Model-Based Mask Data Preparation (MB-MDP) and its impact on resist heating

Aki Fujimura*[a], Takashi Kamikubo[b], Ingo Bork[a]
[a] D2S Inc., 4040 Moorpark Ave, Suite 250, San Jose, CA, 95117, USA;
[b] NuFlare Technology Inc., 8 Shinsugita-cho, Isogo-ku, Yokohama 235-0032, Japan

ABSTRACT

Complex mask shapes will be required on critical layer masks for 20nm logic node, threatening to explode the mask write times. Model-Based Mask Data Preparation (MB-MDP) has been introduced to reduce the shot count required to write complex masks while simultaneously improving resolution and dose margin of sub-100nm features. For production use of MB-MDP, a number of questions have been raised and answered. This paper summarizes these potential issues and their resolutions. In particular, the paper takes an in-depth look at one of the questions: impact of overlapping shots on heating effect. The paper concludes that while heating effect is an important issue for all e-beam writing even with conventional non-overlapping shots, overall dose density per unit time over microns of space is the principal driver behind heating effects. Highly local shot density and shot sequencing does not affect heating significantly, particularly for smaller shots. MB-MDP does not introduce any additional concerns.

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

1. INTRODUCTION

As the semiconductor industry prepares for production of 20nm logic node, it is increasingly clear that wafers of that logic node will be written with multiple patterning of 193nm immersion lithography. Extensive Optical Proximity Correction (OPC), Inverse Lithography Technology (ILT), Source Mask Optimization (SMO), or Computational Lithography (CL) (collectively "OPC" in this paper) will be required to resolve the images on mask with sufficient process window (PW) at the 20nm node. There is a trade-off between wafer image quality and mask write times and mask cost [1] that must be resolved. 20nm production, as any node, requires both good masks and good wafers in an economically viable range. Model-Based Mask Data Preparation (MB-MDP) has been introduced [2][3][4] to reduce variable-shaped beam (VSB) shot count, and thereby reducing mask write times and therefore mask cost in writing complex shapes. Complex Manhattanized shapes with small sub-60nm jogs in the OPC output and even curvilinear "idealized" mask shapes can be written using VSB shots with the MB-MDP method. MB-MDP takes advantage of the inherent roundness of e-beam shots when observed close. As the feature sizes go below 100nm and approach forward scattering range, VSB shots are actually more round than they are rectangular. MB-MDP, by being mask-simulation based, is able to take advantage of this to write complex shapes, such as small diagonal SRAFs efficiently.

2. QUESTIONS ABOUT MB-MDP

By being simulation based, MB-MDP enables overlaps, shot-by-shot dose modulation, and arbitrary shot shapes [2][3][4] that the rule-based conventional fracturing did not. In MB-MDP, each e-beam shot is simulated to see what dose distribution is cast onto the mask surface. MB-MDP then takes the contour shape at the resist threshold of the then generated three dimensional dose distribution map for the mask. The shot configuration is manipulated and optimized to choose the configuration that minimizes write time to create a desired contour with an acceptable dose margin.

The positive impact of MB-MDP has now been clearly demonstrated. As production use of MB-MDP nears, some questions and concerns have been raised about the increased degrees of freedom that MB-MDP offers. The questions and their answers are addressed in this section, and then we will tackle the one remaining question about the effect of overdosing on resist heating in the next section.

- Is MB-MDP effective with only overlapped VSB shots without dose modulation? Yes.

*aki@design2silicon.com; www.design2silicon.com

- Can MB-MDP be deployed on the EBM-7000 machines? Yes, with an option to the machine.

- Does proximity effect correction (PEC) work with overlapped shots? Yes.

- Do loading effect correction (LEC) and fogging effect correction (FEC) work with overlapped shots? Yes.

- How much overlapping and therefore overdosing does MB-MDP deploy? Small areas of 2X overlap and much smaller areas of 3X overlap.

- Is resist vaporization a concern from extreme overheating? No.

- Is critical dimension uniformity (CDU) a concern from heating effects? Not from MB-MDP.

2.1 MB-MDP is effective with overlapped rectangular VSB shots

An earlier paper [5] demonstrated that MB-MDP is effective with only rectangular VSB shots. This is because MB-MDP helps with shot count when the shot count is very large with many small shots being written to write complex patterns. When feature sizes fall below 100nm (common for SRAFs of 20nm logic node) the combined effects of process blur caused by resist, acid diffusion, development, and etching, and beam blur in the short-range are significant. So whether written conventionally or with MB-MDP, these patterns are significantly rounded. MB-MDP takes advantage of this naturally rounding effect in particular to draw non-orthogonal features with less shot count.

