Improvements in the measurement of local critical dimension uniformity for holes and pillars

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Abstract

Background: Accurate measurement of local critical dimension uniformity (LCDU) and local pattern placement errors (LPPE) caused by stochastics is a critical task in metrology for advanced technology nodes, especially for EUV lithography.

Aim: Optimizing the settings of a metrology tool to either reduce biases in LCDU and LPPE measurement, or to reliably measure and remove those biases, is critical to stochastics metrology accuracy.

Approach: Four different scan modes and two different scan orientations are compared for the measurement of staggered arrays of contact holes on a scanning electron microscope (SEM), and both biased and unbiased LCDU and LPPE are compared.

Results: The Hitachi SEM scan modes designed for the measurement of 2D patterns have the minimum sensitivity to scan orientation and differences in X and Y metrology results. Further, measuring and subtracting SEM biases increases the accuracy of the best scan mode results, but also reduces the differences between scan modes by 3X.

Conclusions: SEM scan modes designed for 2D patterns produce lower bias in the measurement of contact hole LCDU and LPPE. Measuring and removing biases produce the maximum accuracy for all scan modes.

Keywords: stochastics, local critical dimension uniformity, LCDU, local pattern placement errors, LPPE, scanning electron microscope, SEM

I. INTRODUCTION

For the printing of holes and pillars at advanced nodes, stochastic variations are often the dominant source of edge placement errors in the patterning process.[1,2] Edge placement errors, in turn are the combination of critical dimension (CD) errors and pattern placement errors (PPE) for those features. Such stochastic variations are generally referred to as “local” variations since they occur at all length scales, including for neighboring features that would not experience “global” variations such as across-slit, across-field, or across-wafer errors. The most common approach to measuring these stochastic variations for the case of relatively dense holes/pillars is to look at the standard deviation of CD or PPE within one SEM image field. If the SEM field of view contains between a hundred and thousands of holes or pillars, three times the standard deviation of CD is called the local CD uniformity (LCDU) and three times the standard deviation of the PPE is called the local pattern placement error (LPPE).

Accurate measurement of LCDU and LPPE is critical for the understanding of stochastic variability in hole/pillar patterning. Depending on the sampling plan, such measurements can be separated into contributions from the mask, wafer patterning process (such as stochastics), and metrology.[3] But of course, proper assessment of the results depends on accurate measurements as a foundation. And accuracy in SEM measurement of stochastic variation is always biased by the random and systematic errors found in the SEM itself. Thus, understanding and minimizing the SEM’s contribution to LCDU and LPPE bias is critical.

This paper will explore ways to minimize SEM bias in LCDU and LPPE and ways to measure and statistically remove the SEM bias that remains. These reductions in bias take two forms: SEM settings, and in particular scan mode settings, that may reduce the amount of bias, and algorithms that enable the measurement and statistical removal of bias.

II. EXPERIMENTAL CONDITIONS

All experimental images were taken on a Hitachi CG6300 CD-SEM at imec. The images were 2048x2048 pixels, with a 0.8 nm pixel size, 500V and 16 frames of averaging. The pattern was a staggered array of holes, hexagonally arrayed with a constant center-to-center distance of 40 nm (in other words, a unit cell of 40 nm x 70 nm). The holes themselves were nominally 24 nm in diameter. For each condition studied, 100 images were collected across the wafer at a single field position.

Four scan modes were compared in two directions. The "Normal" scan mode is the common left-to-right raster scan. The "Scan A" mode is an alternate scan mode optimized for vertical 1D patterns, whereas the "Scan B" and "Scan C" modes are optimized for two-dimensional patterns. Thus, we expect the scan modes B and C to be most applicable to contact holes measures. Due to the nature of the staggered arrangement of holes, rotating the scan directions by 90 degrees for a fixed wafer orientation (equivalent to rotating the wafer by 90 degrees for a fixed scan direction) could produce different results. Figure 1 shows an example while defining the meaning of 0° versus 90° orientations.

