Writing “wavy” metal 1 shapes on 22 nm Logic Wafers with Less Shot Count

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ABSTRACT

The metal 1 layer for the 22 nm logic node will require complex “wavy” shapes. These shapes are decorations on main features and require highly accurate printing in order to meet CD requirements. Despite attempts to reduce mask shot count by lining up the left-right or top-bottom jogs of the edges, the explosion in the required shot count is considered inevitable. This paper demonstrates a new mask writing method using model-based mask data preparation (MB-MDP), on a production e-beam mask writer. MB-MDP is a complementary technology to conventional fracturing. It incorporates e-beam simulation as an integrated part in order to determine the dose and shape of the overlapping shots to draw complex mask shapes with less shot count. Specifically, the new method writes these “wavy” metal 1 wires accurately with a significant reduction in shot count. Resist-exposed SEM images will be shown that validate the mask simulation results. A shot count comparison will be made with conventional methods.

Keywords: Depth of focus, mask, shot count, mask writer, lithography simulation, RET, OPC, ILT, SMO

1. INTRODUCTION

In the conventional semiconductor design-to-manufacturing flow, mask data is prepared by Optical Proximity Correction (OPC), mask rules are checked, and then the instructions for the mask writer are derived in the fracturing sub-step of the Mask Data Preparation (MDP) flow. The fracturing step tessellates the desired mask shapes into constituent rectangles and sometimes also 45-90-45 triangles. Overlap removal is performed redundantly in a conventional mask making flow to assure that no part of the design is being double-dosed, which would create a much larger image on the mask than the design intended.

All production e-beam machines for semiconductor manufacturing, whether for mask writing or for direct writing of wafers, use 50kV e-beam guns using a variable shaped beam (VSB), and sometimes character projection (CP). McDonald et al. [1] demonstrated the use of non-orthogonal shapes for the production of imprint templates. In another PMJ 2010 paper [2] the newly introduced JBX-3200MV machine from JEOL, Ltd. is described. This machine writes circles of 100 nm to 350 nm diameter in one e-beam shot in addition to VSB shots of up to 800 nm x 800 nm (all in mask dimensions). VSB machines write rectangles and 45-90-45 triangles one shot at a time. That is why a sub-step of MDP fractures the desired mask shapes into such constituent VSB shots.

At 22 nm logic or 32 nm-half pitch (hp) technology node, it is anticipated that optical lithography using 193 nm light with immersion technology (193i) will be extended for production use. In order to make sub-wavelength features print with enough depth of focus, and print with sufficient process window, however, an extensive OPC is required, making the mask shapes highly complex. Whether Source-Mask Optimization (SMO), Inverse Lithography Technology (ILT), OPC, or some combination of the various computational lithographic methods, the desired shapes on the wafers have to be highly decorated in order to optimize the wafer yield of these devices. For contact and vias, and for isolated ones in particular where the contact stands alone without any other contacts in the neighborhood, the necessary degree of decoration with sub-resolution assist features (SRAF) is extensive. Efficiently writing these curvilinear SRAFs with reasonable mask write times using circular apertures on the JBX-3200MV is described in another paper [3] also shown at PMJ 2010. This paper in contrast focuses on the MB-MDP technique itself and investigates mask manufacturing quality metrics such as e-beam edge slope.

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2. MB-MDP FOR CIRCULAR APERTURES

In order to print features using circular apertures, a new MDP method needed to be deployed. Conventional fracturing is not sufficient when using circular apertures. This is because a circle does not tessellate a shape. Just as shooting a circle with rectangular shots takes many shots at some resolution limit, shooting a rectangle with only circular shots would take many shots. So in order to take advantage of circular apertures, allowing the shots to overlap on purpose becomes necessary. But overlapping shots create different doses to be applied to different parts of the design. If all shots are of the conventional “1.0” dose amount, the overlapped parts receive 2.0 dose. The parts with 2.0 dose will clearly print larger.

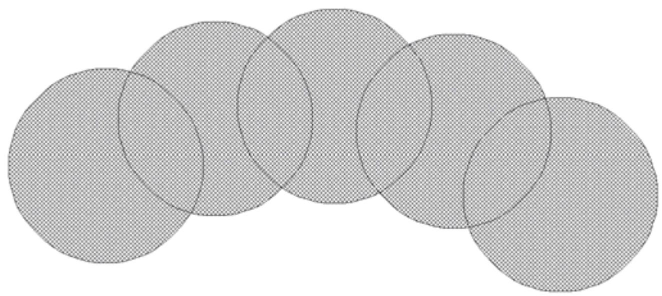

Figure 1. Overlapping circular e-beam shots each written with a dose amount of 1.0 so that the overlapping area receives a dose amount of 2.0.

