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How curvilinear mask patterning will enhance the EUV process window: a study using rigorous wafer+mask dual simulation

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ABSTRACT

It has been known for quite a long time that the best possible process window obtainable for 193i layers is by using ILT correction. These are typically converted (at a high runtime cost) to Manhattan masks both for reasons of mask manufacturability as well as computational efficiency; OPC M3D and rigorous simulators have, until very recently, been optimized for speed to run primarily with Manhattan shapes. We have recently shown that the insertion into production of multibeam mask writers makes writing curvilinear masks possible and that it is preferable to move toward a completely curvilinear paradigm, not only because the ILT is better, but because the mask manufactured will have reduced variability. Recent studies have shown a similar need for ILT-style corrections for EUV, mainly due to more complex thick mask effects. We extend the work using Monte-Carlo methods for mask variability to show that EUV layers more strongly require curvilinear approaches to mask writing in order to minimize the wafer PV bands due to both the tighter overall tolerances combined with the smaller wavelength (13.5 vs, 193) which transfers mask defects to wafer over smaller lengthscales

Keywords: OPC, ILT, Multibeam, M3D, Process-window, Mask variability, MPC, EUV

1. INTRODUCTION

Inverse lithography technology (ILT) has long seen as a way to maximize the overall process window for immersion lithography. However, since ILT natively generates purely curvilinear shapes, which until recently could not be manufactured in high-volumes, the industry searched for ways to accommodate curvilinear ILT mask shapes into a Manhattan representation. A seminal study showed that one way to approach the mask manufacturability problem was by examining how simplifying mask shapes via Manhattanization minimally affected the overall process window. [1] However, previous studies have demonstrated a 30-50% reduction in the overall process window can be obtained by adopting curvilinear over Manhattan shapes for ILT when mask variability is considered. [2] Furthermore, recent studies have indicated that curvilinear ILT is necessary for EUV; there is also a 30-50% advantage in overall process window even when only the wafer plane variability is considered. [3] This paper combines these two studies to demonstrate how curvilinear ILT becomes a necessity for EUV high-volume manufacturing.

2. MANUFACTURING CURVILINEAR SHAPES

Historically, full-chip curvilinear masks could not be written. This section briefly reviews the reasons why, using a curvilinear EUV mask as an example. The test case used for this study is a set of 20nm contact holes at 50 pitch in a staggered configuration, as shown in Figure 1. It is designed to be simple and have an analytical result useful for hand-tuning; we do not rely on any ILT or optical proximity correction (OPC) engine for optimization of the solution. The optimal mask is an offset curvilinear feature, for reasons which will be discussed in the next section.

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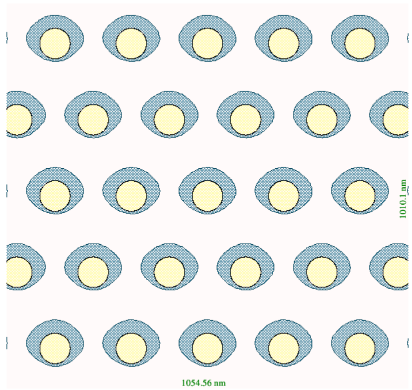

Figure 1. (yellow): Target correction is a set of 20nm holes at 50 pitch in X and Y, in a staggered configuration. (blue): The ideal curved EUV mask to print to target.

Until recently, the only high-volume mask manufacturing tool has been the variable-shaped-beam (VSB) eBeam mask writer, which exposes one rectangle (or unusually, a right triangle) of a pattern at a time. To make mask shapes compatible with this system, the input data (generally the output of OPC or ILT) must be broken into a set of rectangles ("fractured") before the data can be sent to the VSB writer. For mask patterns with curved shapes, it is necessary to fracture the data into a large number of small rectangles to accurately replicate the shape. This causes a dramatic increase in the write times for curvilinear shapes. For practical mask manufacturing, mask write time needs to be limited to 24 hours or less to minimize overall defects. [4,5] Therefore, curvilinear masks cannot be practically manufactured in a high-volume production environment using conventional fracturing methods.

Traditional ILT Manhattanization methods replace the curved features with rectangles during the ILT output step in an effort to simply the mask patterns and reduce mask write times. Such a process is expensive computationally, requiring an MRC-rule cleaning step and a second OPC-like optimization step after the ILT optimization. However, a much smaller number of rectangles is needed to make these masks. Figure 2 shows a representative example of the ILT Manhattanized fracturing.