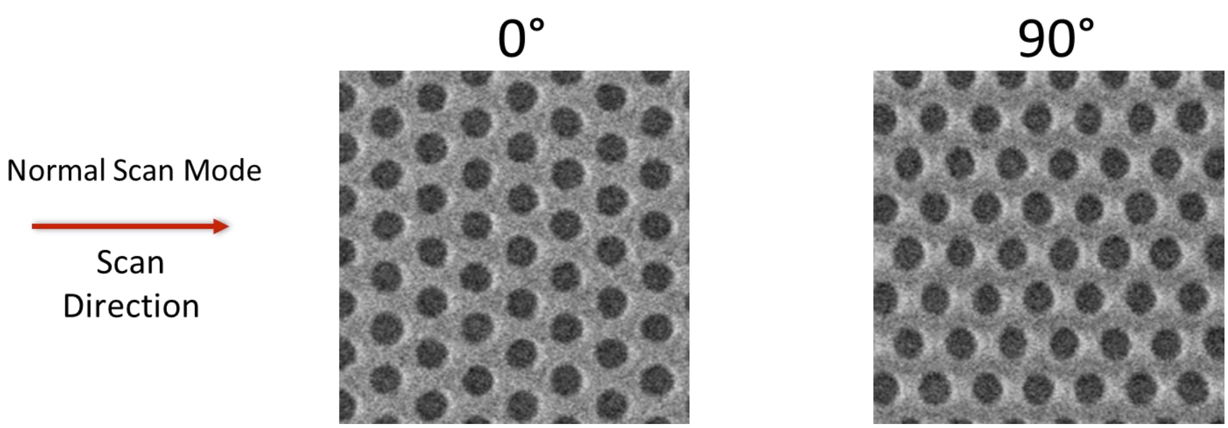
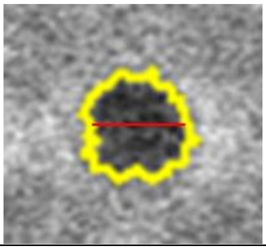
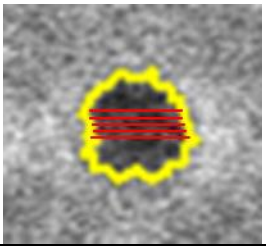
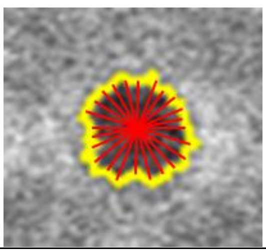
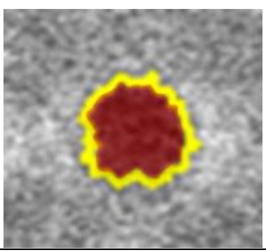
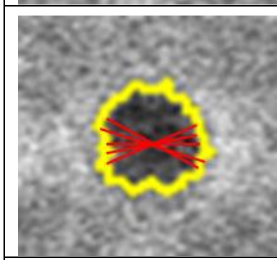
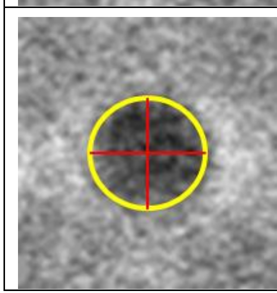


Figure 1. With the scan direction in the 70-nm pitch direction (0°), less charging artifacts (bright regions between the holes) are observed compared to scanning in the 40-nm pitch direction (90°).

An often-overlooked aspect of measuring the CD of holes or pillars is the definition of CD used. Since the actual shape of a contact hole is complex, collapsing that complex shape to a single size number can be accomplished in many ways. Table I shows several common CD definitions in use. This work will use the Average Diameter as the definition of CD, and limited angle range definitions of X CD and Y CD. For comparison purposes, the "X CD" will always be in the 40-nm pitch direction while "Y CD" will be in the 70-nm pitch direction, regardless of the scan orientation. All measurements will be made with MetroLER v4.1.0.

Table I. Different possible definitions of CD for holes or pillars. The uncertainty of any given edge position is σ_e.

	CD Definition	Standard Error
	**Single edge-edge distance** Can be used to measure X CD or Y CD	$\sqrt{2}\sigma_e$
	**Bar CD** Average edge-to-edge distance for N_B rows of pixels Can be used to measure X CD or Y CD, and is most appropriate for square-shaped contacts	$\sqrt{2}\sigma_e/\sqrt{N_B}$
	**Average Diameter** Average edge-to-edge distance for N_D equally spaced angles	$\sqrt{2}\sigma_e/\sqrt{N_D}$
	**Sqrt(Area)** The square root of the area inside the feature Alternate definition is to multiply the Sqrt(Area) by $2/\sqrt{\pi}$.	Complicated, but percent error is similar to Average Diameter
	**X CD** or **Y CD** Average Diameter over N_{XY} limited range of angles Most appropriate for approximately circular contacts	$\sqrt{2}\sigma_e/\sqrt{N_{XY}}$ Standard error for X CD and Y CD may be different, depending on the scan mode
	**X Fit CD** or **Y Fit CD** Best fit ellipse to the detected edges, then analytical determination of width or height Option to allow the major axis angle of the ellipse to float.	Complicated, but often about 10 – 40% higher than Average Diameter Standard error for X Fit CD and Y Fit CD may be different, depending on the scan mode

