Best depth of focus on 22 nm logic wafers with less shot count

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ABSTRACT

The contact layer for the 22 nm logic node faces many technological hurdles. Even using techniques such as multiple-exposure patterning and 193 nm immersion, it will be difficult to achieve the depth of focus and CD uniformity required for 22 nm production. Such difficulties can be mitigated by recent advances in Inverse Lithography Technology (ILT). For example, circular main features combined with complex curvilinear assist features can provide superior CD uniformity with the required depth of focus, particularly for isolated contacts. However, such a solution can lead to long mask write times, because the curvilinear shapes necessitate a higher shot count induced by inefficient data fracturing, even without considering the circular main features. The current approach is to Manhattanize the curvilinear features resulting in a nearly equivalent image quality on the wafer; but a further reduction in mask write times could help lower costs. This paper describes a novel mask-writing method that uses a production e-beam mask writer to write main features as circles, with curvilinear assist features, while reducing shot count compared to traditional Manhattanized masks. As a result the new method makes manufacturing of ideal ILT-type masks feasible from a technical as well as from an economic standpoint. Resist-exposed SEM images are presented that validate the new method.

Keywords: Photo mask, shaped-beam, shot count, mask writer, circular aperture

1. INTRODUCTION

At the 22 nm logic node, an extension of 193 immersion (193i) is likely to be the lithography solution of choice. Other alternatives such as e-beam direct-write, nano-imprint, and EUV are technically promising, but a practical, high-volume solution for 22 nm is unlikely to emerge during the required timeframe. Multi-patterning and other techniques will be required to extend the 193i capabilities, but the solution will also depend on a large amount of decoration with optical proximity correction (OPC) shapes. In the contact and via layers, and particularly for isolated features, extensive use of sub-resolution assist features (SRAFs) will be necessary to produce the required process window. Computational Lithography will therefore be a critical part of the solution, meaning that a huge amount of computation must be performed to calculate the appropriate mask shapes to create the required wafer images with sufficient process window. Source Mask Optimization (SMO) will also play a major role, meaning that the light source may be optimized for the most critical design parts and then OPC calculated for all design parts to be appropriate for that light source. An earlier idea, Inverse Lithography Technology (ILT), derived the optimal mask shapes given a light source and the desired wafer shapes. Instead of moving edges in a trial-and-error fashion, ILT mathematically derives the appropriate mask shapes. All of these are examples of reticle enhancement technologies (RET). Regardless of the name, it is clear that complex patterns will be required on masks to print 22 nm patterns on the wafer with adequate resolution and manufacturing tolerance.

2. IMPACT OF INVERSE LITHOGRAPHY TECHNOLOGY ON MASK MAKING

2.1 Background

ILT tends to generate curvilinear shapes initially [1]. While the benefits of ILT shapes for wafer lithography were clear, manufacture and inspection of masks based on ILT seemed problematic. All precision masks for leading-edge technology nodes are written using variable shaped-beam (VSB) machines with 50 keV e-beam guns. VSB machines write rectangular or sometimes 45-degree triangular shapes. Mask Data Preparation (MDP) fractures all shapes on the mask to constituent non-overlapping VSB shots so that any mask shapes can be written using a VSB machine. The problem with shooting curvilinear shapes, and in particular the small curvilinear shapes that are SRAFs, is that they fracture to an extremely large number of shots. Kim et al. [1] has shown that an isolated ILT contact can take as many as 180-230 shots per contact to draw the mask shape. This contrasts with taking 1 shot per contact at the 45 nm node (to draw one over-sized rectangle per contact), and up to 9 shots per contact for vertical and horizontal assist bars. Since mask write time is largely proportional to the number of shots required, the mask write times for curvilinear ILT masks has until now been prohibitive.

2.2 Viable Mask Write Times

Mask write times are critical for two reasons: The first is mask cost; since the amortized cost of a mask writer and the operating costs are a function of write-time, and since mask yield, particularly due to CD uniformity, degrades as a function of very long write times, mask costs are significantly higher for masks that require a large number of VSB shots. The second reason is mask yield; even if cost was no object, masks that require a very large number of VSB shots cannot be written at all. For very high volume manufacturing of wafers, wafer yield outweighs mask cost concerns. So simply being able to write the masks that yield more good die on the wafers becomes the dominant factor. But for the majority of designs where the wafer volume is less, the mask cost is a critical factor. For them, an appropriate trade-off of mask cost and wafer yield needs to be reached.