2.2 EBM-7000 works with its PEC, LEC, and FEC with overlapping shots

An earlier paper [6] derived proximity effect correction (PEC) to be equally effective in the presence of overlapped shots. Loading effect correction is independent of writing method, since it is only a function of the exposed image on the mask. Fogging effect correction is independent of overlapping since it is a very large scale effect that is only a function of total dose applied to regions (whether overlapping or not). However, unlike in conventionally fractured shot configurations, LEC and FEC must operate on different data for MB-MDP. In conventionally fractured data, the exposed area in a region (or its inverse) is directly proportional to the total dose in that region. In MB-MDP, because of overlapping areas contributing more dose, but not more exposed area, LEC and FEC must be derived from different input data. A specific "D2S Option" has been developed for the EBM-7000 and above for this purpose. In addition, this option enables the data processing of EBM-7000 to accept overlapping shots. MB-MDP is enabled on the EBM-7000 and above with this option.

2.3 MB-MDP produces small 2X overlap and very small 3X overlap areas

MB-MDP improves write times because write time is independent of shot size. Writing a 500nm square shot takes the same time as writing a 50nm square shot. MB-MDP produces slightly more total dose than conventional fracturing because of the overlapped areas where dose energy is "wasted". But it uses less shot count to shoot the same shape for complex shapes, such as jagged, Manhattanized diagonal main or assist features by geometrically taking advantage of the ability to overlap. Taken to an extreme, this ability to overlap can potentially create areas where many shots overlap on top of each other. But MB-MDP focuses on small features, and therefore overlapping areas are typically very small areas. Furthermore, the amount of overlap needed to minimize shot count is typically only two shots, and rarely very small areas of triple overlap. Still, it is important to control behavior, so MB-MDP is equipped with the ability to specify the maximum dose limit allowed on the mask. 3X maximum is a typical specification.

2.4 Resist heating questions for MB-MDP

500nm square shot has far more power output than a triple overdose of a 100nm square shot on top of each other (which would never be generated with MB-MDP) with blanking time in between the shots. So conceptually, MB-MDP deployed with small amounts of overlap should have no worse behavior due to resist (and substrate) heating than conventional fracturing with large shots with critical dimensions.

But still, since overlapping shots is a new idea, all potential concerns need to be properly studied. There are three potential concerns with heating.

- Resist vaporization

- CDU change due to subfield heating

- CDU change due to overlapping

MB-MDP does not cause resist vaporization due to heat. In a series of experiments conducted by NuFlare outside the scope of this paper, it has been shown that resist vaporization is only an issue with extremely high total dose. Overlapping being limited to three shots is more than sufficient to eliminate any concerns about resist vaporization, even if 500nm square shots are triply overlapped on top of each other. Since MB-MDP rarely deploys triple overlap, and since those areas when they occur are very small, there are no concerns for resist vaporization with MB-MDP.

So the remaining question is: does MB-MDP cause CDU issues?

Since MB-MDP improves write times by shooting more electrons in less time, the amount of power applied to the mask is greater than the same shapes being written in conventional fracturing. But since the only time MB-MDP is applied is when the write time is otherwise large because a large number of small shots are being written in a given area, the amount of blanking time is large, and each shot is typically very small. Comparing the dose density per unit time between conventional fracturing and MB-MDP of the same complex shapes, MB-MDP outputs higher power. But compared to any given unit area (say, the 8um square subfield area) printed with 500nm square shots for, say, an equal line-space pattern L:S = 1:1 where L = 500nm, the amount of power applied is extremely low for these complex patterns, whether conventionally written, or written with MB-MDP. Since the machines are designed to write accurately with the maximum shot sizes, the difference in dose density over unit time between conventional and MB-MDP is expected to be negligible for these macro effects.

On the other hand, overlapping shots, or alternatively, worse, double-dosing a given shot may have highly local heating effects. So this is the question: are there local heating effects due to overlapping shots? Or are the concerns over resist heating no different from conventional fracturing?

We would expect double shots with a large rest time in between the shots to be smaller than double shots with a smaller rest time in between. The next section describes a test writing experiment demonstrating this effect. If a large amount of rest time in between the shots yields smaller CDs, then overlapping shots would be said to have an impact on CD uniformity due to heating that would then have to be corrected.

