MB-MDP Enables Circular Shots to Improve Mask Accuracy as Well as Shot Count

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Two of the greatest challenges for mask making at advanced semiconductor nodes, starting at 28 nm and continuing down to 20 nm and beyond, are accuracy and shot count. The mask maker must continually balance the need for accurate masks that result in high wafer yield with the long write-times and high costs of producing the complex masks that provide enough accuracy. Work by eBeam Initiative members has confirmed that using model-based mask-data preparation (MB-MDP) to enable the use of circular apertures in variable-shaped beam (VSB) lithography equipment can reduce shot count. Now, additional work by eBeam Initiative members has demonstrated that these same MB-MDP-enabled circular shots produce more accurate masks as well, as measured by improvement in mask critical-dimension uniformity (CDU). Uniquely, circles improve both sides of the shot count/accuracy balance, and provide a long-term path for future lithographic advances.

Mask Accuracy: The Other Side of the Balancing Act

The pervasive use of complex features, ranging in complexity from Manhattanized to non-orthogonal and curvilinear assist features, to improve mask quality and wafer yield at advanced nodes will cause a further explosion of mask-data volume and will result in untenable mask write-times and costs. eBeam Initiative members have demonstrated that using MB-MDP to produce circular shots can reduce shot count to an acceptable level—even on curvilinear "ideal inverse lithography technology (ILT)" shapes for advanced designs.[1] Of course, shot count is only one side of the balance required for successful advanced-node masks; the masks must also be printed accurately to produce acceptable wafer yield.

Mask accuracy must be evaluated both in terms of average position, size and shape, and in terms of tolerance to manufacturing variation, which includes both variation in the printing of multiple occurrences of the same intended shape on a single mask and mask-to-mask variation. So, for a mask to be deemed "accurately printed," the critical dimension (CD) of the mask features must hit the intended, OPC-assumed target, *and* the mask features must have acceptable CDU given the inevitable manufacturing variation.

Dose Margin and CD Split: Two Important Factors for CDU

Poor CDU on masks always has been recognized as a contributor to poor wafer yield. However, with the emergence of sub-80-nm features on masks, and with some mask

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* D2S, Inc. is managing sponsor of the eBeam Initiative

[1] *"Best depth of focus on 22nm logic wafers with less shot-count"*, Fujimura (D2S), Kim (Luminescent), Komagata (JEOL), Nakagawa (JEOL), Tolani (Luminescent), Cecil (Luminescent), PMJ 2010.

shapes becoming non-orthogonal, poor CDU has started to have a first-order effect on wafer yield.

Acceptable mask CDU is a function of many factors. Two dominant factors in producing good CDU are dose margin and CD split. Dose margin, the inverse of the feature-size sensitivity to the amount of energy provided in the eBeam shot used to produce the feature, should be higher to improve CDU. CD split, a condition that occurs when the CD of a printed mask feature is defined by VSB shot edges from two or more separate eBeam shots, should be avoided to improve CDU. As process technologies have continued to advance, however, managing these two important factors for ensuring good CDU has become increasingly complex.

Dose margin for sub-resolution assist features (SRAFs) at the 20-nm logic node and below is a particular concern for two reasons. First, at these nodes, the width of the mask features becomes less than 60 nm; eBeam writing is not accurate for features below 80 nm in width. The correlation of the desired shot width to the actual printed shot width is sub-optimal for features sized starting at above 100 nm on the mask, and becomes unacceptable for features sized below 80 nm. Even if the size was corrected with some mask process correction (MPC), the problem with dose margin would remain. Dose margin worsens with the decreasing size of the feature, so small features such as SRAFs have worse dose margin. Second, even 100-nm shots with good dose margin at the shot edges have poor dose margin at the corners of the shots. The corners of 60-nm shots have extremely bad dose margin (see figure 1). Curvilinear SRAFs are particularly impacted by this problem, because when VSB-based mask writers write non-orthogonal features, they create the contour edges with corners of the shots. For non-orthogonal features that are less than 80 nm in width, the entire contour edges of the features are written with poor dose margin.