Curvilinear ILT output yields mask write-times that are unacceptable to both of these factors using conventional MDP and conventional mask writers. To optimize ILT shapes for VSB-based mask writing, Manhattanization of these shapes [1] has been enhanced significantly and thus becoming manufacturable in recent years. Manhattanization now provides equivalent lithographic performance with far fewer e-beam shots.

However, the ability to write the original curvilinear ILT masks using production mask writers is desirable for several reasons.

1. Future advances in ILT technology could potentially provide further enhancements in process window and critical dimension uniformity (CDU) if curvilinear shapes could be written on the mask reasonably well, particularly for very high volume wafer production.
2. Since even e-beam writing exhibits short-range blur in the 20-40 nm range, highly Manhattanized curves and angled lines exceed the limits of accurate writing. This means that even if the mask was written perfectly, the input shape is not the same as the produced shape on the mask. While simple corner rounding effects are modeled in ILT, small complex shapes are difficult to model correctly.
3. Since masks are inspected at 257 nm wavelength, even at 4X dimensions highly Manhattanized (stairstepped) curves and angled lines are difficult to certify using the appropriate inspection pixel size. The original ILT shapes are easier to inspect.
4. SMO and other further optimizations of the light source tend to give rise to even more complex shapes, both for assist features and for the main features.
5. CDU of mask shapes, particularly the variation in the open area of a particular shape is worse when much of the target shape is being written with the corners of the VSB shots. The edge slope of the e-beam shot is the shallowest at the corners [2].
6. Mask Error Enhancement Factor (MEEF) is also better for shapes that have less periphery for a given area (light energy being transmitted through that mask opening). Even after corner rounding, Manhattanized shapes have, by definition, more periphery. So the CDU of the mask is better with the original curvilinear shapes, and the MEEF for that variation is also lower, improving the CDU on the wafer further.

While writing curvilinear ILT masks is desirable, the challenge of achieving practical write times remains. The Model Based Mask Data Preparation (MB-MDP) technique can bridge the gap between much needed ideal masks and masks which can be manufactured on today's equipment. As shown below, MB-MDP using overlapping e-beam shots is able to bring shot count for curvilinear shapes back to a level which can be handled on today's equipment.

2.3 Drawing circles with one shot

The benefits of using circles were discussed in the poster session, at PMJ 2010 [3]. Both, for design density and for manufacturing tolerance to error, drawing circles on masks is better than drawing squares or rotated squares on masks.

The only problem with circles on the masks, mask write time and mask cost, is addressed by allowing circles to be shot with one shot using a series of circular apertures. These circular apertures are placed on the second aperture of the new production e-beam mask writer from JEOL, the JBX-3200MV, also presented at PMJ 2010 [4]. The circular apertures are available alongside the conventional VSB aperture, so that the machine is able to write both circles and rectangles equally efficiently.

In the JBX-3200MV, a quantized set of diameters of circular apertures are used to shoot a continuous range of circular sizes. This is accomplished using dose control of individual shots. Every available size of a circular aperture in the machine shoots a small range of sizes via dose control. The combination of multiple diameters available and dose control provides a wide range of circles to be shot on the mask, covering from 100 nm to 350 nm. In essence, this creates a circular "VSB" capability on the machine.

2.4 Overlapping Circles

In addition to being able to draw circles on the mask, such as the main feature for a contact/via, with one shot, a circular aperture has a large advantage in drawing curvilinear or non-orthogonal assist features. A circle is unique in having the same curvature no matter what angle it is being viewed from. A circle is the optimum instrument with which to write curvilinear shapes for this reason. But a circle has one problem in that it does not tessellate a shape. So in order to draw a good curve using a circular stencil with minimum shot count, overlapping the shots becomes necessary. The JEOL VSB machines have always been able to overlap shots, and the JBX-3200MV is no exception.