3. MB-MDP DOES NOT CAUSE CDU ISSUES DUE TO HEATING

The experiment writes the line-space (L:S) pattern depicted in Figure 1 using two methods. First, the shot sequence is controlled to write in each subfield from bottom to top, and left to right, and then bottom left to top right again, writing the same shot list twice in sequence. For any given shot, the resting time in between the shot is large, so we would expect localized heating effect to be minimized. The writing is done in a 4 pass mode, to be consistent with precision writing practices. While heating effect itself is clearly greater in 2 pass writing than in 4 pass writing, the difference between the two writing methods should be similar for 2 pass writing. This first writing method that is expected to yield less localized heating effect is designated "Overlapped (reference)" in the figures.
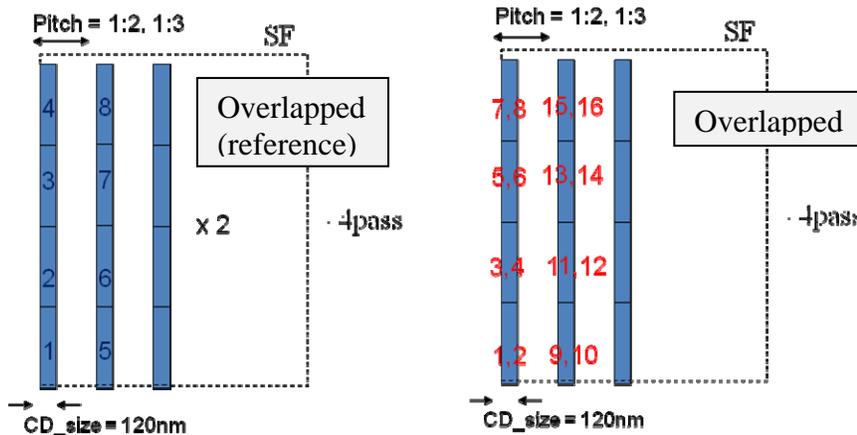

Figure 1. Line-space patterns written with 2 different shot sequences where the reference pattern on the left is twice written sequentially (long time between overlapping shots) and the right pattern is written with just the blanking time between overlapping shots.

Second, the shot sequence is altered to write the subfield so that all pairs overlapping shots are shot immediately with only one blanking time in between. So, first, the bottom left shot of the subfield is exposed, then its overlapped pair, then the pair above, and so on in the bottom to top, left to right sequence for the subfield. This minimizes the resting time in between the shots, and therefore should increase greatly any highly local heating effects (which turns out to be negligible). This is designated "Overlapped" in the figures. The shots of "Overlapped" should print larger than "Overlapped (reference)" if there are any highly local heating effects. Figure 2 shows that we do not see this effect in the measured data for the L:S=1:3 case. CDs of Overlapped are consistently smaller than those of Overlapped (reference). The CD differences plot in Figure 3 shows the negative bias of about 1nm on the average. Since we would see the opposite if the local heating effect is significant, we would like to see another data point. It can be seen below (Figure 7) that the L:S=1:2 experiment produced the same result.

Figure 2. Measured CDs of line-space patterns L:S = 1:3, showing heat accumulation in each subfield.
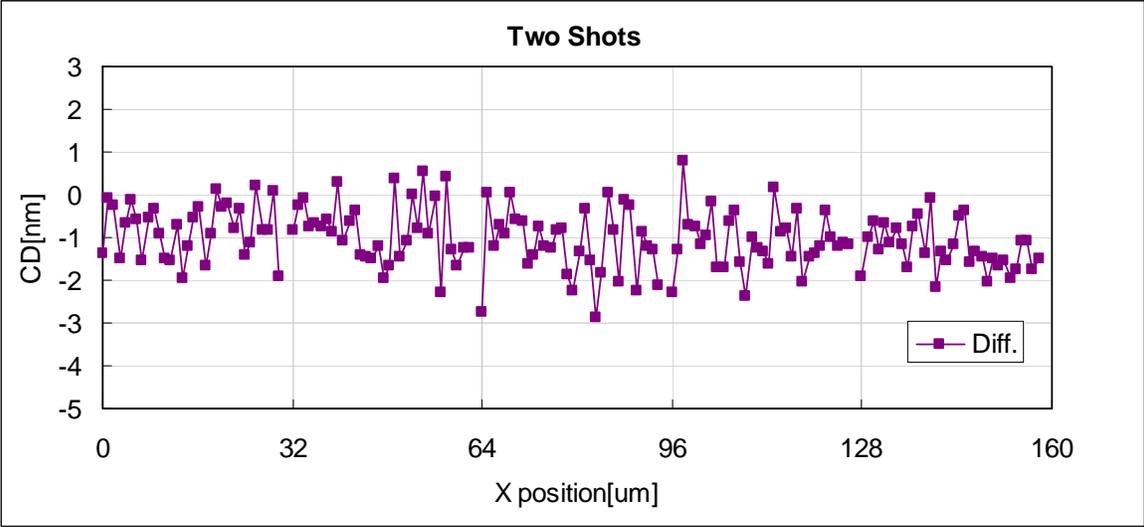

Figure 3. Measured CD difference of overlapped – overlapped (reference) of line-space L:S = 1:3 case.

