

Why the Mask World is Moving to Curvilinear

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ABSTRACT

The photomask industry is experiencing a fundamental shift from Manhattan masks to curvilinear masks. In the recent lithography and mask technology conferences, there were many papers and talks on curvilinear masks, curvilinear OPC, curvilinear ILT, curvilinear mask process correction (MPC), and curvilinear mask formats. Step by step, the photomask industry has started a transition from Manhattan to curvilinear, enabled by the adoption of the new multi-beam mask writers and the advent of practical full-chip curvilinear inverse lithography technology (ILT).

The benefits of curvilinear masks go much deeper than is immediately obvious. In this paper we will share our insight on why the mask world is moving toward curvilinear mask shapes. We will demonstrate that curvilinear masks are more reliably manufacturable. We will evaluate the benefits of curvilinear in terms of process window, mask rules, mask error enhancement factor (MEEF), and mask variation.

Keywords: Curvilinear, Curvilinear Mask, Curvilinear Design, Curvilinear ILT, Curvilinear MRC, Multi-beam Mask Writer

1. ILT AND CURVILINEAR MASKS

Curvilinear masks started with inverse lithography technology (ILT). At the 2006 SPIE Advanced Lithography Conference, the author and Dan Abrams presented the first ILT paper from Luminescent, “Fast Inverse Lithography Technology.”[1] The goal of ILT is to produce a mask that will create the best shape on wafer; it is an inverse problem where the optimal mask is calculated from the desired wafer shape. Luminescent and its partners published numerous papers that show that ideal, fully curvilinear ILT mask patterns produce the largest process window[2-9].

Figure 1 shows the mask pattern created by this first ILT solution on the left. However, because variable shaped beam (VSB) mask writers could not write these patterns, the pattern had to be “Manhattanized” to include only rectilinear shapes so that a VSB mask writer could write them, which is shown in the middle of Figure 1. On the right of Figure 1 are the Manhattanized ILT mask patterns without sub-resolution assistant features (SRAFs).

Fast Inverse Lithography Technology

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Figure 1. Mask pattern created by this first ILT solution (left). “Manhattanized” version of the same pattern (center), Manhattanized ILT mask patterns without SRAFs. (right)[1]. Source: Luminescent/Synopsys

The reason that ILT tends to produce curvilinear mask patterns is related to wafer scanner optics. Figure 2 shows a simple diagram of how ILT works. We create a model for the scanner for forward simulation: starting from a mask pattern, we use the model to then simulate the wafer pattern. We are trying to solve the inverse problem by starting with a wafer target. Then we iteratively solve the optimization problem so that we end up have an optimized mask that will print the desired wafer target.

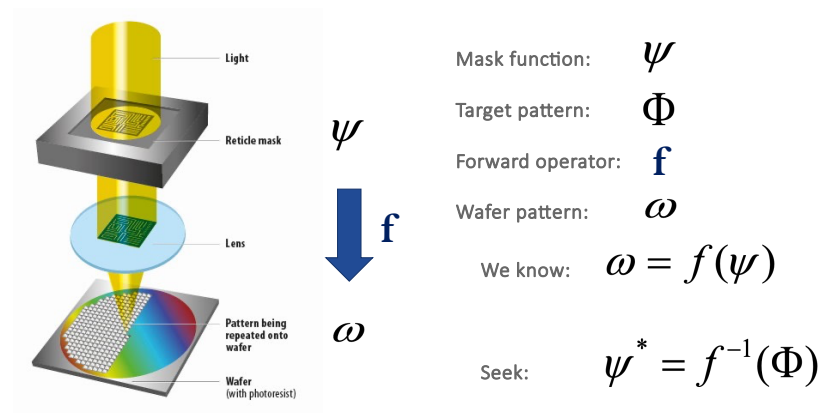


Figure 2. ILT treats mask optimization as an inverse problem, starting with the desired wafer target and calculating the mask that will produce the desired wafer target.

The wafer scanner has band-limited optics, so any 90-degree corners (especially the tip of the corner, which has infinite frequency) will be filtered out of ILT solutions because the scanner cannot produce them (see Figure 3). This is why ILT mask patterns are naturally curvilinear.

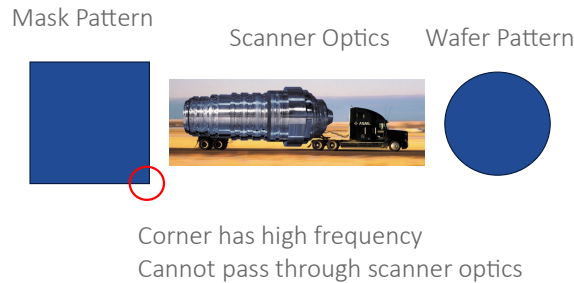


Figure 3. Wafer scanners have band-limited optics, and so cannot produce 90-degree corners. ILT solutions start with a desired wafer target, so ILT solutions are naturally curvilinear.

Leading-edge photomasks have been written by VSB mask writers for the past few decades. VSB uses a single beam with adjustable aperture to create eBeam shots with different dimensions. It is perfect to write Manhattan shapes, because Manhattan shapes are composed of rectangular shots, but it requires too many shots to represent curvilinear shapes. Since mask write time is proportional to the number of shots, as shown in Figure 4, so it is not practical to write curvilinear masks with VSB mask writers.

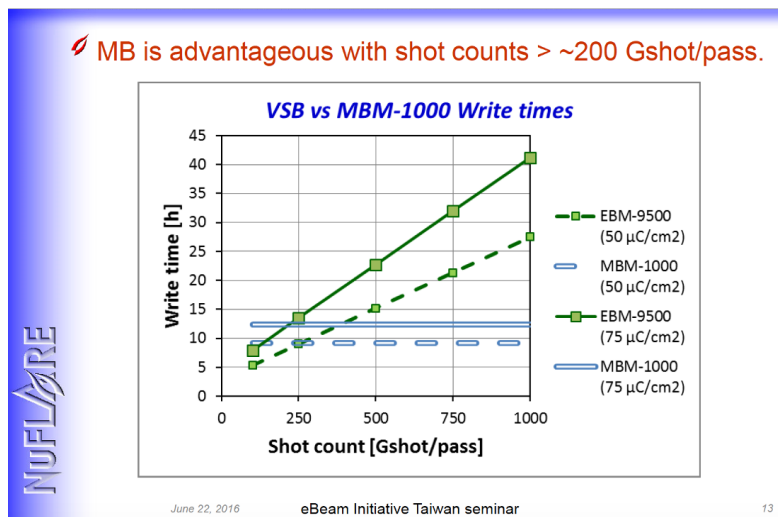


Figure 4. Write times for VSB mask writers are proportionate to the number of shots required to create the mask shapes. Multi-beam mask writers are shape-agnostic, with a constant write time regardless of mask shapes[11]. Source: NuFlare

Multi-beam mask writers are perfect for writing curvilinear masks[10, 11]. They have an array of hundreds of thousands of beams, each of which can be turned on, off, or in fractional dose. Since the write time is only proportional to area, it can write curvilinear masks without any penalty in write time. The rapid adoption of multi-beam writers over the last several years due to the advent of extreme ultra-violet (EUV) lithography has removed the one of the biggest roadblocks to using curvilinear masks in production.