III. RESULTS AND DISCUSSION

The impact of scan direction is seen in Figure 2. The correct answer for the ratio of X and Y CD for the holes is not guaranteed to be 1.0 due to lithography effects such as scanner aberrations and mask topography effects. However, a change in the ratio with scan orientation is evidence of a metrology artifact. The Scan B and C modes, designed for 2D patterns, show the minimum sensitivity to scan orientation, as expected. The Scan C mode shows almost no difference with scan orientation.

CD_X/CD_Y

Scan Mode	**0°**	**90°**
Normal	1.021	0.864
Scan A (1D)	1.018	0.848
Scan B (2D)	0.930	0.916
Scan C (2D)	0.965	0.962

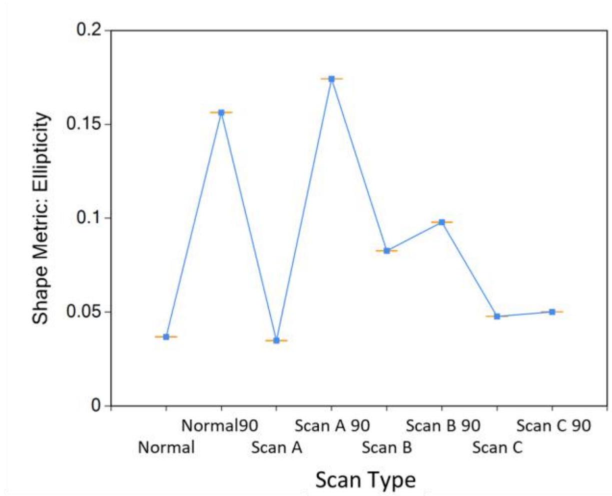
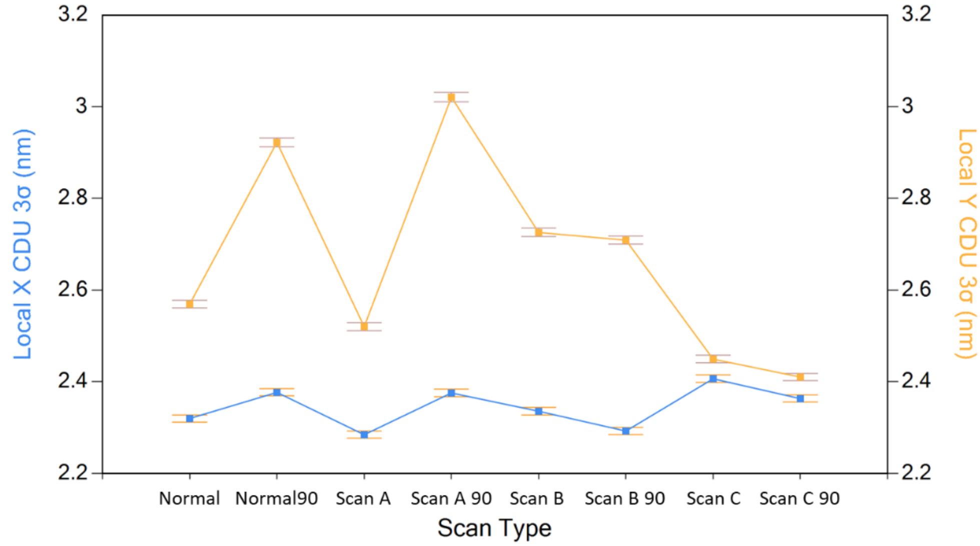


Figure 2. Changing the scan mode affects the sensitivity of the measured contact hole ellipticity to scan direction. The 2D scan modes B and C are least sensitive to scan orientation, as expect, with Scan C showing almost no difference. Note that the X-direction is defined to be in the 40-nm pitch direction, regardless of the scan orientation.