In addition, a control experiment was done where the shots were written without overlapping shots. The placement of the test patterns within the mask was similar to the Overlapped and Overlapped (reference) patterns. Proximity Effect Correction was turned on in the machine for all of these experiments. Only manufacturing variation should be visible in all of the measurements collectively from both sets of the control data. Figure 4 is behaving as we would expect. At far left and far right ends, some systemic biasing is observed due to some long range effects unrelated to heating effects.

There is a 30-35nm bias in the NuFlare process that is observed in the CD measurements being slightly larger than 150nm in the control case, even though the shot sizes are 120nm x 800nm. The double overlapped shots were printing at above 190nm width, just as expected.
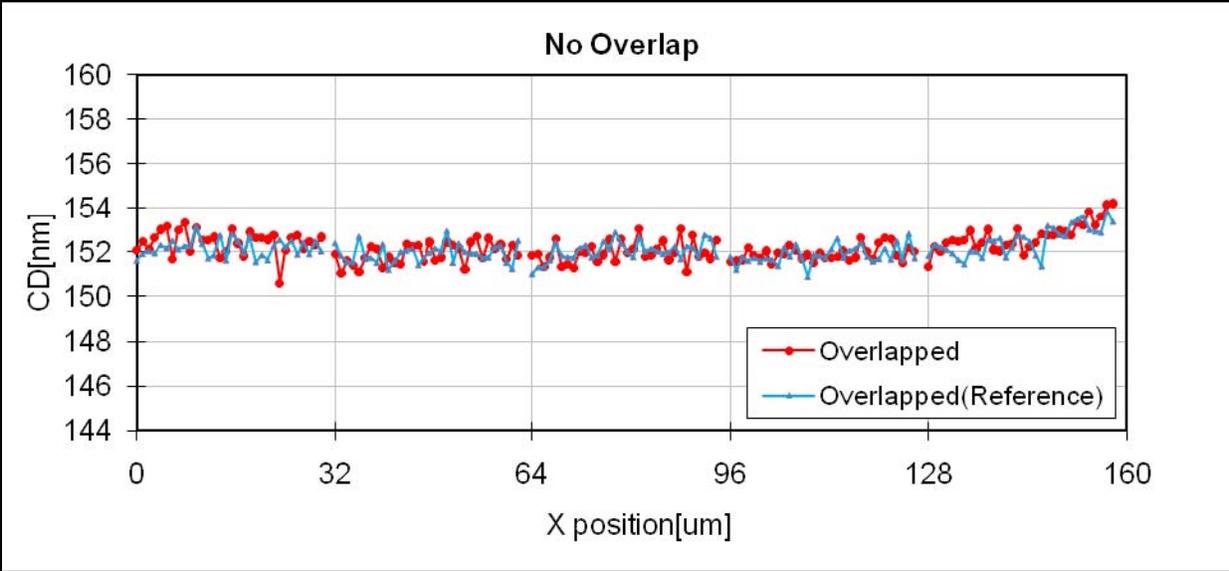
Figure 4. CD measurements for the two writing methods for a single shot (no overlap) case. This is the degenerate case where the two writing methods are not different from each other.
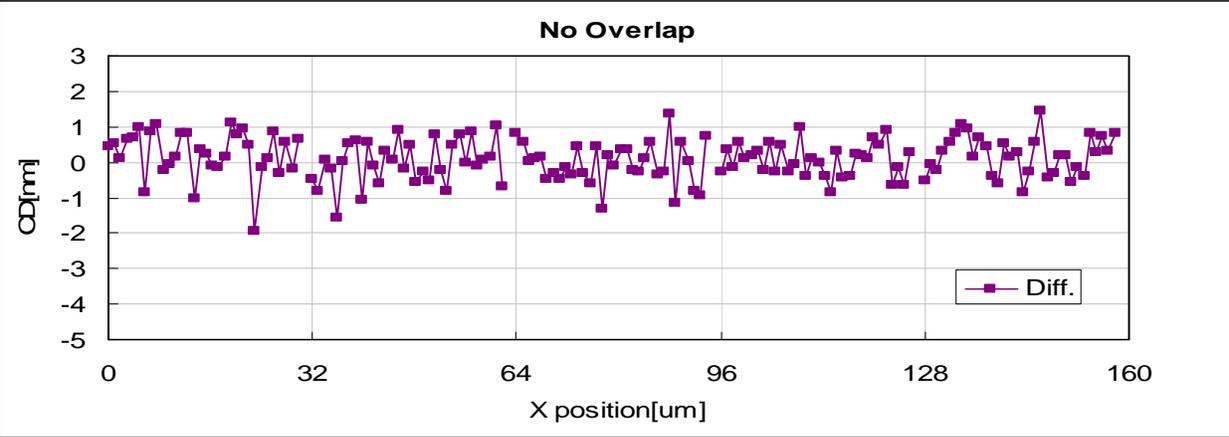