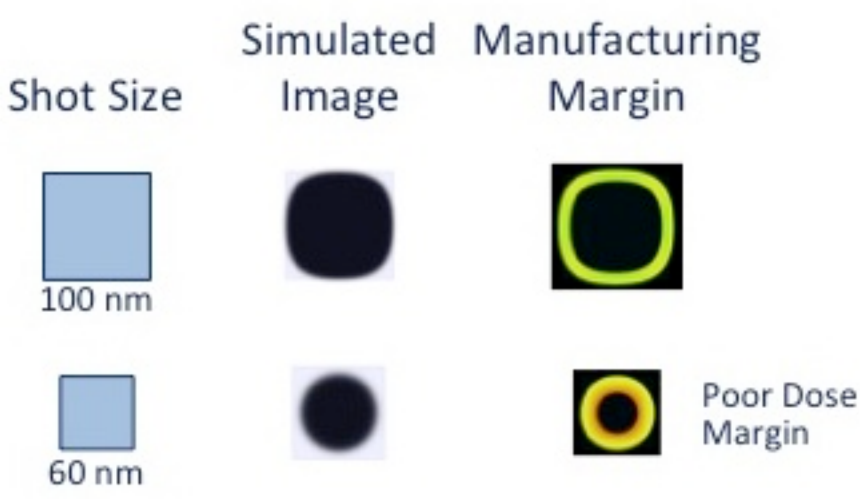


Figure 1. Dose margin worsens with decreasing feature size. Shot corners are impacted the most.

The other key influencer of CDU, CD split, depends on positional accuracy. When both sides of a given CD are the result of a single VSB shot, positional variation of the shot does not change the CD. While the position is changed, semiconductor design rules generally have much higher tolerances with positional accuracy as compared to dimensional accuracy. However, when two or more distinct VSB shots define the measured CD to create a CD split, the positional inaccuracy of each of the shots translates to CD inaccuracy (see figure 2).

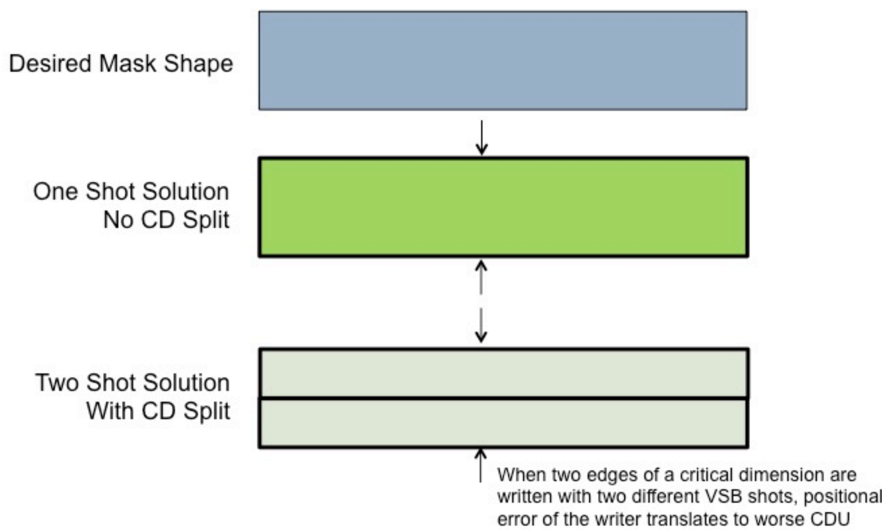


Figure 2. CD split worsens CDU.

Historically, to compensate for the fact that positional accuracy is less controlled by the lithography equipment, designs have needed to be resilient to position (see figure 3). Designs targeted at today's most advanced semiconductor nodes, however, require a proliferation of non-orthogonal SRAFs to ensure the faithful printing of mask features. Any mask feature (or SRAF) with multiple angles and curved lines must be created with multiple shots, and so is vulnerable to the worsened CDU caused by CD split.

