Line-edge roughness across the process window

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Line-edge roughness (LER) varies across the process window and can be correlated to multiple resist-profile variables to provide an improved metric for process setup and algorithmic profile characterization.

It is well-known that gate-length uniformity, or line-edge roughness, strongly influences device performance through timing uncertainties, increased off-state leakage and increased drive currents [1]. LER is known to depend on a number of factors, including aerial image fluctuations, resist material properties, acid diffusion, development details, and reticle roughness. This article explores an area that past studies have largely ignored: the contributions of exposure setup and the film stack to LER and the overall critical dimension (CD) budget.

Perhaps the most significant factor, aerial image contrast, has been shown to exhibit a linear correlation to LER; higher image contrast results in lower LER [2, 3]. In a recent study of the CD budget associated with ArF resists, the LER was shown to account for 36% of the intrawafer CD measurement variation when the various contributions of the CD-SEM (metrology), exposure tool, pattern and track were considered [4]. Thus, the advent of the 70nm node and its use of high-contrast photoresists have contributed to increased interest in fully characterizing the behavior of LER and its dependence upon normal process variations.

Materials, equipment, and analysis

This analysis used a methacrylate-type ArF resist and two sets of organic bottom antireflective coatings (BARC), representing both good and poor performance films, where performance of the BARC is defined by the size of the acceptable focus-exposure window. The data was gathered from wafers printed using binary masks with a target feature width of 70nm (vertical lines) on 140nm pitch (1:1) using a Soluris Yosemite CD-SEM at 300V acceleration.

Variables such as sidewall angle (SWA), profile foot length, and top-rounding were derived using the advanced models of Soluris' critical shape metrology (CSM) system, rather than the commonly used beam small-angle tilt or profile-density function extraction [6–9].

Statistical LER parameters are obtained from linear regression of edge locations from intensity profiles of 10-pixel tall segments. Each segment is independently measured using the standard line-measurement algorithm.

The linewidth roughness (LWR) measurement was performed on each segment of a line using the standard Yosemite CD-SEM line algorithm. The outputs of the line algorithm include the linewidth and absolute location of both the right and left edges. The absolute edge locations (edge 1 and edge 2) were regressed to a straight line to remove any large linear trending from the data. Final statistics were calculated based on the edge difference from the line regression. Finally, the absolute edge locations were used to calculate the LWR measurements.

Final data analysis for process, wafer, and field modeling used TEA Systems' Weir PW analytical software suite. Exposures consisted of a focus/dose matrix corresponding to a 10% exposure latitude and a 0.5µm focus range, which provided variations anticipated under normal production conditions.

LER sensitivity

In the following CSM data, the bottom CD (BCD) response is the width at the bottom of the feature less the feature foot size. Top CD (TCD) is the width measured at the top of the resist, excluding edge-rounding. LER, unless specified otherwise, is the average of the 3σ roughness observed on the left or right sides of the resist wall.

At every focus level the LER was found to vary linearly with exposure dose. The magnitude of the variation was small, being <1.5nm over the 10% dose latitude range that produced acceptable CDs.

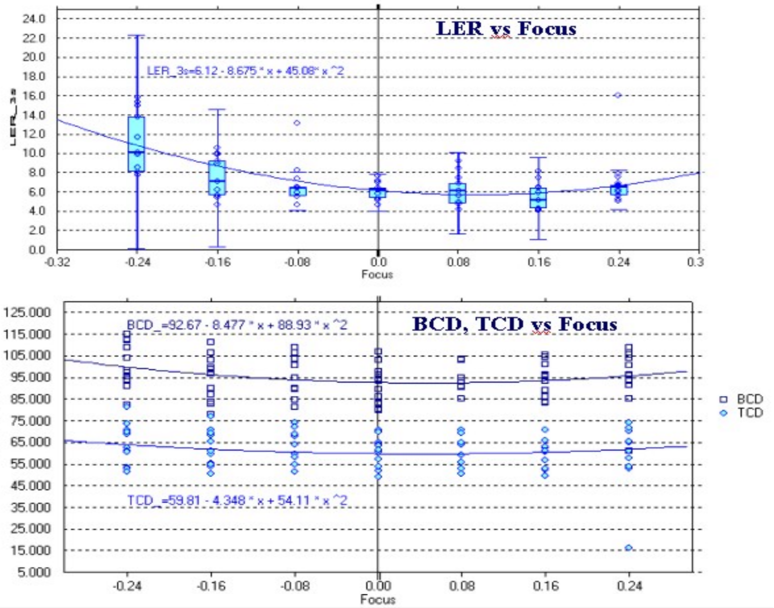

Figure 1. Focus sensitivity of LER and feature size, all doses. Top: LER vs. focus. Bottom: BCD and TCD feature response. The CD variation at a given focus level represents the dose sensitivity.

