Photoresist line-edge roughness analysis using scaling concepts

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Abstract. We focus on the problem of obtaining and characterizing the edge roughness of photoresist lines by analyzing top-down scanning electron microscope (SEM) images. An off-line image analysis algorithm detecting the line edge, and an edge roughness characterization scheme, based on scaling analysis, are briefly described. As a result, it is suggested that apart from the rms value of the edge (sigma), two more roughness parameters are needed: the roughness exponent \( \alpha \) and the correlation length \( \xi \). These characterize the spatial complexity of the edge and determine the dependence of sigma on the length of the measured edge. Completing our previous work on the dependencies of the roughness parameters (sigma,\( \alpha,\xi \)) on various image analysis options, we examine the effect of the type of noise smoothing filter. Then, a comparative study of the roughness parameters of the left and right edges of resist lines is conducted, revealing that the sigma values of the right edges are larger than those of the left edges (due to an imperfect SEM beam alignment), whereas the roughness exponents and the correlation lengths do not show such a trend. Finally, the relation between line width roughness and line edge roughness is thoroughly investigated with interesting conclusions. © 2004 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1759325]

Subject terms: line-edge roughness; photoresist; scanning electron microscope images; scaling analysis; fractal dimension; roughness exponent; correlation length; line-width roughness; noise smoothing filters; edge detection.

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1 Introduction

With the shrinking of the dimensions of microelectronics devices into the sub-100-nm region, precise control of the critical dimension of resist structures is becoming increasingly important. Thus, the influence of resist line-edge roughness (LER) may be crucial to the fidelity of the transferred patterns on the underlying substrate and hence to the device performance.\(^1\)–\(^3\) Therefore, a quantitative characterization of LER of photoresist lines is needed not only for the assessment of fabrication processes and material properties, but also for precise evaluation of device performance. Most commonly, the characterization of LER is achieved by examining the fabricated structures with scanning electron microscopy (SEM), and then measuring online sigma and peak-to-valley values.\(^4\)\(^,\)\(^5\) In spite of its rapidity and ease, this method has the disadvantage that the SEM beam exposure may modify the properties of the examined nanopattern and change LER as time of observation progresses. Furthermore, different SEM instruments use different electron beam settings (alignment, astigmatism, focus) and different software for LER measurement rendering, thus the comparison between resist lines measured with different SEMs are unreliable unless the selected settings are explicitly stated. Because of these disadvantages, an alternative way of measuring LER, based on the off-line analysis of top-down SEM images of the nanostructures, has been proposed and developed.\(^6\)\(^–\)\(^8\)

We start by presenting a methodology for measuring LER, based on the off-line analysis of top-down SEM images. In fact, this methodology consists of two steps. The first includes an SEM image analysis algorithm for the detection of the measured line edge, while the second develops a characterization scheme based on the scaling analysis of LER and thus describing sufficiently both vertical and spatial aspects of LER. This presentation occupies Sec. 2 and is brief, since a more detailed exhibition can be found in our previous work.\(^6\)\(^,\)\(^7\)\(^,\)\(^9\)\(^,\)\(^10\) where one can also find a systematic study of the influence of different image analysis parameters on the roughness descriptors. Here we complete that study in Sec. 3 by examining the effect of the type of the noise-smoothing filter applied on the image. Section 4 deals with the comparison between the roughness descriptors of the left and right edge of a line. It has been noticed that the right edge tends to show a bit larger sigma than the left.\(^7\) We check the statistical truth of this statement by examining the LER of four different resists. Next, Sec. 5 addresses the problem of the relation of LER with line width roughness (LWR), which is in fact the quantity that measures the deviations of the fabricated line from the ideal...
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one (see ITRS roadmap 2002). Finally, Sec. 6 contains concluding remarks and the main findings of the research.