The initial use of ILT in production was mainly in limited areas, in “hotspot” mode. The reason was another roadblock: the difficulties in computing full-chip ILT solutions. One difficulty is runtime, but the runtime can be handled by using GPU-accelerated computing. Feeding chip partitions into a GPU-accelerated computing system can speed the processing of each partition. However, stitching errors and the re-computation required to address them are still show-stopping issues (Figure 5).

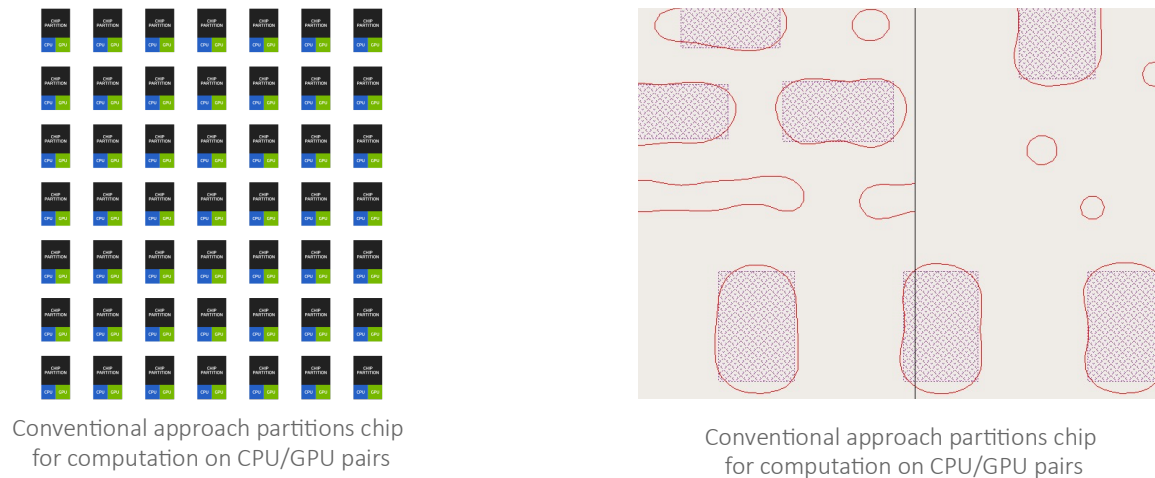


Figure 5. The conventional full-chip approach partitions chips for computation on CPU/GPU pairs. Issues arise when the partitions are stitched back together[12]. Source: D2S

To avoid the time-consuming recursive correction passes necessary to resolve these stitching errors, in 2019, D2S presented [12] a new hardware/software co-designed solution that had the ability to process the entire chip at once: a computational platform that behaved as a single, giant GPU/CPU pair that could optimize full-chip data seamlessly, without partitions (Figure 6).

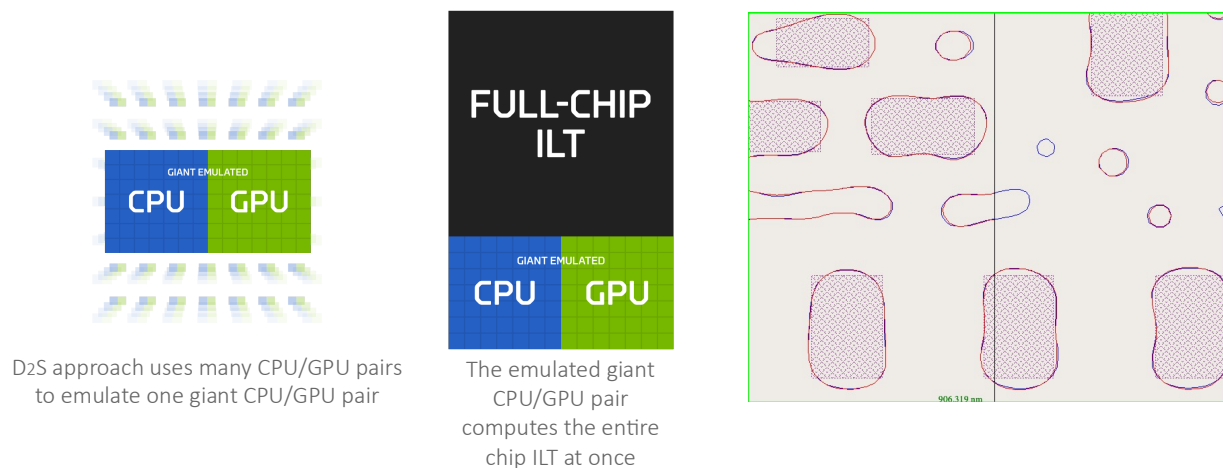


Figure 6. A novel approach emulates a giant CPU/GPU pair that computes the entire chip at once, eliminating stitching issues[12]. Source: D2S

Today, with these roadblocks removed, the photomask industry's confidence in their ability to create curvilinear masks is very high. Figure 7 shows the results from a survey by the eBeam Initiative, an industry group that conducts surveys of industry leaders each year. In 2023, when asked about high-volume manufacturing of curvilinear masks, 87% of the respondents said that they were ready for at least a limited volume of curvilinear masks, with 33% saying they could handle as many curvilinear masks as there was demand[14]. Clearly, the industry is prepared for the move to curvilinear masks.

Confidence Doubled in Handling Curvilinear Mask Demand 87% say leading-edge mask shops can handle at least limited number

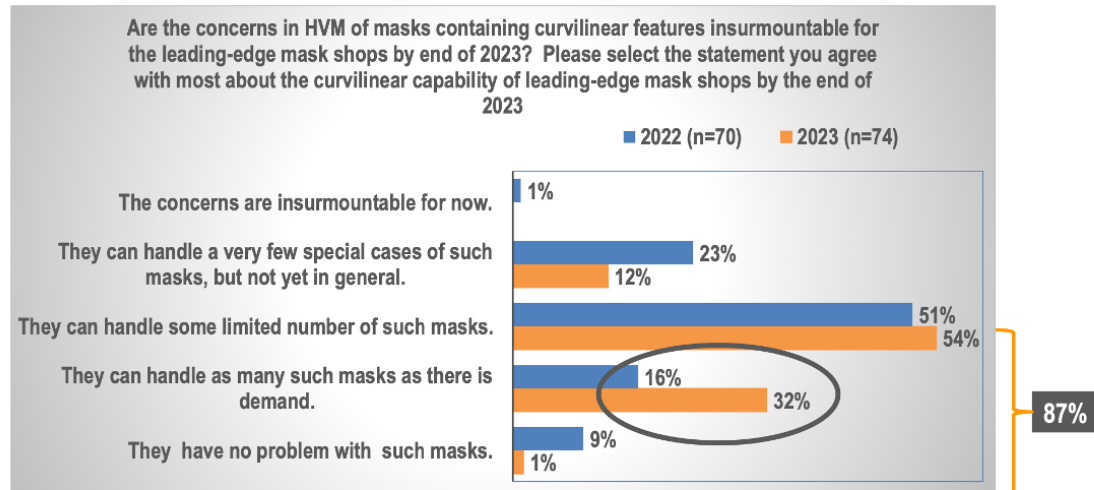


Figure 7. Results of the 2023 eBeam Initiative Luminaries Survey showing that 87% of the respondents are ready for at least a limited number of curvilinear masks. 33% can handle as many masks as there is demand[14]. Source: eBeam Initiative

2. CURVILINEAR IMPROVES PROCESS WINDOW FOR ALL TECHNOLOGY NODES

What has motivated to photomask industry to prepare for these changes is the demonstrated benefits of using curvilinear mask features. Dating back to the first ILT papers, there have been numerous studies that show curvilinear masks can improve process window for all technology nodes and lithography technologies, from 193 dry, 193 immersion, to EUV. One such study was conducted by Luminescent with Samsung[9]. As shown in Figure 8, curvilinear mask patterns for a contact array were generated with different pitches. For each pitch, there is an unconstrained curvilinear ILT mask pattern and then simplified ILT mask patterns, all the way to just horizontal and vertical scaling bars, which was very close to OPC. Then the wafer was printed with dose and focus matrix, and CDs were measured. When we look at the process window, you can see for every pitch the unconstrained curvilinear mask pattern always gives the largest depth of focus in process window.

