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Evaluating Proximity Effects Using 3-D Optical Lithography Simulation

This tool will improve the match of resist image to target device pattern.

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Key Technologies:

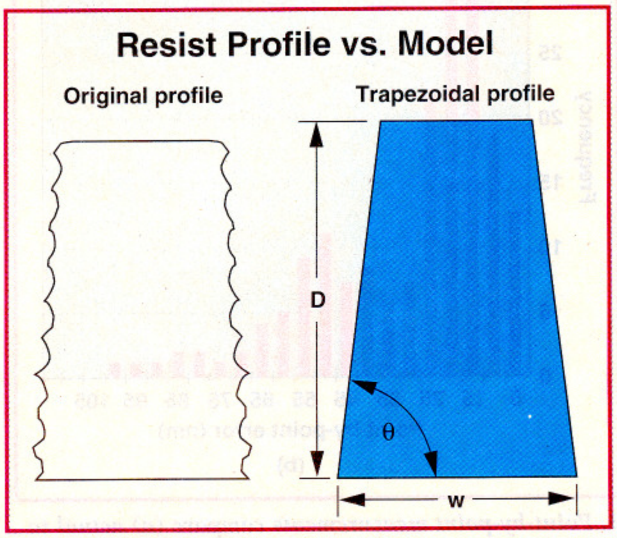
- **Proximity effect**
- **Photolithography**
- **Lithography simulation**

At A Glance:

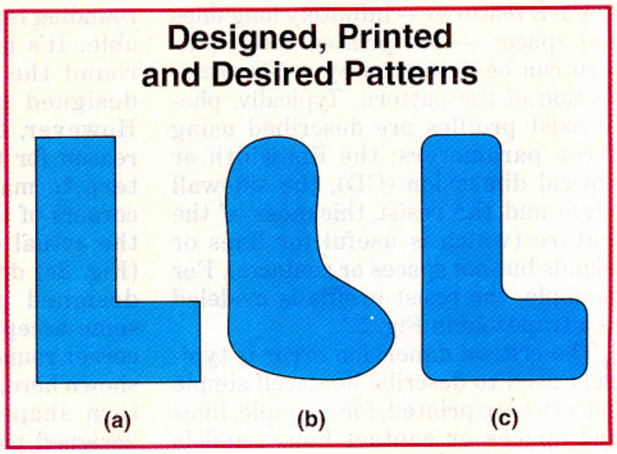
The use of optical lithography modeling as a tool for evaluating proximity effects is described. An extension of the critical dimension error for a one-dimensional mask feature to a critical shape error for a two-dimensional mask feature is presented. Simulation is applied to the evaluation of mask shaping (also called optical proximity correction) using the critical shape error as a metric.

Although it is quite easy to evaluate the effectiveness of printing simple one-dimensional patterns such as lines and spaces, making a quantitative judgment about the quality of a more complicated two-dimensional printed shape is quite difficult. Recently, optical proximity correction (OPC) has been used to change the shape of mask patterns to improve the quality of the final resist pattern. Thus, some obvious questions have arisen. For a given mask shape, how good is the final resist shape? Given two methods for OPC, which is better? What is the depth of focus for a complicated pattern? All of these questions require the use of a quantitative metric to judge the shape of an arbitrary pattern. In this paper, the critical shape error (CSE) will be defined to fill this need.

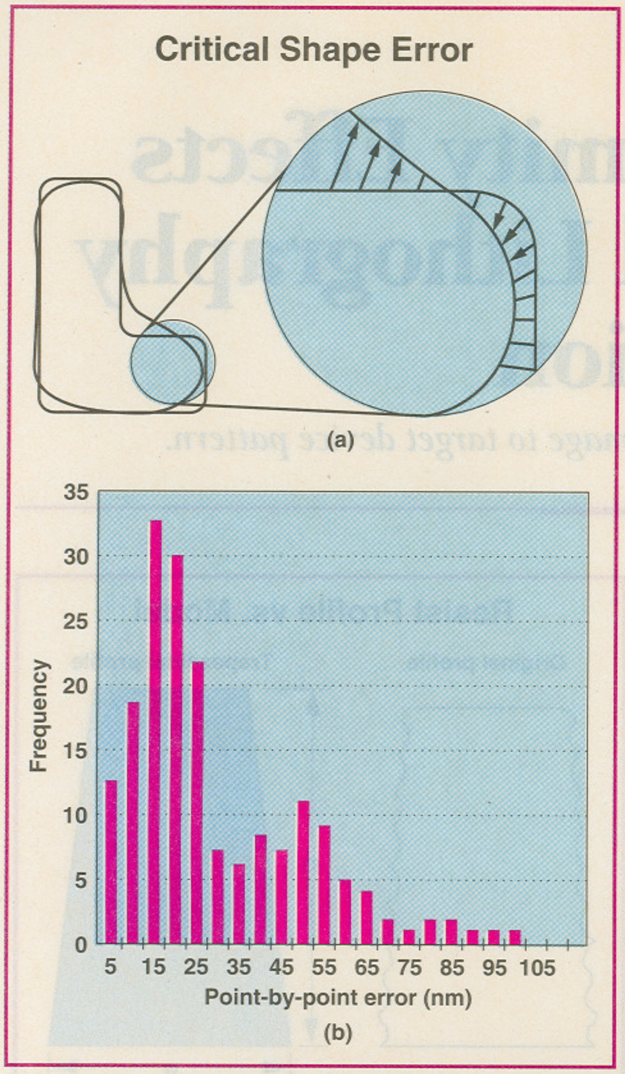
One of the primary advantages for using the critical shape error for 2-D features is its similarity to the critical dimension error for 1-D features. Thus, much of the analysis and evaluation of lithographic results based on the critical dimension error can be used in the same way for the CSE.



