Metrology and Analysis of Two Dimensional SEM Patterns

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Abstract

A variety of techniques to characterize the lithographic quality of top-down two-dimensional patterns are described. Beginning with a top-down SEM micrograph, image processing and feature edge detection are used to extract a polygon representation of the printed pattern. Analysis on the polygon yields metrics such as corner rounding radius, feature area, and line edge roughness. Comparison of two shapes (for example, actual compared to desired, mask compared to wafer, or before etch compared to after etch) produces metrics such as overlapping area and the critical shape difference. Numerous examples of the utility of this approach will be given for SEM images of masks and wafers. The result is a set of numeric metrics of two-dimensional pattern fidelity applicable to lithographic evaluation, improvement and control.

Keywords: SEM Image Analysis, Critical Shape Difference, Corner Rounding, ProDATA, SIAM

I. Introduction

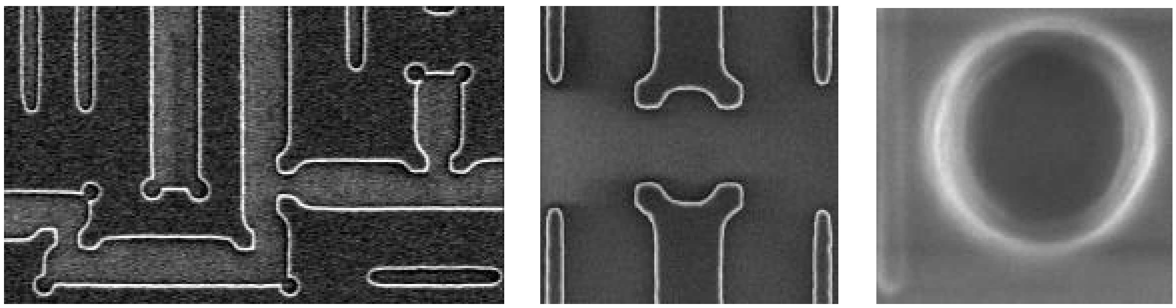
Historically, lithography engineering has focused on two key, complimentary aspects of lithographic quality: overlay and linewidth control. Linewidth control generally means ensuring that the widths of certain critical features, measured at specific points on those features, fall within acceptable bounds. However, as lithography pushes to smaller and smaller features, single number metrics such as the critical dimension (CD) of a feature may not be adequate. The three-dimensional shapes of the final printed photoresist features can, in fact, affect the performance of the final electrical devices in ways that cannot be described by variations in a single width parameter of those features. In such cases, increasingly common today, more information about the shape of a photoresist pattern must be gathered in order to characterize its quality.

This paper will describe a variety of techniques to characterize the lithographic quality of top-down two-dimensional patterns. Beginning with a top-down SEM micrograph, image processing and feature edge detection are used to extract a polygon representation of the printed pattern. Analysis on the polygon yields metrics such as corner rounding radius, feature area, and line edge roughness. Comparison of two shapes (for example, actual compared to desired, mask compared to wafer, or before etch compared to after etch) produces metrics such as overlapping area and the critical shape difference (CSD). Numerous examples of the utility of this approach will be given for SEM images of masks and wafers. The result is a set of numeric metrics of two-dimensional pattern fidelity applicable to lithographic evaluation, improvement and control.

The techniques described in this paper have been incorporated into the software package Klarity ProDATA with the SEM Image Analysis Module (SIAM™).

II. Image Processing

Top down SEM images of two dimensional shapes can have a wide variety of image characteristics depending on the materials used, the patterns imaged, and the SEM imaging conditions. Figure 1, for example, shows three SEM images, each with different amounts of grainy texture, material shading, and structure characteristics. Figure 1a is very grainy, while 1b shows a gradation in the background shading. Figure 1c has a shallow sloped sidewall with uneven shading along the sidewall (darker on the top and bottom, brighter at left and right). The range of graylevels is also different among the images.