In fact, since all e-beam shots are Gaussian convolutions of some short-range blur radius of 20 nm to 40 nm range for the machines intended for the most advanced nodes, the dose received by the mask surface is a continuously variable mountain range of doses, and the actual shape on the mask will be approximately the contour of that mountain range cut off at the resist threshold value as seen in Figure 2.

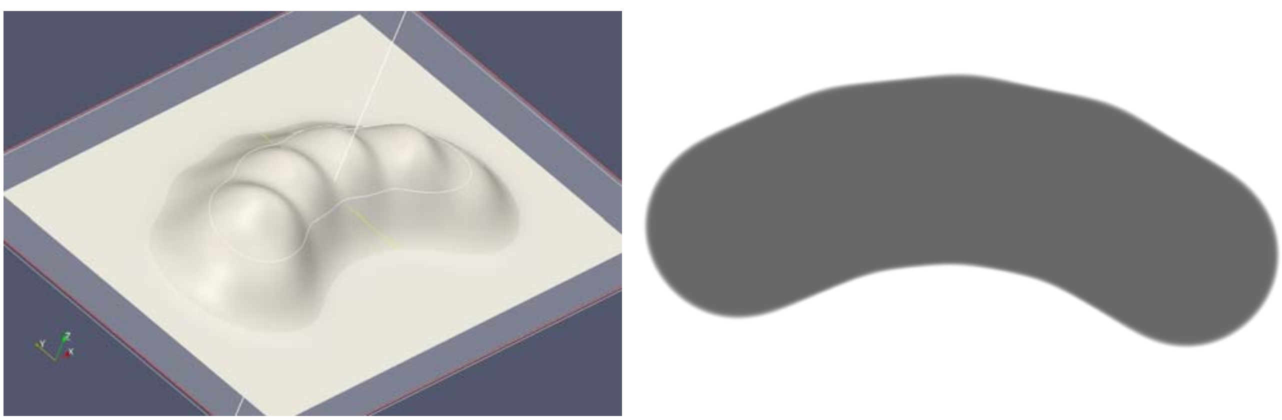

Figure 2. 3D dose map plot of the shapes shown in Figure 1 (left). Contour at 0.5 resist threshold (right).

In order to take advantage of circles, ‘fracturing’ is no longer the appropriate paradigm. A model-based approach is necessary. In a model-based concept, every e-beam shot is simulated to produce the dose map that each shot contributes to the mask surface. Short-range (including forward scattering) as well as long-range (including backscattering) effects are modeled, producing a dose map on the mask surface. That dose map cut off at a certain resist threshold value produces a contour that is predicted to be printed on the mask surface (see right part of Figure 2). In the examples shown in this paper a relative resist threshold of 0.5 was chosen.

By taking the Model-Based Mask Data Preparation (MB-MDP) approach, any character shot, not just a circular or a VSB shot of any dose can be properly modeled. This adds a large amount of flexibility in how e-beam shots are combined to produce the desired shape on the mask.

3. EFFECTS OF SHORT-RANGE BLUR ON SMALL SHOTS

The ability to model the target mask shape based on the placed shots not only helps in case of overlapping circular shots, in fact even when using only non-overlapping, unassigned dose VSB shots, the MB-MDP flow can be useful. This is particularly true for creating small or narrow complex shapes on masks as shown in the following.

At 22 nm logic node, minimum dimensions on wafers are somewhat above 50 nm. SRAFs are typically 30-60% of the minimum dimensions, making them 60-120 nm in width on a 4X mask. With short-range e-beam blur around 20-40 nm radius, many of the SRAFS are small enough to be affected by short-range blur. What is typically considered “corner rounding” affects the entire shot at these sizes as illustrated in Figure 3 and Figure 4.

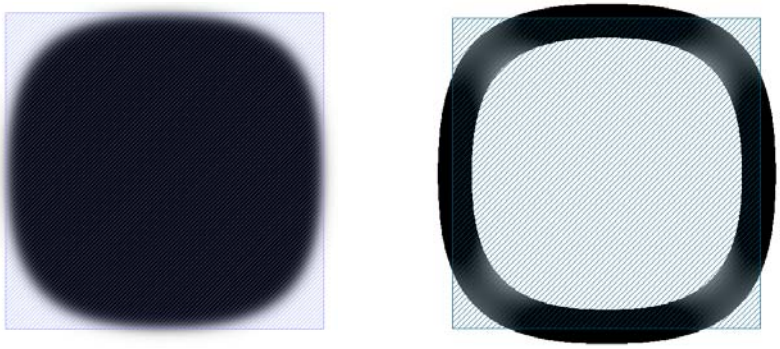

Figure 3. Simulated contour of a 100 nm x 100 nm VSB shot (left) and the corresponding edge slope showing larger than 1.7% dose change per 1 nm slope in black and lower than 1.4% dose change per 1 nm slope in white (right).