LER response to focus is shown in Fig. 1. LER exhibits a second-order sensitivity to defocus and minimizes at the optimum focus setting for the exposure tool. This response is similar to the behavior typically associated with feature-width metrology. As an illustration, feature BCD and TCD size variation, shown in the bottom of the figure, also exhibit the expected second-order response but with a lower normalized sensitivity than LER. The scatter observed in the data reflects the variation derived from different doses of the exposure matrix contributing to the plot.

The curvature of a CD's response to focus can change dramatically with dose and lens aberrations. There even exists an "isofocal" dose at which the feature width is largely independent of focus variation, making process-window best-focus estimates highly uncertain. Conversely, the stable focus curve of the LER variable suggests that LER is a more stable estimator of optimum focus than feature-width measurement. In addition, we'll see that the LER variable is an even better descriptor of the resist profile response.

In this experiment, the LER minimized at 5.7nm when an image defocus setting of +0.096µm was used. Although not shown here, the resist foot length depends on focus in a similar way and is minimized at the same defocus setting as the SWA. The SWA curve, however, indicates a maximum SWA value at best focus. BCD and TCD response, shown in the lower part of Fig. 1, did not vary as dramatically with focus and, in fact, exhibited optimum feature size at slightly different defocus values of 0.048 and 0.040µm, respectively. The greater sensitivity of LER to defocus error and the variable's correlation to optimum settings for both SWA and foot-length profile variables suggest that LER is a better metric for determining optimum profile characteristics.

Similar to a CD process-window analysis, the representation of a 5.7nm ±5% range as a tolerable process variance for LER allows the behavior of the variable to be characterized in relation to the influence of dose and defocus during processing. Unlike the common feature-width process window, however, LER performance now incorporates a full characterization of the most critical elements of the resist profile — namely LER, SWA, and foot length. Also, unlike a CD process window, the LCL now correlates to a hard process minimum LER value that cannot be improved by dose biasing.

The LER process window associated with a properly functioning BARC, shown in the upper portion of Fig. 2, exhibits the type of behavior expected for any process variable characterized by a first-order dose and second-order focus response. Similar to a CD analysis, the optimum focus and dose values for the process are easily calculated from this process window graph if no significant final image bias is attempted from the reticle feature size. A final feature size bias relative to the final reticle size will increase the LER from its minimum (in this case, 5.7nm) value.

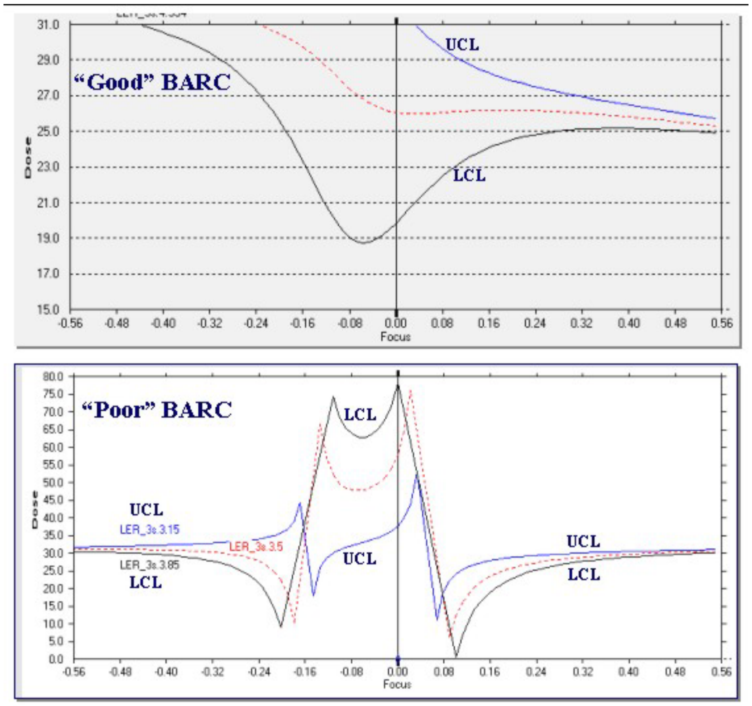

Figure 2. LER process-window behavior exhibited by two BARCs with 5% exposure latitude. Top: Process space for a BARC exhibiting proper contrast. Bottom: A poor-performance BARC process window displays an inverted process window when passing through the best-focus region.