2 Line Edge Detection and Characterization

After taking a top-down SEM image of the resist structures, an image analysis algorithm has to be applied to give the coordinates of the edge points as output. Each pixel in a given SEM image is characterized by its \((x, y)\) coordinates (in pixels) and an integer in the range \((0\) to \(255))\), representing a shade of gray. The basic assumption in the algorithm is that this discrete spectrum of the image grayscale values corresponds to the continuous signal intensity values of the scattered electron beam of SEM. However, real world signals contain noise, and the first task of the algorithm is to reduce it by using a noise-smoothing filter. The effect of the type of smoothing filter on the detected edge is examined in the next section. The parameters involved in this filter (length and width) have to be specified. The smoothed image can be analyzed by using the direct signal or its derivative. We use the direct signal, since it has been shown that it gives results closer to those of on-line analysis. After selecting the type of algorithm, one proceeds to the detection of the edge. The resist line where the detection of the edge is going to be performed is selected by adjusting a specified threshold. On the contrary, the determination of the edge points is simply the pixel with the locally maximum intensity. Although in Ref. 6 we used the outer borders as the edges of a line, here we prefer the maximum intensity profiles, because these are threshold independent and are obtained faster. In general, all these profiles have similar roughness characteristics with minor differences. Before the statistical analysis and characterization of the edge, a tilt correction is performed. In Fig. 1 we summarize the main points of the edge detection algorithm indicating the edge points of the outer, inner, and middle profile.

After determining the edge of the resist feature from the SEM image, the analysis and characterization of its roughness follows. The most widely used parameter for this task is the sigma value of the edge. However, this parameter does not provide a complete description of LER, since it neglects the spatial distribution of roughness along the edge. Furthermore, it depends on the length of the measured edge, especially for small lengths. In the case of self-affine edges, both the spatial complexity of roughness and the dependence of sigma on edge length can be determined by two parameters: the roughness exponent \(\alpha\) and the correlation length \(\xi\). A method for calculating these spatial roughness parameters is based on the study of the correlations among the heights \(z_i\) (distances from the mean of the edge) of the edge points. Assuming that the number of the edge points is \(N\) and their distance is \(d\), the height-height correlation function \(G(r=md)\) defined as

\[
G(md) = \left[ \frac{1}{N-m} \sum_{i=1}^{N-m} (z_i+md-z_i)^2 \right]^{1/2},
\]

quantifies these correlations and therefore gives information about the spatial aspects of LER. In fact, the form of \(G(r)\) is very important for the classification of the type of edge roughness. Statistical persistent regular oscillations in \(G(r)\) reveal the existence of a quasiperiodicity in line edges whose wavelength can be extracted by the position of the first minimum of the oscillations. The exponent of the power law is called roughness (or Hurst) exponent \(\alpha\), and it can be shown that it is connected to the fractal dimension \(D_F\) through a relation, which for lines is \(\alpha = 2 - D_F\). In real self-affine edges, the power law behavior in \(G(r)\) is usually restricted between two limits. The upper limit represents a specific distance after which the height corre-
The significance of the spatial roughness parameters $\alpha$ and $\xi$ is more clearly illustrated through their connection to the image recording and main filter parameters. Although some possible physical reasons such as shot noise from illumination conditions or individual polymer dissolution statistics have also been referred to in Ref. 13, in this work we do not consider $r_o$ as an important LER descriptor.

A typical example of $G(r)$ of a detected self-affine line edge is displayed in Fig. 2. As is shown in this figure, the form of $G(r)$ is in fact characterized by the values of the roughness exponent $\alpha$ (or the fractal dimension $D_F$), the correlation length $\xi$, and the sigma value. The sigma value has to do, by definition, with the vertical dimension of roughness and gives no information about its spatial complexity. The correlation length $\xi$ defines a representative lateral dimension of a rough line edge, which determines the range of height-height correlations. For $r \gg \xi$, the heights of the edge points can be considered uncorrelated. The behavior of the height correlations for $r < \xi$ is described by the roughness exponent $\alpha$, which in fact gives the rate at which these correlations decrease and tend to zero as the distance $r$ increases. Since height correlations for small $r$ amount to high frequency fluctuations, $\alpha$ gives a measure of the contribution of high frequency fluctuations to roughness in comparison with the low frequency ones. In particular, the lower the value of $\alpha$ is, the more important the relative contribution of high frequency roughness becomes.

The same triplet of parameters may also be estimated through Fourier analysis, since they are related to the power spectrum of a self-affine edge, as shown in Fig. 3, where a typical example of the power spectrum of a self-affine edge is shown. Typically, it exhibits a high plateau at low frequency, a power law roll off, and a low plateau at very high frequencies, in correspondence with the behavior of $G(r)$ in the spatial domain. The sigma value can be extracted from the power spectrum through Parceval’s theorem, while the correlation length $\xi$ is related to the inverse of the frequency, at which the power spectrum starts to decrease as a power law. Furthermore, the roughness exponent $\alpha$ is connected to the power $\beta$ of the power law behavior of the power spectrum ($\beta = 2\alpha + 1$). However, in real edges, where only a limited number of edge points can be measured, the appliance of the theoretical predictions need more investigation, which will be the subject of a future work. At present, owing to the presence of more pronounced fluctuations in power spectra, we prefer the analysis through the correlation functions.

