XV, SPIE Vol. 4691, pp. 98-106.

Theoretical Analysis of the Potential for Maskless Lithography

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Abstract

In order to be practical, maskless lithography schemes are limited as to how small the physical address grid can be. Thus, graybeam techniques are used to create a small virtual address grid while maintaining a large physical address grid. One important consideration for maskless lithography is the impact of these small "virtual" address grids on image quality. Using simple simulations of aerial image formation as the summation of Gaussian spots and PROLITH simulations of the projection of square pixels, several important conclusions about the use of graybeam are made. Graybeam results in a non-linear variation in edge position with gray level, with the non-linearity increasing with larger physical address grid size. While this edge position deviation from non-linearity can be calibrated out of the writing scheme, the calibration curve is process dependent. One problem with the use of graybeam is the reduction of image quality as expressed by the image log-slope. For the raster scan case of a physical address grid equal to half of the spot size, the worst case graybeam level has an image log-slope at the edge that is 20% less than the best case. For the projection imaging case of a physical address grid equal to the pixel size, the worst case graybeam level has an image log-slope at the edge that is 15% less than the best case.

Keywords: Maskless Lithography, Graybeam Address Grid, Raster Scan Imaging, Image Quality

1. Introduction

With the cost of masks increasing to the point of dominance in advanced semiconductor lithography costs structures, the idea of a high throughput maskless lithography seems quite appealing. The use of digital micromirrors or other such digitally modulated transmitting or reflecting devices in place of the mask, coupled with a high reduction ratio imaging system, may one day provide enough throughput to make such systems practical from a cost perspective. But what of their performance?

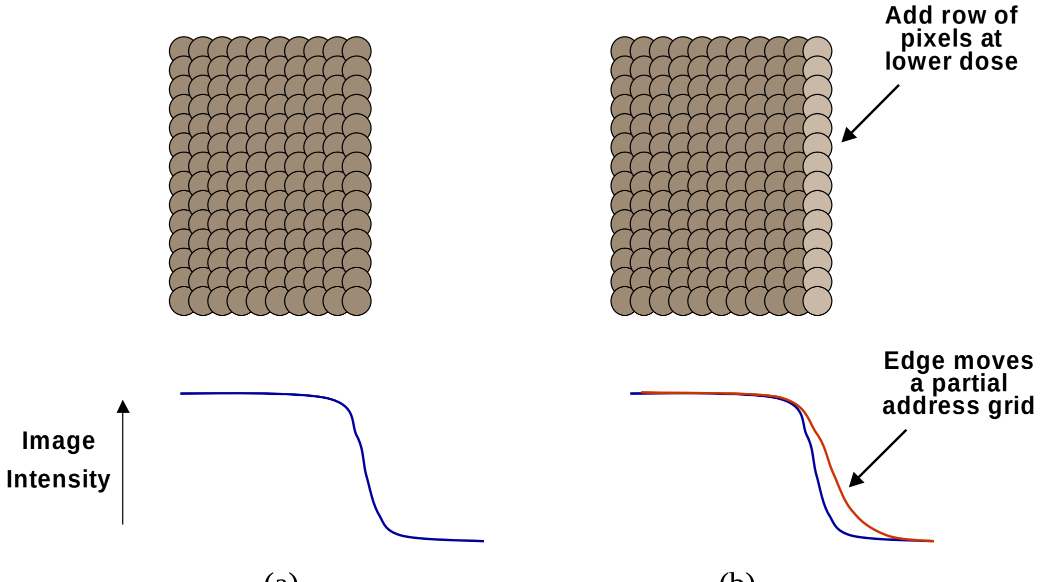
One of the limitations of such maskless lithographic approaches is the relatively large address grid that the digitally modulated "mask" requires. While a small address grid is desirable for greater flexibility in allowable feature sizes and feature placement, either the throughput would have to be reduced considerably compared to a larger address grid, or the complexity of the tool would rise dramatically. As a result, nearly all such maskless types of direct write imaging systems will probably adopt a "graybeam" approach to creating a small virtual address grid while maintaining a large actual address grid. In such a scheme, the placement of an edge is modulated by turning on and off (either completely or partially) adjacent pixels along the edge. While this modulation of energy near the edge of the feature has the desired effect of giving a finer control of the position of the edge, there is a significant negative consequence. By necessity this graybeam approach to reduced virtual address grids results in reduced image quality in the form of lowered image log-slope at the feature edge. This reduced image log-slope in turn leads to reduced process latitude and reduced dimensional control [1].