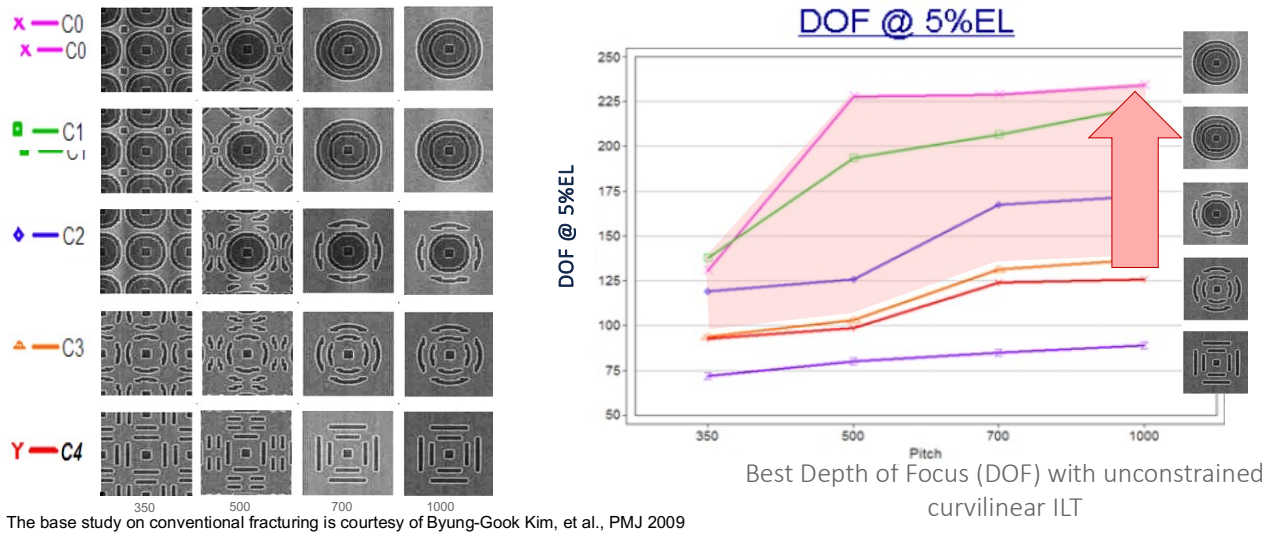


Figure 8. A study of a contact array using varied levels of curvilinearity. The best depth of focus was achieved by the unconstrained curvilinear ILT[9]. Source: Samsung

More recently, in 2020, Ezequiel Russell from Micron [13], showed that for the three contacts shown in Figure 9, using full curvilinear ILT can improve the depth of focus by 85%.

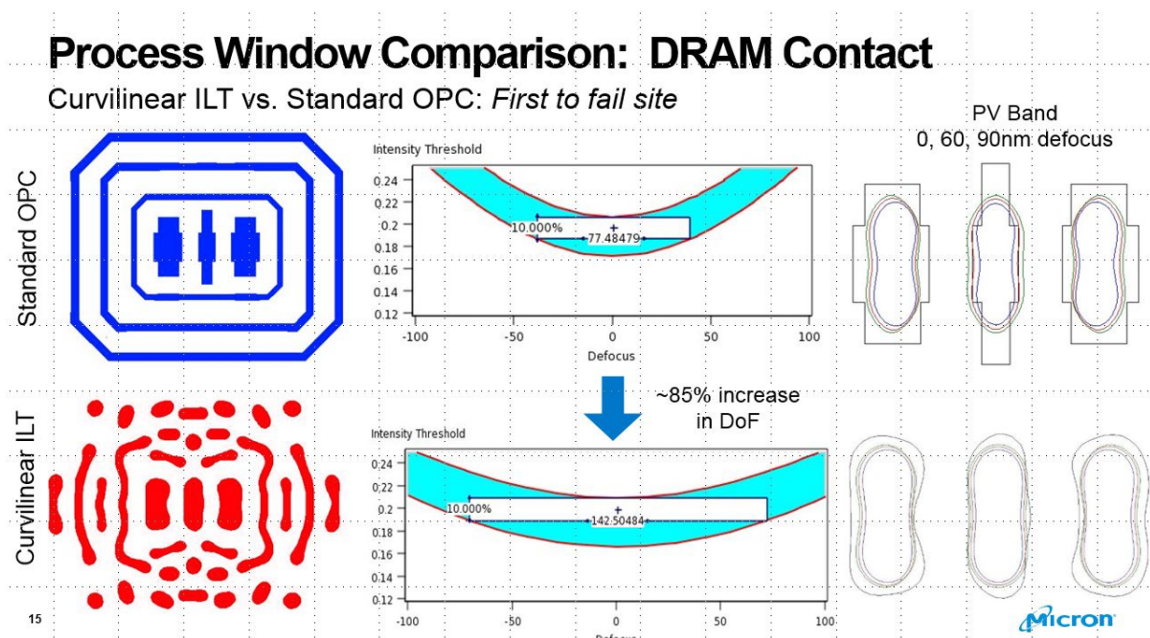


Figure 9. Curvilinear ILT provides an 85% increase in depth of focus compared to standard OPC[13]. Source: Micron

The most significant process window improvement using curvilinear ILT patterns was written using a multi-beam mask writer. The author presented the first GPU-accelerated, full-chip stitchless ILT in 2019. It was the first time that over 100% improvement on process window was achieved compared to OPC at Micron (Figure 10) [12].

