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Model-Based MPC Enables Curvilinear ILT using Either VSB or Multi-Beam Mask Writers

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ABSTRACT

Inverse Lithography Technology (ILT) is becoming the choice for Optical Proximity Correction (OPC) of advanced technology nodes in IC design and production. Multi-beam mask writers promise significant mask writing time reduction for complex ILT style masks. Before multi-beam mask writers become the mainstream working tools in mask production, VSB writers will continue to be the tool of choice to write both curvilinear ILT and Manhattanized ILT masks. To enable VSB mask writers for complex ILT style masks, model-based mask process correction (MB-MPC) is required to do the following: 1). Make reasonable corrections for complex edges for those features that exhibit relatively large deviations from both curvilinear ILT and Manhattanized ILT designs. 2). Control and manage both Edge Placement Errors (EPE) and shot count. 3. Assist in easing the migration to future multi-beam mask writer and serve as an effective backup solution during the transition. In this paper, a solution meeting all those requirements, MB-MPC with GPU acceleration, will be presented. One model calibration per process allows accurate correction regardless of the target mask writer.

Keywords: Mask Process Correction (MPC), Model-based MPC, Mask writer, VSB, Multi-beam, Multi-beam mask writer, Inverse Lithography Technology (ILT), MPC, Mask simulation, Shot count, GPU

1. INTRODUCTION

As semiconductor manufacturing processes advance in pace with Moore’s Law, the photomask industry has been increasingly challenged, especially as it entered the sub-wavelength era. When imaging at subwavelength, resolution enhancement technologies (RET) such as OPC, Phase Shift Masks (PSM), sub-resolution assist features (SRAFs), Source Mask Optimization (SMO), and in particular, Inverse Lithography Technology (ILT), are often required, adding complexity to the mask [1-8]. ILT was introduced by Dan Abrams and the author from Luminescent Technologies in 2006 at SPIE Advanced Lithography Conference [1] - 6 papers from Luminescent and its partners including 2 foundries, 1 memory maker, and 1 mask shop, were presented. ILT has become one of the core lithography technologies with over 200 papers published. The world’s leading semiconductor manufacturing companies all publicly presented ILT as a key lithography technology going forward.

Figure 1: ILT mask patterns with different mask complexity [1].

The ILT mask patterns tend to be curvy and small. Figure 2 [8] shows an example of how the use of ILT can substantially increase lithography process windows. In general, more complex and curvier mask patterns will result in better lithography process windows. However, the resulting mask geometries and assist features, which play a crucial role in increasing the process windows, also make the mask patterns more complex. This creates challenges for every step of mask making, including Mask Data Preparation, Mask Writing, Mask CD Metrology, Mask Inspection, Mask Review, and Mask Repair. Among these steps the most difficult part is mask writing on a VSB mask writer.
The current workhorse for mask writing is the Variable Shaped Beam (VSB) mask writer (Figure 3(a)). It was invented after raster Gaussian beam mask writer by leveraging the fact that the patterns on mask at that time were all Manhattan patterns. It was, therefore, much more efficient to write the pattern sections with different sized rectangular shots. However, such writing mechanism, when writing curvilinear ILT patterns, became very inefficient. To meet the pattern fidelity requirements, the curvilinear patterns had to be decomposed into many small shots, which makes the write time increase over 10X. In addition, the mask process margin became worse because of the smaller shots.

Multi-beam mask writing was invented recently to solve such challenges (Figure 3(b)). A multi-beam writer has a massive array of pixels, each pixel being controlled on or off individually. In one exposure, an entire array area is exposed; therefore, it can write any shape using the pixelization idea such as used on LCD screens. These shapes can be Manhattan (axis-parallel rectilinear shapes) or curvilinear, and the write time is constant no matter what type of patterns are written as long as the data path is fast enough to feed the writer.

Figure 2: Example of Lithography performance gained by using ILT masks with different mask complexity [8].

Figure 3: a). VSB Mask writer: Variable Shaped Beam, single beam, rectangular shape; b). Multi-beam Mask Writer: Massive pixel array; c). Curvilinear ILT mask pattern [8].