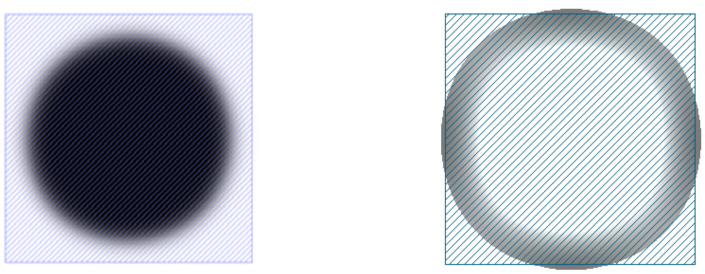

Figure 4. Simulated contour of a 60 nm x 60 nm VSB shot (left) and the corresponding edge slope showing larger than 1.7% dose change per 1 nm slope in black and lower than 1.4% dose change per 1 nm slope in white (right).

In addition, these “corners” have a lower edge slope, contributing to worsened critical dimension uniformity (CDU) on the mask (which depending on the actual MEEF might worsen the CDU control on the wafer even more). On the other side, OPC shapes, particularly SRAF shapes, become increasingly complex and the size of each required shot continues to get smaller. If the shapes are curvilinear, the constituent shots, if conventionally fractured, become potentially as small as the smallest allowed shot size on the machine. When many small shots are placed next to each other, if the shots were all placed accurately, the forward scattering portion of the each other’s shots add up to produce the desired shape with an acceptable slope. But any stand-alone small shots, or ends of a collection of small shots would suffer from these edge slope effects. Very narrow curved lines, such as shapes of SRAFs, will not have reliable line lengths as a result. Particularly for SRAFs, such potential manufacturing variation on the mask may not result in a significant degradation of wafer printing. However, lithographic modeling that accepts a range of outcomes is required for determining good masks from bad. The increasing influence of short range blur on small VSB shots can be seen in Figure 5 and Figure 6. A small rectangular shot of 90 nm x 45 nm shows a very small edge slope at both ends making the actual size on the mask hard to control. When such shots are used to print small SRAFs as shown in Figure 6 the overlapping e-beam blur leads to acceptable edge slopes along the diagonals while the slope at the line ends of the SRAF remains unchanged.

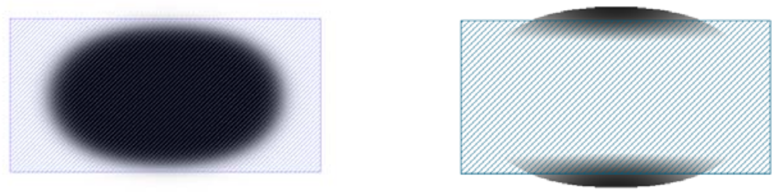

Figure 5. Simulated contour of a 90 nm x 45 nm VSB shot (left) and the corresponding edge slope showing larger than 1.7% dose change per 1 nm slope in black and lower than 1.4% dose change per 1 nm slope in white (right).

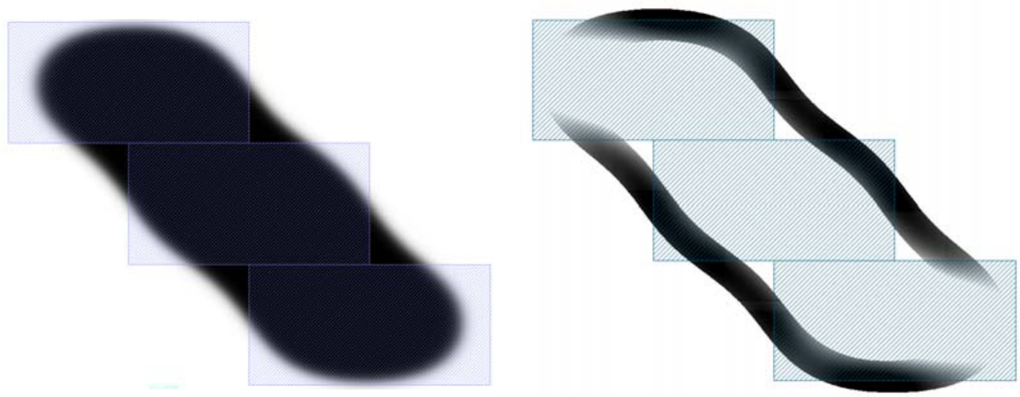

Figure 6. Simulated contour of 3 stacked 90 nm x 45 nm VSB shots shifted horizontally by 45 nm (left) and the corresponding edge slope showing larger than 1.7% dose change per 1 nm slope in black and lower than 1.4% dose change per 1 nm slope in white (right).

Using circular apertures instead of VSB on the new production JBX-3200MV machine as discussed in another paper at PMJ 2010 [3], demonstrates overlapping circular shots producing better edge slope at the line ends of the SRAF. Circles have no corners to round. The line ends are still shallower in edge slope because there are no other adjacent shots to help with their forward scattering. But the forward scattering influence from within other parts of the same shot maximally help the edge slope at the line ends that are shot with circular shots. For non-Manhattan shapes, especially for small curvilinear assist features, circular apertures produce the best edge slopes.