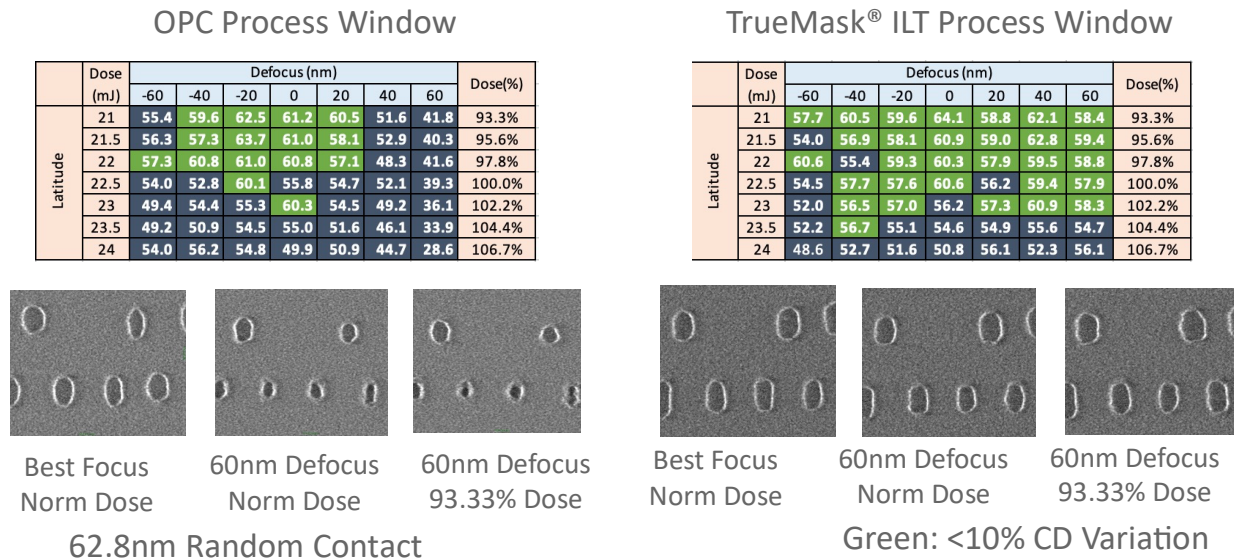


Figure 10. Curvilinear ILT provides over 100% increase in process window on random contact layer compared to standard OPC using a multi-beam mask writer[12]. Source: D2S and Micron

3. CURVILINEAR ENABLES SMALLER PITCHES, SIMPLER MASK RULES

One might ask, if corners are filtered out by scanner optics, as we've discussed, why not just take that as leeway? It turns out that some of the benefits of using curvilinear mask patterns are related to mask rules. First, curvilinear mask shapes can enable smaller pitches. A simple example is shown in Figure 11. Imagine these shapes are part of a contact array. How tightly you can pack the contact array is limited by minimum corner-to-corner mask rules. By changing the target mask shape of the contact from square to circular, using the same mask rules, the pitch can be reduced by 14%. In other words, curvilinear contacts can be packed tighter than Manhattan contacts.

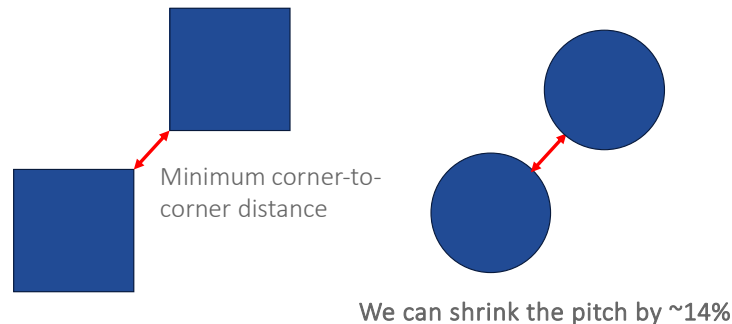


Figure 11. By moving from rectilinear to curvilinear mask features, pitches can shrink by 14%.

In addition, curvilinear mask features present the opportunity for mask rules to become much simpler: only minimum curvature, minimum CD, minimum space, and a minimum area would be required [15]. Figure 12 illustrates this using an intuitive example. In this example, the size of the green ball represents the minimum CD. If the ball rolls along the contour inside a given pattern, and it doesn't get stuck or roll outside the contour, that means it satisfies the minimum CD rule. If it gets stuck somewhere, as shown with the red ball, that means the pattern violates the minimum CD rule.

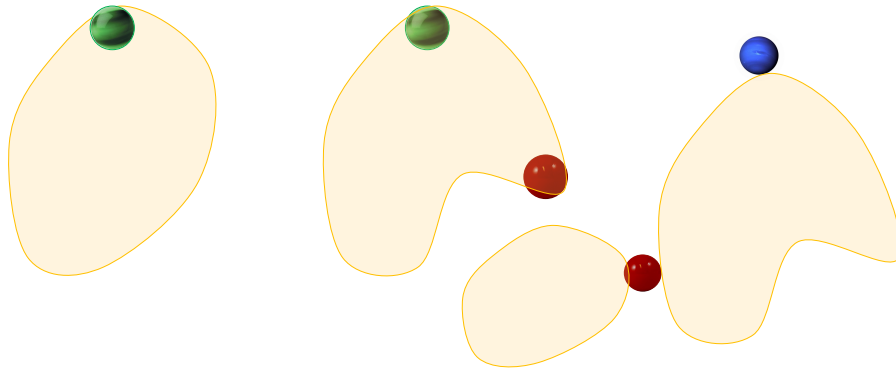


Figure 12. A conceptualization of how design rules might be simplified for curvilinear masks, using only minimum curvature, minimum CD, minimum space, and a minimum area[15]. Source: D2S

And similarly, you can roll the ball outside of the pattern to determine minimum spacing, as shown with the blue ball in Figure 12. Any overlaps into other patterns, as shown with the red ball, would be spacing violations. Of course, this is a conceptual example, but an algorithm can be created based on this concept.

4. CURVILINEAR MASK BENEFITS EXTEND TO MASK DOSE MARGIN, MEEF, RESULTING IN SMALLER MASK VARIATION

There are two problems with Manhattanizing curvilinear ILT mask shapes. First, there is the problem with VSB shot count that we discussed earlier. The other problem is mask dose margin as shown in Figure 13. Just like the wafer print on scanner has process window, mask writing on an eBeam mask writer also has process window. In the case of wafer process window, the two variables are focus and dose. In mask writing, since the eBeam writer has infinite or very large depth of focus, the main variable is dose. Instead of calling it dose latitude in the lithography world, the mask world calls it dose margin. Dose margin is particularly bad for 90-degree corners.

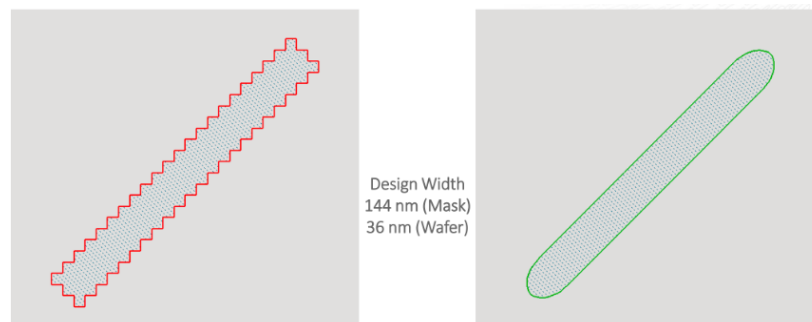


Figure 13. Dose margin is poor for 90-degree corners. Manhattanized curvilinear shapes have many 90-degree corners and so have poor dose margin in comparison to the smooth curvilinear shape.

In Figure 14, on the right, we show the dose margin for Manhattan and curvilinear contact arrays. Dose margin is represented by a pseudo color: the red represents bad dose margin and the green represents good dose margin. The 90-degree corners of the Manhattan contacts clearly have worse dose margin than the smooth curvilinear contacts. One the left of Figure 14, we show a study done by Ryan Pearman et al in 2019[16], showing that while the edges of the square contact had good dose margin, the corners had unacceptable dose margin. At the same time, it shows that circles at any angle have good dose margin.