2. MODEL-BASED MASK PROCESS CORRECTION FOR VSB AND MULTI-BEAM

2.1 MPC requires both shape and dose correction

MPC is similar to Optical Proximity Correction (OPC), but there are also some differences. In OPC, only the mask shape is changed, while in MPC, there is another degree of freedom that can be manipulated – dose. Dose is manipulated by the amount of time the eBeam is exposed for a given shot, thereby changing the energy projected onto the resist-coated surface. Manipulating dose can improve the process window on the mask of a given set of patterns. The process margin on mask is typically called Dose Margin. It is a measure of the resilience of a particular set of patterns on mask to a given dose variation. It is generally considered to be an excellent proxy for resilience to manufacturing variation in general for mask making. Manipulating dose can improve dose margin, particularly for small features on the mask, such as assist features. Figure 4 shows mask patterns with assist features. The colors on the bottom halves of Figure 4 indicate dose margin: red/orange means bad dose margin, green means good dose margin, and yellow is in between. The left most pictures show that without MPC, dose margin is bad on line-ends and also small assist features. In middle picture shows that when shape correction is applied, you can see the dose margin at line-end on the main feature is...
improved, but the dose margin on the small assist feature has no noticeable improvement. On the right picture, both shape correction and dose correction were applied. It shows the dose margin on the small assist feature is significantly improved.

Figure 4: An example showing shape and dose correction in MPC.

2.2 Curvilinear ILT MPC on VSB: Both Dose and Shape Correction Needed

Figure 5(a) shows exposure for two isolated VSB shots, one 100nm square shot and one 60nm square shot. It shows when the VSB shot is smaller, like 60nm, it has an impact on dose margin – the edge of the exposed image is blurring, the image slope is worse (flatter) compared to the 100nm shot, therefore, the process variation band is wider – meaning when dose is changed, the CD variation is bigger than the 100nm case. Because of this, the resulting resist profile (Figure 5(b)) is also shallower. Such effect cannot be corrected by shape correction alone, because just adjusting the shape cannot change the image slope. The only way to make the image slope steeper in such a case is to increase the energy (dose). In contrast with resist development, etching is done by plasma. In theory it has atomic scale resolution. Etching will introduce bias. Such bias is better corrected by shape correction. In summary, for VSB mask writers, both dose and shape correction are needed. Since VSB writers write each individual shot, in theory it can adjust the dose of each shot. This capability is available on advanced VSB mask writers. Another way to adjust the dose on VSB writers is doing overlapping shots – the same area is exposed with multiple shots. For curvilinear ILT masks, one can leverage this to reduce the shot count, and therefore, the write time.

Figure 5: Illustration of exposure, resist development, and etching effects for two different sized VSB shots.

As explained in the introduction, curvilinear ILT mask is a challenge for VSB mask writers. It requires breaking the curvy feature into many small shots, resulting in 2X or more shot count. D2S invented a way to reduce the shot count on VSB writers for curvilinear features by using overlapped shots [10]. As shown in Figure 6, it takes 10 conventional shots to write an angled line. However, if one can allow the shots to be overlapped, it only takes 5 shots to write the same
feature. In addition, because the overlapped area has higher energy, making the edge slope steeper, dose margin is improved.

Figure 6: Illustration of shot count reduction by using overlapped shot to write an angled line.

Once dose modulation and overlapped shots are allowed, the model must consider and model the dose. Figure 7 shows a mask model that incorporates both shape and dose as variables. Figure 7(a) shows the measurements of Mean-To-Target (MTT) for an isolated line. Not only were bias and nonlinearity observed for different features sizes, but the different bias and nonlinearity were also observed for the same features with different doses. Figure 7(b) shows that using a model that captures both shape and dose effects, MPC can correct the CD to target within a 4nm range [11].

Figure 7: Illustration of exposure, resist development, and etching effect for two different sized VSB shots.