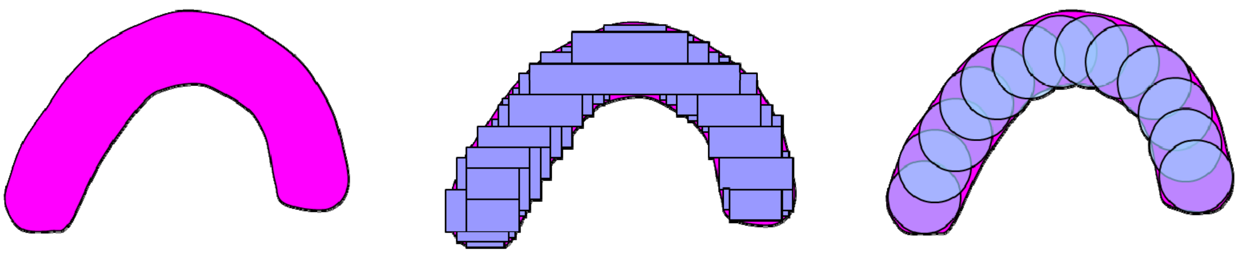
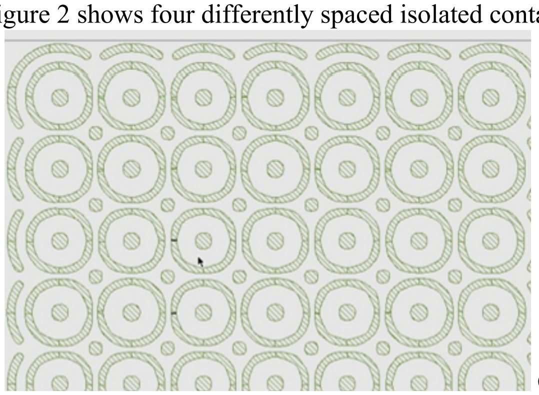


Figure 1. Comparison of conventional type fracturing (center) with MB-MDP using overlapping circles (right) for an ILT-type target shape (left).

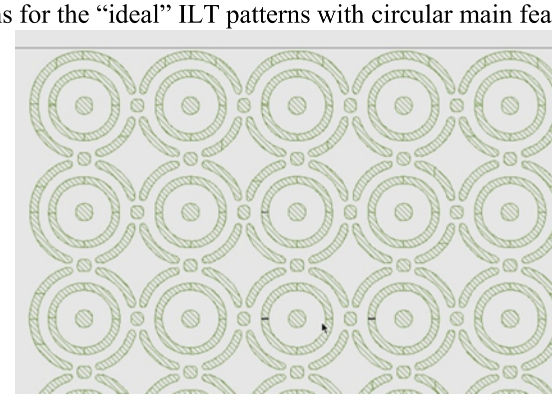
3. TEST PRINTING RESULT OF ILT CONTACT PATTERNS

The patterns used in this study are identical to the ones used by Kim et al [1] except that the main features are drawn as circles for improved mask CDU and improved MEEF, resulting in an improved CDU on the wafer.

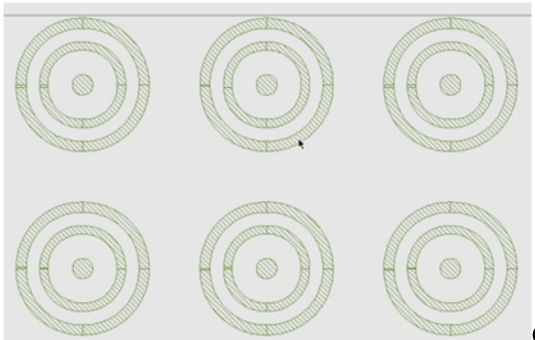
Figure 2 shows four differently spaced isolated contact patterns for the "ideal" ILT patterns with circular main features.



C0-1



C0-2


C0-3

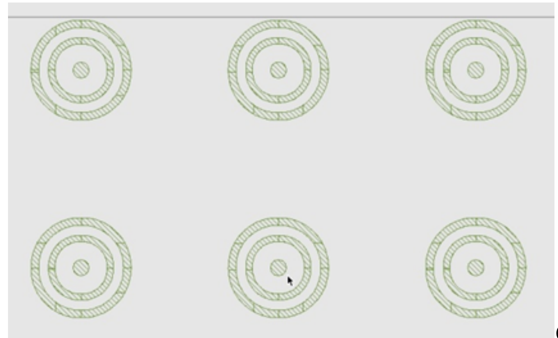

C0-4

Figure 2. Differently spaced isolated contacts with ideal, curvilinear ILT patterns. In wafer dimensions the contact pitches are 350 nm, 500 nm, 700 nm and 1000 nm for the patterns C0-1 through C0-4, respectively.

The contact DICD is 60 nm on the wafer, and is drawn at 320 nm on the mask at 4X. The illumination conditions are NA=1.35, illumination = annular (0.54i/0.82o) unpolarized, and the mask is a binary COG mask [1].