(a) (b) (c)

Figure 1. SEM images from different tools and with different structures and material properties show a wide range of image characteristics.

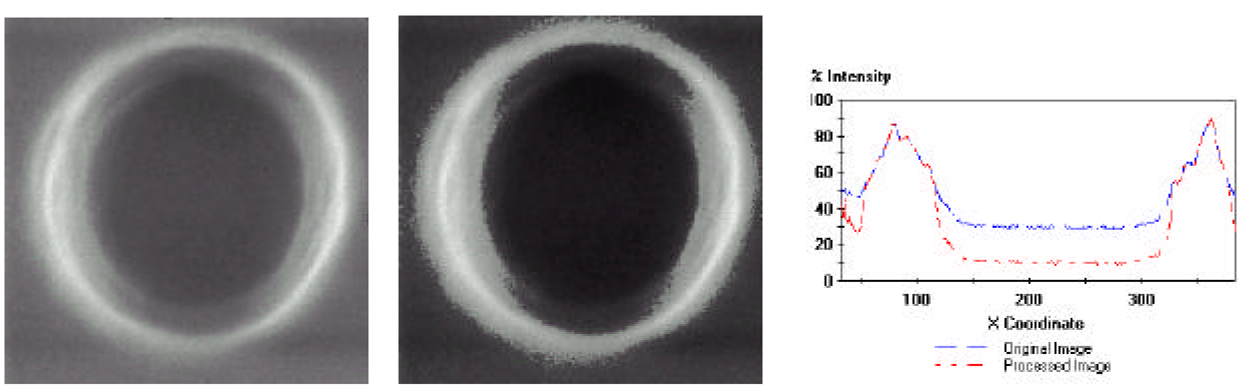
As a first step in characterizing the pattern shapes from SEM images, image processing can be used to make the images more uniform in nature, allowing for easier edge detection. Image processing can include inverting gray levels, automatic scaling of gray levels, band pass scaling, and pixel smoothing. Note that the order in which these processes are performed will affect the final result.

1. Automatic gray level scaling

Automatic gray level scaling is used to make the range of gray levels present in the image more consistent from image to image. A typical bitmap image will use 256 gray levels. If the darkest pixel of a particular image is, say, gray level 23 and the brightest pixel is gray level 214, the use of automatic gray level scaling would change a pixel of gray level g to a new value given by

$$g^* = (g - 23)\frac{256}{214 - 23} \tag{1}$$

Figure 2 shows how much an image can change with this automatic scaling enabled.



(a) (b) (c)

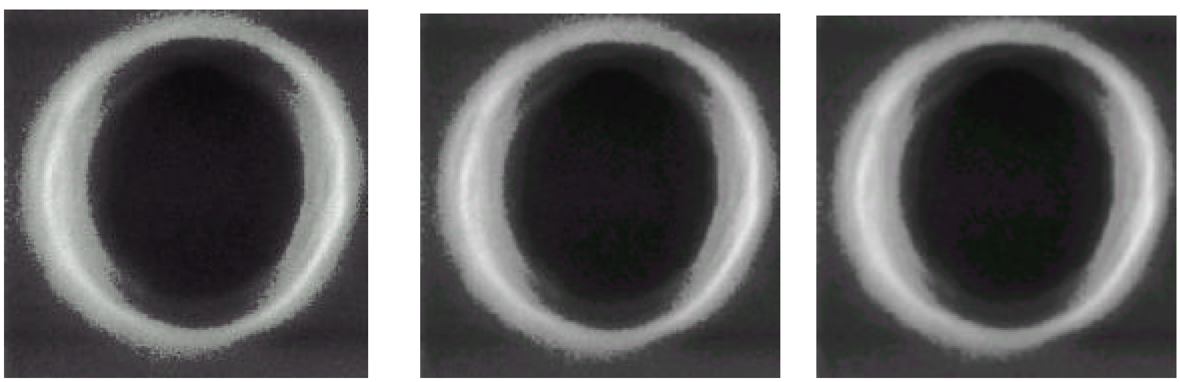
Figure 2. The impact of automatic gray level scaling: (a) original image, (b) after automatic gray level scaling, and (c) a horizontal line scan through the middle of the image showing gray levels both before and after scaling.