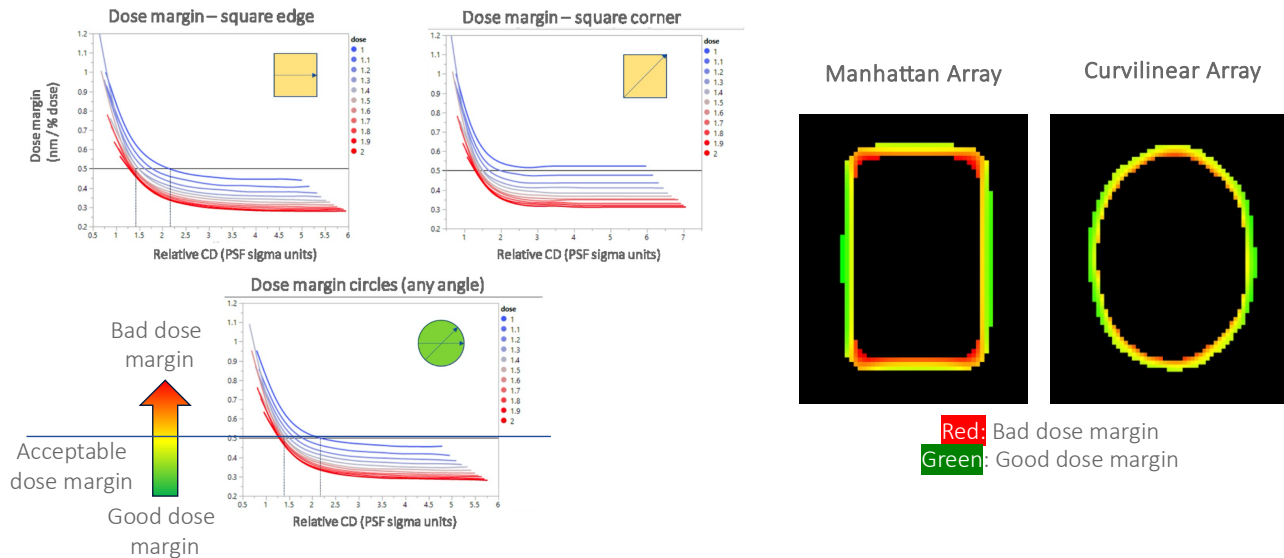


Figure 14. While edges of Manhattan features have good dose margin, 90-degree corners have very poor dose margin, as shown by the red pseudo color. Circles have acceptable dose margin at any angle, as shown by the green/yellow pseudo color[16]. Source: D2S

Curvilinear shapes have less variation on wafer or smaller mask error enhancement factor (MEEF). In a 2022 study, Abhishek Shendre et al found that in comparing the MEEF of a Manhattanized diagonal line to a curvilinear diagonal line, the smooth curvilinear line had ~28% improvement in MEEF over the Manhattanized line [17] (Figure 15).

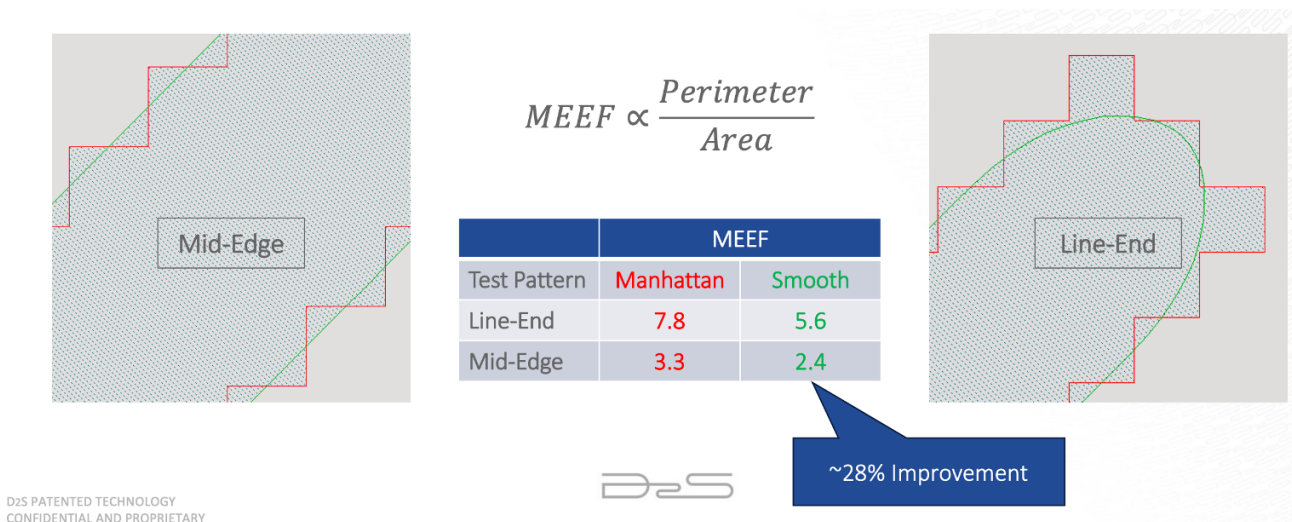


Figure 15. Both the mid-edge and line-ends of Manhattanized patterns have worse MEEF than the smooth curvilinear patterns[17]. Source: D2S

As shown in Figure 16, this is very intuitive, and it is the fundamental reason why curvilinear is better. Think of moving the edge of a shape by a unit of 1. If it is a Manhattan shape, such as a square, the edges in the X and Y direction are moved by 1, but the corners are moved by 1.4. While in a curvilinear shape, such as a circle, the edge in every place on the circle

is moved by 1. This means the same change on mask will cause more variations on wafer with the Manhattan shape than the curvilinear shape.

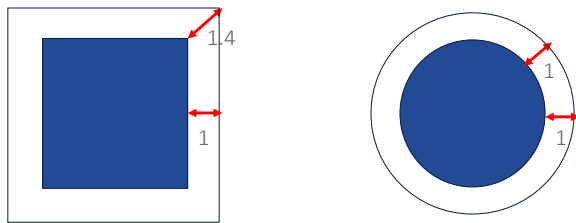


Figure 16. Moving a rectilinear shape by a unit of 1 causes the corners to move by 1.4, causing greater wafer variation, as compared to the circle, which is moved by a unit of 1 in every place on the circle.

Curvilinear shapes are created more faithfully in the mask process. The mask process involves bias processes, such as etching. For the same reason as the explanation above, curvilinear shapes have less variation in the mask process as well. Figure 17 summarizes the findings of a joint study with Micron and D2S. In this study, we created contact arrays, both curvilinear and Manhattan [18]. We made 6 copies on each array on the mask. We took measurements every four nanometers from four locations on each contact array (left edge, center, a corner, and the bottom), including hundreds of contacts each for a total of millions of measurements.