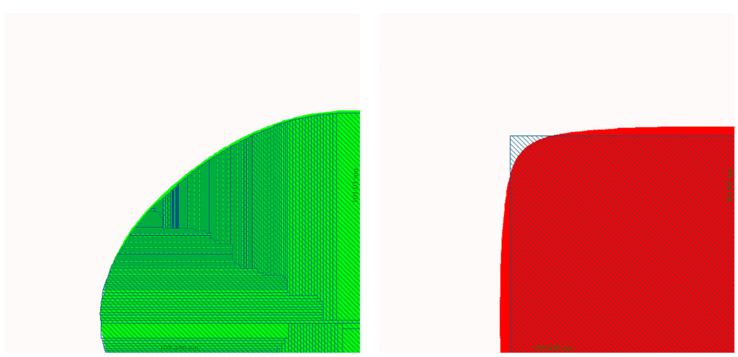

Figure 2. Shows the difference between fracturing using curvilinear shapes (left) and Manhattan shapes (right). The fracture on the left uses many rectangles to create a smooth curved shape, while the fracture on the right needs only one since the target shape is a rectangle. Overlaid is the simulated mask contour produced from the set of shots.

A closer look at the mask shapes in Figure 2 reveals that the mask patterns do not generally print to size. Typical EUV production models have print biases for small features, which requires mask process correction (MPC) to correct for the error. Usually MPC would simply size the midpoint of each edge of the rectangle to print to target as shown on Figure 3. Since this is an EUV main feature, and there is a significant amount of corner rounding, correction is required to create a mask shape that accurately reflects the desired OPC output. Different MPC corrections styles will be reviewed in a later section. Alternatively, there are model-based mask data preparation (MB-MDP) methods that pattern curvilinear

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features while simultaneously using a fewer number of overlapping shots. Such techniques work by relying on the low-pass filtering of the optical system: they typically match the desired mask shape by area-averaging over a small length scale. In this case, the mask pattern was already created with the mask process radius of curvature in mind, so it was possible to recreate the desired mask shape almost exactly.

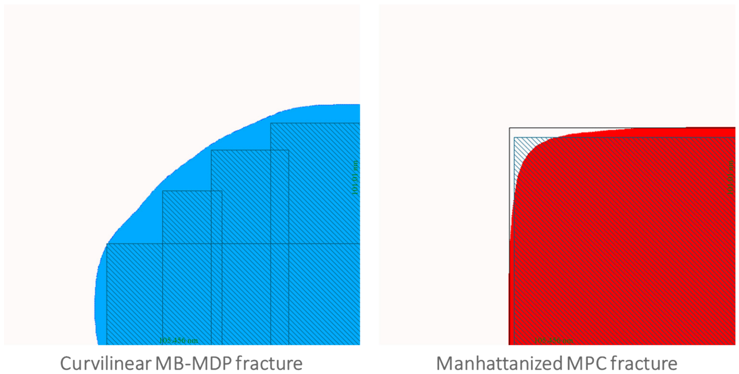

Figure 3. Examples of MPC applies to the target shape. (right) The rectangle has been sized smaller to print the mask contour edges to the correct size. (left) MB-MDP techniques are used to create a much smaller number of shots that still print the desired curved shape.

In the past couple of years, new mask writing tools arrived on the market. [6,7] Multi-beam mask writers are now available and have as a key advantage the ability to write any mask shape without runtime cost. This means that curvilinear shapes are just as manufacturable using multi-beam tools as are Manhattan shapes. The multi-beam tools rasterize an image of the desired mask pattern into a greyscale bitmap of varying doses. This bitmap is processed, and each pixel is assigned to a dose delivered by a small number of individual beamlets (either 10 or 20nm squares in size). MPC needs to be applied to these features as well, which can be done using a curvilinear version of MPC either before sending the data to the mutli-beam tool or using a multi-beam tool which can adjust pixel doses to do the MPC during mask writing time. [7] Example of both kinds of MPC are illustrated on Figure 4.