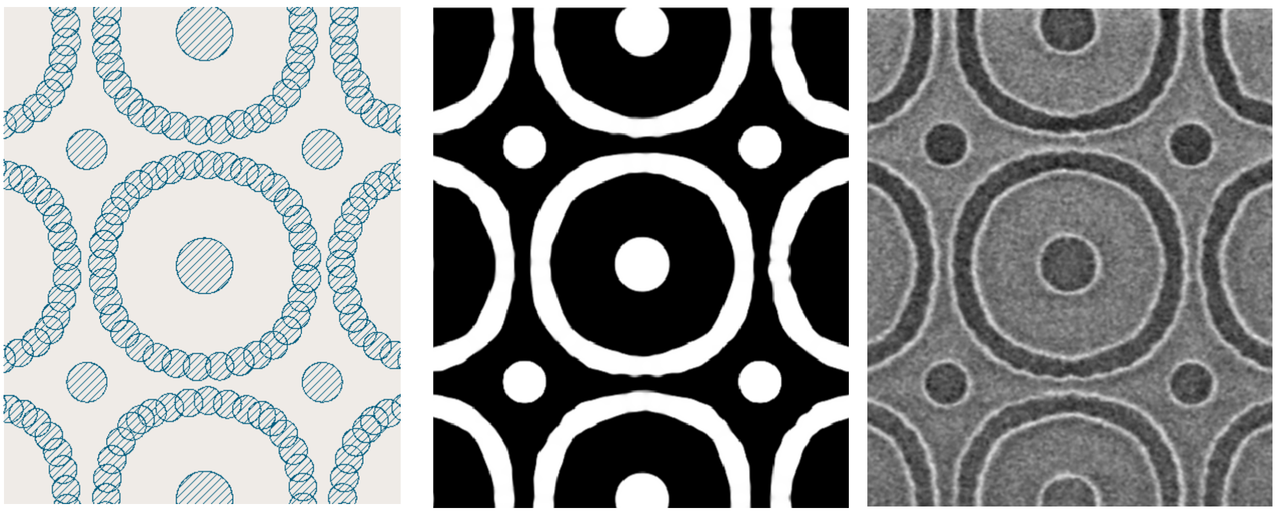


Figure 3. MB-MDP results for 350 nm pitch contacts (pattern C0-1) using overlapping circular shots (left), simulated e-beam mask image (center), and the corresponding mask SEM image (right).

Figure 3 shows the overlapped circular shots used for the assist features, and the single circular shots used for the main features and the "in-between" circular SRAF in the C0-1 pattern on the left and the e-beam simulated projected mask image using these shots in the center. The SEM image of the test exposure results on the JBX-3200MV with the circular apertures is shown on the right of Figure 3. All SEM pictures shown here are resist exposed, pre-etch SEM pictures.

Figure 4 through Figure 6 show the MB-MDP results for contact pitches of 500 nm, 700 nm, and 1000 nm, respectively.

Note that the simulation pictures and the printed pictures both show waviness in the SRAF rings. A certain amount of line width roughness (LWR) is acceptable to produce equivalent lithographic results on the wafer. So this represents a shot-count vs. wafer quality trade-off. An increased number of shots with lower dose for each shot will produce smoother (less wavy) SRAF rings. Correspondingly, more shots may be used to produce more wavy patterns, if that proves to be sufficient for wafer printing using these mask patterns. A lithographic comparison of various shot count tradeoff is planned for future work.

Figure 4. MB-MDP results for 500 nm pitch contacts (pattern C0-2) using overlapping circular shots (left), simulated e-beam mask image (center), and the corresponding mask SEM image (right).

