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Invited Paper

Improvement of Mask Write Time for Curvilinear Assist Features at 22nm

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ABSTRACT

In writing 22nm logic contacts with 193nm immersion, curvilinear sub-resolution assist features will be desirable on masks. Curvilinear sub-resolution assist features are good for high volume chips where the wafer volume outweighs considerations for mask write times. For those chips, even 40 hour write times are tolerated for mask writing. For lower-volume production of SOC designs, such write times are economically unacceptable. 8 to 12 hours of write times are feasible for these designs. Previous papers at 2010 Photomask Japan described model-based mask data preparation (MB-MDP) techniques using circular apertures on production e-beam writers writing curvilinear ideal ILT patterns that reduced e-beam write-times by nearly a factor of two over conventional approach writing Manhattanized ILT patterns. This puts the curvilinear assist features within the realm of high-volume production. However, the write times are still too long for SOC designs. This paper describes a new technique that reduces mask write time further. Resist-exposed SEM images will be shown, written by JEOL JBX-3200MV. E-beam shot count comparisons for an ideal ILT mask pattern will be made with the conventional methods, demonstrating a 44% decrease in blanking time. In addition, a comparison study is shown indicating that an ideal ILT mask pattern that would take 63 hours with conventional fracturing can be written in about 14 hours using MB-MDP. AIMS projected images demonstrate the pattern fidelity on the wafer.

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

1. INTRODUCTION

The previous papers from Photomask Japan 2010 [1], [2], [3] introduced Model-Based Mask Data Preparation (MB-MDP), a new approach to mask data preparation that uses e-beam simulation as the basis for determining the e-beam shot sequence. Particularly by using circular apertures in the second aperture of the JBX-3200MV [4], more accurate writing of curvilinear patterns can be written accurately with better dose margin with less shot count. In particular for ideal ILT patterns with circular contacts where the sub-resolution assist features (SRAF) are curvilinear and the main features are written as circles or near-circles on the mask, the technique was proven to be highly effective in reducing write times and increasing dose margin on mask, while also improving mask error enhancement factor (MEEF) and depth of focus (DOF) on wafer.

As 22nm/20nm node approaches, it is becoming increasingly clear that an extension of the 193nm immersion lithography technology will be used at least for logic devices. Multi-patterning with complex assist features is required to print the critical layers. How complex is complex enough? That is the key question that represents the trade-off between mask cost and wafer quality. Mask write times exceeding 40 hours are practically impossible to manufacture. Further, write times exceeding 8-12 hours are operationally difficult for mask shops that need to handle a large variety of masks (whether in-house or merchant). From the device manufacturer's perspective, the increased write times are reflected in increased mask costs, therefore higher NREs and delayed revenues from longer turnaround times. Ultimately the entire semiconductor industry suffers from less design starts at the leading edge nodes, moving more and more of the value derived from electronics systems to application and embedded software, away from semiconductors.

The most sophisticated optical proximity correction (OPC) solutions that produce the best wafer results would generate curvilinear shapes. Light is naturally radiating, even with off-axis illumination. In writing contacts and line ends, 193i

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creates circular and semi-circular contours on wafer. DOF on wafer is enhanced best with shapes that are equidistant from these circular and semi-circular edges. It makes sense that the most effective shapes on masks are curvilinear.

Tolerance to manufacturing variation is also improved with curvilinear mask shapes. Because e-beam too is naturally rounding, a circular shot is the only shot where the edge slope and therefore dose margin is uniformly good for the entire boundary of the shot. The better dose margin on mask improves Critical Dimension Uniformity (CDU) on the mask and combines with the better MEEF of a circle to contribute to better CDU on the wafer. But curvilinear shapes are in the "impossible 80 hour mask" category today, as demonstrated in an experiment from this paper. MB-MDP helps with this issue.

In addition, we note that the explosion in mask shot count, particularly in the contact layer, comes principally from SRAFs. SRAFs must be wide enough to help transmit enough light energy to help the main features. And SRAFs must be narrow enough to avoid being printed themselves. SRAFs for 22nm/20nm logic nodes therefore tend to be blobs, non-orthogonal lines, or curvilinear lines that are anywhere from 40nm wide to 80nm wide on 4X mask dimensions. Any non-orthogonal line is a problem for VSB shot count, but narrow non-orthogonal lines are particularly troublesome.

Hence we end up with the unfortunate situation of having the SRAFs that don't even print on the wafer taking up the majority of the shot count on the mask. We propose an alternative writing methodology that is a more appropriate trade-off of the desired accuracy of SRAF printing and the amount of time required to write the SRAFs.

2. WRITING IDEAL ILT MASKS WITH VSB ONLY

A test mask representing a typical Ideal Inverse Lithography Technology (ILT) mask with curvilinear shapes was produced for Dai-Nippon Printing, Ltd., by Luminescent Technologies, Inc. Luminescent is able to produce Manhattan ILT shapes with far better shot count characteristics with nearly equivalent wafer characteristics, but this study was designed explicitly to test mask making of the curvilinear, original Ideal ILT masks. For this test, three small clips of the data were cut out for the detailed study as shown in Figure 1.