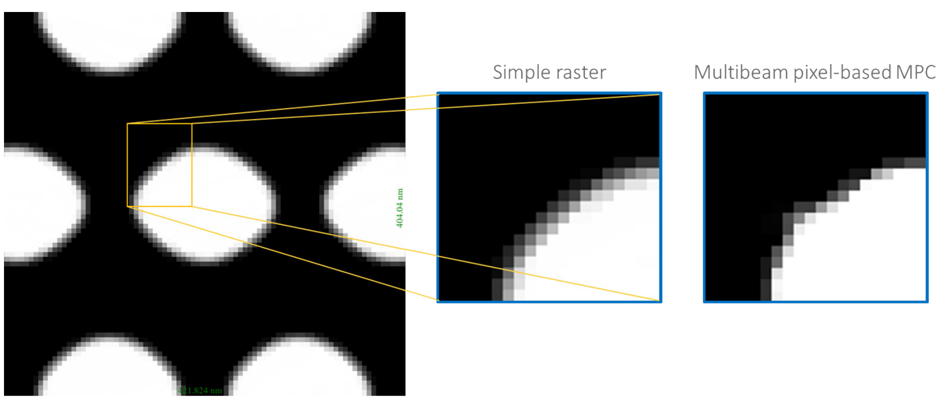

Figure 4. (left) Example multi-beam mask writer rasterization of the curvilinear EUV mask shape. (middle) Zoomed in view of the center contact greyscale pattern, after MPC. (right) Zoomed in view of the same center contact greyscale pattern after inline pixel dose MPC.

3. MANHATTAN AND CURVILINEAR ILT INEQUIVALENCE

Recent studies showed that Manhattan and curvilinear shapes could have optical equivalence for immersion lithography. [2] Three corrections are presented from that study: A fully curvilinear ILT, a curvilinear ILT assist feature with Manhattan core, and a pure Manhattanized ILT solution.

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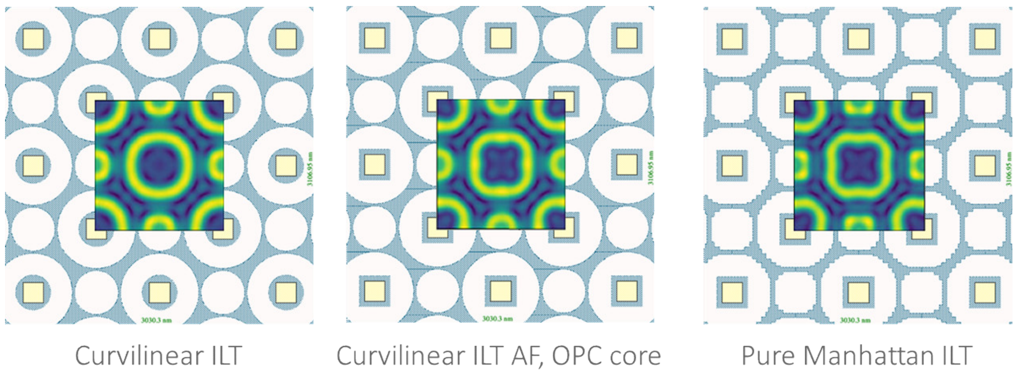

Figure 5. Corrections of a set of contacts for the immersion lithography case of Reference [2]. This is a set of 50nm contacts at 310nm pitch. (left) is the analytical curvilinear output. (middle) is the same assist features as in the left, but a square main feature. (right) is the fully Manhattanized correction. All print to the same 50nm target with similar process window. Overlaid is the band-limited mask for all three corrections.

Overlaid on the corrections in Figure 5 are the band-limited masks. These masks are only shown for the magnitude of normal incidence illumination for clarity; they are derived from the diffraction orders captured by the optical system, transformed back to real space. They are an equivalent representation of the continuous-tone-mask (CTM) used during ILT optimization and represent the mask features that are optically important. It is important to understand that there are an infinite number of mask patterns that can create the same (or very similar) band-limited masks, and that it is the similarity of the three band-limited masks which determine the similarity of the optical image. While there are an unlimited number of ways of constructing the masks, there is a straightforward way to guarantee similar Manhattan band-limited masks from their curvilinear counterparts for immersion lithography: ensure mask patterns are at the same place, and where one cannot match them exactly, ensure that the area is conserved over the resolution limit of the optical system. For immersion lithography, this corresponds to approximately 35nm, on the wafer scale. Because this is a relatively long length scale, it is relatively straightforward to convert curvilinear patterns to Manhattan patterns, obtain similar band-limited masks, and guarantee the solution is at a similar position in the ILT optimization space.

Table 1. Optical conditions for the EUV system used in this paper.