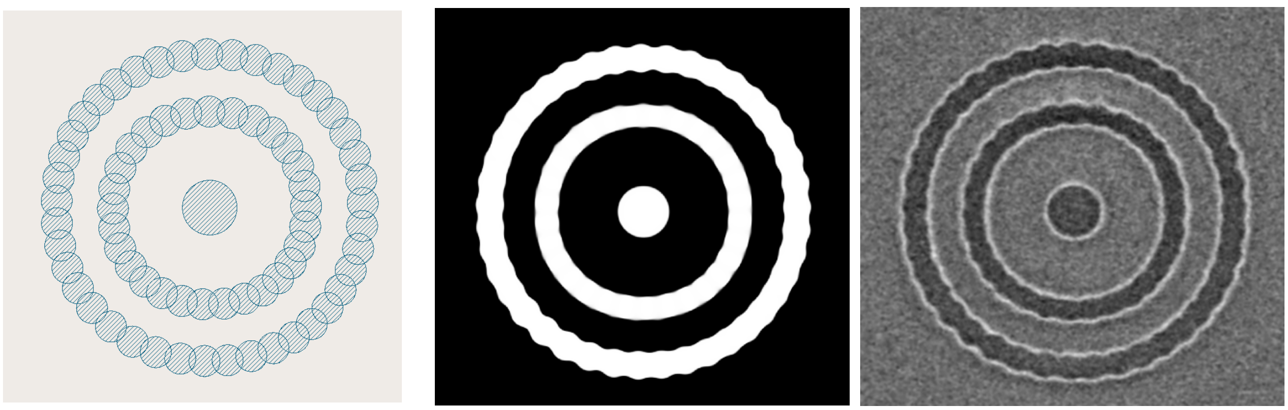


Figure 5. MB-MDP results for 700 nm pitch contacts (pattern C0-3) using overlapping circular shots (left), simulated e-beam mask image (center), and the corresponding mask SEM image (right).

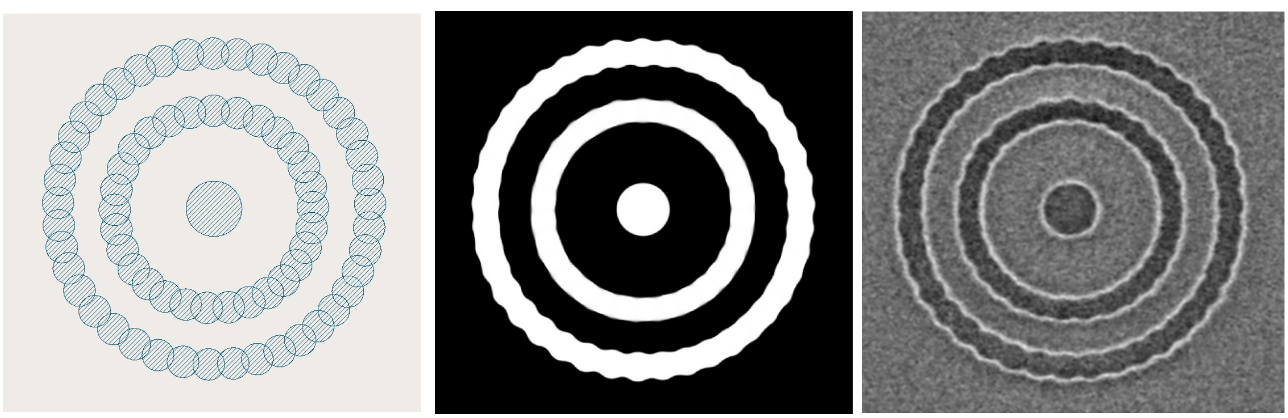


Figure 6. MB-MDP results for 1000 nm pitch contacts (pattern C0-4) using overlapping circular shots (left), simulated e-beam mask image (center), and the corresponding mask SEM image (right).

4. SHOT COUNT AND ACCURACY RESULTS

Table 1 demonstrates the accuracy and shot count comparisons for the four cases. Since the shot count is dominated by the shots required to shoot the SRAF rings, the more "integrated" SRAFs of C0-1 use the least amount of shots per contact. Most actual designs are a mixture of isolated and dense contacts, so the average shots per contact will be less than indicated here.

Table 1. Comparison of accuracy (per pixel edge error and contact area error) and the number of shots used for the 4 test cases shown in Figure 2.

	Per Pixel Edge Error			Area of Main Features				
Test case	**Mean**	**Sigma**	**Maximum Dist. Err**	**Minimum Area Err**	**Maximum Area Err**	**Average Area**	**Shots**	**Shots Per Contact**
C0-1	1.626	3.46	22.0	0.99971	1.000315	1.000003	**2077**	**42.4**
C0-2	0.80	4.0	22.0	0.99167	1.007628	1.000173	**1957**	**78.3**
C0-3	3.111	5.14	18.97	0.99938	1.000255	0.999988	**639**	**71.0**
C0-4	2.384	5.82	20.0	0.99938	1.001277	0.999093	**639**	**71.0**

The accuracy shown in Table 1 is measured as follows. The "per-pixel edge error" is measured as a comparison of the target shape edge vs. the simulated shape edge. A comparison against a post-etch mask SEM is planned for the future, but will require a collaboration with a mask shop with appropriate equipment. Every 1 nm pixel where the edge of any shape in the simulated edge is off from the target edge, the distance is computed and tabulated. Values for mean error, maximum error, and its spread, sigma are recorded. The maximum error is not a statistical calculation. It is the actual worst error found on the test pattern taking all pixel errors into account.