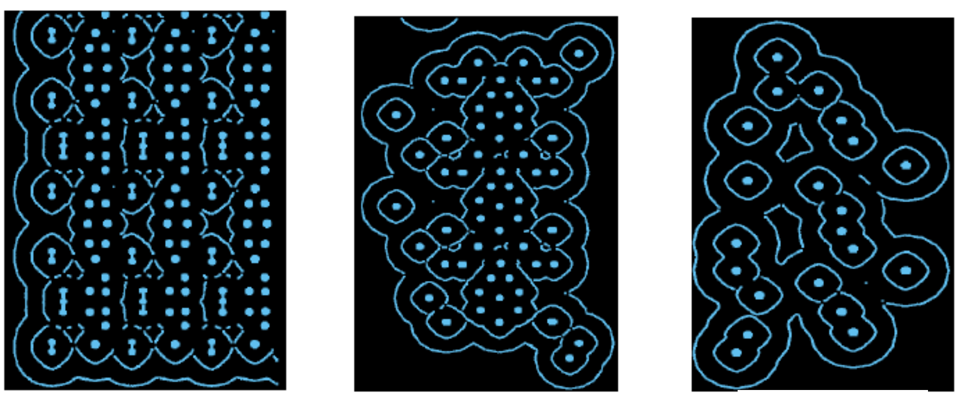

Figure 1. Target data: 3 clips. Pattern and measurement courtesy of Dai-Nippon Printing, Ltd.

The clips have contacts of approximately 300nm on mask, and SRAFs that are approximately 60nm wide. A relatively high density clip of 10µm x 13µm and two sparse clips of 10µm x 15µm and 15µm x 10µm were extracted, representing the range of SRAF to main feature ratios present in the overall mask pattern. When the main feature contacts are close to each other, there is no space for the SRAFs and there is also less need for the SRAFs. This helps decrease the shot density (both in shots per area and shots per contact) because SRAFs are the main culprit for the exploding shot count.

The shots for the clips were prepared by conventional fracturing and also by MB-MDP from D2S, Inc. Both results were printed on the same resist by DNP using the JEOL JBX-3040MV machine. The MB-MDP results were improved later and then re-printed again. CD-SEM images were taken from all results and area measurements for the main features were taken and compared. AIMS pictures of the resulting masks were also taken to compare the conventional fracturing results and the MB-MDP results.

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In Figure 2, we zoom in on a 1µm x 1µm portion of the higher density clip to demonstrate the MB-MDP shot list prepared by D2S, Inc. from the initial attempt prior to Photomask Japan, 2010. These results were shown by Naoya Hayashi of DNP in his keynote speech at the eBeam Initiative luncheon in Yokohama, Japan on April 14, 2010, and also at the ASET Mask D2I, The 4th Annual Meeting in Yokohama, Japan on April 15, 2010 [6]. For these patterns MB-MDP used rectangular VSB-shots only, without any circular shots. This is because the production machine installed at DNP is not equipped with the circular apertures.

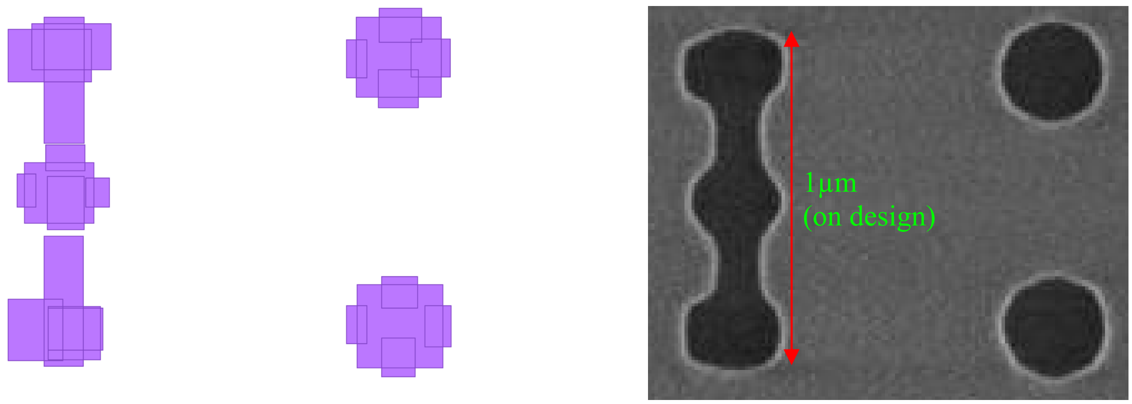

Figure 2. Initial MB-MDP results with shot configuration on the left and SEM image on the right. Pattern and measurement courtesy of Dai-Nippon Printing, Ltd.