This paper will examine graybeam virtual address reduction schemes and explore their impact on image quality. Different graybeam approaches will be compared. Edge position calibration curves will be generated and the influence of the lithographic process on these calibration curves will be explored.

2. Graybeam Fundamentals

The use of graybeam techniques to reduce the virtual address grid size from an edge placement perspective has been commonly known for some time [2]. A review of these techniques will be given here.

Typical mask making tools in use today have spot sizes on the order of 100nm - 250nm (full width half maximum, FWHM) and use physical address grids (the actual grid used to place these spots) that are 1.5X to 2X smaller than the spot size. However, the design of integrated circuits today requires the flexibility to place edges on a grid of 5nm or smaller. This mismatch of the physical address grid and the required design grid is resolved by creating a virtual address grid through graybeaming. The principle is illustrated in Figure 1.



(a) (b)

Figure 1. The principle of graybeam: an edge of pixels (a) is moved a partial address grid by adding a new row of pixels at a reduced energy (b).

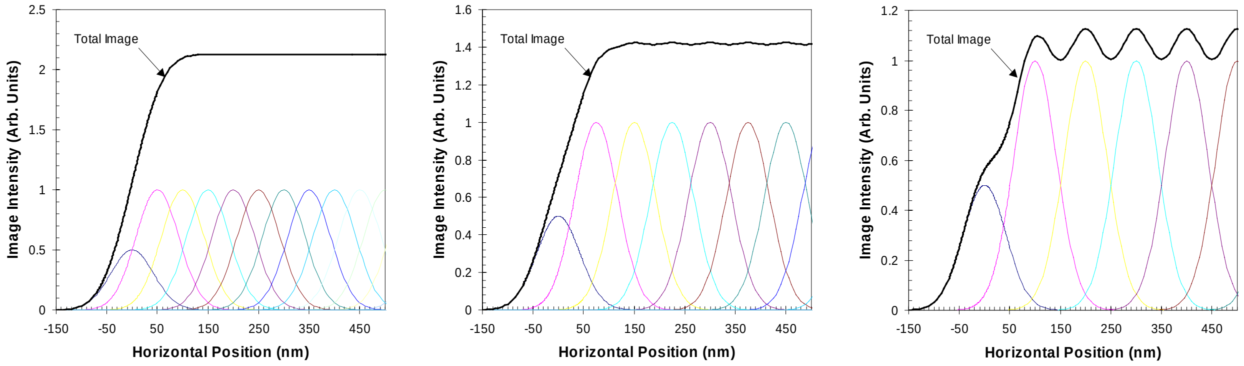
As Figure 1 illustrates, an edge is formed between a group of “on” pixels next to a group of “off” pixels. This edge can be moved one physical address grid by simply turning on the next row of pixels. The edge can be moved a smaller amount, however, by adding a row of pixels at a reduced exposure dose. The amount that the edge moves is a function of the dose of the pixel. To a rough approximation, the edge moves linearly from zero to one physical address grid as the pixel dose is varied from zero to completely on.

In real exposure tools, there is a finite number of “gray levels”, exposure dose values of a partially on pixel. Typical tools may have between 8 and 64 different allowed gray levels (in addition to fully off). As an example, consider a writing tool with a 100nm physical address grid and 64 levels of gray allowed for the pixel dose. The “virtual” address grid of this tool is then 100/64 = 1.56nm.

As Rieger et al. pointed out [2], however, the actual edge position of the graybeam image is not perfectly linear with gray level. Thus, a more accurate calibration curve of edge position versus gray level is required. Additionally, a very significant, though not well publicized, side effect of graybeam edge positioning is the impact of this technique on aerial image quality. In particular, the log-slope of the aerial image will be degraded when a graybeam pixel is used to move the edge of a line.