To illustrate the concept of using LER as an improved overall metric for profile response, we compared the performance of several different resist and BARC selections. Two of the BARCs used allowed us examine the generic response of a poor-performance BARC structure and its potential influence on LER.

Quite surprisingly, the characterization of the poor-performance BARC by this method in both cases resulted in a dose-region inversion occurring over the range of acceptable process focus. Note how the UCL and LCL surface contours cross over within the range of what should be acceptable process defocus. This behavior is caused by a drastic change or inversion of the slope of the LER vs. dose curve within this region, relative to its slope outside of the range of acceptable focus.

The LER metric invokes response characteristics of both resist profile SWA and foot length. The BARC's poor reflection-cancellation efficiency does, in fact, influence the behavior of one or both of these two parameters and, in turn, changes the response level of the LER to dose.

BARC performance and LER

Selection of the proper BARC is a critical step in setting up the process. Poor BARC selection often results in difficult process control because of increased standing wave effects and loss of feature contrast.

As would be expected, the optimum focus of the resist-BARC systems used in this experiment did not change from BARC to BARC. However, the SWA was lowered from an optimum 85.0° to 83.3° with a corresponding rise in LER from 5.7nm to 11.2nm (3σ) when a poor-performance BARC was employed. The shallow SWA changes that accompany poor feature contrast result in structures that are difficult for both standard CD-SEM algorithms and scatter-based metrology to measure. In addition, the post-etch process results do not correlate well to a simple shift in SWA, so some other physical mechanism must be resulting from the use of the poor BARC.

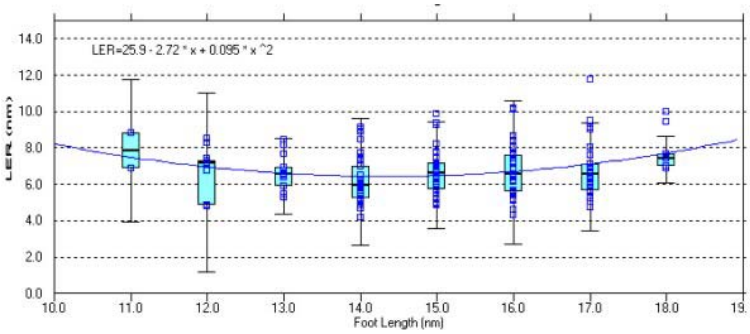

Figure 3. LER vs. foot length.

In the metrology algorithms used, the foot length is derived from a fitted arc that is tangent to the SWA-derived profile edge. An examination of the LER response to the profile foot length, as shown in Fig. 3, provides a clue to the mechanism of process window degradation. LER values minimize at a left-side foot length of ~14.5nm. Interestingly, this minimum value of LER corresponds to LER measured at the optimum focus calculated from the data of Fig. 1.

The curve of Fig. 3 implies that the feature's foot length is not minimized at the optimum focus point of the system, but rather varies with defocus and other factors, including dose. However, any variation of the foot length from this optimum 14.5nm size does result in increased values of LER. The obvious question, then, is how does foot length vary with focus?

If we plot the feature-profile foot length for both the right and left sides of the same structure as a function of image defocus, we obtain the cyclic curves shown in the top panel of Fig. 4. Once again, these curves are for dense packed features (1:1 duty cycle) for 70nm lines located near the lens center at optimum dose.

Note from this figure that there is a difference between right- and left-side foot-length response. This phenomenon is expected and results from localized exposure perturbations caused by dense-structure proximity effects of scatter. Local illumination characteristics such as the phase and effective numeric aperture can also result in asymmetric profile changes that increase in magnitude from the center to lens edge. However, the interesting observation here involves both the offset and phase behavior of the curves for the good vs. bad BARCs.

Recall from Fig. 1 that the optimum focus was achieved at +0.096μm defocus. This focus corresponds to a crossover point for the right- and left-side foot-length curves in the top graph of Fig. 4, thereby minimizing the LWR — the mean LER — at best focus.

Gate length, and therefore transistor performance, is sensitive to LWR rather than LER. LER, if uniform and in phase on both sides of a gate, presents a constant conductor cross-section profile area for the transistor's drive current. LER that is out of phase on both sides of the line results in cross-sectional area changes across the gate and, therefore, higher resistivity on some gates. This gives way to poor device operational characteristics.