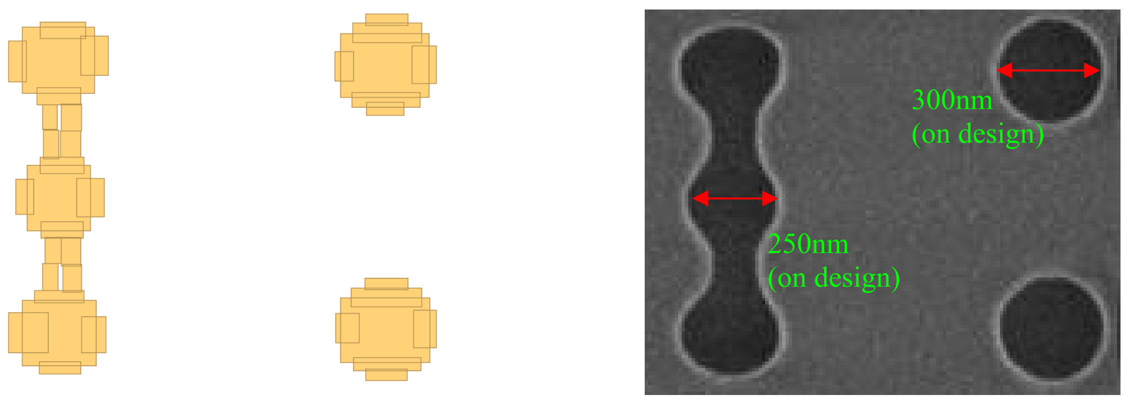

Figure 3. Improved results for pattern and CD uniformity. Pattern and measurement courtesy of Dai-Nippon Printing, Ltd.

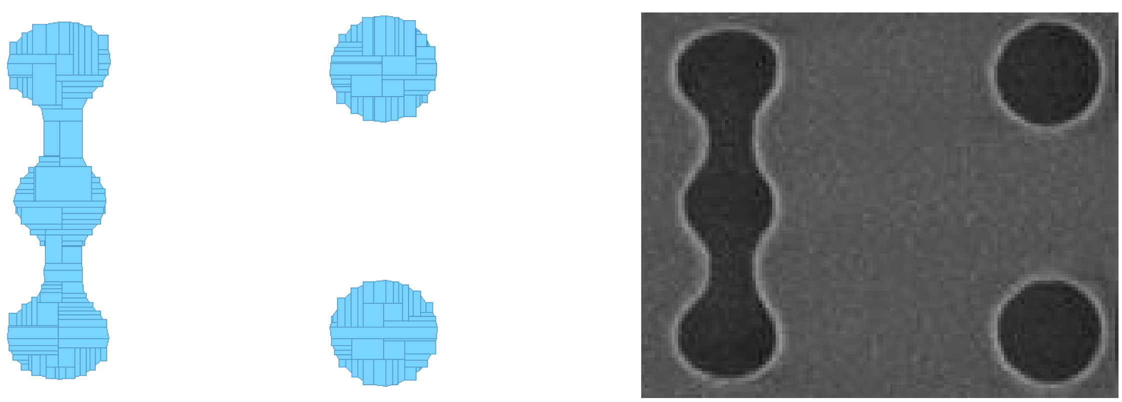

Figure 4. Conventional fracturing results with 8x larger shot count compared to MB-MDP results. Pattern and measurement courtesy of Dai-Nippon Printing, Ltd.

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In Figure 4, the same area is shown for conventional fracturing of the input shapes. There is a noticeable difference in the resulting SEM shapes. The initial MB-MDP results (Figure 2) show distinctly more square-type shapes. This was a result of the model difference between the assumption made during MB-MDP and the actual conditions during writing. In MB-MDP, unlike in conventional fracturing, the model parameters for the anticipated writing conditions must be provided at "fracturing" time. Being model-based, this is a natural consequence, but it is different from the conventional methodology. Last-minute bias compensation, for resist batch changes for example, can be anticipated and accommodated by MB-MDP. But the e-beam and resist models for the writing conditions must be known at the time of shot sequence preparation in MB-MDP.

In Figure 2, it is also noticeable that there is a gap in the shots shown on the left. This gap is small enough that there is no impact on the SEM image on the right. If manufacturing conditions were to be perfectly repeatable every time, there would actually be no issue with these gaps. In fact, the gaps can be created purposefully to reduce the amount of total dose on the mask, thereby lowering back scatter, thereby improving edge slope and dose margin in the overall design. Reducing total dose also helps with reducing other e-beam effects such as heating and charging effects. Particularly for filling large areas, or for writing reverse images, purposefully creating gaps can be useful. For the edge slope of that particular contour edge, however, gaps that appear at the contour edge can be bad. Any small variation in manufacturing conditions can be exaggerated, contributing to CDU differences on the mask, and ultimately on the wafer.

Therefore two things need to be fixed in the initial results. Firstly, the more correct electron beam parameters need to be used. Conceptually, this means that more correct degree of corner rounding must be anticipated by MB-MDP, potentially at the cost of increased shot count. Secondly, the edge slope issue has to be addressed by eliminating the gaps at the contour edges.