The significance of the spatial roughness parameters $\alpha$ and $\xi$ is more clearly illustrated through their connection to the way sigma depends on the measured edge length $L$. Figure 4 shows the variation of sigma with the length of the edge sampled. Sigma is not constant, but is an increasing function of length $L$ of the edge. The functional form of the curve resembles the form of $G$. Indeed, as it is shown in Fig. 4, the sigma($L$) curve of the self-affine edges has the
same behavior as the $G(r)$ curves: a power law for small $L$ followed by a saturation at large $L$. In accordance with related literature, the examination of a large number of edges revealed to us that the exponent of the power law is very close to the roughness exponent $\alpha$, while the value of the length $L$ after which $\sigma(L)$ saturates, is about 6 to 10 times the correlation length determined by the form of $G(r)$.

3 Effect of the Noise-Smoothing Filter
The course for obtaining the edge profile from the top-down SEM images requires first a noise removal filter application on the original SEM image and then the application of a line-edge determination algorithm.

Noise removal filters include: linear, median, and adaptive filtering. Details can be found in the MATLAB Manual, the software platform on which the code was written. The filter used in the current work was the Gaussian-noise-smoothing one, to be in agreement with the on-line noise-smoothing filter of the SEM. However, all the filters mentioned before were tested with the same parameters. It was found that Gaussian, adaptive, and median filtering give almost the same values of sigma, while linear filtering gives lower values of sigma, since it greatly reduces the high frequency components, and therefore results in a closer to the original edge of resist lines.

Fig. 4 The sigma value as a function of the length $L$ of the line edge sampled. For small $L$, it rises according to a power law ($\sigma \sim L^\alpha$) and, then, for $L>(6-10)\xi$, saturates. In the same plot we show the rescaled height-height correlation function $G(r=L/8)/\sigma$ of the same edge to reveal its resemblance to the $\sigma(L)$ curve.

4 Left and Right Edge Roughness
Is there any systematic difference in the roughness parameters of the left and right edge of any resist line? This is the question we deal with in this section. Although many studies on LER assume that there is no such difference, some researchers support that they have observed differences between left and right edge sigma values. However, it is not clear how general this difference is. To illuminate this issue further, we proceed to a systematic comparative study of all roughness parameters ($\sigma$, $\alpha$, $\xi$) of the left and right edge of four resists by using the methodology presented in Sec. 2. The resists are acrylate based and are denoted as $f$, $g$, $h$, and $k$. The line structures of $f$ and $g$ resists have been examined by a KLA8100 SEM instrument, whereas resists $h$ and $k$ have been measured by a Hitachi SEM instrument. More details about the operation of these SEMs can be found in Ref. 6. The images taken by Hitachi have pixel size equal to 2 nm, whereas the KLA images of resists $f$ and $g$ have been taken using two magnifications, resulting in two image pixel sizes: 1 and 2 nm, respectively. Hence,
totally we analyzed six groups of resist line structures (four resists and two magnifications for two resists) with more than ten lines in each of them. The values of the roughness parameters of each group shown in the following figures are, in fact, the averages over the values of the lines of the corresponding group. In all cases, the width of the resist lines is equal to 100 nm.

The results of our study are schematically shown in Fig. 6. Figure 6(a) depicts the average sigma values of the right edges as a function of the corresponding values of the left edges. To make the comparison more straightforward, we have drawn the line $\sigma_{\text{left}} = \sigma_{\text{right}}$. We observe that almost all points lie above the straight line, which means that $\sigma_{\text{right}} > \sigma_{\text{left}}$. The difference is about 10 to 20% of $\sigma_{\text{left}}$. This asymmetry is a real effect (not eliminated by more statistics) and probably originates from the limited accuracy of the electron beam alignment with respect to the substrate. If the alignment is perfect, this asymmetry may be removed. An interesting application of this finding is to use this difference as a monitor for the SEM beam settings.