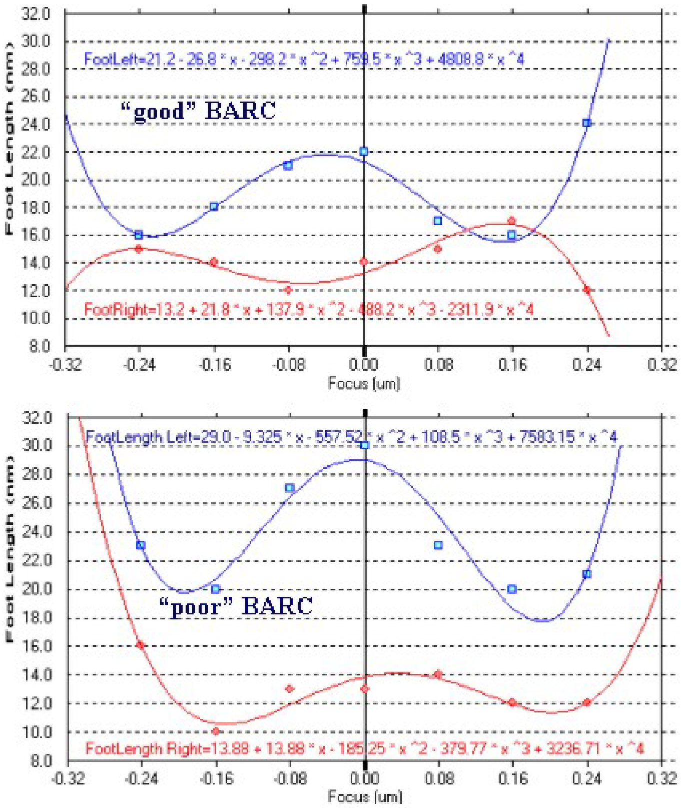

Figure 4. Feature foot-length response to defocus. Top: Response for a BARC exhibiting proper contrast. Bottom: A poor-performance BARC's response curves.

According to SEMATECH, "The phenomenon of variation of a linear feature's width...along its length is called linewidth roughness (LWR)" and "…the (2003) ITRS now specifies LWR over a window of spatial frequencies" [1].

Contrast the top graph of Fig. 4 with that of the poor BARC response shown on the bottom of the figure. This response shows a significant difference in right- and left-side response with no foot-length crossover. Coupled with data showing near linear dependence of foot length on dose, the absence of crossover will produce an LER response that reverses its response to dose change over the best-focus region, but never minimizes the total contribution to LER.

Summary

Line-edge roughness strongly depends upon process variables such as focus, dose, and underlying BARC performance. Similar to feature size, the LER parameter exhibits first-order response to dose and second-order variation with focus. LER also correlates to the square of SWA deviation and feature foot length, exhibiting a sensitivity of the variable to any changes in either parameter. With a properly operating BARC, LER will be minimized at SWA and foot-length values that correspond to those achieved at optimum focus. LER, unlike feature-width variables, incorporates a sensitivity to changes in the full feature profile, and is a stable and more repeatable metric of tool defocus.

LER is highly sensitive to BARC performance, which can be seen in the generation of a standard process window for the variation of LER as a function of dose and focus. Proper BARC performance results in a process window that exhibits a focus-dose control surface similar in response to that of any linewidth feature.

LER values are not minimized at the minimum foot length of the profile, but rather exhibit a quadratic response with a minimum that suggests a preferred foot length for the system. Foot-length response to focus examined for a single feature's left and right edges is cyclic and can be modeled with a base-cubic function. Left-and right-side foot lengths should be symmetric about the optimum focus of the tool; however, scatter and optical aberrations will always result in asymmetric response.

Proper BARC operation results in an in-phase response of the left-and-right feature foot lengths. LER is minimized if the feature's foot-length curves cross over or their difference minimizes at optimum focus.

Poor BARC behavior exhibits strong variations in left-right foot lengths that are out of phase in their cycle over focus. This phase shift results in LER variables that can never be optimized, which exhibit an increased range of variation in the linewidth uniformity across the field and wafer as exposure, focus, and dose perturb locally.

LER is therefore an excellent parameter for process characterization that provides improved focus setup, and the response of which indicates profile degradation resulting from image-profile changes in the process and film stack. ■

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