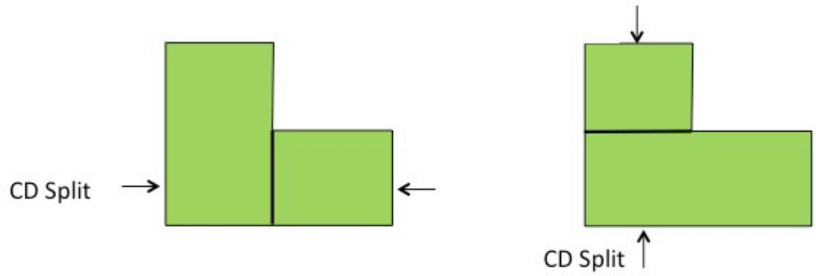


Figure 3. If both dimensions are critical, there is no way to avoid CD split. One must choose the more critical of the two dimensions to have the more stable CD.

As shown in figure 4, there is no way to avoid CD split on non-orthogonal lines using rectangular, non-overlapping shots.

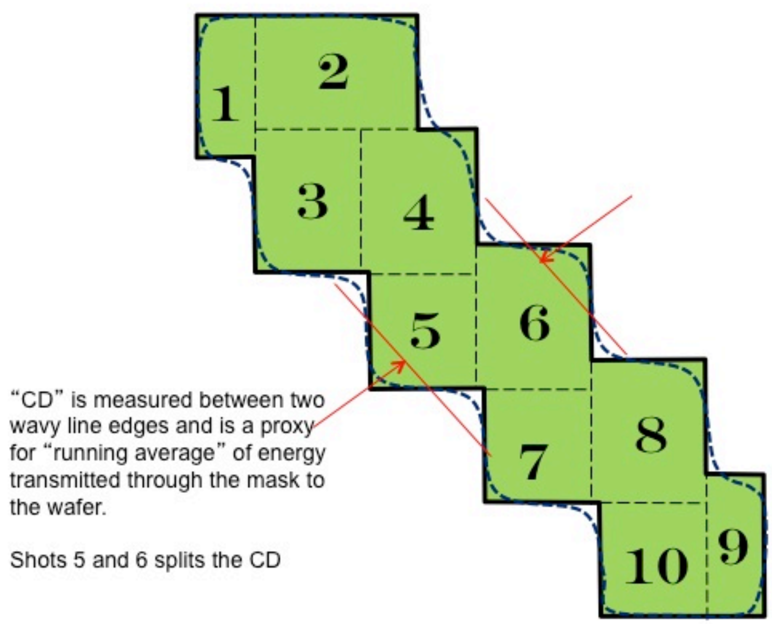


Figure 4. Using conventional fracturing with rectangular VSB shots, non-orthogonal lines will suffer from CD split.

The positional inaccuracies introduced by CD split can have a significant negative impact on CDU, even when dose margin is well controlled. Statistically, the CDs of features with CD split may vary by an additional 1 nm or more as compared to features without CD split. Advanced designs with an abundance of non-orthogonal features and SRAFs are particularly at risk.

Circles Yield Good Dose Margin, Avoid CD Split

The good news is that circular eBeam shots offer a means of both improving dose margin and avoiding CD split. These improvements are the product of the fundamental nature of circles: a circle is the only shape where the contour looks exactly the same from any angle. eBeam is naturally rounding, so writing a round shape is the most natural, easiest, and most accurate way to write curvilinear features.

Work by eBeam Initiative members has confirmed that circular shots have the best dose margin of any VSB shot, both by themselves and when overlapped to create non-orthogonal features (see figure 5). This is true even for features sized below 80 nm.