In addition to the per-pixel edge error, for the main features only, the total area of the simulated image is compared to the desired total area in the original data. Again, in this case, the minimum area error and the maximum area error are not statistical numbers. They are the actual minimum and the maximum of all contacts on the test case. Because the amount of energy transmitted through the shape on the mask during wafer processing is the most important factor in preserving CDU, in addition to the edge errors and other factors, the area error of the simulated result is explicitly measured and optimized for in selecting the circular aperture and the dose amount.

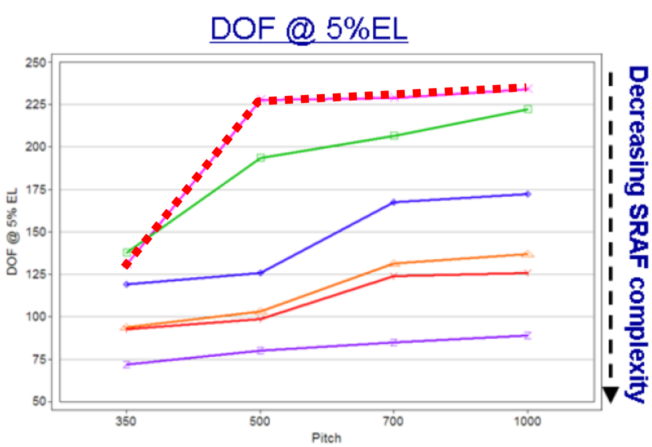


Figure 7. Depth of Focus (DOF) at 5% exposure latitude for contact pitches of 350 nm to 1000 nm and decreasing complexity of sub-resolution assist features (SRAFs) from top to bottom. The patterns used in this study have the most complex SRAFs (red dashed line).

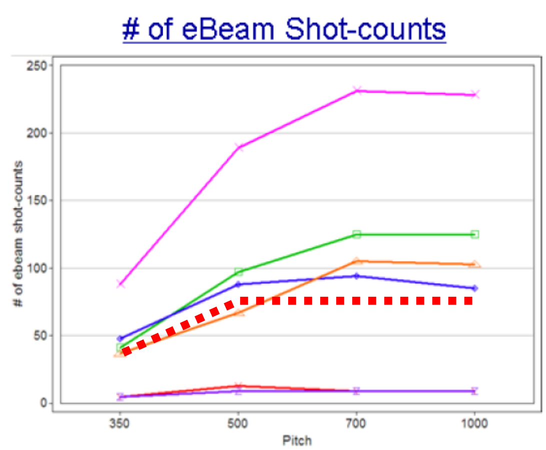


Figure 8. E-beam shot count vs. contact pitch and decreasing SRAF complexity from top to bottom. While the top line shows the conventional shot count for the most complex SRAFs the red dashed line shows the largely reduce shot count for the same SRAFs achieved with MB-MDP.

The red dashed lines in Figure 7 and Figure 8 demonstrate the trade-off of e-beam shot count for mask writing vs. the depth of focus achievable using 5% exposure latitude in wafer writing. The red dashed lines are shown as an overlay of a result from Kim et al [1] demonstrating that significantly lower shot count can create the same depth of focus. Without increasing the shot count, the main features can be shot as a circle, further enhancing the CDU on the wafer.

5. PRINTING A RANDOM LOGIC CONTACT LAYOUT

To test the concept further, a 32 nm logic node test pattern shrunk to 22 nm was processed by Luminescent Inverse Synthesizer™ to produce two alternative ILT results. Figure 9 shows the "ideal" ILT results with circular contacts and curvilinear assist features. Figure 10 shows the Luminescent-optimized Manhattanized version of the ILT mask that has been designed to require less e-beam shot count using conventional (non-overlapping) VSB shots. The Luminescent-optimized Manhattanized mask is demonstrated to produce equivalent DOF to the ideal ILT mask with significantly reduced shot count. A conventionally fractured ideal ILT shape as in Figure 9 would require thousands of shots, while the Luminescent-optimized Manhattanized mask requires only 620 shots in the conventional writing mode of the JBX-3200MV with a maximum VSB shot size of 800 nm on a side.