2. Band pass scaling

Band pass scaling is used to convert pixels near the extremes of bright and dark into completely bright and dark. For example, the background of an image may be close to black, but with some variation. Setting a lower band pass scaling to, say, 20%, would take all pixels below a 20% gray level and make them completely dark. Likewise, setting an upper threshold of 80% would turn all pixels above this threshold to pure white. In general, such filtering would only have a cosmetic effect on the image so long as these threshold levels are not near the edge detection threshold (as described in the following section). However, the band pass scaling can influence the next image processing step, pixel smoothing.

3. Pixel smoothing

Noise in the image, due in part to the pixelization process itself, can sometimes be reduced through a simple pixel smoothing process. In this process, the gray level of a given pixel is changed to be the gray level of that pixel averaged with all its nearest neighbors. This process can be repeated for any number of passes. The advantage of pixel smoothing is that an individual noisy pixel will have less influence on subsequent edge detection. The disadvantage is that edge definition in the image is smoothed out, adding some uncertainty as to the true position of the edge. Figure 3 illustrates how different numbers of smoothing passes can change the look of an image.



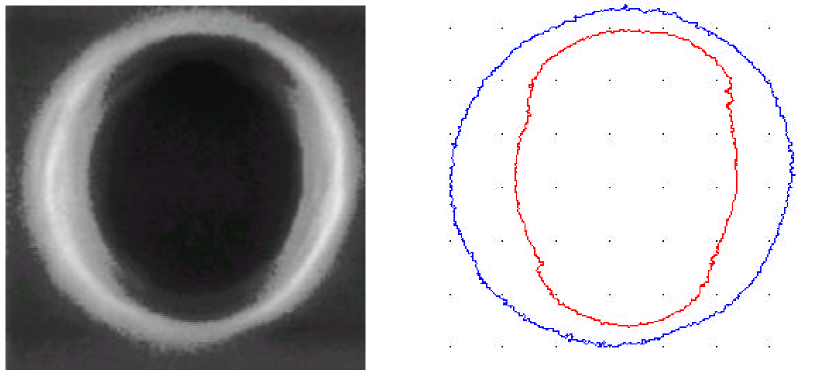
(a) (b) (c)

Figure 3. SEM images with (a) zero, (b) one, and (c) three passes of pixel smoothing.

III. Feature Detection

Once an image has been processed, the next step is to detect the edges of the features of interest. All of the example images shown here display edges as a bright band, though not all images will have such characteristics. The first step in edge detection is to use a simple threshold value (typically near 50% for an image with autoscaled gray levels). Figure 4 gives an example of edge detection showing the detection of both sides of the bright bands that define each edge. These two edges (in this case, an inner and an outer edge) create an "edge band" that defines the region where the final edge position will be specified.

Once the edges that determine the edge band region have been defined, these edges can be used to derive a single polygon representing the feature. This feature polygon is called the *critical shape*, a two-dimensional analog to the critical dimension. First, however, there are three issues that have to be addressed in order to properly define the critical shape.



(a) (b)

Figure 4. The processed image (a) used to detect the inner and outer edges (b).

1. Small polygon filtering

Every transition in the image past the edge threshold gray value will produce an edge that, in turn, will make up a polygon. In other words, whenever two pixels next to each other have gray levels above and below the selected edge detection threshold level, an edge will be placed between the two pixels. Because of noise in the image it is possible that small clusters of isolated pixels will cross this edge threshold value, giving a number of small nuisance polygons. These can be filtered out by simply removing all polygons whose areas are less than some specified value.

2. Broken feature edges

A serious problem in the analysis of real SEM images is the possibility that an edge will be "broken", so that a complete polygon representation of the feature is interrupted. Figure 5 shows an example of how the selection of an edge threshold value that is appropriate for the majority of the image may result in a spot where the edge will become discontinuous. The broken edge problem can be solved by automatically connecting such edges whenever their distance apart is less than some threshold value.