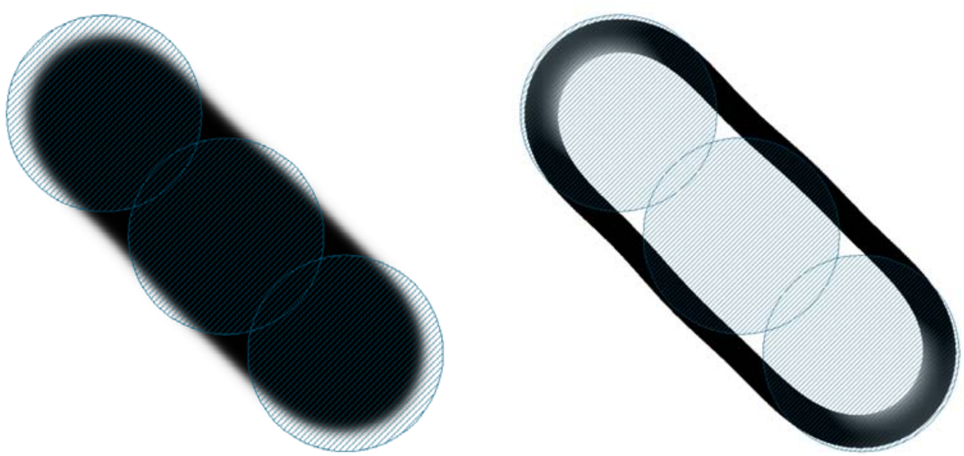

Figure 7. Simulated contour of circular shots of 72 nm diameter producing a similar mask shape as the 3 stacked VSB shots shown in Figure 6 (left) and the corresponding edge slope showing larger than 1.7% dose change per 1 nm slope in black and lower than 1.4% dose change per 1 nm slope in white (right).

As more and more complex SRAFs are required on masks for small geometries, forward scattering of 50kV electron guns and resist-related short-range blur become significant. In order to accurately take those effects into account during MDP, e-beam simulation is required. Since e-beam simulation for printing such small SRAFs is required anyway, conventional restrictions of not assigning dose to individual shots until long-range PEC, and not overlapping any shots (which produce double and triple dose areas) can be removed. Now it is possible not only to assign individual doses to shots and let those shots overlap but it is also possible to use any shape to be projected, enabling character projection to be "fractured." Fracturing is the wrong terminology for this case because the mask shapes are not being divided up into the primitive shapes, hence our naming of this technique as MB-MDP. With the larger degree of freedom small complex mask shapes can be written with a lower number of shots and optimized edge slope.

4. MB-MDP FLOW

MB-MDP is additive to the conventional mask data preparation flow deploying conventional fracturing. There are many shapes on every mask layer that are best shot using conventional fracturing [5]. However, for small, complex, or curvilinear shapes on the mask, particularly those shapes that are heavily affected by short-range blur, it may be advantageous to deploy MB-MDP. Two alternative flows are possible. One is to deploy conventional fracturing first, followed by MB-MDP where conventionally fractured shots are improved using MB-MDP either in shot count, edge slope, or both for certain of the shapes. The other is to divide the design into conventional parts and complex parts where the conventional parts are handled by conventional fracturing and complex parts are handled by MB-MDP. In this approach, however, unless the sections of data are sufficiently isolated from each other, MB-MDP needs to be able to "see" the conventionally fractured shots for proximity effects. Figure 8 depicts the MB-MDP flow being added to the conventional flow.