Figure 8 shows a result of curvilinear ILT MPC for VSB mask writers. From Figures 8(a) and 8(b), one can see that without model-based MPC, the simulated mask pattern has pattern fidelity issues, such as line-end shortening and CD errors, and in the worst case, the line is not resolved on the mask, causing serious necking problem. On top of that, this results in a large number of shots and smaller shot sizes. Figures 8(c) and 8(d) are the model-based MPC results using overlapped shots. One can see that the shot count compared to Figure 8(a) is significantly reduced, and the simulated mask contour matches the target very well.
Figure 8: MPC result on curvilinear ILT mask using VSB mask writer, where (a) shows the curvilinear ILT mask pattern fractured in conventional shots, (b) is its simulated mask contour (solid pink) and target (orange contour); (c) shows the overlapped shots to write this pattern, and (d) shows simulated mask contour (solid green) and target (black contour).

Figure 9 shows the Edge Placement Error (EPE) distribution for this ILT pattern with and without model-based MPC: without MPC, the largest EPE is over 10nm, while with MPC, all EPEs are smaller than 4nm.

2.3 Curvilinear ILT correction on Multi-beam: Both Dose and Shape Correction Needed

For multi-beam correction, there are similarities to VSB and there are also things that are unique to multi-beam. As explained in the introduction section, multi-beam writes a large number of pixel arrays. These pixels form mask patterns. Once the mask pattern is exposed, the rest of the mask process – resist development and etching, are the same as in a VSB case. Therefore, what we have discussed in section 2.2 for VSB, such as dose modulation, is required to improve resist image contrast and dose margin (Figure 10(b)). Etching bias is better corrected by shape correction (Figure 10(c)), just as the case with VSB writing.

Figure 10: Illustration of exposure, resist development, and etching effect for multi-beam mask writer.
When MPC is mentioned for multi-beam, in general it refers to shape correction, in particular, a shape correction that works for curvilinear geometries, because multi-beam was designed to write curvilinear ILT mask patterns. Such shape correction is required to calculate from after-etching target (commonly referred as AEI) to after-resist target (commonly referred as ADI). It can also be used to reserve calculate any process bias as long as the forward model or simulation is provided. Since this MPC has to handle curvilinear geometries, it requires a geometry engine that is designed for curvilinear geometries, the conventional EDA framework that handles Manhattan patterns will not work any more. Another paper of this conference discusses a curvilinear geometry engine from D2S for this purpose and its applications[15]. Such a shape correction for curvilinear geometry is required for all multi-beam mask writers, including both IMS multi-beam mask writer and NuFlare mask writers.

2.4 PLDC for the NuFlare MBM-1000

What is unique on multi-beam mask writer is the individual pixel dose control. Since multi-beam is writing such massive number of pixels, unlike in VSB writer, each shot is a unit for dose modulation. In theory, one can manipulate each individual pixel. The benefit of manipulating each pixel is to give maximum flexibility to improve the edge contrast and profile. However, considering the size of all pixels in a mask represented with different intensity, such calculation has to be done inline; otherwise, the data volume will be too high and just transferring the data would be longer than the mask write time. Another paper of this conference discusses such a correction method implemented for NuFlare’s MBM-1000 system called Pixel-Level Dose Correction (PLDC) [12].

Figure 11 shows a result of curvilinear ILT PLDC for the MBM-1000. From Figures 11(a) and 11(b) one can see that without correction, the simulated mask pattern has pattern fidelity issues, such as line-end shortening and CD errors. In the worst case, lines do not resolve on the mask, causing serious necking problem. Figures 11(c) and 11(d) are PLDC results by manipulating each pixel. One can see that the simulated mask contour matches the target well.

![Image](https://example.com/image.png)

Figure 11: PLDC result on curvilinear ILT mask for multi-beam, where (a) shows the curvilinear ILT mask pattern converted by multi-beam without correction, (b) is its simulated mask contour (solid red) and target (black contours); (c) shows the multi-beam PLDC result with dose modulation on each individual pixel, and (d) shows simulated mask contour (solid green) and target (black contour).
2.5 Mask model portability between multi-beam and VSB

There is a situation that every customer of multi-beam mask writer will be facing when they adopt multi-beam mask writer into production: how to back up the multi-beam mask writer when the system is down. Since most of the customers, if not all, will only have 1 or 2 multi-beam mask writers in the beginning, what if this writer is down? In such a case, ideally one would need to write the mask on their existing VSB mask writers. The question is whether this is feasible, and how to make it work.