Figure 5. Delta CD of each position of the No Overlap case.

Due to machine availability, the EBM-6000 [7] was used but the following factors suggest that the EBM-7000 [8] and above are better for heat-related behavior.

Maximum shot size is reduced from 800nm square to 500nm square. Shot size is the single largest factor in heating by far. All of the shot area is being exposed simultaneously without any blanking time to cool it down. The EBM-7000 has reduced current (I) from the EBM-6000.

I(EBM-7000) = 200A x 500nm^2 = 500nA, while I(EBM-6000) = 70A x 800nm^2 = 448nA.

Energy per shot (50keV*I) is nearly the same in both systems, so we expect the impact from heating to be the same in both systems.

In addition, in a far less significant impact to heating effect, subfield size is reduced from 32µm^2 to 8µm^2 from the EBM-6000 to the EBM-7000. This has the effect of enforcing a more restrained shot sequence across the writing frame. Shots are spread out across time with a more certain distribution, reducing the worst case concentration of shots in geometric proximity over time proximity.

These experiments purposefully exaggerate the overlap effect. Overlapped areas are extremely large compared to what is expected from MB-MDP. Because MB-MDP primarily helps with small complex shapes, overlap areas rarely exceed 1000nm^2. These experiments show overlapped areas of 160,000nm^2 and 400,000nm^2. Since heating effects are largely a function of shot size, if the effects are minimal with these experiments, MB-MDP shots with its far smaller degree of overlap will have no measureable effect.
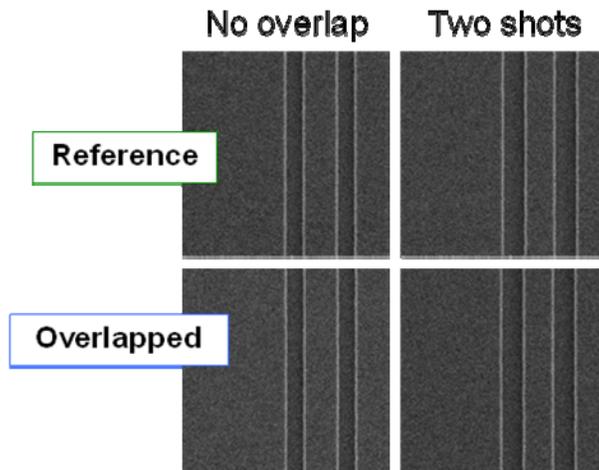

Figure 6. SEM images of the L:S = 1:3 case showing two shots on top of each other printing wider lines in both writing methods

The experimental results for L:S = 1:2 case further demonstrates the same conclusions as seen in Figure 7 below.

The "reference" case where there was more rest time in between the overlapped shots produced larger CD than the "overlapped" case where overlapped shots were written immediately on top of each other. If overlapping the shots caused resist heating effects, we would expect to see the opposite. We conclude that overlapping shots per se do not cause any resist heating effects. The suspected causes for the unexpected behavior are still under investigation.

Even though overlapping the shots per se do not cause resist heating problems, these experiments clearly show that heating of the substrate in the macro scale does produce CD differences. On the plots, these are observed as a periodic increase in CD sizes, and then a sudden drop. This pattern matches exactly where the subfield changes are, repeating every 32µm. The shots are written in the left to right order, but many other subfields above and below these patterns are written in between the two subfields that write the patterns being measured here. The left side of the subfield has a substantial amount of time to cool after the right edge of the subfield to the left had been written. The "No Overlap" cases see very little variation between the left and the right side of the subfields. But the "Two Shots" cases see much more variation. This is not due to overlapping shots per se, but rather because of the increased total dose within the subfield. In this highly exaggerated test, the Two Shots case doubles the total dose applied in the subfield. Even though