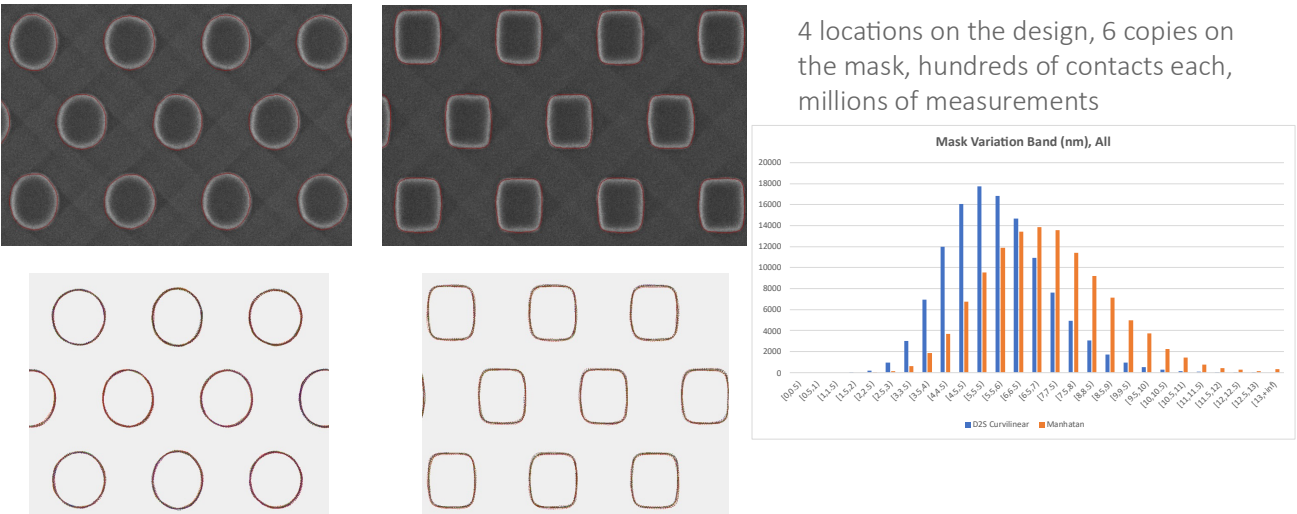


Figure 17. Curvilinear mask patterns (blue on the graph at right) have less variation and a tighter distribution of variation in comparison to the Manhattan mask patterns (orange on the graph at right)[18]. Source: D2S and Micron

In this study we first collect SEM images for all 6 copies of contact array at the same 4 locations (left edge, center, a corner, and the bottom), then we use proprietary software to align the 6 copies of image for each location. The alignment considered the distortions that the SEM image could introduce, including shift, rotation, and scaling. Once the images were aligned, the contours were extracted using proprietary software. Since we had multiple contours on each contact, the variation band was formed, and the bandwidth were measured every 4nm. Then we looked at the statistics to measure the mask variation band in the plot on the right, with curvilinear represented in blue and Manhattan represented in orange. We can see that the blue curve is shifted to the left compared to the orange, meaning that it's closer to zero. We can also see that the distribution of the blue curve is narrower, showing less variation.

Figure 18 shows the mean, standard deviation, and max variation for both the Manhattan (in orange still) and the curvilinear (in blue). In all cases, curvilinear contacts show significantly less variation, especially those in the corners

with more SRAFs. Recall, these are measurements from the same mask written by the same multi-beam mask writer. The only difference is the pattern. One is a curvilinear pattern, the other one is the Manhattan pattern, but the curvilinear pattern on mask has a 20% smaller variation than Manhattan pattern. That is very significant, because with MEEF, this will translate to the smaller variation on wafer as well.

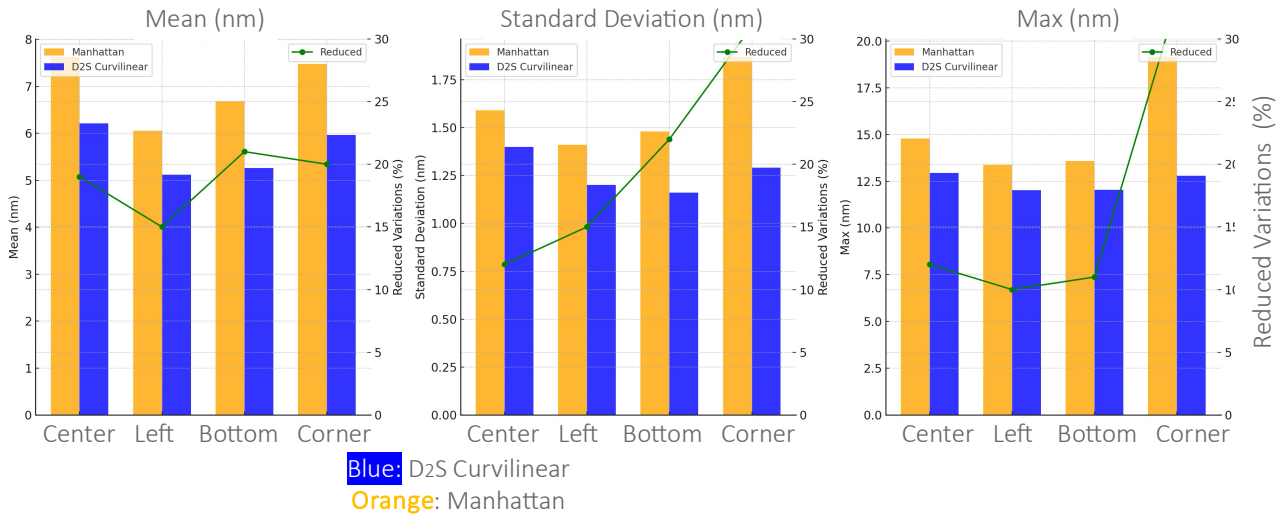


Figure 18. Mask variation for Manhattan (orange) and curvilinear (blue) mask patterns. Mean, standard deviation, and max all show less variation for the curvilinear mask features[18]. Source: D2S and Micron

5. WITH MWCO, CURVILINEAR BENEFITS ARE POSSIBLE WITH VSB MASK WRITERS

We have discussed how the multi-beam mask writer solved the write time problem for curvilinear masks and we have shown that Manhattanized versions of curvilinear shapes do not yield the same benefits as true curvilinear shapes. So, is there any hope that VSB could be used to write true curvilinear masks that reap the full benefits? The answer is, yes.

The key to reducing mask variation is to reduce the number of corners. Using fewer shots means there are fewer corners, which will reduce the mask variation. In 2021, this author and colleagues at D2S and Micron introduced the concept of mask wafer co-optimization (MWCO) [19]. Starting with an ILT solution, then using overlapping shots to reduce shot count, MWCO uses double simulations – the mask simulation, and then the wafer simulation – and based on the *wafer* result, iteratively moves those shots to minimize edge-placement error (EPE), as shown in Figure 19. MWCO uses overlapping shots on small assist features, which generally comprise the majority of shots. For main features we use fewer larger shots that are not overlapping.

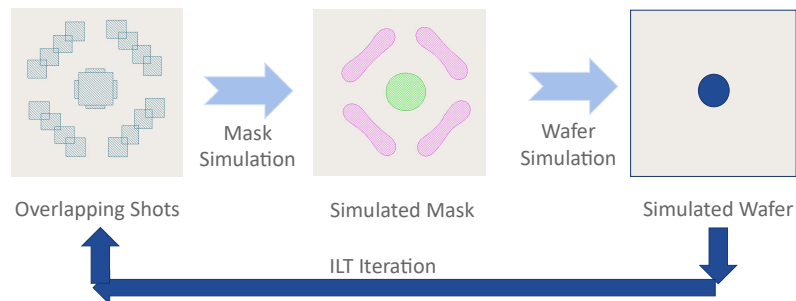


Figure 19. MWCO creates overlapping shots to reduce the shot count of SRAFs. Mask and wafer simulations are performed and the wafer results are used to move the overlapping shots to optimize wafer EPE.