1. Comparison of an actual, complex photoresist profile with its trapezoidal model used to determine linewidth, sidewall angle and resist loss.



2. Printing of a 2-D pattern provides three distinct shapes: (a) the designed pattern (with 400nm minimum width), (b) the final printed pattern (top down view) and (c) the desired pattern (with 100 nm corner rounding).



3. Point-by-point measurements compare (a) actual to desired shapes and results in (b) a frequency distribution of errors.

Measuring feature size in 2-D

For 1-D features — infinitely long lines and spaces — the printed resist pattern can be described by a 2-D cross-section of the pattern. Typically, photoresist profiles are described using three parameters: the linewidth or critical dimension (CD), the sidewall angle and the resist thickness of the feature (which is useful for lines or islands but not spaces or contacts). For example, the resist profile is modeled as a trapezoid in Fig. 1.

The critical dimension error is typically used to describe how well simple patterns are printed, for example, lines and spaces or contact holes, and is defined as the difference in the actual profile width from the desired profile width. Thus, the size of a 1-D feature is described by one number, the critical dimension error. Can this concept be extended to a 2-D feature? An analysis method proposed by Tsudaka et al.[1] for describing the shape of a 2-D printed pattern lays the foundation for the critical shape error, an extension of the critical dimension error to two dimensions.

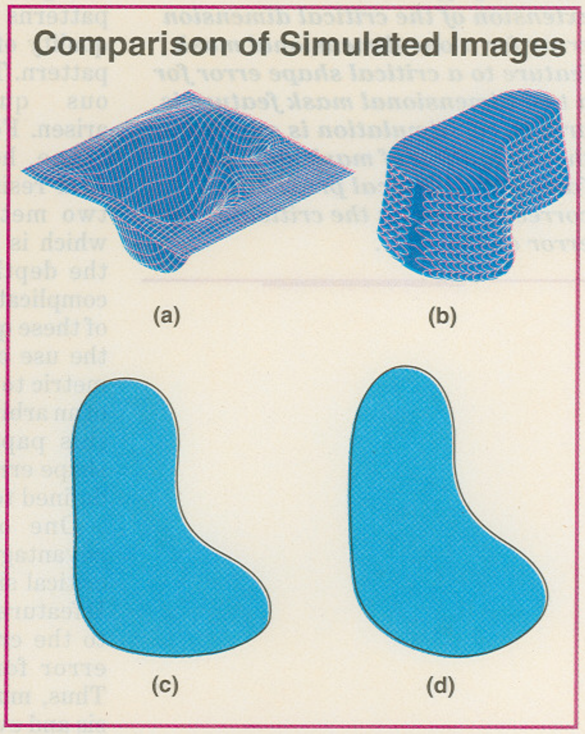
Printing of a 2-D pattern provides three distinct shapes: the design, the final printed and the desired pattern. Consider a 2-D mask feature (Fig. 2a) giving rise to a resulting 2-D top-down view of the resist image (Fig. 2b). To describe the error in the actual resist image from the target or desired resist image, one must first define the target image. Although it would be easy to assume that the original mask pattern is the target for the resist pattern, this is not actually the case.