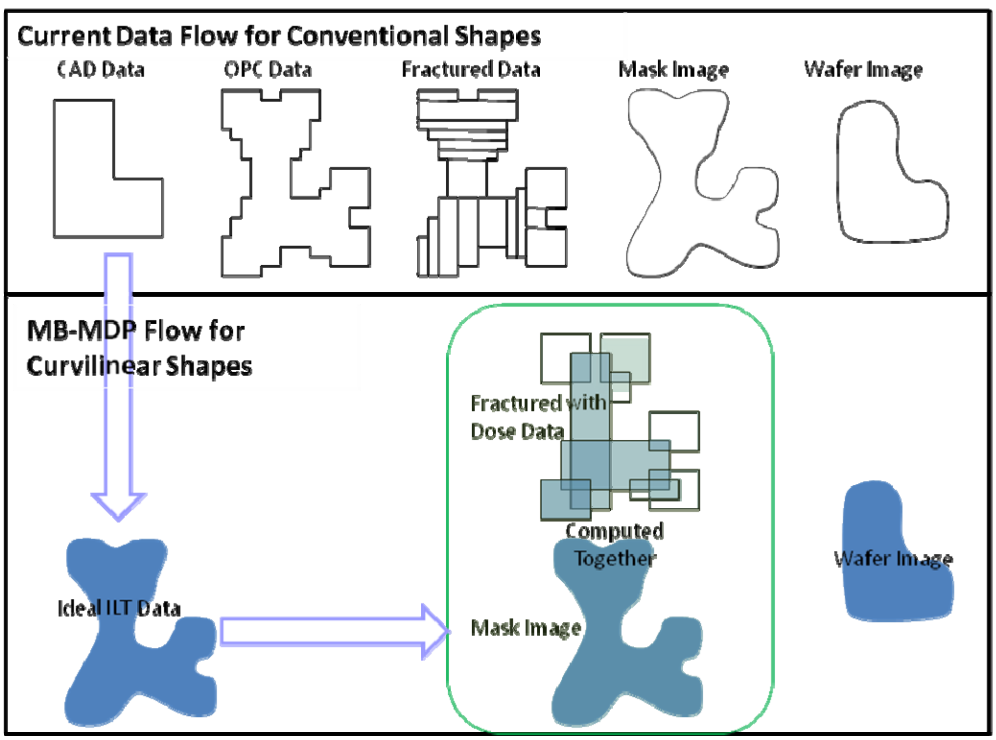

Figure 8. The Model Based Mask Data Preparation (MB-MDP) included in the conventional fracturing flow where MB-MDP processes curvilinear shapes while rectangular shapes are fractured conventionally.

As shown, complex shapes, such as ideal ILT shapes, are input into the MB-MDP flow. However, since ILT incorporates mask models as part of the computation, the actual target shapes for MB-MDP are not the original ILT shapes but the e-beam simulated ILT shapes. MB-MDP computes the shape, size, and dose of shots required to produce the target mask image.

In the center of Figure 8, only VSB shots are indicated. The various shadings imply different doses assigned to each shot. Long range as well as short range mask effects are modeled in this process. So in this sense, fracturing (meaning determining the shots), dose assignment, simulation, and PEC are all performed together in the same MB-MDP step.

5. MB-MDP FOR OVERLAPPING VSB SHOTS

Mask shapes on poly or metal layers have a large number of orthogonal lines where OPC, etching correction and other factors introduce waviness. Using MB-MDP, with overlapping dose-assigned VSB shots, such shapes can be written more efficiently than with conventional methods. Figure 9-A) depicts a simple example where the desired mask shape is a line with a convex notch on both sides of the line. The width of the "backbone" is 168 nm (on mask) and the middle part is 200 nm wide. Figure 9-B) shows the conventional fracturing. Figure 9-C) shows the result of an e-beam simulation. A small amount of corner rounding is evident. Finally, Figure 9-D) shows the SEM picture of a resist exposed mask.

An alternative way to shoot this shape using MB-MDP is to take a backbone shot that is overlapped by one shot as seen in Figure 9-E). The middle section ends up being overdosed in effect, expanding the edge out, producing a simulated picture as Figure 9-F) and a SEM image as Figure 9-G). The small corner rounding is similar to the conventional fracturing case.

Two shots are required for MB-MDP whereas three shots are required for conventional writing. In addition, the second shot is a ghost shot requiring less than a full dose. The write-time for the MB-MDP shots is less than 2/3 because one of the shots is not at a full dose.

The edge slope of the expanded part is affected by the size and dose of the ghost shot. A specific case where edge slope optimization, not shot count reduction or shape modification, is the goal was reported by Martin et al. [4]. Further study of the effects of the different combinations of sizes and doses on edge slope and on manufacturing variation is planned for the future.