As seen in Figure 20, an ILT pattern fractured with conventional shots (left) uses almost 10X the number of shots as an OPC solution. By using overlapping shots alone, the number of shots can be halved (center). However, using MWCO with overlapping shots (right) yields a curvilinear solution that uses fewer shots than the OPC solution. Using fewer shots also means that the write time for the MWCO solution is shorter than for the OPC solution. In this case, the entire curvilinear mask was written in less than 12 hours on a VSB mask writer.

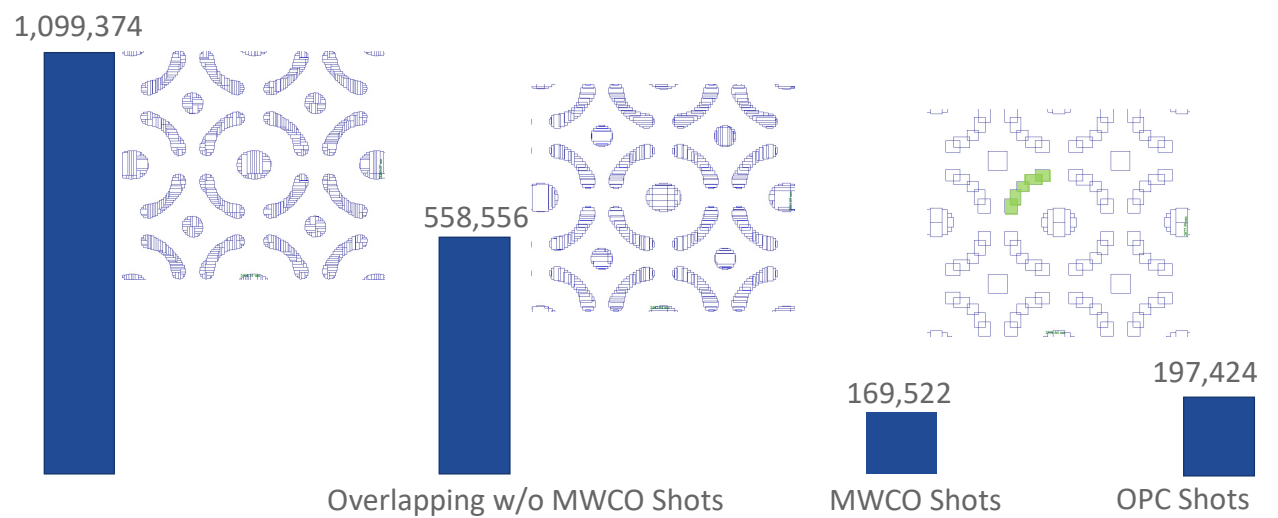
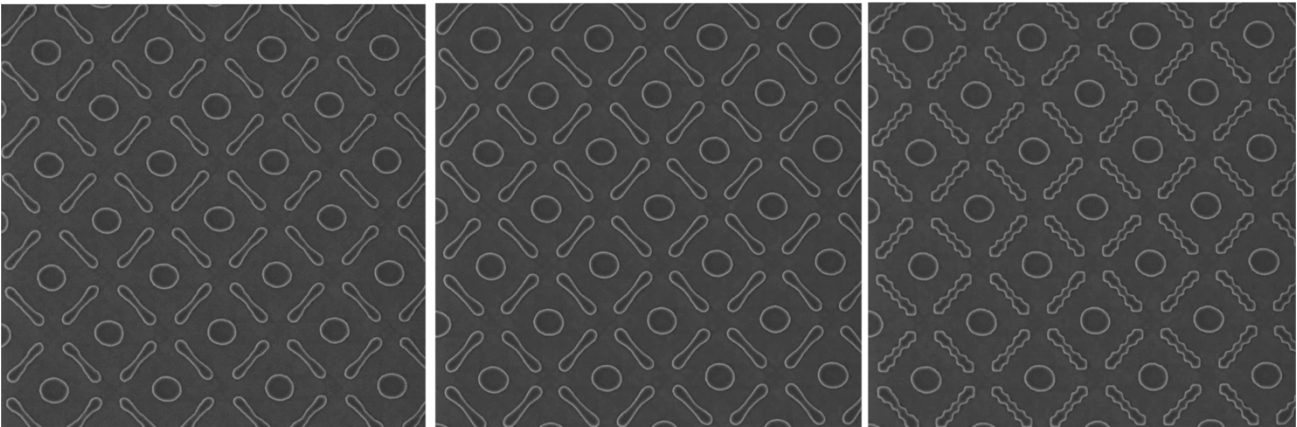


Figure 20. An ILT pattern for a contact array is fractured using conventional shots (left), overlapping shots without MWCO (center) and overlapping shots using MWCO (right). The MWCO solution had fewer shots (and therefore a shorter write time) than the OPC solution. Source: D2S

Figure 21 shows the curvilinear mask patterns from Figure 20.



