Robust Estimation of Line Width Roughness (LWR) Parameters

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Estimation of line width roughness (LWR) parameters is necessary for semiconductor process optimization, comparison of next-generation lithography (NGL) processes as well as device performance simulation. A complete description of LWR can be provided by three parameters: root-mean square (RMS) roughness or standard deviation of line width from its mean (σ), correlation length (ξ) and roughness exponent (α).

Scanning electron micrograph (SEM) image is the most practical source of data for estimating LWR parameters. However, the primary challenge in estimation of the aforementioned LWR parameters is the limited availability of data. A typical SEM image consists of 8-20 lines of 300-1500nm length. It has been recognized that for a given line, in the presence of correlation between line widths at a given separation, the estimate of σ for a finite length of line can be significantly biased. Furthermore, for NGL technologies like double-patterning, the number of lines available to estimate each lithography step is cut in half since alternate lines are produced from different processes. Thus, there is need for an estimation procedure that performs robustly for arbitrarily *short* and *fewer* number of lines.

Our procedure for estimating LWR parameters is a confluence of fractal concepts developed to understand surface growth phenomena and spatial statistics. Using a *block of blocks* bootstrap technique for dependent data and a *weighted least squares* (WLS) fitting procedure, we fit a specific form of a variogram model. Block of blocks bootstrap is used to estimate the variance of a variogram, which in turn provides the WLS weights. Additionally, the bootstrap approach also allows us to estimate the error in the estimated LWR parameters, a vital requirement that has not been addressed by any of the previously reported procedures on this subject. We use the term *robust* in this article to describe the stability of the proposed inference procedure in the presence of limited data without the central assumption of a Gaussian process. Moreover, our procedure works even when CD of lines in the SEM image vary with some unknown local distribution or if there is a systematic difference in CD (by design or otherwise) between the lines. This aspect of our procedure (a) prevents non-LER sources of variation from being attributed to LER and (b) it allows for more flexibility in capturing SEM images in that we do not need a special test structure with all lines with same designed CD; any IC layout region with straight lines and arbitrary CDs would suffice.

We validate our procedure with simulated roughness profiles with deterministic LWR parameters. We also use actual profiles from variety of different mainstream NGL processes such as *litho-freeze-litho-etch* (LFLE) double patterning, self-aligned double patterning (SADP), and EUV as well as alternatives such as directed self-assembly (DSA) and nano-imprint lithography (NIL).

Figure 1: Estimates of $\hat{\sigma}$ for three scenarios (a) no local CD variation exists ("ideal"), (b) local CD is Gaussian with $N(0,0.25)$ ("Gaussian"), and (c) local CD variation is Triangular with lower limit -0.5nm, mode 0, and upper limit of +0.5nm ("Triangular"). $\hat{\sigma}^2_{LWR}$ is the naive and biased estimate, $\hat{\sigma}^2_{LLE}$ is the estimate computed using the LLE method , and $\hat{\sigma}^2_{BBB}$ is the estimate computed using our *block of blocks bootstrap* method. Note that LLE method attributes local CD variation to LWR while our estimate robustly estimates $\hat{\sigma}$ only due to LWR. The roughness profiles were simulated with $\sigma^2 = 1$, $\xi = 20$ and $\alpha = 0.5$.

Figure 2: Estimates of (a) $\hat{\alpha}$ and (b) $\hat{\xi}$ for three scenarios described earlier. Note that our method robustly estimates the value of $\hat{\alpha}$ and $\hat{\xi}$ in all three scenarios. The roughness profiles were simulated with $\sigma^2 = 1$ and $\xi = 20$ in (a) and $\sigma^2 = 1$ and $\alpha = 0.5$ in (b).

Figure 3: Comparison of estimated σ^2 using our method with the LLE method. Results shown here are for 28nm half-pitch NIL process. The LLE method for correcting bias in the estimate of $\hat{\sigma}^2$ tends to attribute effects of local CD non-uniformities to LWR.

Note: LLE is used to reference the method proposed by Leunissen, Lawerence and Ercken (Micoelectronic Eng. vol. 73-74, no. 1 pp. 265-270, 2004)