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Measuring Line Edge Roughness: Fluctuations in Uncertainty

Line edge roughness (LER) is the deviation of a feature edge (as viewed top-down) from a smooth, ideal shape – that is, the edge deviations of a feature that occur on a dimensional scale smaller than the resolution limit of the imaging tool that was used to print the feature [1]. Line width roughness (LWR) is defined similarly. As one might expect, the same measurement tools and techniques used to measure the width of a feature are often used to measure its roughness, with the scanning electron microscope (SEM) being the most common tool. Unfortunately, doing a good job of measuring roughness is extremely difficult and fraught with pitfalls. Very different approaches are required for measuring the roughness of a feature compared to measuring the width of that feature.

First, measuring the uncertainty in an edge is a much more "noisy" exercise than measuring edge itself. Assuming only (normally distributed) random errors in edge position measurement, for n measurements of an edge (or width) used to determine its roughness, the relative uncertainty in the measured roughness (with roughness expressed as the standard deviation of the edge position, σ_{LER}) can be estimated as

$$\frac{\Delta\sigma_{LER}}{\sigma_{LER}} \approx \frac{1}{\sqrt{2n}} \tag{1}$$

To measure the LER to 10% precision, 50 measurements of edge positions must be made. While this may seem like a lot of measurements, there is any easy way to get many more than this. By taking an image of the rough feature (Figure 1) and processing it off-line to determine edge position, it is very easy to extract hundreds of edge deviations from this one image and thus calculate σ_{LER} with sufficient precision.

But while the precision of an LER measurement can be easily quantified and controlled, how about the accuracy of the measurement? In particular, is such a measurement unbiased, meaning that as the precision error of the measurement goes to zero, does the measured edge deviation ($\sigma_{measured}$) approached the actual edge standard deviation (σ_{LER})? In general the answer is no. There are two main sources of bias (also called systematic error) commonly encountered in LER measurement: SEM noise, and the measurement's finite frequency content.

The difficulty in measuring uncertainty (such as the uncertainty in a feature edge) is that any uncertainty in the measurement itself (such as noise in the SEM signal) adds in quadrature to the thing being measured. Unlike measuring the mean value (such as measuring the feature width), errors don't cancel on average when making many repeated measurements. As a result, the measured roughness is biased – it appears greater than the actual roughness [2]:

$$\sigma^2_{measured} = \sigma^2_{LER} + \sigma^2_{SEM\ noise} \qquad (1)$$

SEM noise comes from the limited number of electrons detected and shows up as the noisy "snow" that effectively defines the look and feel of an SEM image. Low electron dose, defocus of the beam spot, and stigmatic error all contribute to increased SEM noise. Optimal SEM operation results in $\sigma_{SEM\ noise}$ not much lower than 1 nm [3], which is on the order of the roughness of many of the features being measured.

When measuring feature critical dimension (CD), SEM noise is often dealt with by pixel averaging (binning). Such image smoothing techniques, however, smooth out the true roughness in the image just as much as the SEM noise. The best way to correct for measurement noise bias is to turn off all pixel smoothing algorithms and instead carefully measure the SEM noise directly (preferably on the exact sample of interest) and subtract it from the measured roughness value using equation (1) [2]. Although it may involve taking multiple images of the same sample (thus making measurements slow), the results can be made as accurate as patience allows. Unfortunately, since 193 nm resists react physically to electron exposure producing resist shrinkage, they have strict limits on the total electron dose that can be tolerated.

The second source of bias in LER measurements tends to always make the measured LER less than the actual LER. The fundamental roughness of a feature edge has not only a magnitude but a frequency content as well. For a measured edge deviation $\Delta(y)$, where y represents the different points along the line where the edge is measured, its spatial frequency behavior is best captured by examining its Fourier transform. A very convenient way of viewing this frequency content is through the Power Spectral Density (PSD), defined as the square of the magnitude of the edge deviation Fourier transform.

$$PSD(f) = \left| \int_{-\infty}^{\infty} \Delta(y) e^{-i2\pi f y} dy \right|^2 \qquad (2)$$

(Similarly, the LWR PSD can be defined in the same way.) The PSD shows the square of the roughness (that is, the edge variance) per unit spatial frequency.

For a type of roughness called "white" noise, the PSD is a constant for all spatial frequencies. But resist roughness is not white noise, and the behavior of the PSD as a function of spatial frequency can be very revealing. The interesting behavior comes from the fact that a given point on the edge is correlated with nearby points, but not with points far away. The correlation of different edge points is described by their correlation function $R(\tau)$:

$$R(\tau) = \lim_{L \to \infty} \frac{1}{L} \int_{-L/2}^{L/2} \Delta(y)\Delta(y+\tau) dy \qquad (3)$$

where τ is the distance between two points along the line. The PSD is the Fourier transform of the correlation function (under some constraints that are thought to apply here).