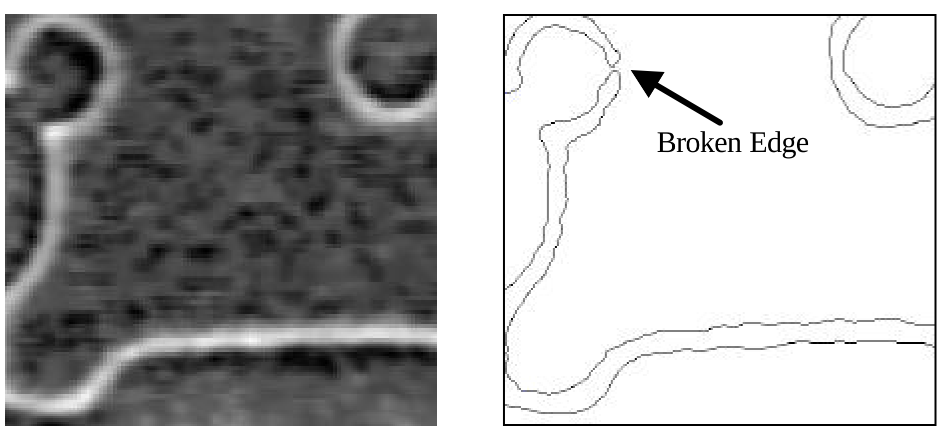


Figure 5. Broken edges are a common problem for images with low contrast edges.

3. Creating the critical shape

The edge threshold detection creates polygons that, in general, represent the two sides of a single edge. By appropriately associating these two polygons as the sides of a single edge, the final step in the feature detection algorithm is to create a single polygon between these two edge polygons. A continuum of positions, from inner to outer, can be chosen between the two edge polygons. Once chosen, the single polygon created is the resulting critical shape for the feature. Complications such as edge polygons that touch the outer edges of the image must be handled correctly as well. Figure 6 shows an example of the final critical shapes for a typical SEM image.

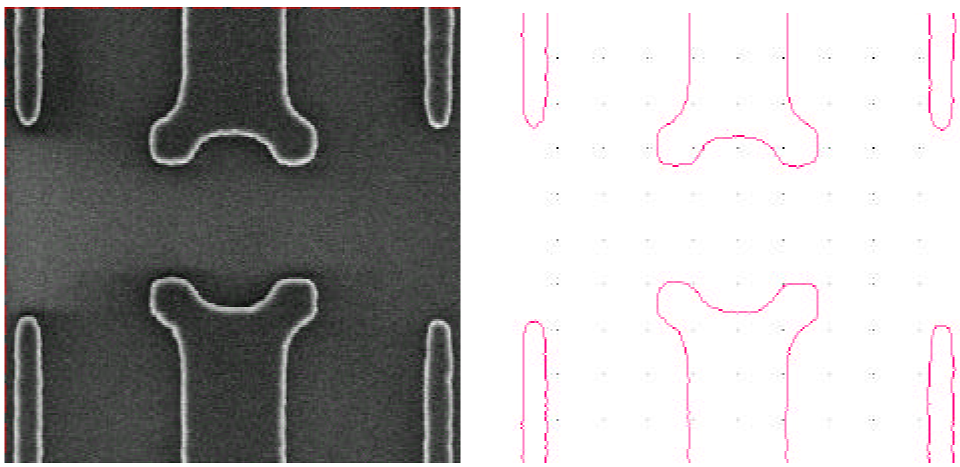


Figure 6. A typical 8250R SEM image of a chrome on glass reticle and the resulting critical shapes.

IV. Shape Analysis

Once a critical shape has been determined for a feature on an SEM image, several types of analysis can be performed. Lithographically important metrics such as line edge roughness, corner rounding radius, feature area, feature width, and effective contact hole width can be computed.