The results of these changes are reflected in the MB-MDP results shown in Figure 3. With a slight increase in shot count, both issues have been resolved. The resulting SEM picture on the right reflects a nearly identical mask image as that produced by conventional fracturing in Figure 4. The shots on the left of Figure 3 still have gaps, but the gaps are in the interior of the design where edge slope and dose margin is not an issue.

Figure 5 shows the CD-SEM of the close-ups from each of the three clips printed with dose modulation using the MB-MDP shot sequence. The zoomed up versions that show more details are nominal dose versions ("dose 3 (0%)") of the left most (Dense3) and the right most (Sparse3) pictures in the table. The near-circular main features show very well as do the narrow curvilinear assist features. All features demonstrate good fidelity through the -10% to +10% dose modulation range. CD Stability on dose error is measured and plotted in Figure 7.

Figure 6 plots the difference in the square root of the GDSII input area vs. the square root of the area on the SEM for both the Conventional fracturing case and for the MB-MDP case. There are some notable differences including a general positive offset. Some of these are due to lack of model calibration in this test run. The mean of the 20 measured contacts was 0.6 for the MB-MDP case, and 0.7 for the conventionally fractured case. The three-sigma value of the plotted differences were 4.7nm for the MB-MDP case and 3.7nm for the conventional case. The 20 contacts have different shapes and different sizes in the GDSII. These differences include the differences in how the shapes are shot. An example of a difference among the contacts can be seen in Figure 4 for conventional fracturing and Figure 2 for MB-MDP fracturing in the two circular contacts there. The MB-MDP results by comparison have an increased variation which needs to be investigated and fixed. The cause is under investigation, but expected to be insufficient compensation during the MB-MDP step.

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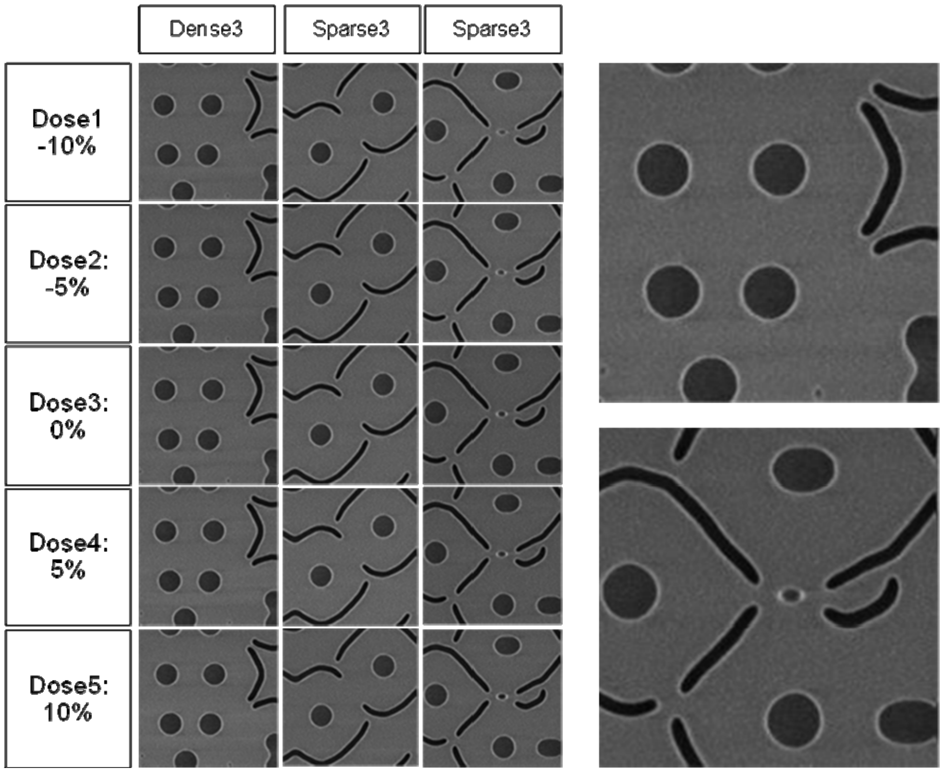

Figure 5. CD-SEM pictures of three different ILT clips at various dose levels shows good mask image fidelity. Pattern and measurement courtesy of Dai-Nippon Printing, Ltd.