the doubling of the shot count doubles the writing time, the substrate under the subfield is continuously heating, and this increases the CDs.
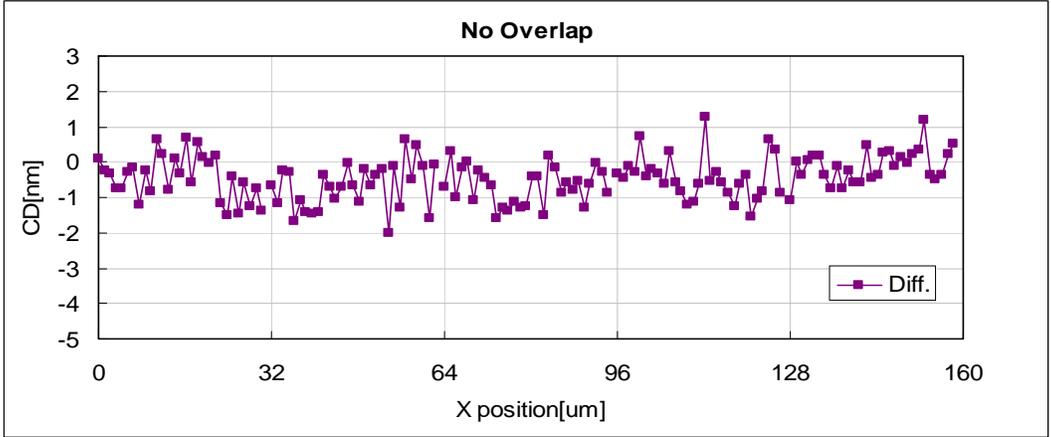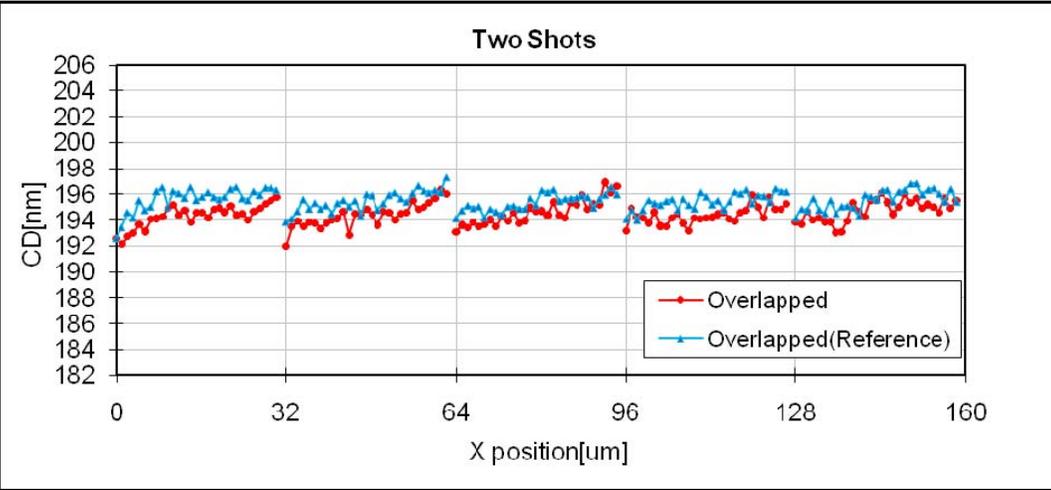