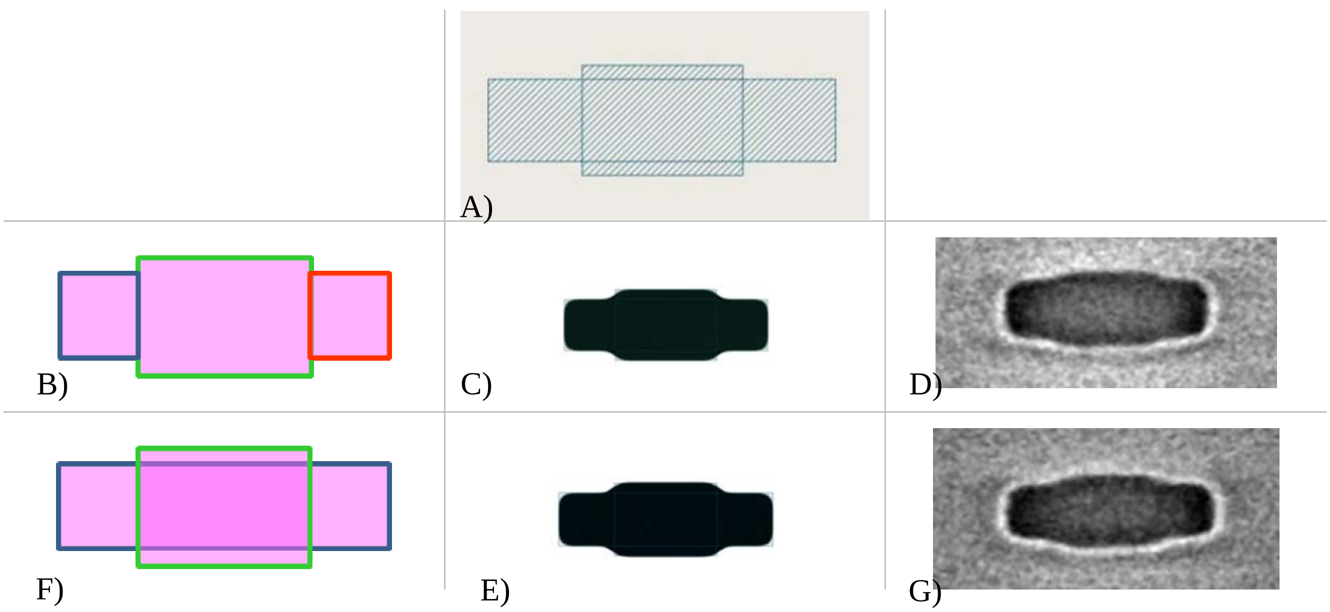

Figure 9. Comparison of a "wavy" line fractured conventionally or with MB-MDP. While the conventional method needs 3 shots for this example, the new method needs only 2 shots. Since the overlapping shot uses less than the full dose the mask write time for the new method is even shorter than 2/3 of the conventional method.

Figure 10 A)-G) shows a similar progression using three overlapped shots, creating a three step staircase. The backbone is 168 nm wide (on mask) and the widest part is 232 nm. In this situation, three shots, two of which are less than a standard dose create the desired mask shape in MB-MDP instead of five shots for conventional writing, taking approximately half of the write time.

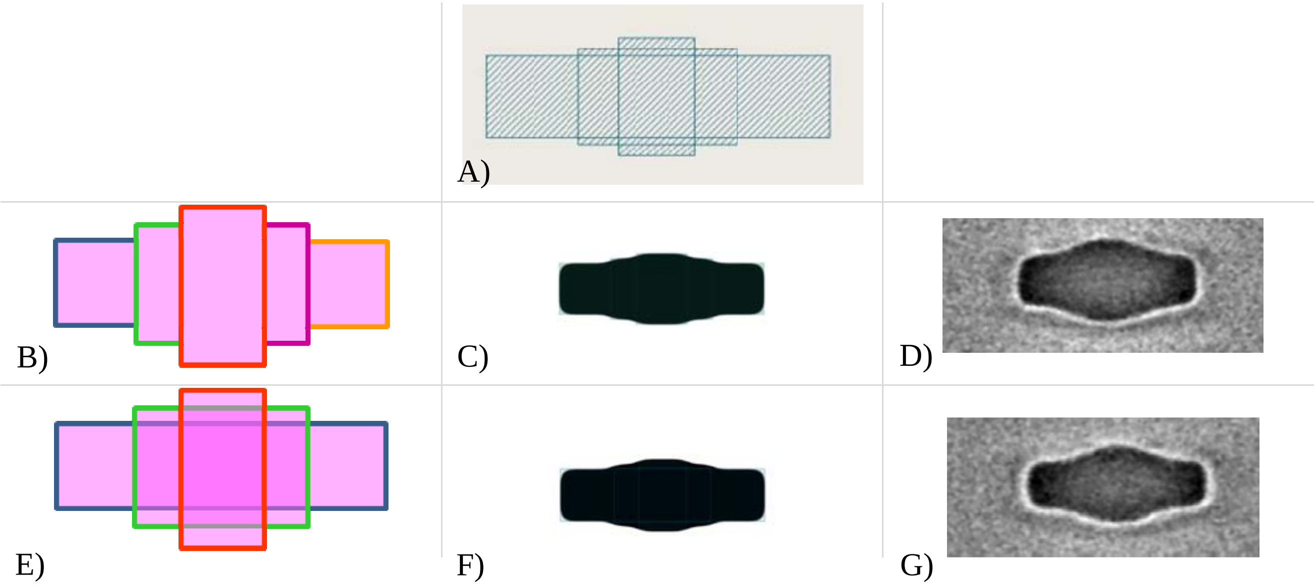

Figure 10. Comparison of a 3-step staircase line fractured conventionally or with MB-MDP. While the conventional method needs 5 shots for this example, the new method needs only 3 shots. Since the overlapping shots use less than the full dose the mask write time for the new method is only about half of the conventional method.