A very simple and common model for roughness correlation is to assume that very close points are perfectly correlated, and then the degree of correlation falls off exponentially with distance.

$$R(\tau) = \sigma_{LER}^2 \, e^{-\left(|\tau| / L_c\right)^{2\alpha}} \tag{4}$$

where σ_{LER} is the magnitude of the LER, L_c is called the correlation length, and α is called the roughness exponent (also called the Hurst exponent). Correlation lengths for 193 nm resists have been reported to be in the range of 10 – 100 nm. For the special case of $\alpha = 0.5$, the PSD can be calculated analytically [4]:

$$PSD(f) = \frac{2\sigma_{LER}^2 L_c}{1 + (2\pi f L_c)^2} \tag{5}$$

A plot of equation (5) is shown in Figure 2. At frequencies below $1/2\pi L_c$ (length scales larger than the correlation length), the PSD becomes flat (white, uncorrelated noise). Above this frequency, the PSD falls off as $1/f^2$ (fractal behavior).

By Parseval's theorem, the area under the PSD curve must equal LER variance (σ_{LER}^2), and integrating equation (5) over all frequencies does give this result. But when measuring LER, only a certain range of frequencies can be covered. In particular, the minimum possible frequency sampled by the measurement is determined by the maximum distance between measurement points along the line (that is, by the size of the measurement box, L_{box}).

$$2\pi f_{\min} = \frac{1}{L_{box}} \tag{6}$$

Any low-frequency roughness at frequencies less than this minimum will not be seen by the measurement. As a result, the roughness measurement will be biased, producing a value less than the actual roughness.

Using the model PSD of equation (5), the impact of missing these low frequency components can be calculated.

$$\sigma_{measured}^2 = 2\int_{f_{\min}}^{\infty} PSD(f)\,df = \sigma_{LER}^2 \left[1 - \frac{2}{\pi}\tan^{-1}\left(\frac{L_c}{L_{box}}\right)\right] \tag{7}$$

If L_{box} is chosen to be much greater than the correlation distance L_c, the measured roughness approaches the actual value. Figure 3 shows a plot of the square root of equation (7), something often called a $\sigma(L)$ curve [5]. The measured value of LER or LWR approaches the actual value as the length of the line being measured approaches infinity. But for finite (and thus real) measurement lengths, the measured roughness is always less than the actual roughness. According to this simple model, when the measurement box is ten times the correlation length, the measured roughness is about 3.2% too low. If the measurement length is reduced to five times the correlation length, the measured roughness will be systematically low by about 6.5%. It is important to note that the amount of bias encountered for a given L_{box} depends on L_c, and is thus resist and resist process dependent.

Measuring LER has two common systematic errors. SEM noise biases the measurement upward, and can only be corrected by characterizing the noise and subtracting it out. Smoothing algorithms typically employed for improved edge detection during CD measurement should never be used when measuring LWR or LER. Second, the finite frequency range of measurements means that very low frequency roughness will not be captured, biasing the measurement downward. This bias can be reduced by using very long measurement lengths, or by characterizing the correlation length and correcting the measurements using equation (7). Unless both of these biases are controlled and corrected for, any given LER measurement may be higher or lower than the actual roughness, possibly by a large amount. And since the biases are dependent both on the SEM (tool and measurement process) and on the resist (material and resist process), comparing biased measurements is extremely problematic. Most of the LER literature provides no description of how LER is measured, and thus whether these biases have been accounted for. It's no wonder that the industry has been so slow in understanding LER trends and mechanisms.

References

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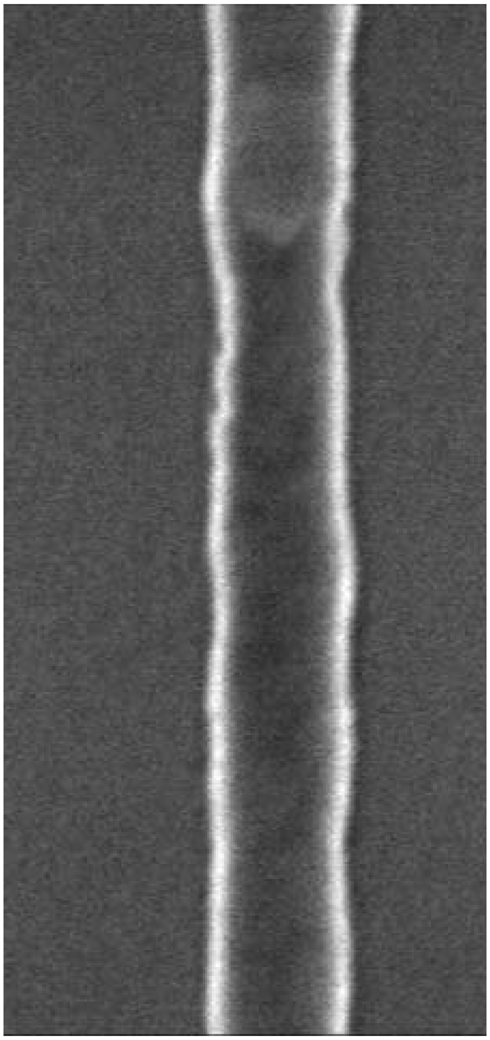

Figure 1. LER, as described by the three sigma deviation of an edge from a straight line, is measured with high precisions by capturing the image of a long segment of a line.