3. Graybeam Raster Scan Simulations

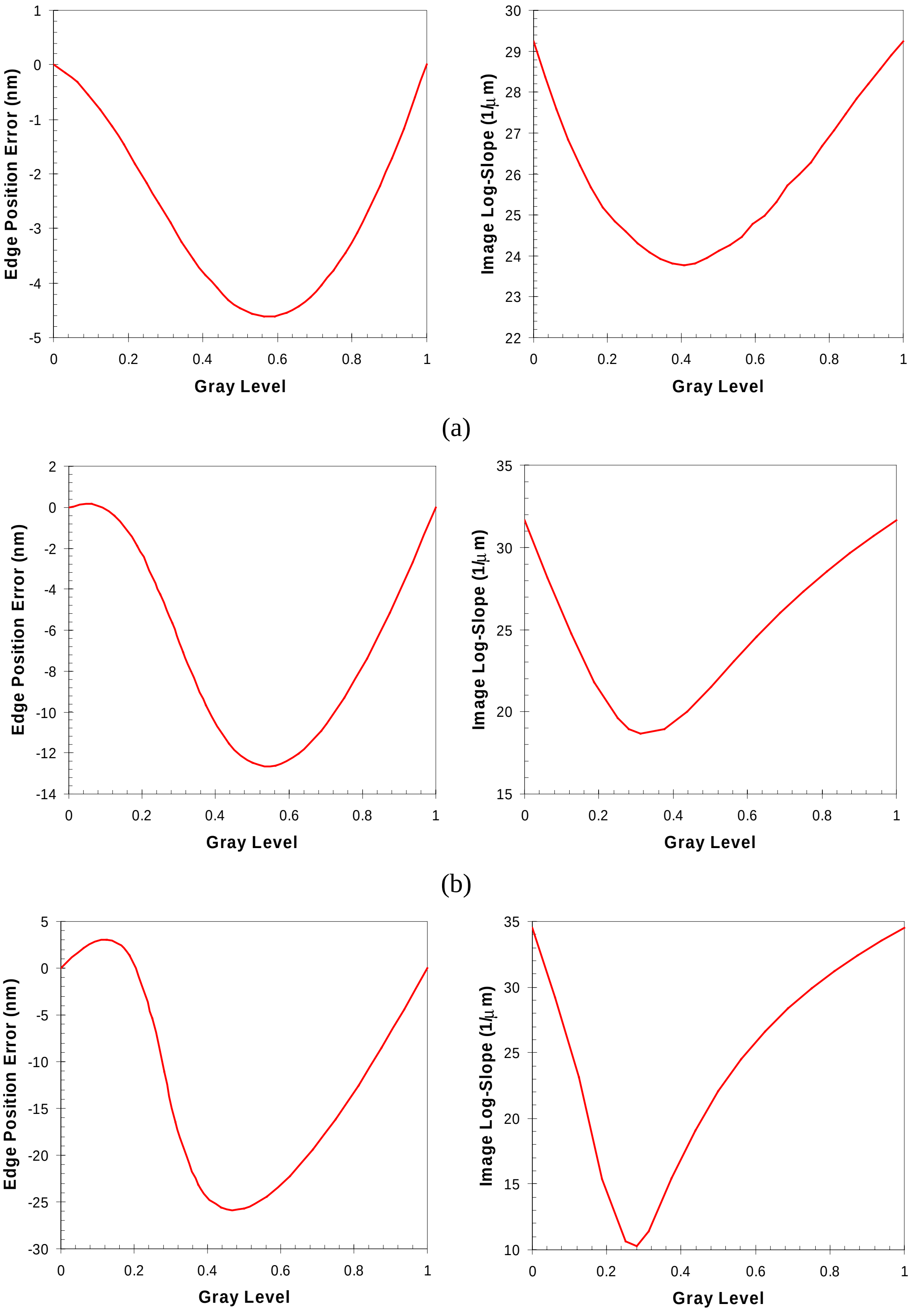
Simulations of raster scan aerial image formation presented below use the simple summation of Gaussian spots as described previously [3]. For this work an isolated edge pattern is created through the summation of 100nm FWHM Gaussian spots. Physical address grids of 50nm, 75nm and 100nm are used. The position of the edge of the aerial image is calculated as the position of an aerial image contour of either 0.3 or 0.5 relative to the average value in the clear (bright) area. Image quality is assessed using the image log-slope [4] measured at the actual edge position. Figure 2 illustrates the types of summations used to calculate the image of an edge.



(a) (b) (c)

Figure 2. Example summations of 100nm Gaussian spots for physical address grids of (a) 50nm, (b) 75nm, and (c) 100nm. In this case, the edge pixel is set to 50% gray level.

For each physical address grid, the position of the edge and the image log-slope were calculated with results shown in Figure 3. For this figure, the edge position was measured at an aerial image threshold intensity level of 0.3 (a typical value for most photoresist processes). The edge position is shown as an error from the linear approximation.



