Shape-Dependent Mask CD Uniformity Impacts Tradeoffs in Design Rules and Wafer Quality at 20-nm and Below

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The increasing complexity in mask designs—in particular the growing use of complex sub-resolution assist features (SRAFs) at 20-nm-and-below process nodes—has given rise to new mask quality and cost challenges. The proliferation of complex mask features has made shape-dependent mask critical dimension uniformity (CDU) an important new factor that impacts both design rules and wafer yield.

To create complex mask features, OPC groups expend a great deal of effort to compute precisely the desired shapes on the mask. However, the benefits from this effort are partially lost when the shape on the mask has a low tolerance to manufacturing variation. The complex mask features required for leading-edge, critical-layer masks have a shape-dependent mask CDU problem. In this way, we have the undesirable effect that the more precisely the shape is calculated, the less likely that the exact shape will print reliably on the mask. However, if the masks with complex features can be written more reliably, the benefits from these complex mask shapes—even ideal inverse lithography technology (ILT) shapes—will be realized fully, which will make a positive impact on wafer yield and/or design rules.

New mask-manufacturing technologies and techniques have emerged to address these challenges, including model-based mask-data preparation (MB-MDP), mask process correction (MPC), eBeam dose modulation, and the use of overlapping eBeam shots and circular shots. These techniques have demonstrated, through multiple industry collaborations, an ability to improve shape-dependent CDU. For the first time in many years, a new set of ideas in mask data preparation has emerged to make critical contributions to tightening design rules and improving wafer yield.

Design Rules, Wafer CDU and Mask CDU

A critical part of any new node is the establishment of design rules. Design rules govern how much functionality can be squeezed into a given area on the wafer, while still having that wafer yield predictably well. There is constant tension between the design-side desire for liberal design rules and the manufacturing need to maintain predictable yield. The design rules for each technology node are a result of a careful tradeoff among many different, often competing, factors.

Wafer CDU is one factor that has always been important to the establishment of design rules. Wafer CDU is a measure of the statistical variation, often expressed as a standard deviation, of CD when a given feature is repeated many times on a wafer. Lower variation in CD is better; however, it is always a tradeoff. Each wafer CDU degradation is met with consequences in terms of design rules.

Poor wafer CDU forces more margin into design rules to account for the possibility that a particular instance could be manufactured too large or too small. For example, a spacing rule between features may need to be broadened to avoid bridging adjacent features on the finished wafer. Or, a minimum feature size may need to be larger to account for the possibility that an instance of that feature could be too narrow once manufactured, causing an open circuit.

As an example, the inability to maintain tight control on wafer CDU at advanced nodes has caused redundant contacts and vias to be required in order to maintain yield. Because contacts and vias are the smallest-sized features in both the X and Y dimensions to write on a wafer, they are the hardest to yield predictably. Design rules have already been modified to require techniques such as double vias to account statistically for poor CDU on single vias. Double contacts and vias negatively impact chip area, and therefore the performance of, and the power required to implement, a given functionality.

Wafer CDU is impacted by a variety of factors, including lithography performance, and therefore the quality of optical proximity correction (OPC). For the first time, wafer CDU for the sub-20-nm logic nodes is also significantly affected by shape-dependent mask CDU.

Shape-Dependent Mask CDU and Wafer Quality

Shape-dependent mask CDU has become a topic of increasing concern because mask shapes are becoming increasingly complex (less rectangular, and more an orthogonal approximation of a curvilinear shape), and mask patterns are now approaching critical sub-80-nm dimensions.

The ability to use ideal (i.e., truly curvilinear) ILT shapes on masks, rather than Manhattan approximations, has been shown to yield better wafer quality[1]. Previously, it had been assumed that ideal ILT shapes were not practical because such shapes could not be written on the mask within reasonable write times. While this was and still is true for conventional fracturing approaches, recently introduced MB-MDP techniques enable the writing of ideal ILT shapes on the mask in write-times equivalent to those needed to write complex "Manhattanized" shapes that are fractured conventionally. This new mask-data preparation technology enables the use of ideal ILT shapes to optimize the wafer performance. The remaining problem with these types of shapes, especially at smaller process nodes, is shape-dependent mask CDU.