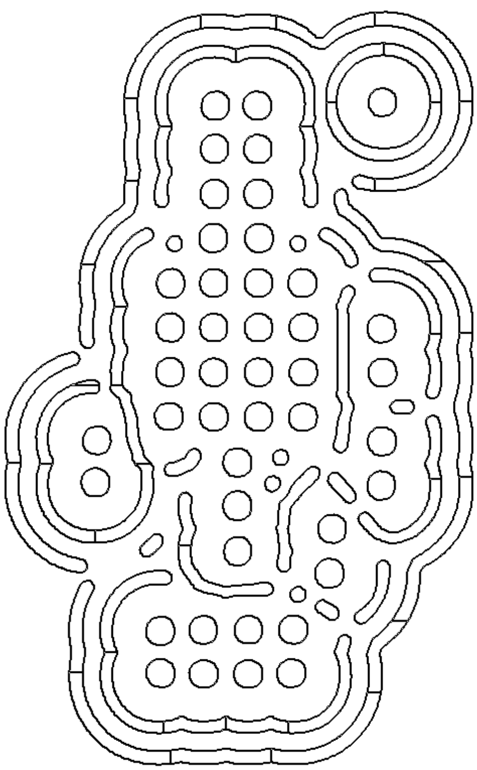


Figure 9. Ideal ILT mask of a random logic contact layout using Inverse Synthesizer™.

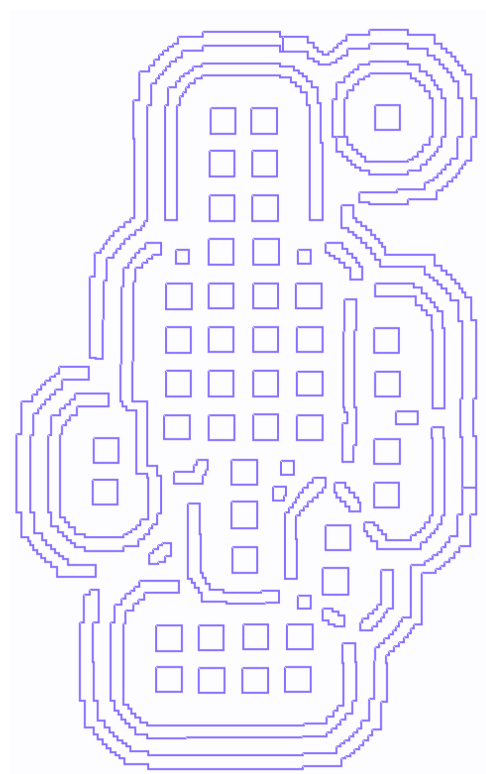


Figure 10. Optimized Manhattan version of an ILT mask for the same contact layout shown on the left.

On the other side using MB-MDP with overlapping circles the shot count for the ideal ILT mask can be reduced even below the value achieved with the Manhattanized mask (Figure 11). Using the same mask writer JBX-3200MV in a mode allowing for overlapping circular shots in combination with rectangular VSB shots, the mask can be written with only 484 shots. This represents a shot count reduction for the ideal ILT mask of approximately 22% compared to the conventionally fractured Manhattanized mask. Since the overlapping shapes are shot with a lower dose the shot count reduction translates into an even higher reduction in mask write time.

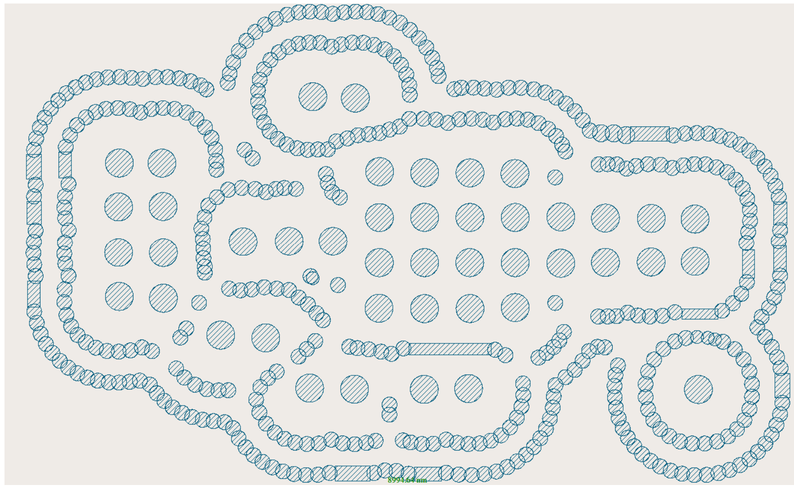


Figure 11. MB-MDP results using overlapping circular e-beam shots for a 22 nm random logic contact layout achieves a 22% reduction in shot count compared to the conventionally fractured Manhattanized mask shown in Figure 10.