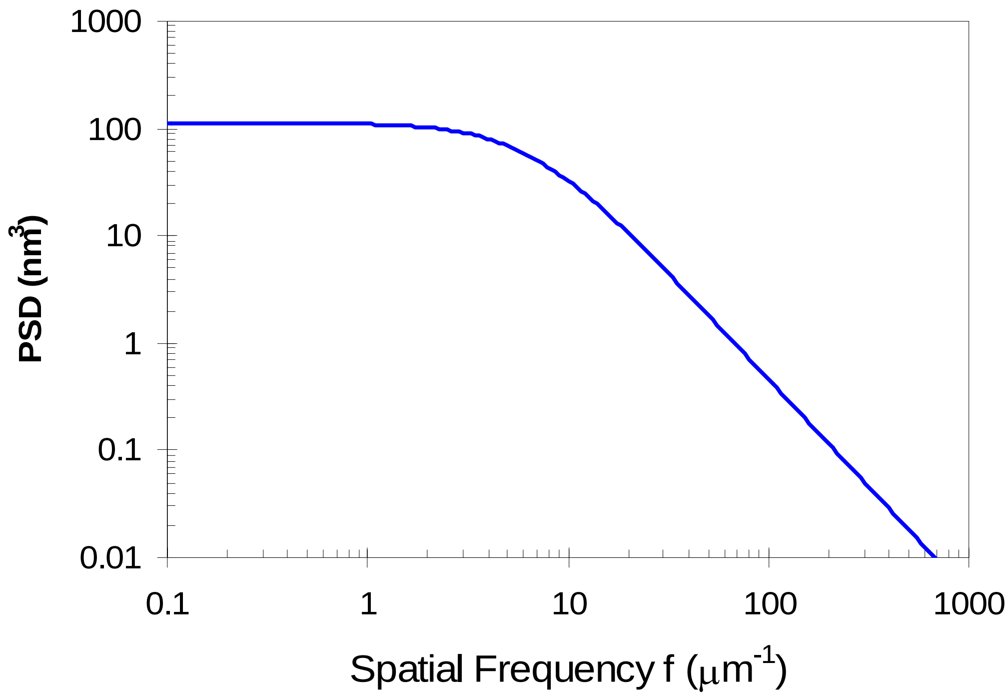

Figure 2. An idealized PSD with σ_{LER} = 1.5 nm and L_c = 25 nm.

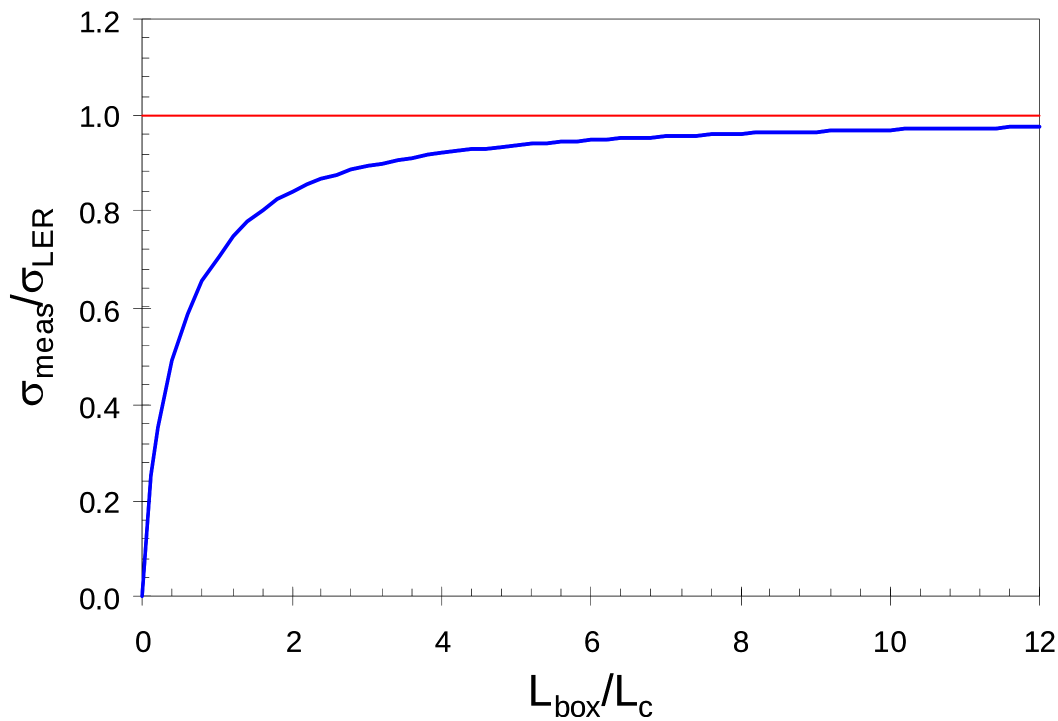

Figure 3. A plot of the measured LER relative to the actual value as a function of the size of the measurement box used. The measured value approaches the actual value as the length of the line being measured approaches infinity.