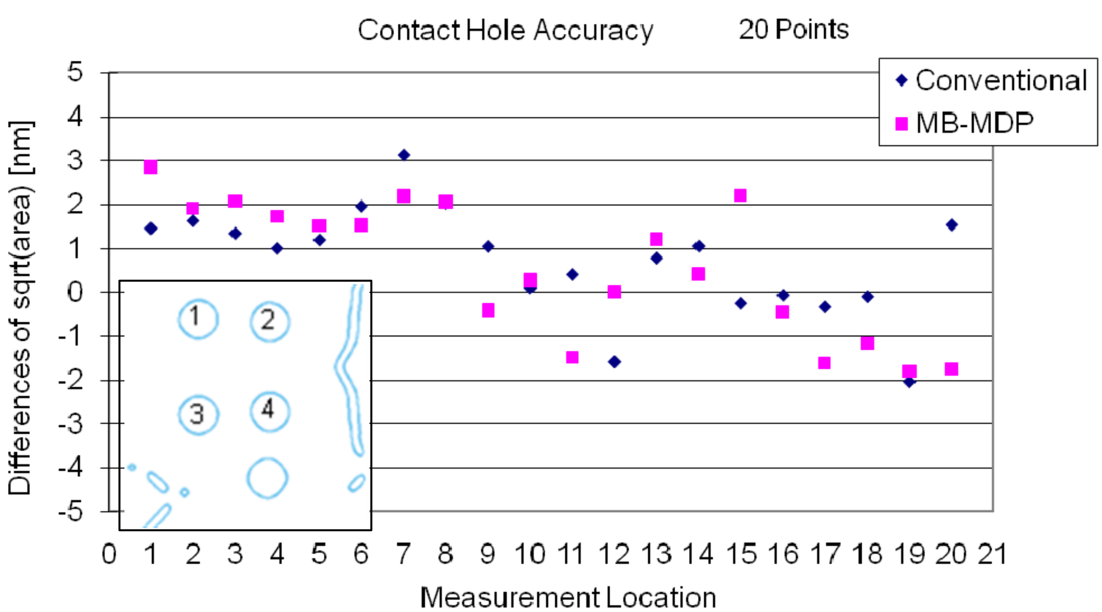

Figure 6. Contact hole accuracy comparing the square roots between GDS and SEM through area extraction by HOTSCOPE *SEM MFG:75K on resist. Each dot represents the difference in square root of area between GDS and SEM.

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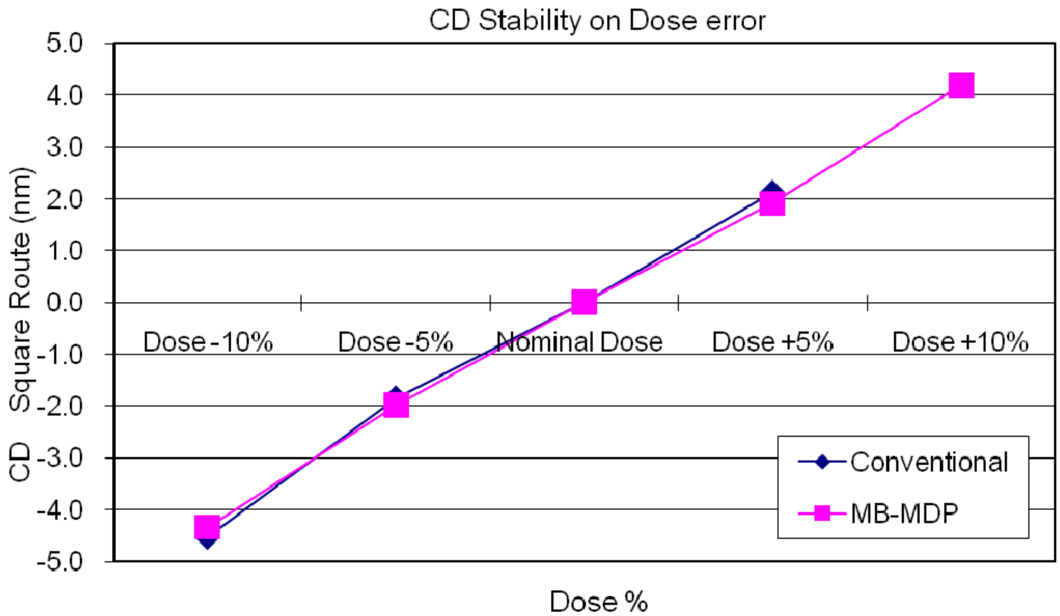

Figure 7. CD stability is nearly identical for conventional and MB-MDP. SEM MFG:75K on resist.