Even with purely orthogonal Manhattanized shapes, when the orthogonal jogs in the shape outline become smaller, the actual shape written on the mask becomes more and more curvilinear. This natural rounding effect is due to forward-scattering of VSB-based mask writing. This rounding always causes 90-degree corners and thin

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[1] Timothy Lin, Emile Sahouria, Nataraj Akkiraju, Steffen Schulze, "Reducing shot count through optimization based fracture," Proc. SPIE 8166 (2012).

features to have poor dose margin, which results in poor mask CDU. Complex SRAFs, whether Manhattanized or ideal, are a combination of both of these "problem" shapes and so introduce the shape-dependent mask CDU issue at the 20-nm logic node and below.

In mask writing, there are three principal issues that contribute to CDU problems: dose margin, slivers and CD split. All three issues are shape-dependent with complex Manhattanized or ideal mask shapes. And all three issues are reduced with MB-MDP techniques.

Dose Margin

In VSB-based eBeam writing, dose margin is used to model a collective effect of various sources of manufacturing variation, including variations in eBeam current or dose as well as resist conditions such as sensitivity, distance, thickness and temperature. Good dose margin makes mask shapes resilient to these sources of variation. Conversely, poor dose margin makes shapes more vulnerable to variation.

At the 20-nm-and-below process nodes, mask patterns are approaching sub-80-nm dimensions. eBeam writing is less predictably accurate as feature sizes drop below 80 nm, an effect that is commonly referred to as the "linearity" problem. But in addition, there is a dose margin problem, and therefore a CDU problem. Specifically, there is a shape-dependent CDU problem.

Previously, most mask shapes were orthogonal and VSB shots were larger than 100 nm in one dimension. Because 100 nm is sufficiently larger than the forward scattering radius of the eBeam and its effects on the resist, the dose margin of CDs (almost always measured orthogonally) was stable across different shapes on the mask. Dose margin was still an important criterion, but the issues at this point came mostly from backscatter correction, also called proximity effect correction (PEC). A large amount of backscatter would produce poor dose margin, so areas that are dense or opaque masks would have worse dose margin. However, the issue was fairly uniform across all mask shapes.

Now that mask shapes have smaller features, and more and more of the mask is written with the corners of the VSB shots, the dose margin issue has become shape dependent.

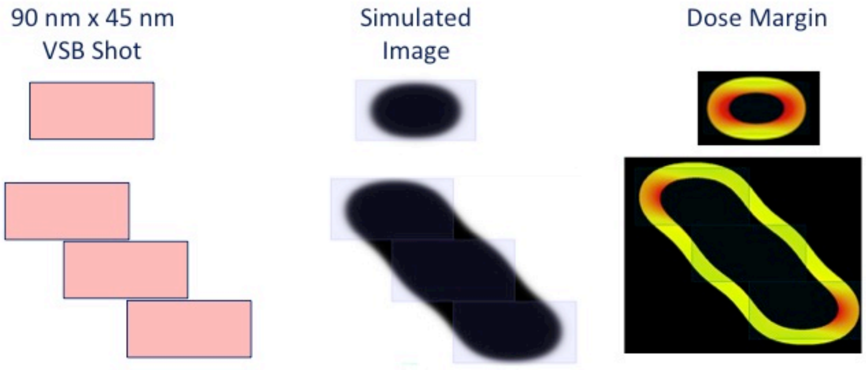


Figure 1. The single 90 nm x 45 nm shot (top) has poor dose margin. The same shot, when repeated and stacked three in a row has acceptable dose margin. The impact on CDU is shape dependent.

As shown in figure 1, a drawn 90 nm x 45 nm rectangle (top left) will appear on the mask as an oval (top center). The width will be unreliable because the dose margin is relatively poor in that dimension, as illustrated by the red color (top right). However, if the same 90 nm x 45 nm shot was repeated in a stair-step fashion (bottom left) to create an approximately diagonal line (bottom center), the dose margin, and therefore the CD, of that diagonal line is acceptable (bottom right). The two extreme ends of the line still have poor dose margin, but that direction is not likely to be the CD for this kind of shape, and the impact to the area of the mask shape is less significant. For features sized below 80 nm for VSB-based mask writing, dose margin is shape dependent. Therefore, for these features, CDU is also shape dependent.