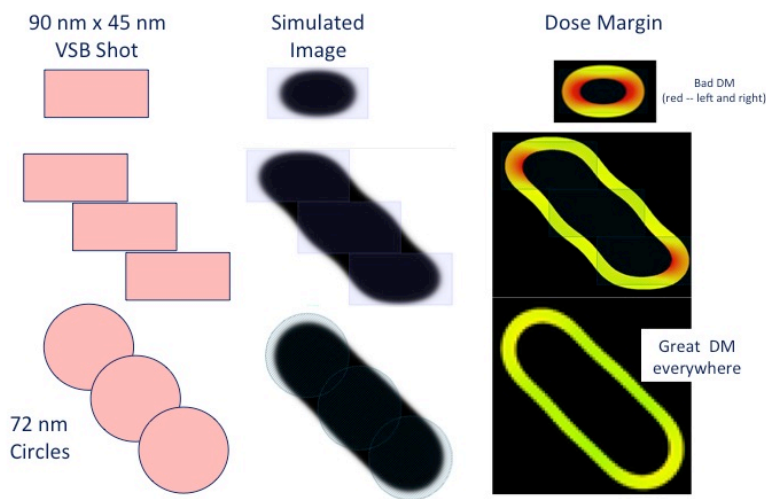


Figure 5. Dose margin is best with circular shots.

In terms of CD split, circles uniquely have a CD that is defined by the diameter of the circle, so CD split does not occur, regardless of the angle, as shown in figure 6.

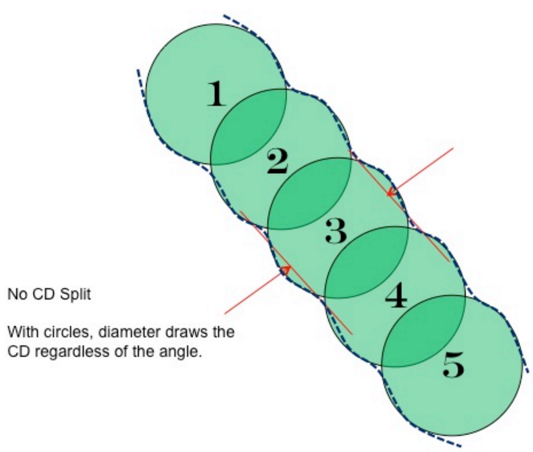
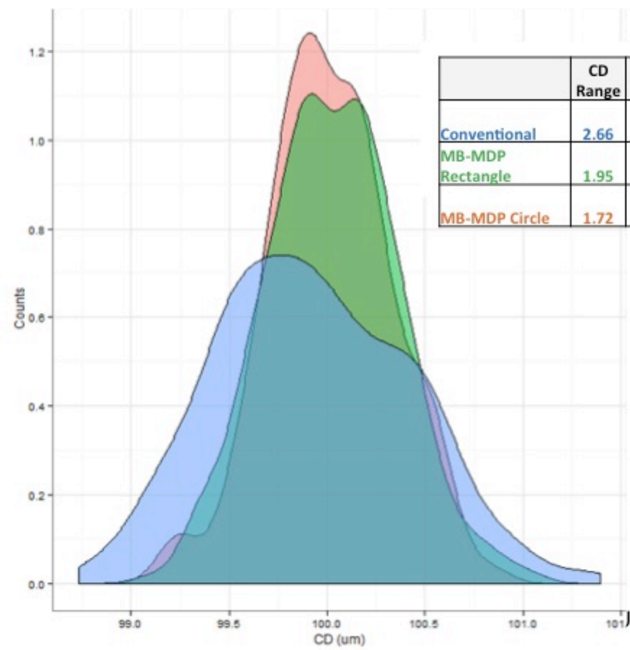


Figure 6. Circles avoid CD split.