In contrast to sigma values, the roughness exponent $\alpha$ seems to be independent of which edge (left or right) we choose to analyze, as shown in Fig. 6(b). The situation is a bit more complicated in the behavior of the correlation lengths. In some cases, the right edge is characterized by larger $\xi$, while in other cases the opposite is true. Therefore, it seems that the correlation length $\xi$ is affected in a non-

Fig. 6  The average values of the roughness parameters (a) sigma, (b) roughness exponent $\alpha$, and (c) correlation length $\xi$ and their standard deviations for the right and left edges. Note that sigma of the right edge tends to be larger than that of the left edge [see Fig. 6(a)]. The roughness exponents seem similar [Fig. 6(b)], while the correlations lengths are different but not in a systematic way.

Fig. 7  The relation of $\sigma_{\text{left}}^2 + \sigma_{\text{right}}^2$ to $\sigma_{\text{left}}^2$ is shown. Note the equality between these values, revealing that the edges are sufficiently uncorrelated (see text).
systematic way by the kind (left or right) of the line edge we analyze.

5 Line Edge and Line Width Roughness

The main concern of roughness studies is the line width roughness (LWR), since actually this affects the CD control and hence the performance of the fabrication device. Obviously, the line width is given by the difference of the left edge from the right, and therefore a relation between LER and LWR is expected to exist. However, interesting aspects of this relation are not known yet. For example, given two self-affine edges, is their difference self-affine? Or, in the case of a positive answer to the previous question, how are the descriptors of LER connected to corresponding LWR descriptors? Before proceeding to the statistical exploration of these questions, let us present some theoretical comments on these.

It can be easily shown that

\[ \sigma_{\text{width}}^2 = \sigma_{\text{left}}^2 + \sigma_{\text{right}}^2 - \frac{2}{N} \sum_{i=1}^{N} z_{l,i} z_{r,i}, \]

where \( z_{l,i} \) and \( z_{r,i} \) are the distances from the mean values of the left and right edge, respectively. The latter term of Eq. (3) expresses the correlation between the two edges, and when it equals to zero (uncorrelated edges), an important consequence on the first question can be drawn. Self-affinity of the left and right edges amounts to power law behavior of their \( \sigma(L) \) functions, and hence the \( \sigma_{\text{width}}^2(L) \) is a sum of two power laws. In general, the sum of two power laws is not a power law itself, except for the obvious case where the exponents of two power laws are equal. In fact, this is our case. In Sec. 4, we showed that the roughness exponents of the left and right edges of the investigated resists are almost identical, and consequently the \( \sigma_{\text{width}}^2(L) \) behaves as a power law and the line width exhibits a self-affine character. The only prerequisite is the absence of correlations between the left and right edges, which can be proven by showing the equality between \( \sigma_{\text{width}}(L) \) and \( \left[ \sigma_{\text{left}}^2(L) + \sigma_{\text{right}}^2(L) \right]^{1/2} \) [see Eq. (3)].

In Fig. 7, we depict the relation between these quantities for all the groups of the top-down SEM images of the resists \( f, g, h, k \). All the points lie almost on the equality line [with a deviation smaller than 5\% of the \( \sigma_{\text{width}}(L) \)], indicating the absence of correlations between left and right edges, and hence, according to the previous argument, the self-affinity of the line width. In addition, the roughness exponent of the line width has to be equal to those of edges. Both self-affinity and equality of the roughness exponent has been verified by analyzing LWR according to the scaling analysis method developed in Sec. 2.

As regards to the correlation length \( \xi \) of the line width, the previous theoretical analysis leads to the expectation that \( \min(\xi_{\text{left}}, \xi_{\text{right}}) < \xi_{\text{width}} < \max(\xi_{\text{left}}, \xi_{\text{right}}) \). Our calculations show that this is indeed the case. The correlation length of the width lies between the minimum and maximum of the correlation lengths of two edges.

6 Conclusions

We show that line edges are self-affine structures, and thus LER and LWR can be described by a set of three param-

![Fig. 8 A sample result window displayed by our software tool.](image)
eters: sigma, correlation length, and roughness exponent. The sigma value of LER increases with the length of the line edge sampled, following a power law with the exponent being the roughness exponent. After approximately 6 to 10 times the correlation length, the sigma value stabilizes. The sigma($L$) curve is completely characterized with the triad of parameters discussed. A comparison between the sigma values of the left and right line edges reveal inadequate beam alignment and hence can be used for monitoring the relevant SEM settings. Furthermore, left and right line edges are not correlated but have the same spatial roughness parameters, permitting thus the line width roughness to be also self-affine and described by the same parameters. The edge detection and analysis procedure is developed as a software tool, an application of which is shown in Fig. 8.

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