(a)

(b)

(c)

Figure 3. Simulations of the aerial image edge position error and the image log-slope at the edge using physical address grids of (a) 50nm, (b) 75nm, and (c) 100nm.

As can be seen from Figure 3, the non-linearity of the edge position with gray level increases quite dramatically with physical address grid. For a physical address grid size 2X smaller than the spot size (Figure 3a), the deviation of the actual edge position from linearity is only about 5nm (less than 10% of the physical address grid size). For the case of an address grid equal to the spot size (Figure 3c), the deviation from linearity is greater than 25nm (more than 25% of the physical address grid size).

Even the highly non-linear response of the large address grid graybeam writing strategy can be compensated for by incorporating the above edge position response as a calibration curve for the writing tool. Unfortunately, there is no way to compensate for the degradation in image log-slope that accompanies the use of graybeam. As graybeam pixels are added to the edge the quality of the image decreases. The image log-slope is at its maximum when the last row of pixels is fully on (corresponding to gray levels of 0 or 1). The image log-slope reaches a minimum at a gray level of about 0.3, not coincidentally equal to the aerial image threshold value used to set the edge position. For a physical address grid size 2X smaller than the spot size (Figure 3a), the image log slope drops by about 20% at the worst case for this isolated edge. For the case of an address grid equal to the spot size (Figure 3c), the image log-slope decreases by an incredibly large amount, more than a factor of 3.

The significance of the decreasing image log-slope can be appreciated by realizing that the exposure latitude of a feature is directly proportional to the image log-slope at the feature edge. A 20% reduction in image-log slope will translate into *at least* a 20% reduction in exposure latitude for the feature [5]. In fact, almost any process latitude related to feature edge position will be directly proportional to the image log-slope. Figure 4 illustrates how a 25% reduction in image log-slope (ILS) affects develop time latitude, the sensitivity of the feature edge position to changes in develop time.

Although an aerial image threshold value of 0.3 is commonly used to estimate the edge position of an aerial image in optical lithography, raster scan imaging can be made simpler (in terms of data biasing, for example) by using a 0.5 threshold value. From a resist processing perspective, this is equivalent to lowering the exposure dose. Figure 5 compares the resulting edge placement calibration curves for the 50nm physical address grid using image thresholds of 0.3 and 0.5. As Rieger pointed out [2], the 0.5 image threshold leads to the most linear edge placement response. However, this higher image threshold value produces an edge with a much lower image log-slope (about 30% less than the 0.3 threshold case), as seen in Figure 6. Thus, the reduction in image quality with graybeam level will be even more noticeable using the higher image threshold (lower exposure dose) process. More importantly, the change in the shape and magnitude of the edge position-to-graylevel calibration curve with image threshold value indicates that this calibration curve is process dependent.

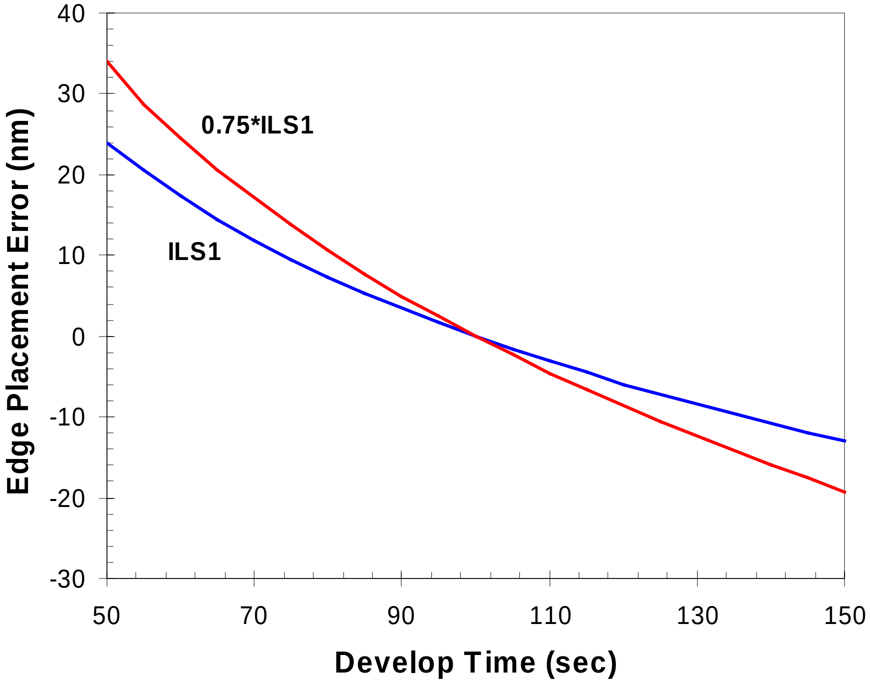


Figure 4. A reduction in image log-slope (ILS) results directly in a reduction in the develop time latitude of the position of the edge.