The original mask pattern is composed of elementary shapes like rectangles which necessarily have sharp corners. When printed in photoresist, these corners are always rounded to some extent. A certain amount of corner rounding is perfectly acceptable. It's not necessary to round the corners of the designed pattern layout. However, there is also no reason for the printed pattern to match the square corners of the design. Thus, the actual desired pattern (Fig. 2c) deviates from the designed pattern due to some acceptable amount of corner rounding. In the case shown here, the desired pattern shape is simply the designed pattern of Fig. 2a with corner rounding using a 100 nm radius of curvature (1/4 of the minimum feature size). Defining the maximum acceptable rounding radius is an important part of determining a realistic value for the CSE.

The CSE is determined by finding the point-by-point difference between the actual printed resist shape and the desired shape (Fig. 3a). Using a reasonably spaced distribution of measurement points, for example, 20 nm between points, the features in Fig. 2 have about 200 points with which to measure the difference in shapes. The result is a frequency distribution of errors as shown in Fig. 3b. The absolute error is used — the direction of the error, positive or negative, is ignored. This type of distribution is non-normal and is often bimodal. The first peak at small errors comes from the long edges of the features and the second peak at larger errors is due to the corners of the pattern.

Once a distribution is determined, some characterization of the distribution can be used to describe the overall shape error. For example, the average error (CSE_{avg}) could be used or the error which is greater than 90 percent of the point-by-point measurements (CSE_{90}). For the distribution in Fig. 3, some results are given below:

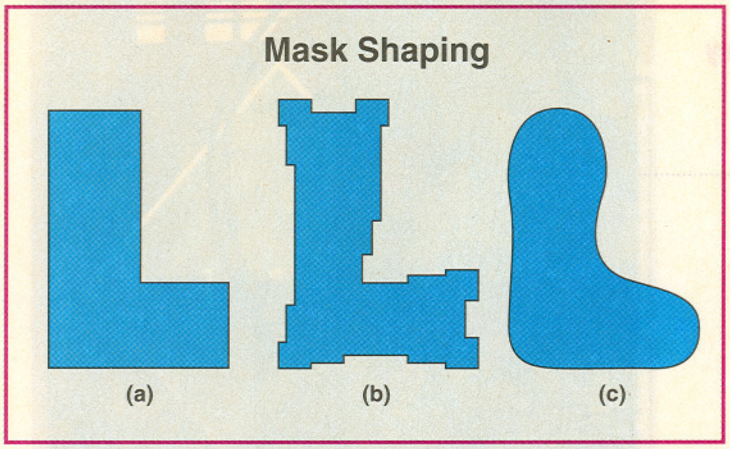
CSE_{avg} = 26.9 nm
CSE_{80} = 46 nm
CSE_{90} = 55 nm



4. Comparison of simulated images showing (a) the aerial image, (b) the 3-D photoresist profile, (c) an aerial image contour and (d) a top-down "measurement" of the photoresist profile.

CSE_{95} = 65 nm
$CSE_{99.7}$ = 91 nm

The 95 percentile (2σ criterion for a normal distribution) captures both peaks of the bimodal distribution and appears to be an adequate reflection of the overall error. The 99.7 percentile (3σ criterion for a normal distribution) gives essentially the maximum measured error and is probably not as significant in terms of the critical shape error as in other applications of error analysis. The average CSE appears to be an adequate measure of the overall shape error as well, but may fail to point out some problem areas of the feature.



5. Mask shaping and the resulting resist image: (a) the designed pattern with 400 nm minimum width, (b) the corrected mask shape after OPC and (c) the final printed pattern (top down view).

The analysis described can be modified to weigh certain portions of the pattern shape more heavily than others. For example, if line-end shortening is of critical importance to the lithographic application, more measurement points can be added to the line ends, thereby weighing the frequency distribution accordingly. For small patterns such as the one shown in Fig. 2, an even distribution of measurement points is probably the best.

This approach can be applied to actual photoresist images, but is particularly applicable to simulated images. In addition, the CSE of an aerial image as well as the final photoresist profile could be determined. Figure 4 compares a typical aerial image contour taken at a 30 percent intensity level to a measured contour of a photoresist profile. In this case, "measured" means using a suitable algorithm for converting a 3-D resist profile to a top-down outline. As expected, the photoresist profile is worse than the image (i.e., has a larger critical shape error). A perfect photoresist could do no better than to reproduce the aerial image exactly.