1. Line edge roughness

Although many definitions are possible, one simple approach to line edge roughness calculations is to fit a straight line through a nominally straight edge of the critical shape and define the "roughness" as the standard deviation of the fit to the critical shape (Figure 7). Alternately, the maximum deviation of the shape to the line fit can be used.

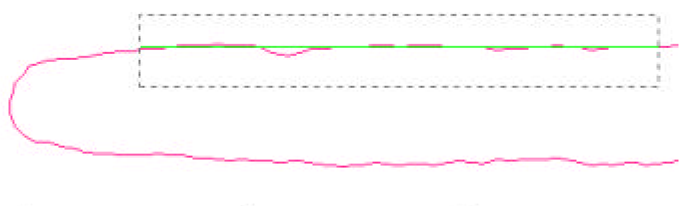


Figure 7. Line edge roughness calculations by fitting a straight line through a nominally straight edge.

2. Corner rounding

Like line edge roughness, there are several possible metrics that can be defined that relate to corner rounding. The simplest, of course, is to fit a circle to a rounded corner and take the radius of that best fit circle as the corner rounding radius. Figure 8 shows an example of such a calculation.

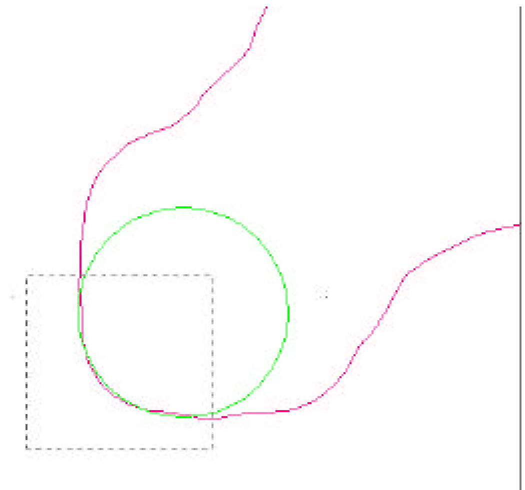


Figure 8. Corner rounding measurement where a circle is fit to the critical shape in a selected region.

3. Feature area

The area of a feature can easily be measured, either by using the entire feature (Figure 9) or by cropping the feature to a selected region. Separately, the ability to measure feature area enables the simple calculation of an effective contact hole width, defined as the square root of the contact hole area.

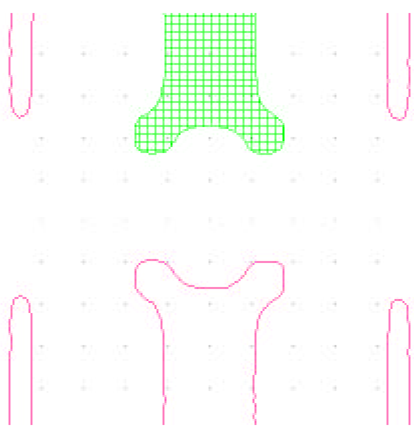


Figure 9. Feature area measurement.

V. Shape Comparisons

One of the most valuable uses of feature shapes extracted from SEM images is the ability to compare different critical shapes. Everything from designs to reticle images to wafer images before and after etch can be compared to each other (Figure 10). Given two critical shapes overlapped on top of each other, metrics such as the distance between edges, overlapping area, and the critical shape difference (CSD) between them can be computed. Figure 11 shows an example of the comparison between a reticle and the original design. The overlapping area calculation includes a measurement of the area common to the two plus the two areas contained in one but not the other shape. The critical shape difference calculations determine the point by point difference between the two shapes, generating a collection of vectors representing the distance between a point on the first shape and the second shape (Figure 11b). Analyzing this collection of vectors provides a histogram of vector lengths (Figure 11c). Further analysis of this histogram provides one of several possible metrics such as the average CSD, the maximum CSD, or a "percentile" CSD (the value of the CSD such that the given percentile of vector lengths are smaller than this value).