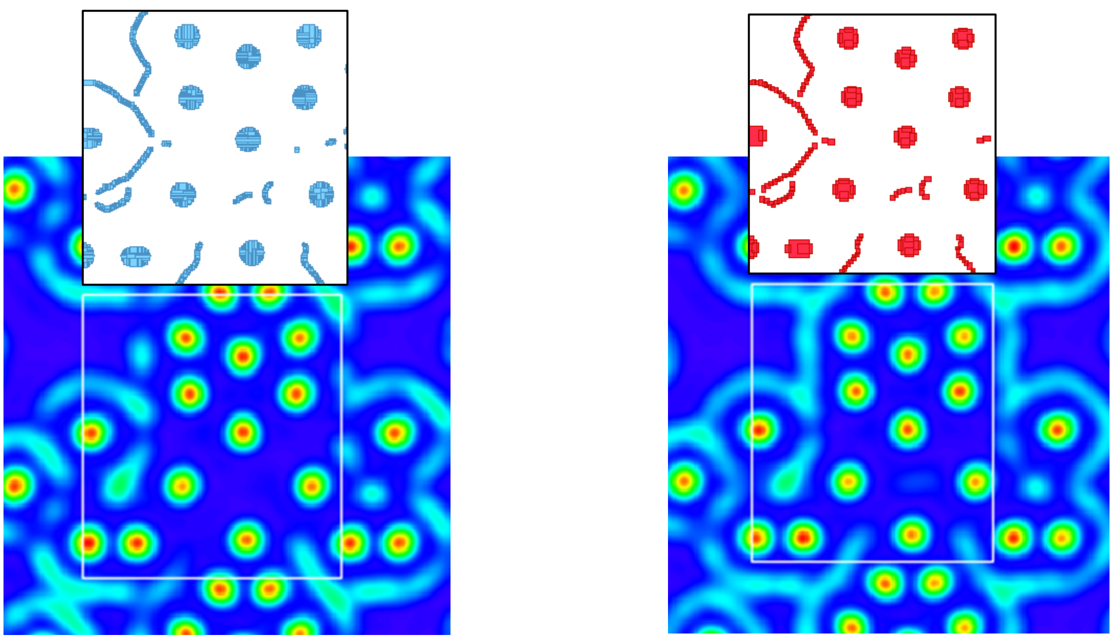

Figure 8. AIMS projection of the energy projected through the mask on the wafer using the same illumination conditions used to produce the OPC shapes. The left shows the conventionally fractured and the right shows the MB-MDP version.

The pictures from AIMS in Figure 8 reflect that the intensity around SRAFs is more uniform with MB-MDP, and that the main features print well on both the conventional and the MB-MDP masks. The difference in the shot count of the two cases is reflected in Table 1.

An average of 4.4 : 1 shot count reduction for the three clips is achieved by MB-MDP over conventional fracturing. Approximately the same reduction in write times can be expected. Simulating the write times assuming 18uC/cm2 resist

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sensitivity with JBX-3200MV, an entire mask of these patterns would have simulated write times of 63 hours for conventional fracturing and 14 hours for MB-MDP. Further reduction is desired in write times. One way to do this is with circular apertures, as we discussed in PMJ [1]. Another way to do this, whether using circular apertures or using rectangular VSBs, is to do alternating shots for SRAFs in 2-pass writing. This is the next topic.

Table 1. Comparison of shot counts between the mask written with Conventional fracturing and the mask written by MB-MDP. Conventional fracturing of the whole test pattern generates 8,870,000 shots.

	Area	Conventional Shot Count	MB-MDP Shot Count	MB-MDP Shot / Area	Conventional : MB-MDP
	μm^2	M	N	N / μm^2	M : N
Dense3	126	14,610	3,090	116.0	4.7
Sparse3	156	14,461	3,362	92.7	4.3
Sparse4	110	10,396	2,577	94.5	4.0
Total	392	39,467	9,029	101.1	4.4

3. "ALTERNATE SHOT" FOR SRAFS IN 2-PASS WRITING

As noted earlier, particularly for the contact layers, SRAFs that are designed not to print on the wafer take the overwhelming majority of the shots and therefore the write time of an MB-MDP mask. In the ideal ILT shapes of Figure 5, for example, in conventional fracturing, drawing the near circles take many shots also. With MB-MDP, even without circular apertures, the near circular features can be shot with 5-7 VSB shots typically with good shape accuracy and area precision. For MB-MDP masks of ideal ILT shapes, SRAFs dominate the shot count. The SRAFs however require less precision than main features because these features do not print. Since the 22nm/20nm lithography requires a closely collaborated trade-off between mask write times and wafer quality, we propose that a good trade-off for MB-MDP patterns is to reduce write times of SRAFs by slightly sacrificing CDU of the SRAFs.

The proposed method creates overlapping shots to write SRAFs, but shots alternate at twice the normal dose in each of the two passes as indicated in Figure 9.

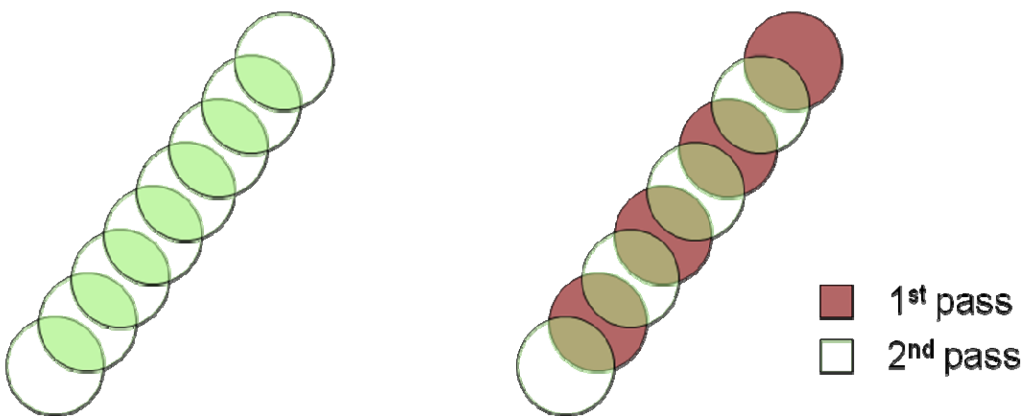

Figure 9. On the left, these circular shots are written at half dose in each of two passes. On the right, these circular shots are written at full dose in only one pass per shot. Alternating shots are written in each of the passes.