Slivers

Using the VSB approach, there is a small but unavoidable error introduced because the first beam aperture and the second beam aperture are overlapped to "cut" the rectangular VSB shot. This small error in the X and Y dimensions, as well as in angular distortion, becomes much greater for small shots, where the error represents a greater proportion of the shot. This is particularly pronounced for narrow shots with a high aspect ratio. This is often referred to as the "sliver" issue. As shown in figure 2, allowing overlapping shots can eliminate the need for sliver shots to produce the desired shape.

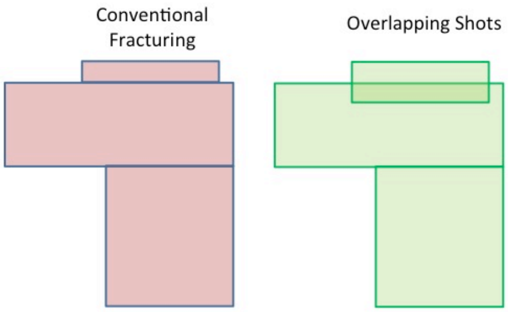
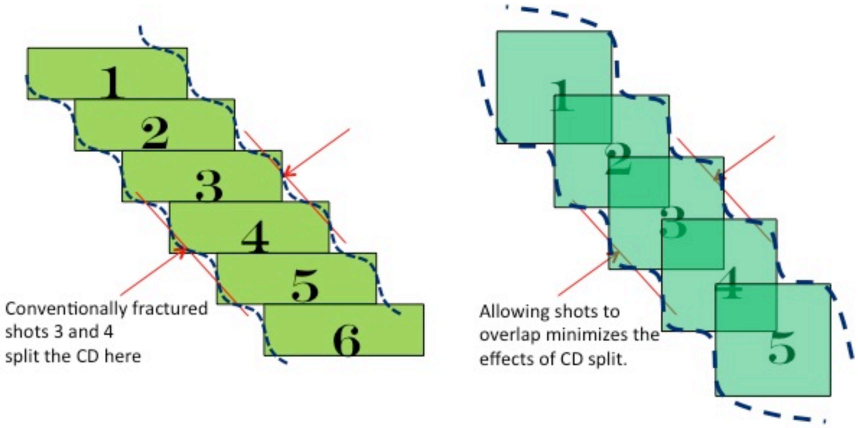


Figure 2. When creating the feature shown above, conventional fracturing cannot avoid slivers (left). Allowing overlapping shots eliminates the need for sliver shots to produce complex mask shapes in most cases (right).

CD Split

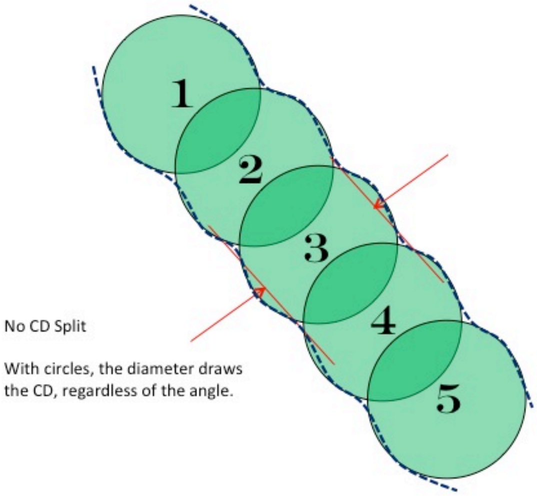
Another source of CD variation is CD split[2], a condition that occurs when two or more distinct VSB shots define the measured CD. CD split is a CDU issue because positional variation translates to CD variation where there is CD split. Masks with only rectangular shapes minimize CD split. Masks with complex shapes (whether ideal curvilinear or Manhattanized approximations) have significant CD split issues if conventionally fractured. Allowing overlapping shots substantially reduces the CD split problem, as seen in figure 3 below. The use of circular eBeam shots is even more effective for reducing the CD split problem, as shown in figure 4.



Conventionally fractured shots 3 and 4 split the CD here

Allowing shots to overlap minimizes the effects of CD split.

Figure 3. CD split can be reduced substantially through the use of overlapping eBeam shots.



No CD Split

With circles, the diameter draws the CD, regardless of the angle.

Figure 4. Because the diameter of a circle draws the CD regardless of the angle, circular eBeam shots are even more effective for reducing CD split.