Optical parameters	
Wavelength	13.5nm
NA	0.33
Source	Quasar
Source angle	45 degrees
Outer sigma	0.9
Inner sigma	0.4

The conclusion changes we as move to EUV lithography. Figure 6 shows the curvilinear and Manhattan corrections for the test system. We define the optics in Table 1, typical for use in VIA/cut layers. All simulations are done using optical imaging only. Neither resist nor stochastic effects are considered. While such effects are important, we will assume that a larger process window provided by the optical system will translate directly to improved process window after resist processing. Furthermore, the optical simulations are performed as accurately as possible using a GPU-accelerated mask 3D rigorous simulator. [8] A full EUV absorber stack was simulated using four source locations centered in pole of the source using conditions found to be convergent to under 1e-4 of image intensity.

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Table 2. Typical EUV mask information and key mask 3D computational parameters

Mask Stack	n	k	thickness
Substrate	0.999	0.00182	
Multilayer (x40)	0.923	0.00622	2.78nm
	0.999	0.00182	4.17nm
Capping	0.089	0.016	2.5nm
Absorber	0.948	0.032	75nm
	0.957	0.023	12nm
Mask grid (XY):	1nm		
Mask grid (Z):	1nm		

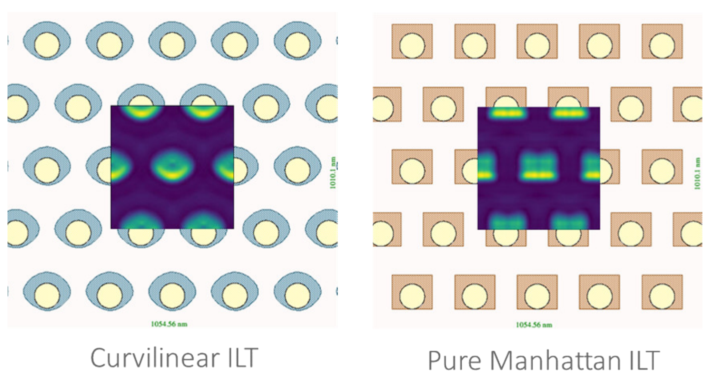

Figure 6. Corrections for EUV contact test case used in this paper. (left) is the curvilinear correction. (right) is the Manhattanized correction using rectangles. Both print to the same 20nm target with similar process window. Overlaid is the band-limited mask for all three corrections. Notice the masks look significantly different, and observe the stronger effective mask contribution at the bottom of each feature.

It should be noted that the corrections for EUV lithography are more complicated than that of immersion lithography due to the non-normal incidence (6 degrees) of the optical axis (chief-ray angle, or CRA) for the reflective optical system. Because the reflection coefficients of the mask are not symmetric about the CRA, the diffraction orders are not symmetric, either and the effective mask pattern gets shifted downward. [9] Further complicating the correction is the presence of mask 3D (M3D) effects, particularly mask shadowing. [10] A complex phase effect, the shadowing induces different diffraction behaviors depending on if the mask pattern edge is parallel or perpendicular to the CRA, which in turn creates additional asymmetry in X vs Y, and results in the shifted, distorted shapes for correction.

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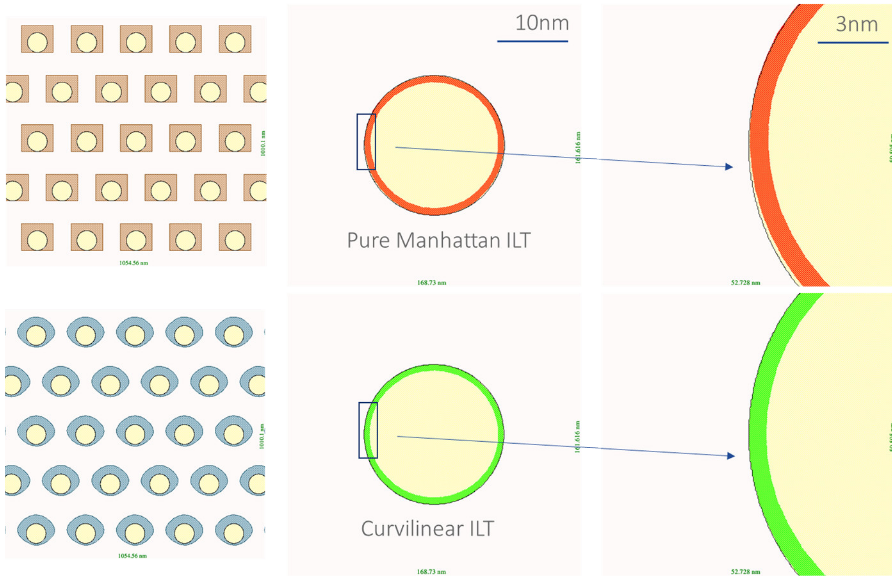

Figure 7. Comparison of the shapes of the EUV curvilinear vs. Manhattan correction. (left) are the corrections, the same as in Figure 6. (middle) shows the +/- 30nm focus bands, similar in both cases, and critically prints to size in X and Y. (right) is a zoom in on the shape. While the curvilinear mask prints to a circle, the rectangle mask is a distorted circle.