Two-pass writing is the common method for writing masks. Four-pass writing is sometimes practiced for enhanced accuracy, sacrificing writing speed. In two-pass writing, half of the desired nominal dose is shot in each of two passes. The purpose of two-pass writing is to enhance accuracy by averaging out the errors. Even if the two passes shoot exactly the same shot list in exactly the same sequence, any particular error caused by manufacturing imperfection has a reduced effect. Statistically, errors average out, making the inaccuracies less in two-pass writing than in one-pass

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writing. In addition, shots may be fractured differently over the two passes, and other systemic errors such as stitching errors across stripe boundaries may be minimized.

In MB-MDP with systemically overlapped shots, such as is the situation in a non-orthogonal assist feature, the need for two-pass writing is reduced. Since adjacent shots are not designed to abut exactly, the impact of a given 1nm error in the direction of the adjacent shot is reduced. More importantly, even though accuracy of SRAFs is important, the balance between accuracy and write time for SRAFs is more in favor of write time.

Figure 10 shows the VSB and circular shots selected by MB-MDP, originally presented at Photomask Japan, 2010 [3], [5]. Figure 11 shows the SEM photograph of the MB-MDP writing result.

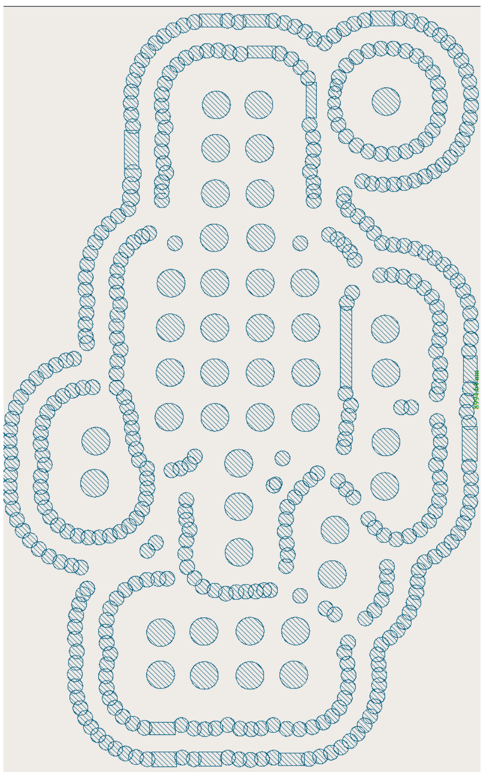

Figure 10. VSB and circular shots prepared by MB-MDP for an ideal ILT mask generated with Inverse Synthesizer™ [3], [5].

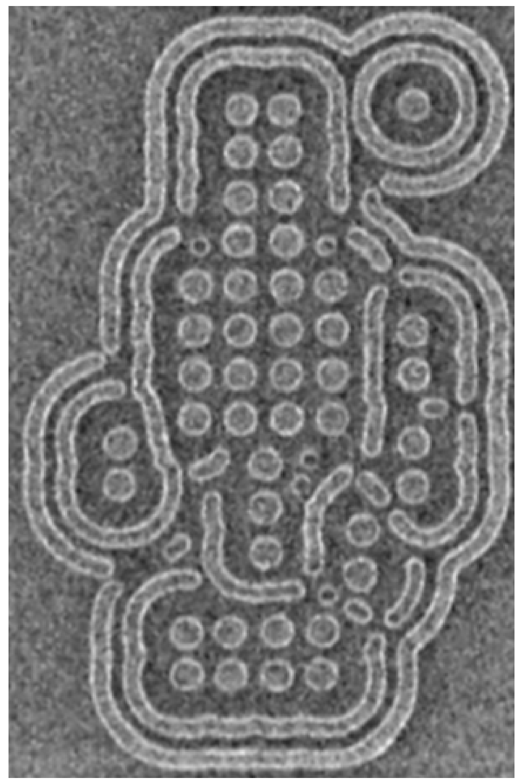

Figure 11. Resist exposed pre-etch SEM picture of the MB-MDP shots shown in Figure 10.

The above pattern written using the Alternating approach using the JBX-3200MV is shown in Figure 12. The main features are written in two passes as before. Only the SRAF features are written using the Alternating approach. The total dose of each shot is the same, so there is no modification of the shot sizes. The writing takes advantage of the machine's ability to write with VSB as well as circular apertures, to assign a distinct dose to each shot, and to overlap shots.