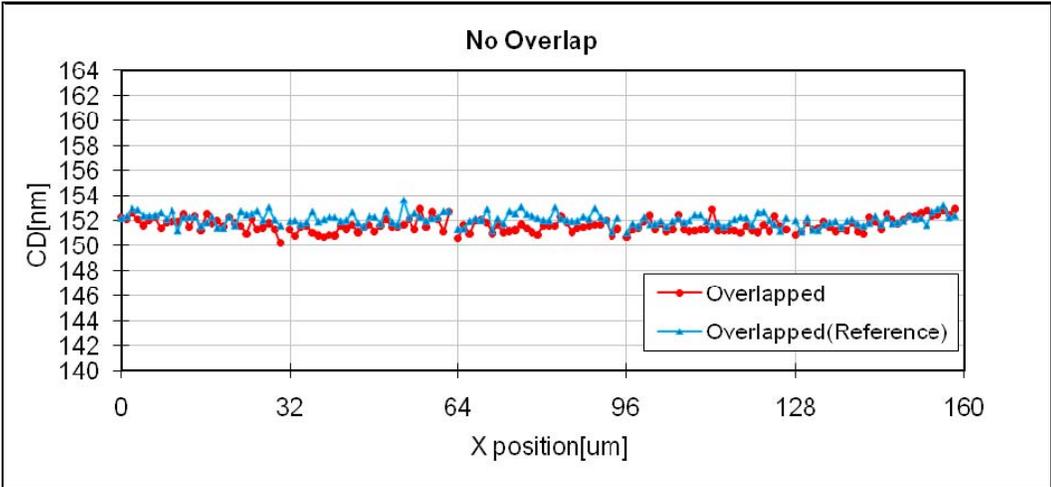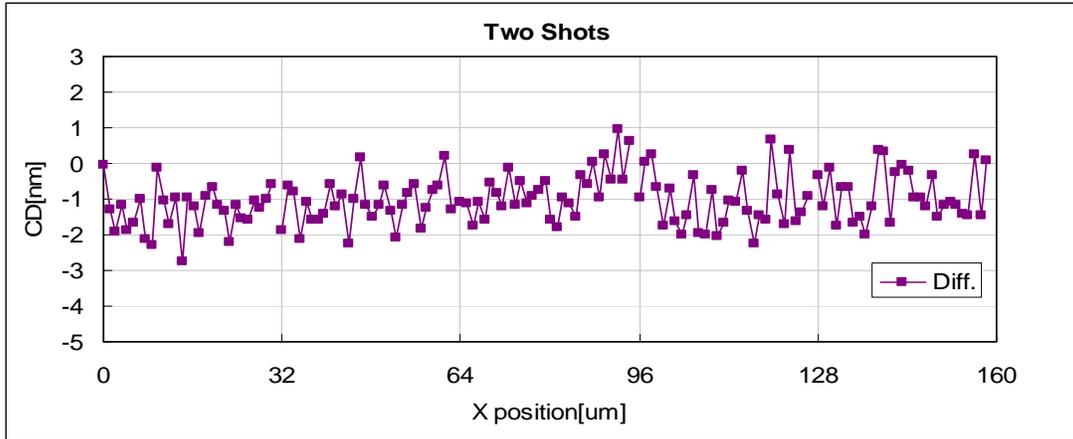
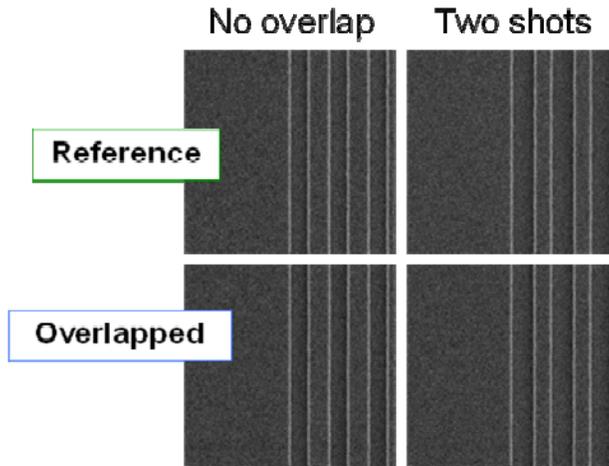Figure 7. CD plots comparing the two writing methods for the L:S = 1:2 case.