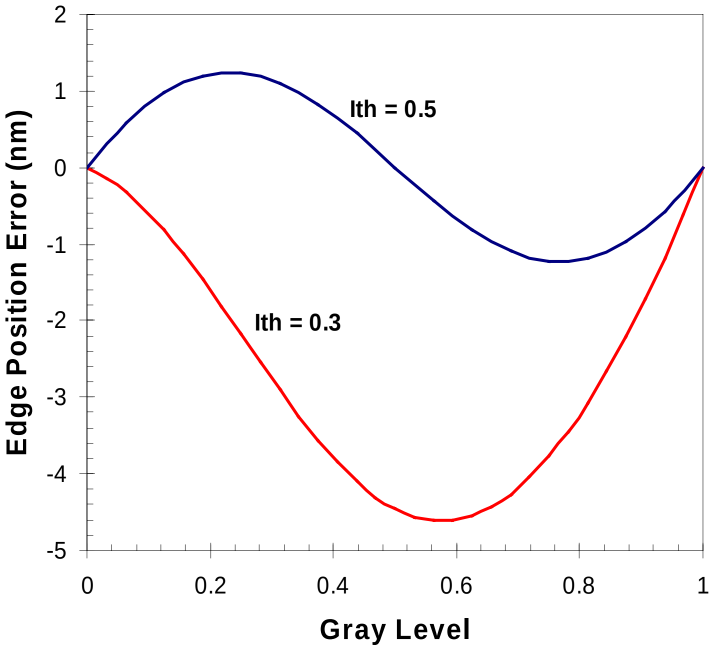


Figure 5. Changing the image threshold value (equivalent to changing the exposure dose) results in a change in the edge position calibration curve. An image threshold value of 0.5 leads to a minimum deviation from linear behavior. A 50nm physical address grid was used with a 100nm spot size.

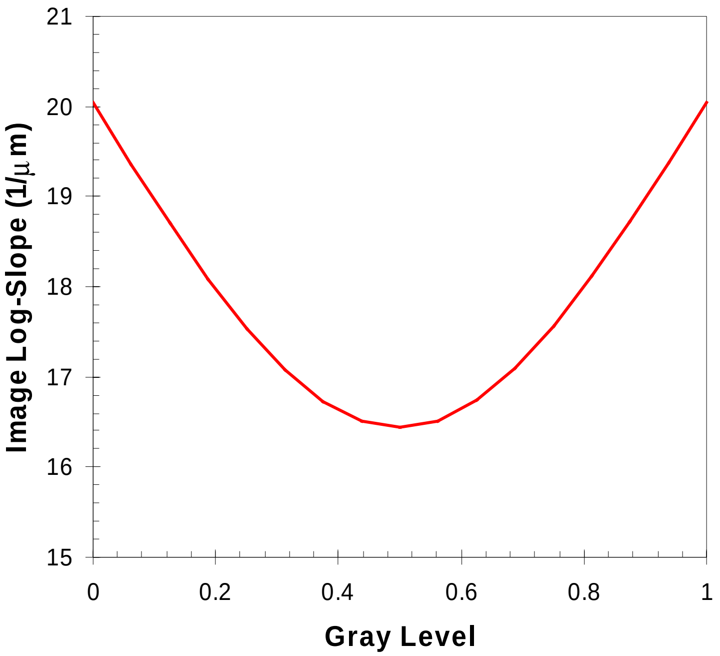


Figure 6. Decrease in image quality using graybeam calculated using a 0.5 aerial image threshold value. A 50nm physical address grid was used with a 100nm spot size.

4. Graybeam Projection Imaging Simulations

While the summation of Gaussian spots approximates the behavior of many direct write approaches to maskless lithography, a more promising technology for wafer production may be the projection of a digitally addressable “mask-like” structure such as an array of micromirrors. In a scheme like this, a small square mirror would reflect light to create a pixel. By turning the mirror away from the optical path, the “brightness” of the pixel can be controlled. These pixels are projected to the wafer using an optical system similar to today’s steppers or step-and-scan systems.