Figure 11 A)-G) shows another progression using three overlapped shots, this time creating a circular via shape. A conventionally fractured approximation of a circle would be a nine shot VSB sequence as seen in B). With three shots this 308 nm (on mask) diameter approximated circle can be written using MB-MDP.

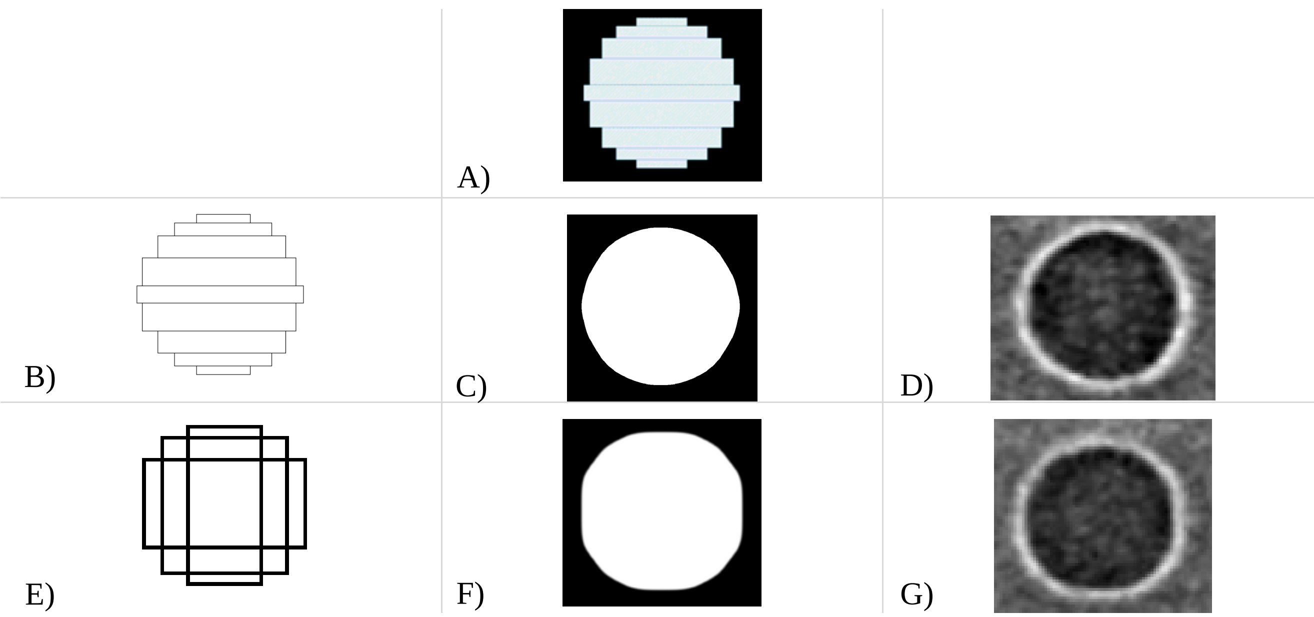

Figure 11. Comparison of a 308 nm diameter (mask dimensions) 3-step staircase contact/via fractured conventionally or with MB-MDP. While the conventional method needs 9 shots for this example, the new method needs only 3 shots.

6. WAVY METAL1 LINES USING CIRCULAR SHOTS

An extension of the stair-step application of overlapping VSB shots can write arbitrary metal 1 (or poly) wavy lines, whether for printing main features or for non-printing SRAFs. There are shapes for which this technique is effective, and there are also shapes for which this technique does not help reduce write times. For example, if there is no left-right symmetry in the stepping, the particular technique demonstrated above will not be helpful for reducing write times.

In situations, however, where the desired mask shapes for the metal wires are to bulge in a more continuous "wavy" fashion, such as demonstrated in Figure 12 there is an even more effective technique for writing the mask with more accuracy using far reduced shot counts. In this example, the trunk of the wires are 168 nm on mask and the widest part of the bulge is 337 nm wide.

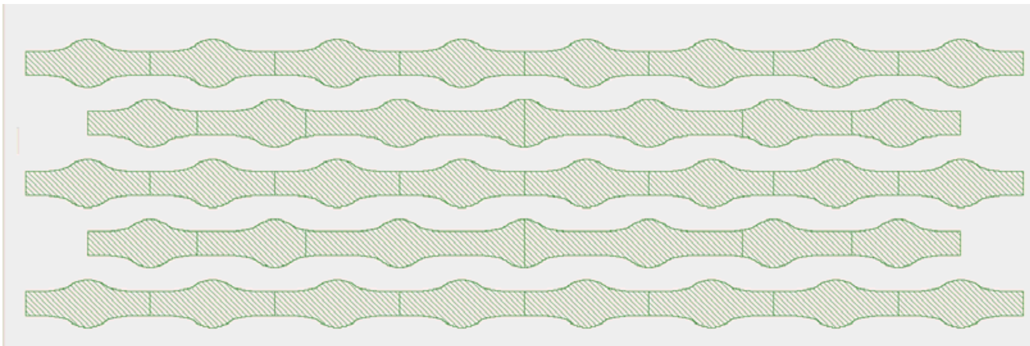

Figure 12. Desired mask shape of wavy metal 1 wires.