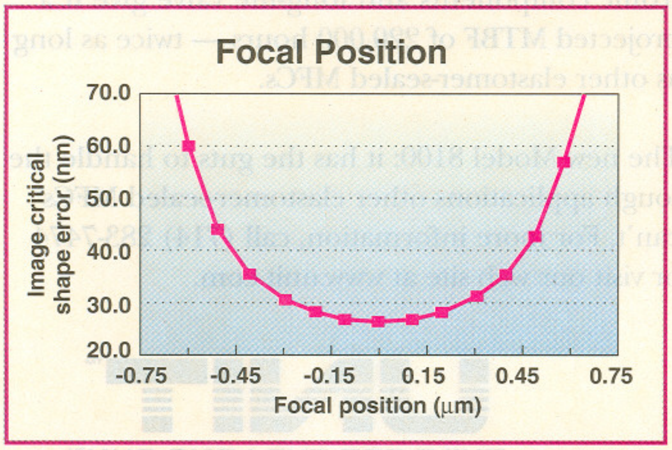
Application to OPC analysis

Recently, optical proximity correction (OPC) has become an accepted method of improving the final resist pattern.[2, 3] Originally OPC was thought of as a method for correcting line-size variations as a function of the proximity of other features,[3] thus the name optical proximity correction. However, the application today is more generic: can we change the shape of the mask pattern to obtain better lithographic results? This mask shaping problem is a super-set of the OPC problem, but the term OPC is so commonly used that it now encompasses any mask shaping application.

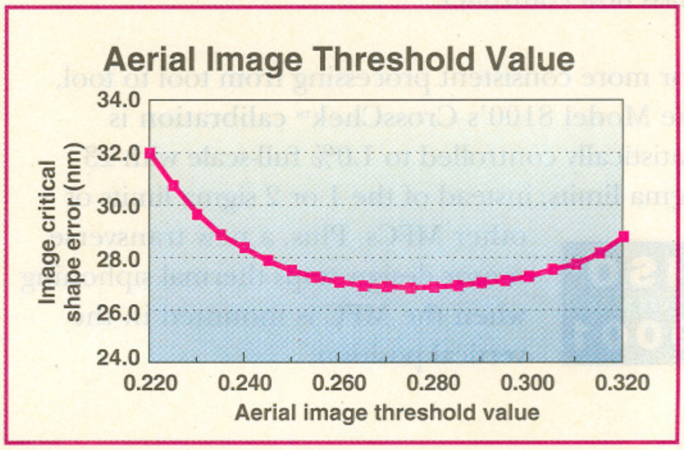
Consider the simple mask pattern and resulting resist pattern of Fig. 2. Can mask shaping be used to improve the final resist pattern? The CSE is the metric used to quantitatively judge the effectiveness of any such mask shaping effort.

Figure 5 shows a mask which has been shaped to reduce the CSE. The result of the OPC has been to reduce the CSE_{avg} from 27 nm to 14 nm and the CSE_{95} from 65 nm to 36 nm using the same target shape of Fig. 2c. Such a significant reduction in CSE is the primary motivation behind the current interest in mask shaping. With the definition of the critical shape error given here, a true metric of the effectiveness of an OPC algorithm can be used.

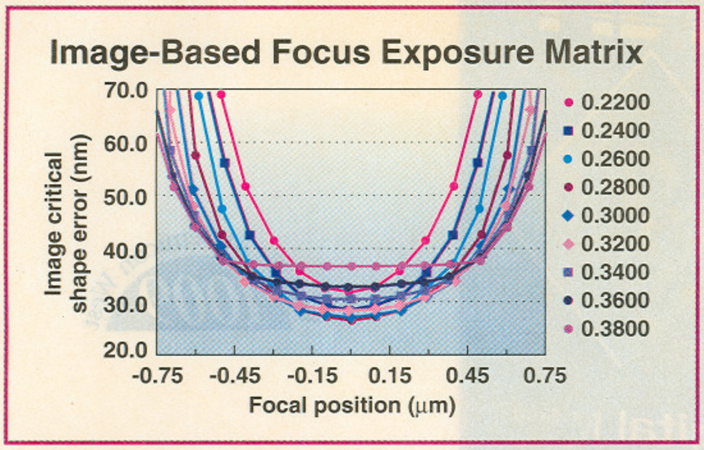
Creating the pattern with the smallest CSE at best focus and best exposure may be desirable, but the optimum OPC would result in the lowest CSE over a desired range of focus and exposure errors.[1] Using the CSE as a metric, the response of the pattern to various errors can be judged in the same way that critical dimension errors are used for 1-D features. For example, focus latitude can be evaluated by plotting the CSE versus focus, as in Fig. 6. In this figure and in the results that follow, the aerial image, calculated with PROLITH/2,[4] with an image contour of 0.275 was used as an estimate of the final printed resist shape. Although this gives only an



6. The CSE_{avg} degrades as the image goes out of focus.



7. The threshold value must be chosen to minimize the CSE.



8. The equivalent of a focus-exposure matrix using the image-based critical shape error.

approximate result, it is sufficient to illustrate the concepts.