The write time of the Alternating approach is shorter because the blanking time in between the shots is reduced by half. In this particular example, there are 484 shots required to write the pattern. Of them 44 are for main features, and 440 are for assist features. Some of the assist features are long rectangular VSB shots. These are shot without the Alternating method to maintain CDU. All 57 shots are shot with half dose in each of two passes. The remaining shots are shot with the Alternating method. In the first pass, 206 shots were written at twice the nominal dose of a single pass. In the second pass, 221 shots were written at twice the nominal dose of a single pass. The shot counts are different because some SRAF "lines" are drawn with odd number of shots, and one closes on itself to form a circle.

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The writing time of the original MB-MDP method is the sum of twice 484 times half the nominal dose and twice 484 times the blanking time (assuming that there is another pattern to be written after this one). The "twice" comes from the two passes. The dose of each shot is half because it is for one of the two passes.

The writing time of the Alternating approach is twice the sum of 57 times half the nominal dose and 57 times the blanking time, plus the sum of (206 + 221) times nominal dose and (206 + 221) blanking times. The difference is 484 * 2 = 968 blanking times vs. 57 * 2 + (206 + 221) = 541 blanking times. The additional reduction in blanking time using the Alternating method translates to a 44% savings.

Additional savings in write times can be explored, if reduced dose amounts for larger shots can be used to write the SRAFs. Concern over edge slope and dose margin prevented the use of that technique for this project.

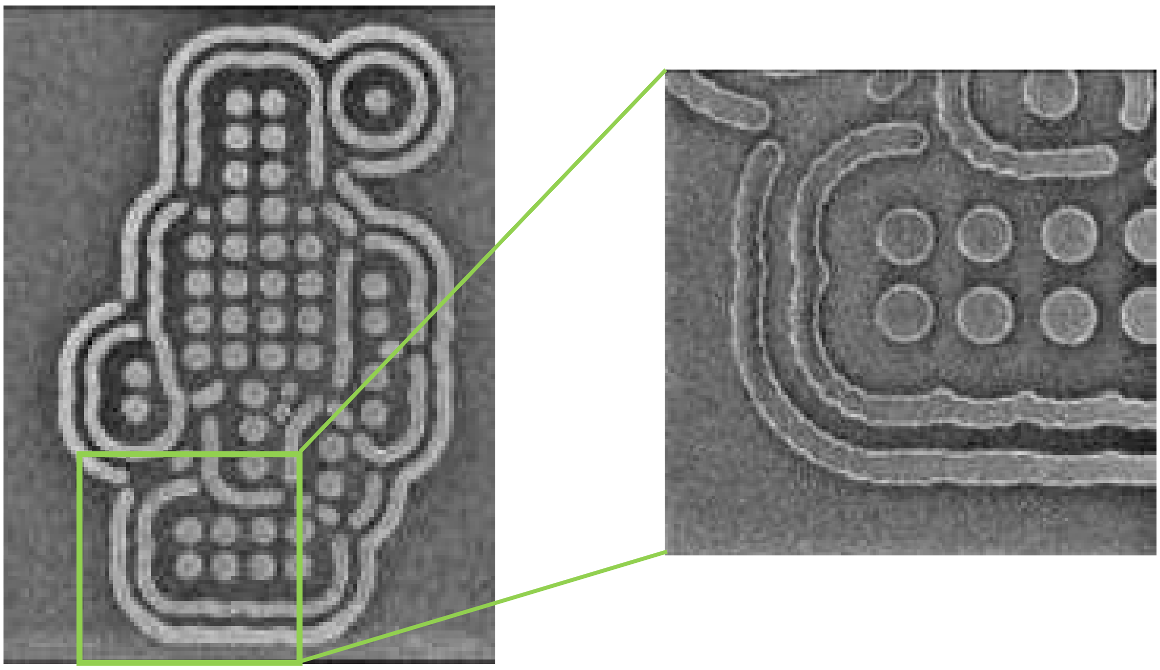

Figure 12. Resist exposed pre-etch SEM picture of the MB-MDP shots shown in Figure 10 writing SRAFs with alternating shots at twice the normal dose in each pass of a two-pass mask write.

4. CONCLUSIONS

The MB-MDP approach was applied to curvilinear ILT shapes using only rectangular VSB shots demonstrating an estimated 4.5X write time reduction over writing the same shapes conventionally. A new Alternating method is proposed whereby the SRAFs are written using overlapped circular or rectangular VSB shots where alternating shots are shot at twice the normal dose in each of the passes in two-pass writing of the masks. Test printing results were shown, including an AIMS result comparing the projected wafer performance of the mask written conventionally vs. the mask written with MB-MDP.

Being able to write complex curvilinear shapes on mask with reasonable write times enable an increased degree of freedom in the balance of mask cost and wafer quality for 193i lithography of 22nm/20nm logic devices.

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