Figure 8. SEM images of the L:S = 1:2 case.

To understand the effect of dose density (per subfield) on CD, we extended the experiment to even more unrealistic dose densities for the two test cases. For both L:S = 1:2 and 1:3 cases, triple overlap and quadruple overlap cases were constructed and written with both shot sequences ("Overlapped" and "Overlapped(reference)"). The results are shown in Figure 9.

Of the five subfields measured, the average of the average slopes of the middle three subfields are plotted for each of L:S = 1:2 and 1:3 cases. In L:S = 1:2 case, Overlapped # = 1, which is the same as "No Overlap" in the earlier figures, would have shot density of 33%, while Overlapped # =2 would have 66%. Since pattern densities of greater than 50% rarely occurs in real patterns, even if shot with overlaps, dose densities of greater than 60% would be rare. Even though PEC reduced the actual dose used, these doses are much greater than any real pattern would use.

It is clear that thermal effects are significant for CD control. Since overlapping shots immediately on top of each other do not shoot larger than overlapping shots with ample rest time in between the shots, thermal effects are not local effects. Specifically, the act of overlapping on its own does not seem to impact CD control.
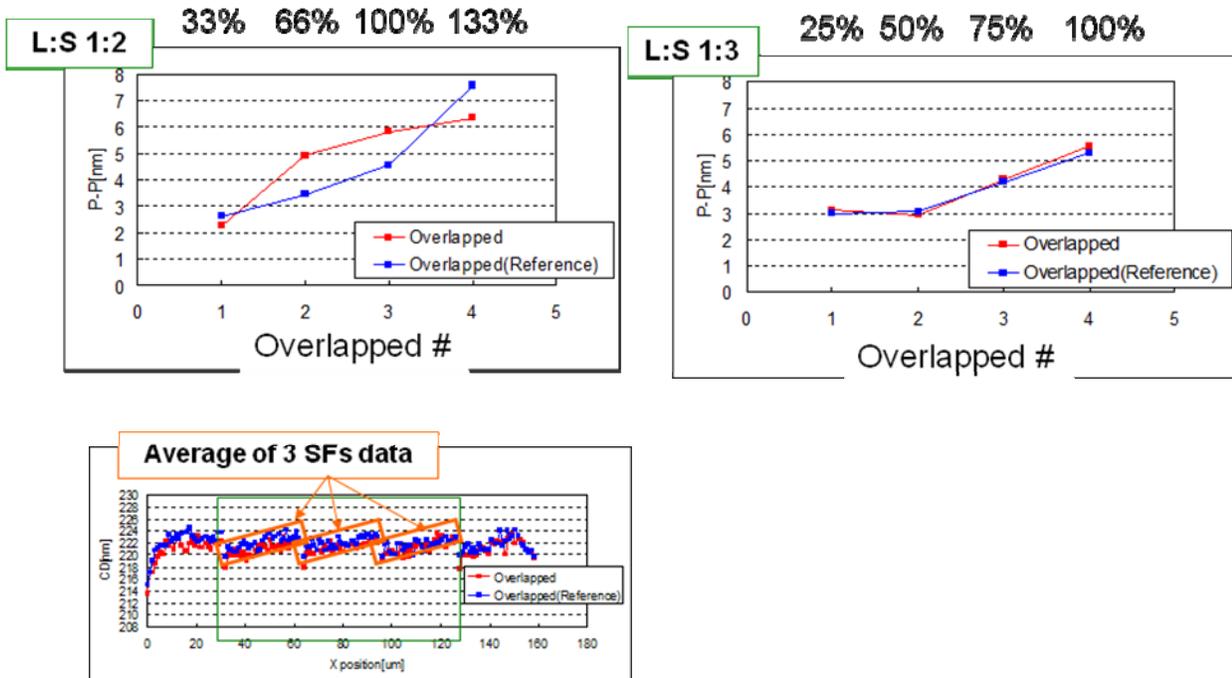
Figure 9. Unrealistically high dose densities (per subfield) showing thermal effects on CD.

However, in MB-MDP, there is a 10-30% of the exposed area being overlapped depending on the pattern. This increases the average dose per unit area by 10-30% before PEC decreases it. These experiments show that there is CD sensitivity to dose density over subfield sized ranges. While this sensitivity is not specifically a result of overlapping shots, the increased dose density of patterns written with overlapped shots may be a concern if a subfield is written with large overlapped shots. The only way a large amount of dose can be applied in a short amount of time is if large shots are used.

MB-MDP needs to refrain from applying large overlapped shots in areas where a subfield sized area is written with large shots (and therefore, quickly). The effectiveness of MB-MDP is not affected by this restriction, however. MB-MDP is effective in reducing shot count when shot counts are already very high. Dose density over unit time is very low in these situations

We conclude that dose densities of 50%, even for 100% overlapped shots of 120nm x 500nm areas have no adverse effects from resist heating. MB-MDP shots that are applied to much smaller shots, and with overlapped areas that are much smaller will have no issues with resist heating.

4. SUMMARY AND CONCLUSIONS

MB-MDP reduces mask write times with the NuFlare EBM-7000 and above using overlapping VSB shots. In this paper, we examined a number of potential issues about MB-MDP. In particular, two potential questions about thermal effects were examined. First, it was determined that resist heating in the immediate location of the shots is not an issue. Overlapping shots has no effect on CD control. Then, it was determined that increasing dose density over unit time over subfield-sized areas has an effect on CD control, if the shots are large, and dose densities are above 50%. Though this effect is independent of overlapping per se, MB-MDP increases dose density per unit time over conventional fracturing for a given pattern. Shot count is decreased, so subfields are written faster, and shots are overlapped, so total dose per subfield is increased. But MB-MDP is applied only where shot densities are high and shot sizes are small to begin with. In the range of patterns over which MB-MDP is applied, CD changes within a subfield due to substrate heating is considered to be negligible.

There are no outstanding questions remaining for production use of MB-MDP.

ACKNOWLEDGEMENTS

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