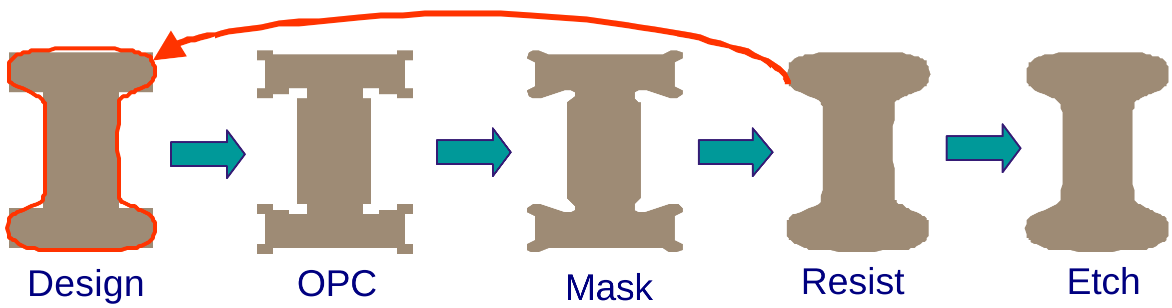
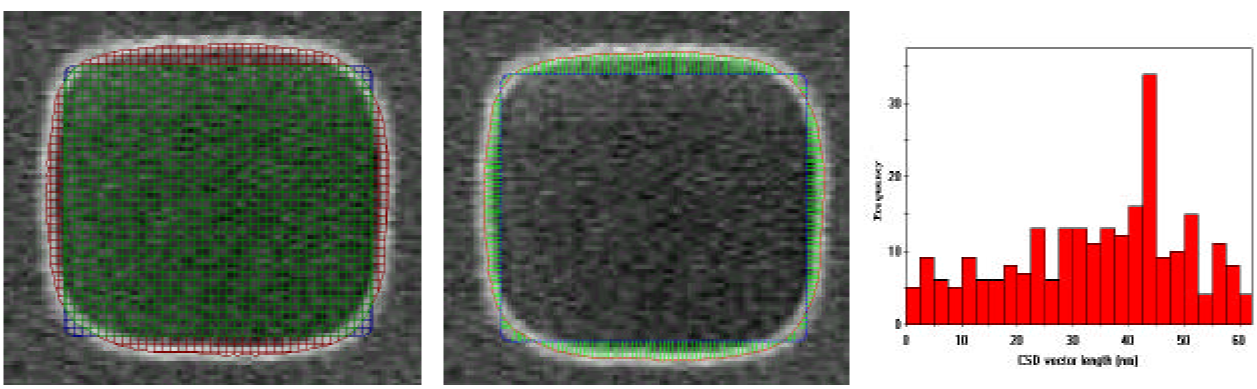


Figure 10. The comparison of a resist critical shape to the original design is one example of how critical shapes can be analyzed.



(a) (b) (c)

Figure 11. Analysis of overlapping critical shapes, such as this design to reticle comparison, can be used to calculate (a) overlapping areas, and (b) critical shape difference vectors, resulting in (c) a histogram of critical shape difference vector lengths.

VI. Conclusions

A comprehensive collection of shape detection and analysis tools has been described that can be used to extract useful lithographic information from top down SEM images of a wide variety of pattern shapes. The combination of image processing and edge detection is used to create critical shapes, mathematical polygon representations of the features on the SEM image. Given these critical shapes, any number of analyses become possible, such as line edge roughness, feature area, and corner rounding, among others. By overlapping two critical shapes, their difference can be concisely and accurately described. Comparisons of design to reticle to wafer are possible, as are evaluations of the effects of tool or process changes and the shapes of complex patterns. With tools such as these, quantitative metrics of lithographic quality can be established for any number of important feature shapes rather than being limited to simple one-dimensional linewidth values.

The technologies described in this paper have been incorporated into the software product Klarity ProDATA with the SEM Image Analysis Module.