Simulations similar to those presented above for raster scan imaging were carried out using PROLITH v7.1. Perfectly square 100nm pixels were assumed with no gaps between pixels. The physical address grid was fixed at 100nm. The projection tool had a numerical aperture of 0.8, partial coherence of 0.5, and a wavelength of 248nm. The results of edge placement non-linearity and decrease in image log-slope with gray level are shown in Figure 7. The trends are similar to those shown above for raster scan imaging, with a maximum loss of 15% image log-slope at the worst gray level setting. Note that multi-pass exposures as a techniques to reduce the effective physical address grid is expected to offer some improvement, though these simulations have not yet been carried out.

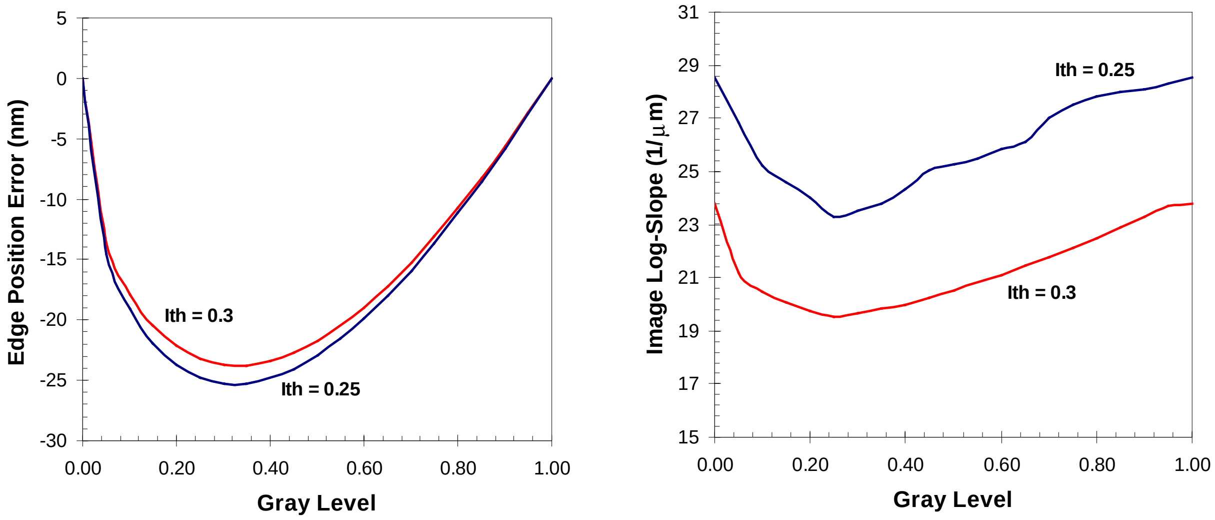


Figure 7. Simulations of the aerial image edge position error and the image log-slope at the edge for projection imaging of square pixels for a pixel size and physical address grid of 100nm.

5. Conclusions

Using simple simulations of aerial image formation as the summation of Gaussian spots and as the projection of ideal square pixels, several important conclusions about the use of graybeam to reduce the virtual address grid of a maskless lithography tool can be made. First, graybeam benefits greatly from the use of a smaller physical address grid. The common use of a physical address grid equal to one half the pixel size is certainly justified by the simulations presented here. Of course, going to even smaller physical address grids would be beneficial, but defeats the purpose of using graybeam.

While the edge position deviation from non-linearity can be calibrated out of a writing tool, the variation of the calibration curve with image threshold level (Figures 6 and 7) shows that the calibration curve is process dependent. Any significant process change could result in the need for a new edge position calibration curve.

Finally, one of the hidden difficulties of graybeam, often ignored by the proponents of graybeam as a means of reducing the virtual address grid, is the reduction of image quality as expressed by the image log-slope. For the raster scan case of a physical address grid equal to half of the spot size, the worst case graybeam level has an image log-slope at the edge that is 20% less than the best case. For the projection imaging case of a physical address grid equal to the pixel size, the worst case graybeam level has an image log-slope at the edge that is 15% less than the best case. This leads to the interesting but unwanted result that the ability to control the critical dimensions on a reticle is a function of the exact positioning of the feature edges relative to the physical address grid.

Future work will extend the results presented here to include an analysis of multiple exposure passes (the so-called multi-pass gray technique).

6. References

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