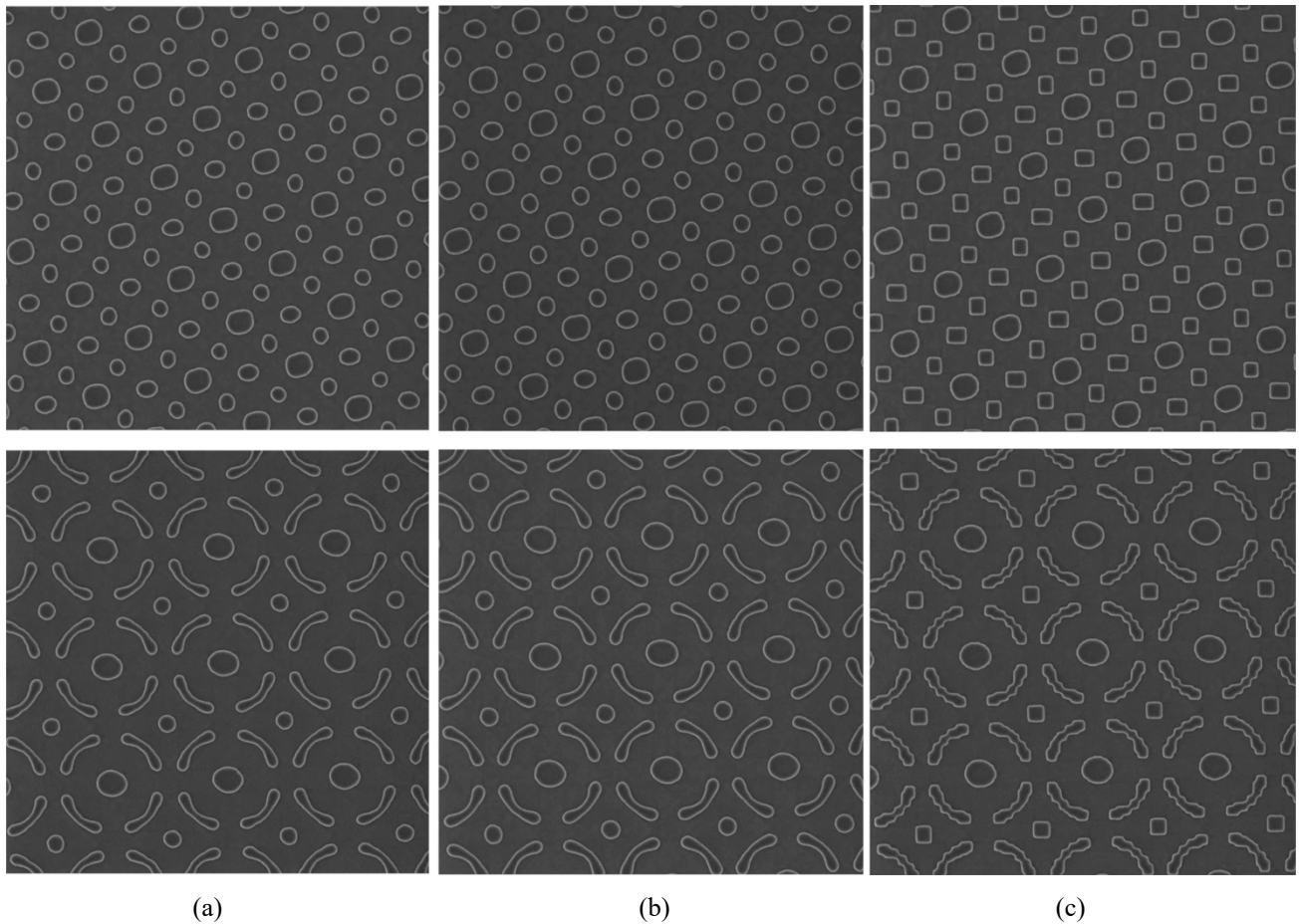


Figure 21: Mask SEM images of VSB shot for three contact arrays with (a) conventional shots, (b) overlapping without MWCO, and (c) MWCO [19] (Source: Micron)

Figure 22 is the process window plot produced from this experiment. The x-axis is the focus, the y-axis is the dose change. Since there are 61 sites, the ratio of the number of sites meeting the process window requirement to the total number of sites was plotted [13]. A CD variation of 10% is used as the process window criteria. The pseudo color from green to red represents process window from good to bad. Overall, curvilinear ILT using overlapping shots without MWCO and curvilinear ILT using overlapping shots with MWCO enlarged the green (or non-red) region by over 2X, especially the DoF. Comparing overlapping shots without MWCO and with MWCO, the MWCO is slightly better, showing the benefit of optimizing wafer EPE instead of mask EPE while only using half the number of shots as the overlapping shots without MWCO case.

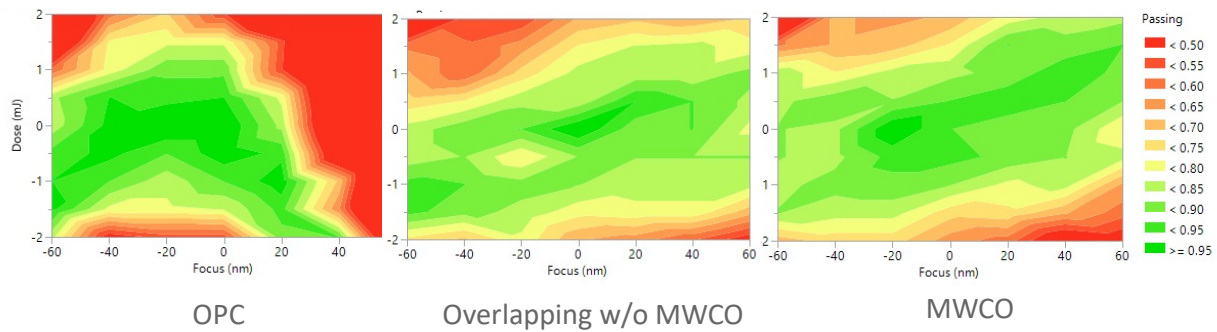


Figure 22. Process window plot produced from the wafers. The red pseudo color represents areas outside the process window; the green pseudo color represents areas inside the process window. The MWCO solution has more than 2X the process window as the OPC solution. Source: D2S and Micron

6. CONCLUSION

Curvilinear masks provide multiple, substantial benefits for both mask and wafer quality. Knowing this, the photomask industry has been preparing and is now ready to produce curvilinear masks in production. There are still some challenges to resolve, as shown in Figure 23 [14], which presents the responses of industry luminaries in the eBeam Initiative 2023 survey, ranking the concerns about producing curvilinear masks. Datapath was the top concern, which prompted work on the Multigon format standards. None of these concerns is insurmountable and many, such as datapath and mask metrology, have proposed solutions in the works already.

No Major Change in Curvilinear Mask Making Concerns



Please rank your biggest concerns in producing masks with curvilinear* shapes. n≥71

#1: Mask shop software infrastructure



N/A=14%

#2: Mask Inspection



N/A=13%

#3: Mask Metrology



N/A=14%

#4: ILT software



N/A=13%

#5: Access to Multi-beam Mask Writers



N/A=16%

#6: Mask Repair



N/A=15%

Note: 1-6 on X-axis indicate # of respondents that ranked that question as that ordinal number with 1 = highest

* The survey question included "Curvilinear shapes can be piecewise linear polygons of some resolution, Bezier, B-spline or other curved-edge descriptions, but excludes shapes that only contain Manhattan or 45-degree straight edges."

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Figure 23. Responses from eBeam Initiative Luminaries Survey 2023, showing that the biggest concern about curvilinear masks is the mask shop datapath[14]. Source: eBeam Initiative

OPC, mask rule checking (MRC), mask process correction (MPC), mask data preparation (MDP), and other data processing steps have traditionally inherited the polygon-based geometry manipulation from EDA which had been primarily focused on manipulating Manhattan rectangles efficiently on CPUs by moving or analyzing vertices and edges. Just like computer displays moved from vector-based to pixel-based screens, the pixel is ideal for processing curvilinear

shapes (or any shapes – pixels are shape-agnostic) [17]. This is not a new finding. All the mask and wafer equipment related to imaging are already pixel-based, including mask and wafer inspection, SEM machines, and mask repair tools.

Although OPC is edge based, or polygon based, ILT is pixel based. Now, multi-beam mask writers are also pixel-based. So, it makes sense that MRC, MPC, etc., all could become pixel based. MPC has already been introduced in the pixel domain, as pixel-level dose correction (PLDC). Since PLDC can be done in real time, the turnaround time needed for MPC becomes zero [21]. This opens opportunities to have the entire tapeout flow in the pixel domain. It is important to note that pixel data does not mean the data volume will be bigger than polygon data, since pixel data can be compressed.

Curvilinear masks are good for semiconductor manufacturing because 1) they are better for wafer manufacturing by significantly expanding the wafer process window; and 2) they are better for mask manufacturing because manufacturable targets are more reliably manufacturable and produce fewer nuisance defects.

But the most remarkable effect of curvilinear masks is that curvilinear masks enable curvilinear design, i.e., curvilinear wafer targets. The “Manhattan assumption” of the last four decades of semiconductor manufacturing had become engrained as a manufacturing limitation in VSB writing. With multibeam writing of masks, the mask writing community has lifted that manufacturing limitation. This represents a large new opportunity.

The industry is starting to work on studying the benefits [20, 22]. Just as manufacturable shapes are more reliably manufacturable on masks, manufacturable curvilinear designs are more reliably manufacturable on wafer as well. The EDA industry has not worked on enabling curvilinear designs because they hadn’t been manufacturable until recently. Studying the potential benefits in power, performance, area, yield, and cost with judicious applications of curvilinear designs would be a good research topic for future works.

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