Conventional fracturing of this shape would take more than 3200 shots No OPC program would output shapes like these because conventional fracturing would render this impractical. OPC programs would output a much more stair-stepped (stair stepping with larger jogs) set of shapes instead.

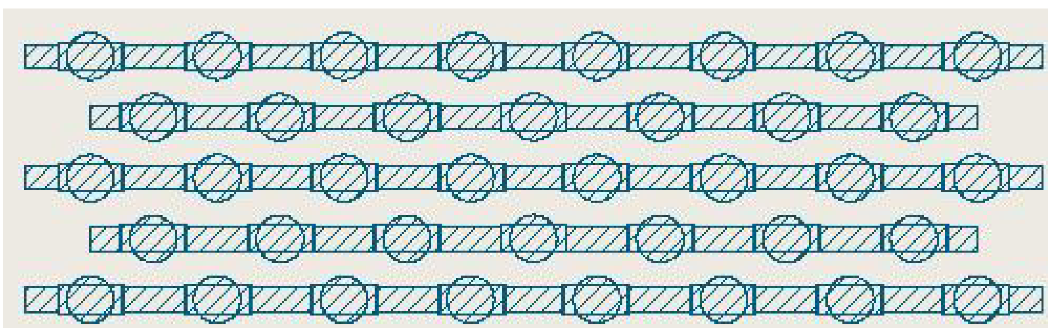

Figure 13. MB-MDP solution using a combination of circular and VSB shots.

Figure 13 shows the MB-MDP solution using a combination of circular and VSB shots. This version takes 117 shots for the pattern. Figure 14 and Figure 15 show the SEM of the conventional writing and the MB-MDP versions. The shapes of the smooth wavy lines written on mask are indistinguishable, but MB-MDP writes these patterns with reasonable mask write times.

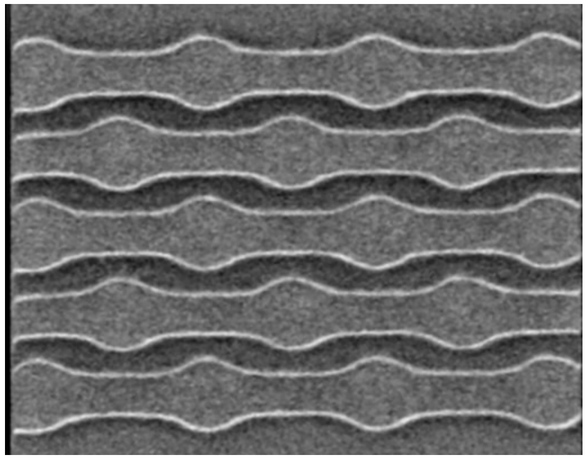

Figure 14. SEM image of the conventionally fractured wavy lines shown in Figure 12.

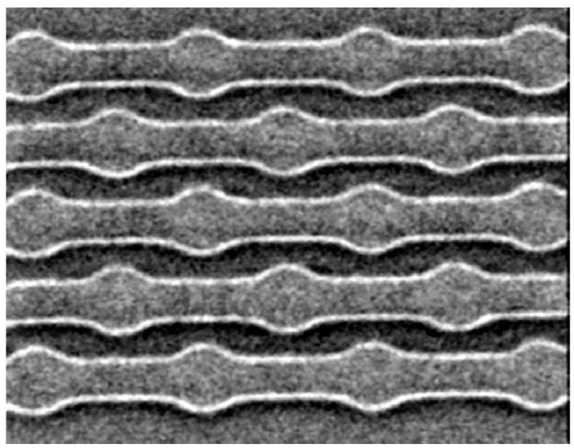

Figure 15. SEM image of the MB-MDP solution shown in Figure 13.

7. SUMMARY

For complex, curvilinear, or small shapes on a mask which are not friendly for conventional mask writing methods, a new Model-Based Mask Data Preparation (MB-MDP) method was described. MB-MDP combines shot list preparation (traditionally called fracturing), mask simulation, and proximity effect correction for both short-range and long-range effects. It outputs a shot list that has overlapping, dose assigned shots of either VSB-only, or VSB shots combined with circle shots, or any other character projection characters.

MB-MDP is complimentary to conventional fracturing and is shown to reduce shot count and therefore mask write times. The concept has been demonstrated by resist exposures on mask, creating stair-stepping metal 1 patterns and wavy metal 1 lines.

Further studies of MB-MDP are under way, including post-etch study of manufacturing variation, and the effectiveness of proximity effect correction in the context of MB-MDP.

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