Even though both corrections give similar focus behavior (see Table 3), two subtle differences are observable. First, the band limited masks in Figure 6 are significantly different, which reflects not only the much smaller wavelength, but also the differences in curved vs. Manhattan shapes relative to the M3D effects. Given that ILT optimizes the curvilinear CTM, there can no longer be any expectation that the Manhattanized counterpart is near a minimum. This results in the second difference: the Manhattan correction is a distorted circle. While the X and Y CD match the target at the midpoints, there are distortions in the final contour due to the EUV lithography M3D effects. This simple rectangle is not the optimal solution and while a much more sophisticated Manhattanization is required to create a fully symmetric contour, it will not be addressed in this paper. Unlike the immersion lithography case where the band-limited masks and optical results were qualitatively similar, both are significantly different under EUV conditions.

4. MASK VARIABILITY IMPACT ON WAFER PROCESS WINDOW

We will now compare how the different ways to make the mask will impact the overall process variability on wafer. In this section, for brevity, we consider only four cases: printing the ILT Manhattanized mask of Figure 6 using a VSB or multi-beam tool, considering two different MPC approaches, or printing the purely curvilinear ILT mask using a VSB tool with MB-MDP as well as using the multi-beam tool using inline MPC. As noted, MPC must be applied to the mask shapes to ensure the mask process did not introduce an overall print bias. This mask model is shown in Table 4 and is typical of advanced node models used for leading process nodes at many mask manufacturers.

Wafer process variability is assumed to be dominated by the focus behavior over +/-30nm from best focus. Mask variability is considered explicitly through stochastic variation of the position and dose for an individual eBeam exposure. Using Monte-Carlo techniques, every shot (for the VSB tool) or pixel (for the multibeam tool) is adjusted in position and dose by randomly sampling from a 5% dose or 0.2nm position one-sigma distribution. This distribution will be dominated by the dose effects; balancing the dose and position effects does not change the conclusions of this study. The perturbed shots/pixels are then simulated using the same mask model used for MPC to create a distorted mask contour. The process is repeated over 200 times to create a set of mask process bands that represent 6-sigma deviations from the ideal mask. We use this worst-case mask variability to simulate the effect on wafer. The industry standard practice is “Manhattan ILT,” “VSB tool”. Notice that the mask variability is a large component of the overall process variability; ignoring it will give overly optimistic results.

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Table 3. Wafer and Mask+Wafer process variability summaries. The data is split into the different correction schemes, for which a focus band is calculated for +/-30nm defocus. Mask effects are broken into the two kinds of mask writers and the kind MPC applied. A mask variability EPE band is computed, and then the wafer focus band is computed using the worst-case mask variability band.

Correction scheme	**Wafer Focus Band (nm)**	**eBeam tool**	**MPC applied**	**Mask EPE Variance (nm, 4x)**	**Wafer+Mask Focus Band (nm)**
Curvilinear	0.7nm	VSB	MB-MDP	2.6nm	1.9nm (0nm print bias)
		Multi-beam	Inline Pixel-based	1.0nm	1.2nm (0nm print bias)
Manhattan	0.8nm	VSB	Edge-based MPC	4.2nm	4.6nm (-2nm print bias)
		Multi-beam	Area-based MPC	1.5nm	1.3nm (+1nm print bias)
			Edge-based MPC	1.5nm	1.6nm (-2nm print bias)

Two factors emerge from this data. First, the kind of mask writer used has a tremendous impact on the wafer variability, with the multi-beam mask writer having 50-80% reduction in variability compared to current industry practice. The reason for this is easy to understand: the mask error correlation length in the mask stochastics. For VSB tools, the entire edge of the shot moves all at once, which means the entire feature shifts in the same direction. Contrast the case for the multibeam tool, where several pixels would have to move in unison to generate the same mask error as the VSB tool. Therefore, the mask error band for multibeam tools must be statistically smaller than that of VSB tools, as long as the VSB shots themselves are larger than 10nm on mask scale. Since VSB shots are typically 40nm and above, the new multi-beam mask writers will have less variability than the older mask writers. Of course, if the VSB tools were written with data fractured down to 10nm sizes, they would approach the multi-beam writers in stochastic mask error contribution. This comes at a high cost of mask write time, and, ultimately, mask yield.