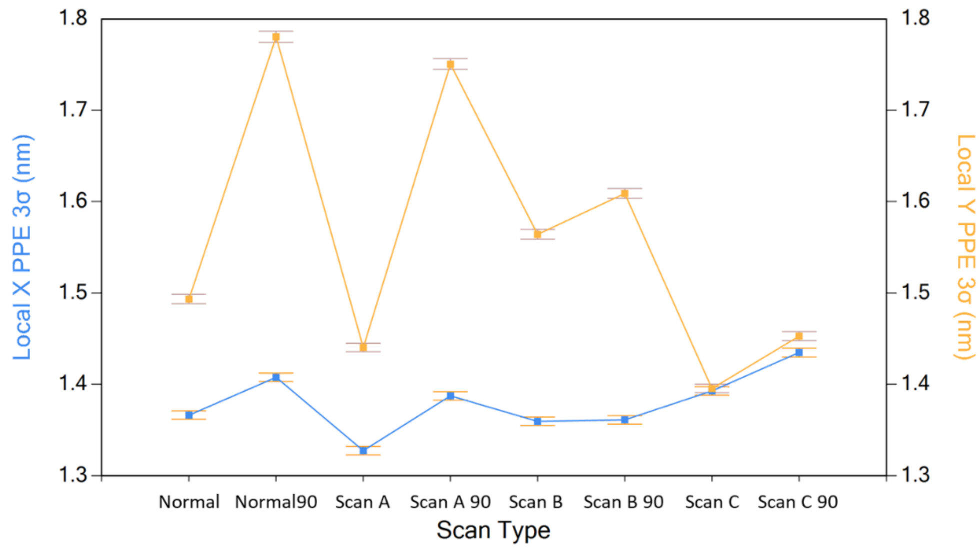
Likewise, changing scan orientation should not change the LCDU of X CD and Y CD nor the LPPE in the X and Y directions. Figure 3 shows that the Normal and Scan A modes (1D pattern modes) have large sensitivity to scan orientation compared to the Scan B and C modes (2D pattern modes). Further, the Scan C mode measures the X and Y CD LCDU to about equal and the X and Y direction LPPE to be about equal.

One source of bias when measuring LCDU is across-SEM-field variations.[3] When measuring over a large number of pixels (in this case 2048x2048) it is not uncommon to see a 0.5 – 1.5 nm systematic variation in hole CD across the field. That variation will be hidden by the stochastic variations for one image, but can be revealed by averaging many independent images together. For example, if the 3σ LCDU of a process is 1.6 nm, then the 1σ variation in the mean CD at one point in field after averaging 100 images would be $\frac{1.6}{3}/\sqrt{100}$ = 0.06 nm. Figure 4 shows the systematic across-SEM-field variation found for these contact holes for the case of Normal scan mode. In this case, all images came from the same location in the scanner field, but different locations on the wafer. Thus, Figure 4 shows a combined systematic mask + litho + metrology variation across the SEM field.

Subtracting out this systematic CD variation will remove that source of bias and produce a more accurate LCDU value. Further, if the systematic across-SEM-field variation is a function of scan mode, removing that variation should allow the scan modes to better match each other in LCDU results. Figure 5 shows that the systematic across-SEM-field variation for Normal scan mode is much larger than the other scan modes.



(a)



(b)

Figure 3. Changing scan mode and scan orientation for the measurement of (a) LCDU of X CD and Y CD, and (b) LPPE in the X and Y directions shows that the 2D B and C scan modes have the minimum sensitivity to scan orientation.