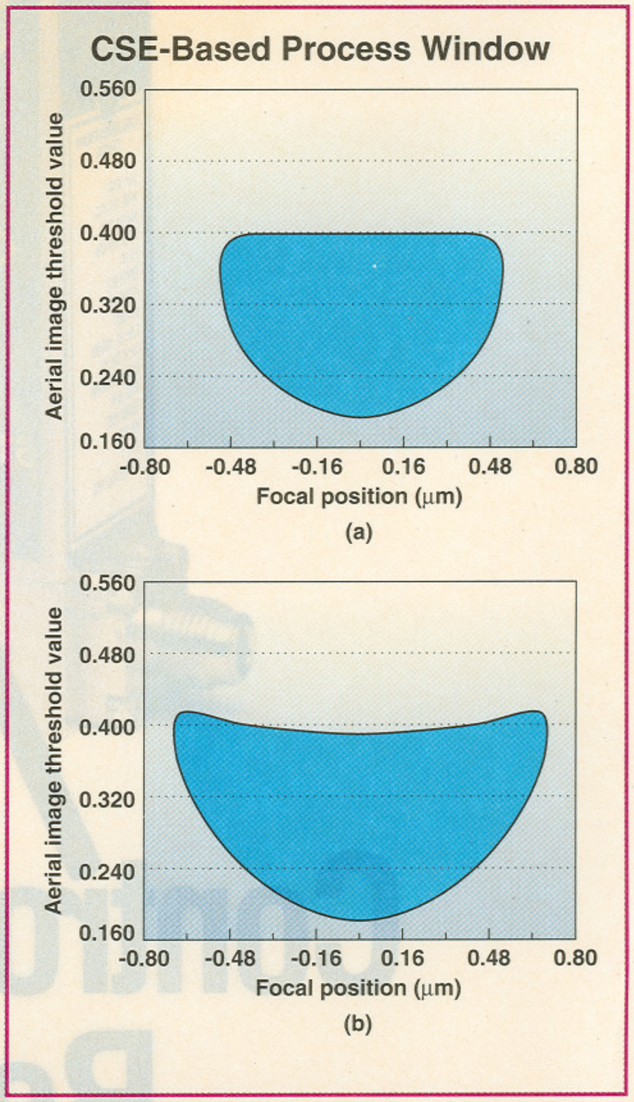
PROLITH/3D

PROLITH/3D provides full 3-D resist simulations to calculate the CSE of the final photoresist pattern. Thus, both changes in the mask shape and changes in the lithographic process can be evaluated. As a first estimate of the effectiveness of mask shaping, one simple (and computationally fast) approach is to use the shape of the aerial image as an estimate of the shape of the final printed pattern. When using an aerial image to judge the printed image, the image contour value (intensity value at which to measure the shape) plays the role of exposure dose. Thus,"proper exposure" means finding the image contour value which minimizes the CSE. For example, the 0.275 contour gives the minimum CSE_{avg} for the uncorrected mask pattern of Fig. 2 (Fig. 7). Combining a variation of focus with an exposure-like variation in image threshold value gives the equivalent of an image-based focus-exposure matrix (Fig. 8).

As seen from Figs. 6-8, one of the primary advantages of the use of the critical shape error for 2-D features is its similarity to the critical dimension error for 1-D features. Thus, much of the analysis and evaluation of lithographic results based on the critical dimension error can be used in the same way for the CSE. Consider the focus-exposure matrix based on the CSE. As is commonly done for the critical dimension error, the data can be plotted in contour form, giving rise to a process window of acceptable focus and exposure for a given maximum allowable error.

Figure 9a shows the CSE based process window for a maximum allowable CSE_{avg} of 40 nm. Figure 9b shows the same window for the OPC corrected mask. The width of the window (focus latitude) is extended — but not the height (exposure latitude). Also, the dramatic improvement seen in-focus with the use of OPC translates into only a slightly larger process window. Some OPC results can give smaller process windows, in effect trading off better in-focus performance with worse out-of-focus performance. The systematic use of the critical shape error allows these trade-offs to be explored quantitatively.

The critical shape error, an extension of the 1-D critical dimension error to 2-D features, provides a rigorous metric to judge the quality of printed resist patterns. This metric allows for the optimization of OPC algorithms, resist processing and other lithographic variables, ultimately resulting in an improved match between actual and desired device patterns. ☐



9. The equivalent of a focus-exposure process window using the image-based critical shape error (CSE_{avg}) as the response and substituting image threshold value for exposure dose. Shown are the results for the (a) uncorrected and (b) OPC corrected masks shown in Fig. 5.

References

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