One key aspect of providing compatibility between multi-beam writing and VSB writing is model compatibility. Fortunately, the mask model for multi-beam and VSB are the same. As shown in Figure 12, other than the exposure system being different, once the eBeam hits the resist, the rest of the mask process, such as resist exposure bake, development, dry etching or wet etching, are identical (assuming they both use the same resist and etching process). There are effects such as thermal effects and charging effects that impacts the writing differently in each type of a machine, but a union of the models works because 1) the physics and chemistry underlying the effects are the same; and 2) effects accentuated by the machine type are corrected for in the machines. Therefore, one can develop a single mask model that is used for both VSB and multi-beam. D2S has developed TrueModel\textsuperscript{®}[11] as such a model. TrueModel mask model handles both 1D and 2D features, including curvilinear ILT mask patterns, working for both 193 and EUV and supports all multi-beam mask writers as illustrated in Figure 13.

Figure 12: Illustration of mask process for both VSB and multi-beam mask writers [11].

Figure 13: Illustration of D2S TrueModel, a single model that handles both 1D and 2D features, including curvilinear ILT mask patterns, working for both 193 and EUV and supports all multi-beam mask writers.
2.6 GPU is Good for Mask Model and Simulation

Graphical Processing Units (GPU) were originally designed to accelerate the performance of computer games. Unlike CPUs, GPUs have a large number of cores, each core running the same operation, such as calculating the shading of each pixel, in parallel. Later on, it was extended to do general parallel programming when NVIDIA introduced CUDA[13]. Each core becomes a mini-computer, programmed to run fairly complicated, but the same algorithm in parallel. Since GPUs of today have thousands of such cores, its speed, when implemented correctly and coordinated with a CPU that it accelerates, is much faster than a multi-core CPU on its own. For example, a convolution is a common operation in image processing. It is used for all kinds of filters to smooth an image or highlight edges in the image by using different kernels (Figure 14(a) [14]). Convolutions are hardware implemented in GPU, and can be called with a single command. In mask modeling, Gaussian kernels are common. Running a Gaussian convolution in GPU coordinated with CPU is much faster than CPU only. As shown in Figure 14(b), the GPU-accelerated version is more than 5 times faster than the CPU-only version [11].

![Figure 14: (a). Illustration of a convolution, (b). Comparison of run time of running a single Gaussian convolution on 80um x 80um mask area with 10nm pixel size.](image)

For mask model and mask simulation, GPU is good for both dose correction and shape correction. Because of its single-instruction, multiple-data (SIMD) architecture, GPU is in general good for any simulation of nature. Most simulation-based processing can benefit. But it is particularly great when manipulating pixels in a multi-beam system since pixel manipulation is exactly what GPUs were born to do. GPU acceleration also works well for optimizing overlapped shots for VSB writers. Where the benefits of GPU acceleration are not so obvious is for all-angled geometry engine. Another paper in this conference [15] demonstrated that GPU acceleration can achieve over 10X advantage over CPU-only implementations because all-angled geometries can be made to process the large numbers of edges in parallel.

3. CONCLUSIONS

As semiconductor manufacturing processes advance in pace with Moore's Law, lithography continues to be one of the most challenging areas. Curvilinear ILT, a computational lithography technique introduced over 10 years ago, has now the biggest obstacle for production use removed by the emergence of multi-beam mask writers. Multi-beam mask writing is ideal for curvilinear ILT because of the constant write time. On the other hand, VSB mask writer needs to write curvilinear ILT as a backup of multi-beam. Both dose and shape corrections are required on VSB and multi-beam mask writers. With TrueModel, a single model can be used for both, enabling ILT portability. GPU-accelerated PLDC enables inline pixel-level dose correction for the NuFlare MBM-1000. GPU-accelerated model based-MPC enables curvilinear ILT for any VSB or multi-beam mask writers.

4. REFERENCES