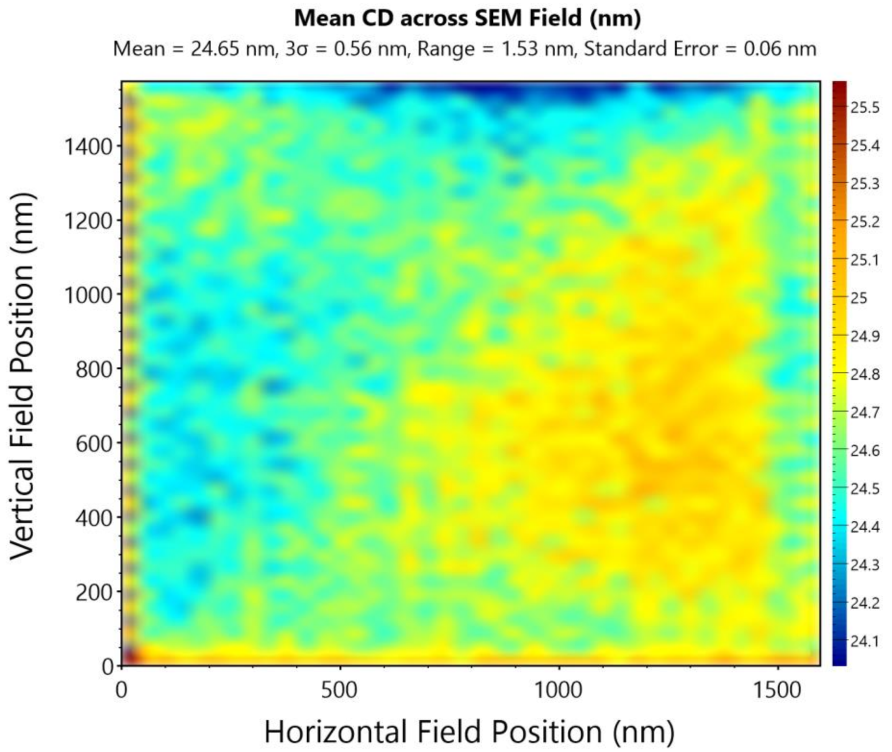


Figure 4. The systematic across-SEM-field variation of CD determined by averaging together 100 images, Normal scan mode, 0° scan orientation.

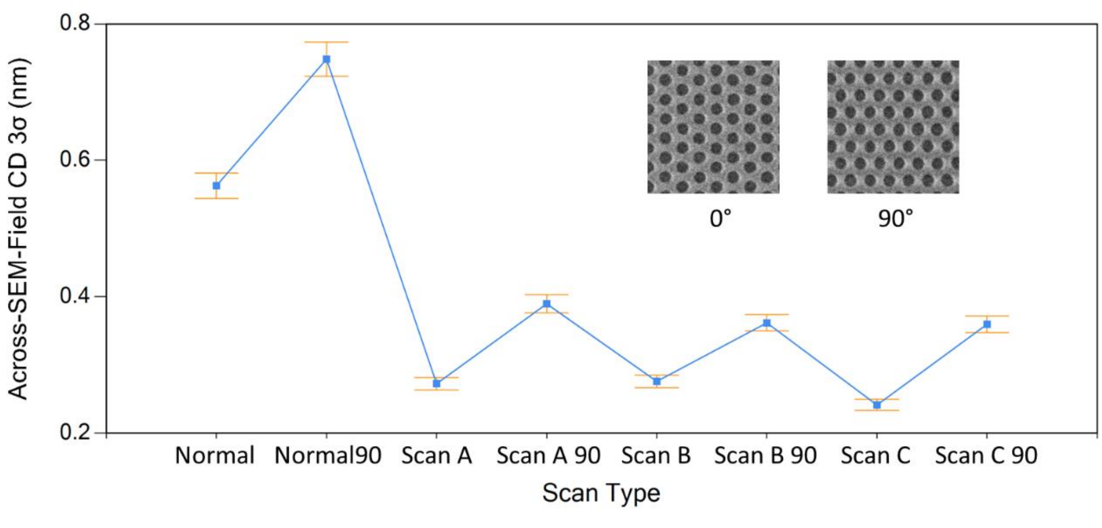
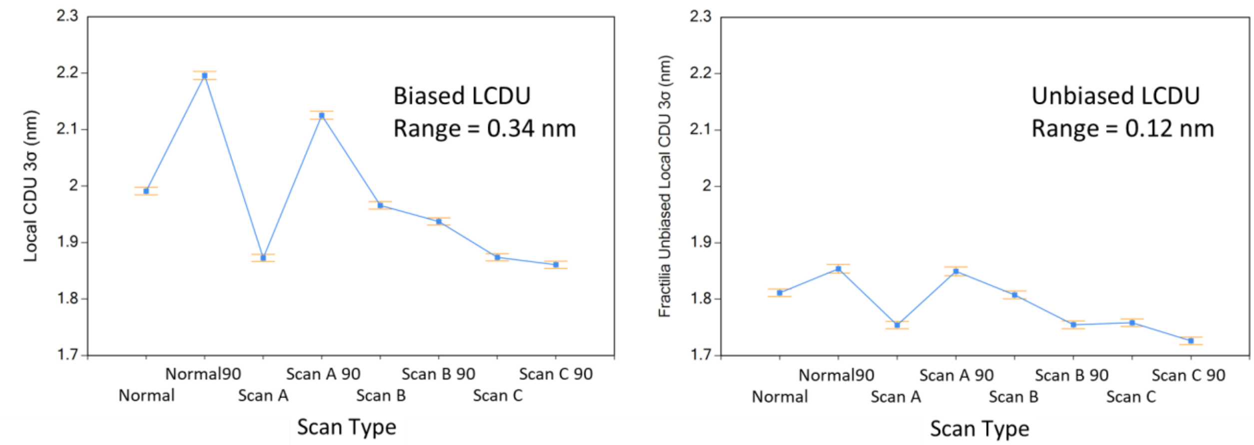


Figure 5. The systematic across-SEM-field variation of CD as a function of scan mode and orientation.