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[2] Ryan Pearman, Robert Pack, "MB-MDP enables circular shots to improve mask accuracy as well as shot count," Whitepaper, D2S, Inc., February 13, 2012.

All three major contributors to mask CDU—dose margin, slivers and CD split—are shape dependent. All three are improved with new techniques that are enabled by MB-MDP.

New Mask Manufacturing Technologies Improve Shape-Dependent Mask CDU, Leading to Tighter Design Rules and/or Better Wafer Quality

Since the introduction of VSB mask writing, the range of technologies used in mask manufacturing has remained fairly static. Today, in response to the challenges posed by the 20-nm-and-below process nodes, new mask manufacturing techniques such as MB-MDP, MPC, dose modulation and circular-shaped and overlapping eBeam shots offer distinct advantages. All impact shape-dependent mask CDU, which in turn improves design rules and/or wafer quality.

MB-MDP is a new, model-based mask-data preparation technology. Traditional fracturing techniques for mask data preparation look at the desired drawn shape and find the combination of adjacent (non-overlapping) rectangles (and potentially some triangles) that will create those shapes. In contrast, MB-MDP is based on mask simulation. By fully simulating the energy deposited on the mask by each eBeam shot, MB-MDP is able to match shapes much more flexibly. MB-MDP can use any shape aperture (including circles), it can overlap these shots and it can assign a dosage level to each shot. The end result is better mask accuracy in terms of both faithful reproduction of each shape and manufacturing variation.

In addition, because MB-MDP simulates the effects of shots on the mask plane and produces the desired contour at the resist threshold, MB-MDP provides built-in MPC. Much as OPC corrects lithographic process effects, MPC corrects mask process effects such as fogging, development and etch loading, and eBeam proximity effects[3]. MPC also can be used to correct the size of mask features less than 80 nm wide that are impacted by eBeam errors.

Until now, all shots have been considered to be “full strength” for mask-data preparation purposes. However, dose modulation helps to improve CDU of sub-80-nm features that would otherwise print smaller than intended[4]. Oversizing the data (purposefully drawing larger shapes with the knowledge that they will write smaller on the mask) can also correct small shapes, but the dose margin will not be as good as compared to increasing the dose. The capability to have per-shot dose control gives more flexibility with less impact on mask write-times.

The newly introduced ability to use circular apertures in VSB stencils has a number of benefits. First, the use of circular shots to create contacts and vias improves depth

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[3] G. Chen, J-S. Wang, S. Bai, R. Howell, J. Wiley, A. Vacca, T. Kurosawa, T. Nishibe, T. Takigawa, “Model based short range mask process correction” PMJ 2008.

[4] Aki Fujimura, “Model-based mask data preparation using overlapping shots: making optical lithography cost-effective for 20-nm devices,” Whitepaper eBeam Initiative 2011.

of focus and CDU for these critical and ubiquitous features.[5] Next, the use of circular shots to create complex mask features such as curvilinear SRAFs reduces shot-count significantly for these shot-intensive features.[6] Finally, circles have also been demonstrated to improve shape-dependent CDU for advanced masks.[7]

While this new generation of mask manufacturing technologies is still in development, many have been demonstrated through industry collaborations to improve shape-based CDU[8]. Some of these emerging technologies are already available for limited commercial use, and others are in the process of commercial implementation.

Conclusion

As process technologies approach 20-nm-and-below nodes, the application of new mask manufacturing technologies such as MB-MDP, MPC, dose modulation and circular shots can have critical influence on shape-dependent mask CDU, which in turn impacts design rules and/or wafer quality. More than ever before, the mask manufacturing techniques used for any given design can now have far-reaching impact on the output of the entire design-to-manufacturing chain.

Moving forward, process development teams will need to consider shape-dependent mask CDU, and the enablement of complex, even ideal ILT, patterns as critical factors for reducing the tradeoffs between improving wafer yield and tightening design rules. Design teams will benefit from more liberal design rules enabled by the tighter control of shape-dependent mask CDU afforded by these new mask-manufacturing techniques. Likewise, wafer manufacturers will benefit from the increased wafer quality and yield provided by masks with better shape-dependent mask CDU.

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[5] Aki Fujimura, "Circles: one key to successful lithography at advanced nodes," Whitepaper, eBeam Initiative, 2010.

[6] Ibid.

[7] Ibid.

[8] Pearman, Pack, *op cit*