Second, regardless of the tool used to write the mask, curvilinear shapes themselves print with lower variability (again, by around 30-50%) than the Manhattan shapes. This is mainly because the curvilinear shapes are smooth, and can be printed with high contrast by the mask process, whereas the Manhattan corners are sharp and the contrast there suffers. This implies that the printability of the curvilinear features, if they meet the size and curvature requirements of the mask process, is always more consistent, which will reflect in lower variability on the wafer plane.

5. MPC AND MANHATTAN SHAPES

A closer look at Table 3 shows the difference in overall process variability using two different kinds of mask correction: edge matching, most commonly done for MPC, and area matching, usually done for MPC on assist features. These two correction styles are shown in Figure 8. For EUV (and for immersion lithography, as well), mismatches in area and main feature edges each independently result in print biases. Mismatched area means a smaller 0^{th} diffraction order, a reduction in overall energy captured by the feature, thus in the overall size of the feature. Mismatched edge placement results in the classic MEEF-like effect, with the subsequent pattern bias depending on the direction of the error.

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Table 4. Parameters used in the EUV mask model. The parameters are typical of those used for leading-edge masks.

Gaussian kernels	
Sigma	Weights
10	0.30
30	0.45
100	0.15
500	0.10
Threshold:	0.41

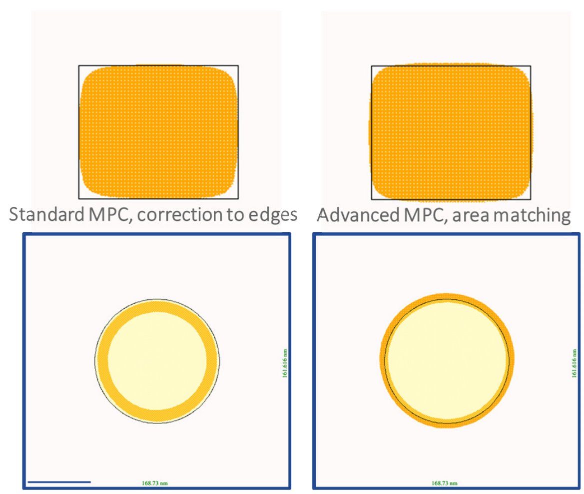

Figure 8. Comparison of two different MPC styles for the rectangle contact. (top) are the mask contours relative to the target. (bottom) are the wafer process bands. (left) is standard MPC where the goal is to match the center of the long edges. The area loss creates a process bias on wafer and makes the wafer feature smaller. (right) is an area-matching MPC, which is closer to the desired wafer target, but now has a process bias due to MEEF effects per edge. Other, more complex, corrections will be needed to print the wafer contours properly.

Such area loss effects are unavoidable for Manhattan shapes, in particular, and for sharp corners in general. They are also large relative to the EUV feature sizes. It is not simple to balance the effects of area loss by oversizing to account for it; simply matching the area overcorrects for the print bias due to the edge-based MEEF effects. Significantly more complex MPC is required to obtain the ideal mask shape, which requires computing the optical image (critically including M3D) to determine MPC convergence. Taken to the practical limit, the only way to guarantee that the mask can be corrected to the desired mask shape is to limit OPC or ILT shapes to those that can be manufactured in the first place. Such a system requires a revision to the mask rule checks (MRC) to include items like minimum area and maximum curvature supported the by mask process, which will be a subject for an upcoming study.

6. CONCLUSION

Curvilinear masks create better wafer results than Manhattan masks, by at least 30% in focus variability. Furthermore, it is possible to manufacture these curvilinear masks today using new multi-beam mask writer tools which contribute another 50% process window gain. The total gain for EUV features is predicted to be as much as 70%. As such, there is no reason to maintain the status quo of ILT Manhattanization, which was only minimally acceptable for immersion

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lithography. Specific EUV effects combined with the tight lithography error budgets require curvilinear corrections for EUV. Not only will the wafer results be more resilient to process window variation, but the actual runtime of the ILT itself will benefit as compared to the standard practice today. Without the need for expensive Manhattanization steps in the ILT correction flow, the ILT runtime should significantly reduce, potentially fast enough for full-chip correction. Furthermore, it may be possible to implement the new curvilinear MRC requirements as constraints during the ILT optimization directly, minimizing or eliminating another separate MRC check. The OPC and mask industry should move forward together with these methods.

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