Another source of bias in LCDU and LPPE measurement is random edge detection noise that leads to random errors in CD or PPE, biasing the local uniformity measures higher (see Table I). Measuring and removing this bias also lowers the LCDU and LPPE. But since the random noise bias will in general differ with scan mode and direction, removing this bias is expected to lower the difference in LCDU measurement between the different scan modes. Figure 6 shows that the different scan modes and directions produce biased LCDU values with a range 0.34 nm, but the unbiased LCDU (with both random and systematic errors removed) varies by only 0.12 nm, a 3X improvement. Further, biased LCDU with distortion is 7 – 18% higher than unbiased LCDU without distortion across the various scan modes. Finally, Figure 7 shows the same LPPE outputs as in Figure 3, but with the systematic across-SEM-field variations removed.



(a) (b)

Figure 6. LCDU as a function of scan mode and orientation, with (a) systematic and random biases included, and (b) systematic and random biased removed to produce an estimate of the "unbiased" LCDU.

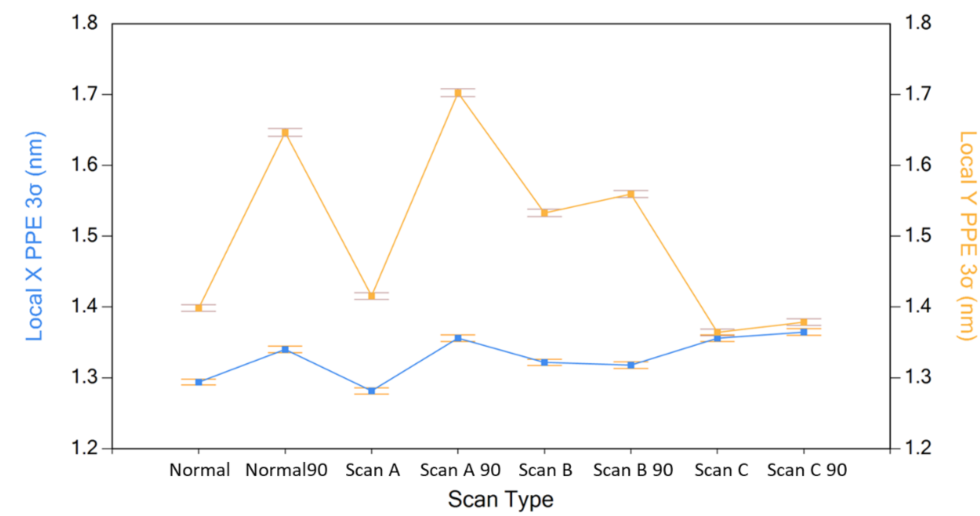


Figure 7. LPPE in the X and Y directions as a function of scan mode and orientation, after the removal of systematic across-SEM-field variations.

IV. CONCLUSIONS

CD-SEMs employ scan modes optimized for different pattern types. Scan modes designed for vertical 1D patterns (such as the Normal and Scan A modes in the Hitachi CD-SEM) are not designed to be optimal for 2D patterns. The results of this study fulfill this expectation. When measuring a very tight pitch staggered array of contact holes, the Normal and Scan A modes (1D scanning modes) show the greatest differences when changing the scan orientation. Further, the Normal mode, especially when the scan direction crosses the tightest pitch, shows the greatest bias in LCDU measurement. The B and C scan modes (2D scanning modes) show lower bias and reduced scan orientation dependence. The Scan C mode also shows the smallest differences between X and Y LCDU and LPPE.

The results of this study also show the importance of measuring and removing systematic and random biases in LCDU and LPPE measurements. About two thirds of the differences between scan modes and orientations in the measurement of LCDU come from different biases found in these scan modes. Thus, the choice of a best scan mode combined with measurement and removal of biases produces the most accurate and trustworthy stochastics metrology for contact holes.

References

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