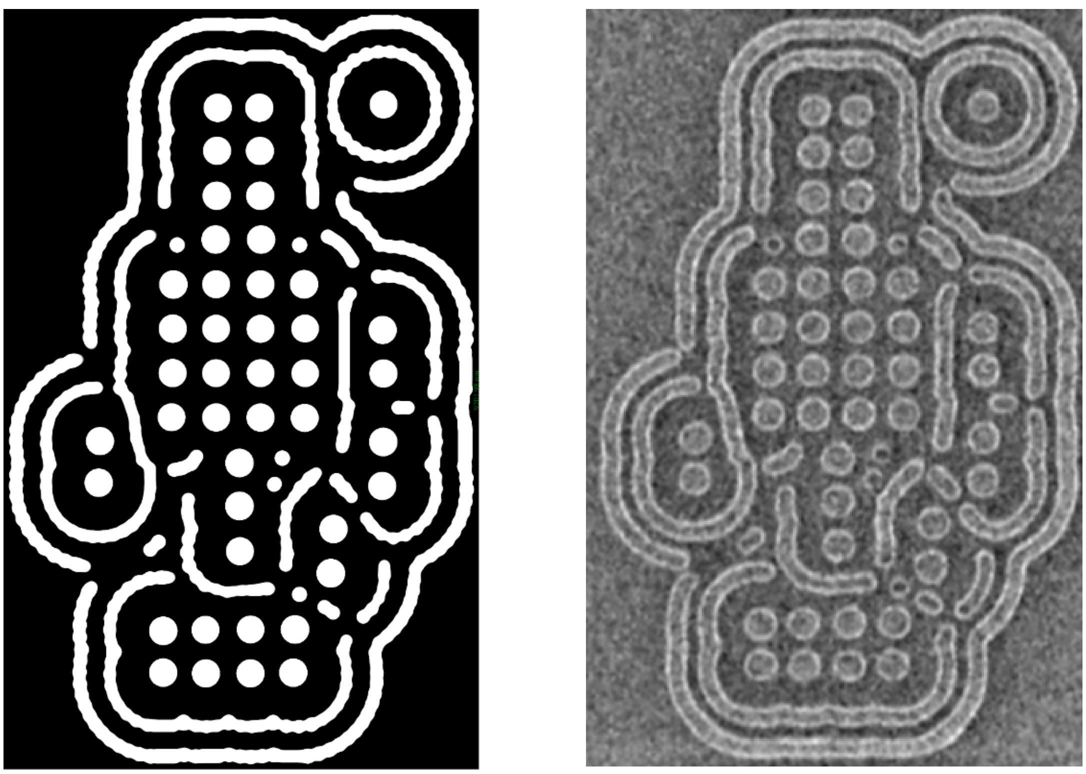


Figure 12. Simulated e-beam mask image (left) and resist exposed pre-etch SEM picture (right) of the ideal ILT mask shown in Figure 9. The contact mask diameter is 320 nm and the SRAFs are around 150 nm.

As shown in Figure 12, the simulated e-beam mask image very well matches the resist-exposed, pre-etch SEM image of the ideal ILT mask.

6. CONCLUSIONS

Contact layers at the 22 nm technology node require complex mask shapes as generated by methods like the Inverse Lithography Technology (ILT) in order to achieve acceptable contrast, depth of focus and mask error enhancement factor. However, in the past, ideal ILT masks consisting mostly of curvilinear shapes were not manufacturable because conventional fracturing methods produced e-beam shot counts which exceeded practical limits. The new Model Based Mask Data Preparation (MB-MDP) method described in this paper enables practical manufacturing of ideal ILT masks. By using circular overlapping e-beam shots on a production e-beam writer, shot count for circular contacts and curvilinear assist features is well within the limits of today's e-beam writers. Even compared to a Manhattanized version of an ILT mask the shot count is about 22% lower when using the new method for an ideal ILT mask.

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