Recently, eBeam Initiative members collaborated to confirm the mask CDU benefits of circular shots. As seen in figure 7, compared to conventional MDP methods, MB-MDP yields significantly better mask CDU. The figure represents the results of a Monte Carlo simulation where the shot position and shot dose were simulated to vary by one standard-deviation sigma of 1.5 nm and 5% respectively. The simulation included 300 different instances of a 100-nm-wide, 30-degree diagonal line, drawn using three writing methods: conventionally fractured lines, MB-MDP of rectangular VSB shots, and MB-MDP of circular shots. In this comparison, the shot count is made constant across all writing methods. The X-axis of the chart is the measured simulated CD for a particular instance, and the Y-axis represents the number of instances out of the 300 with that CD (smoothed). Narrower and taller shapes on the graph represent better CDU. The MB-MDP with circles clearly has the best CDU, while MB-MDP with rectangular VSB shots is second best. Holding shot count constant, the improvement in mask CDU from using circular shots is about 35% whereas for rectangular shots it is about 32%.



	CD Range	CD Sigma	CD Sigma Improvement	LWR	Shots/um
Conventional	2.66	1.378	0%	4.13	20
MB-MDP Rectangle	1.95	0.944	32%	2.83	20
MB-MDP Circle	1.72	0.901	35%	2.70	20

Figure 7. MB-MDP-enabled circles improve mask CDU.

The benefits of circular shots enable shot count to be reduced while achieving better CDU. Figure 8 shows CDU simulation results of the same diagonal pattern created with the same number of shots as in figure 7 (purple) to a 41% reduction in shot count (green) in a progression of plots. Shot count is shown for each in units of shots/um and decreases as you go up in the plots from purple to green. The axes for each sub-plot are as before with the X-axis corresponding to a given CD value and the Y-axis in each case to the number of instances with a specific CD. As a comparison, the CDU simulation of the conventional shots with the same conditions as figure 7 is repeated at the top in faded green. This demonstrates that the same nominal line width may be drawn with significantly fewer shots.

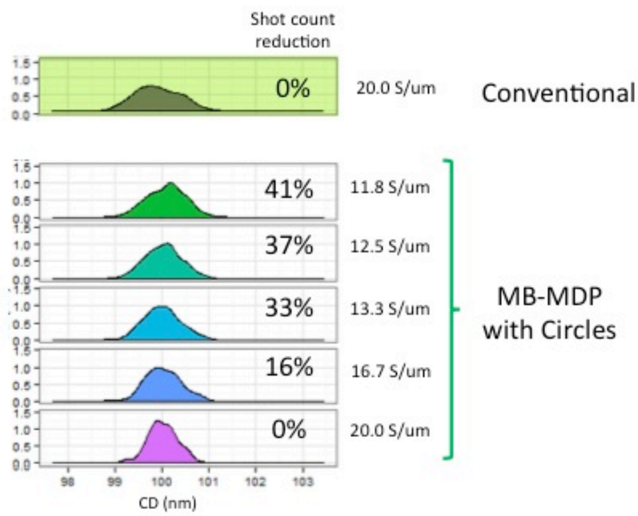


Figure 8. MB-MDP with circles reduces shot count and improves CDU.

Since the "designed" line-edge roughness in the generated contours of the diagonals written with circles is far superior to those written with VSB shots (see figure 5), both greater shot count reduction and better CDU are achieved with circular shots with MB-MDP.

These results confirm the advantages of both rectangular VSB and circular MB-MDP for one specific 100-nm ideal diagonal line case. eBeam Initiative members are continuing this investigation for general cases, including complex ILT mask technology and multi-resolution write technology, where the advantages of MB-MDP are expected to be of significant practical advantage for both CDU and shot count reduction.

Conclusion: Circles Offer a Smoother Path for Advanced Nodes

For advanced nodes where non-orthogonal SRAFs are required, circular eBeam shots enabled by MB-MDP offer unique advantages, both in terms of shot count and in terms of mask accuracy (as measured by CDU). Continued collaboration across the design-to-manufacturing chain will be necessary to make circular shots widely available. The benefit of such collaboration clearly would be a smoother path for complex designs at advanced nodes.