Topography Description Model for 3D Exposure Simulation

Mumit Khan, Srinivas Bollepalli and Franco Cerrina

Center For X-ray Lithography, 3731 Schneider Dr., Stoughton, WI 53589

ABSTRACT

The problem of accurately describing the topography of a mask arose in x-ray lithography, where the absorber structures have dimensions of several hundred wavelengths and may have topography. However, the application of phase shifting structures and a refinement of the image formation calculation even in optical masks has recently raised the same issue for the case of optical lithography. This paper reports the design and implementation of Topography Description Model (TDM), a rule-based 3D topography generator that allows the user to describe the exposure system, such as a system comprising of mask, gap, resist and wafer. The paper illustrates some applications of TDM to real-world studies, such as studying the effect of absorber side-wall slope on the final image and optimizing XRL masks.

Keywords: Topography, 3D Exposure Simulation, Modeling

1. INTRODUCTION

The image formation in x-ray lithography faces two challenges: an accurate and verified physical exposure model, and an accurate representation of the exposure system to be modeled. The physics of image formation in x-ray lithography is well understood and several implementations of the physical models have been used with good success.[1] The complication of image formation in x-ray lithography stems from the details in the exposure system itself: mask topography, absorber slope variations, non-uniform materials, roughness in the mask as well as topography, non-uniformities, pre-exposures and so on in the photoresist material. Interestingly, some of the same problems are now facing the description of advanced optical masks. To accurately model the image formation in 3D, we need to supply the exposure model with detailed topographical description of the system; to solve this problem, we have developed Topography Description Model (TDM), a rule-based 3D topography generator that allows the user to describe the exposure system, such as a system comprising of mask, gap, resist and wafer. TDM combines the nominal layout that describes the 2D mask layout, and a process description (such as absorber material, bias and absorber sidewall slope characteristic of the process, resist material, etc) and creates the virtual 3D exposure system. A post-processor then generates the appropriate input for image formation codes; for a model based on Beam Propagation Method, the post-processor uses a solid-modeler to generate the 2D "slices" and the image is then propagated through the slices. The TDM post-processor is capable of producing any format that the image formation models might require, such as regular grids, finite-element meshes, and polygonal formats and all these various formats are annotated with the material properties of the physical system. Even though the current TDM implementation has been used mostly with image formation codes for x-ray lithography, the algorithms implemented are quite extensible to other technologies as well.

2. BACKGROUND

Until quite recently, most of the exposure simulators assumed that the masks have perfectly vertical side-walls, no roughness, no defects, etc. This was never really the limitation of the exposure simulators, but rather the limitation of the framework in which the exposure system is described. Our first effort in introducing non-uniformity in the mask came with adding a slope to the absorber sidewall.[1] The solution was quite limited in its use however and we started investigating a general mechanism for describing the non-uniformities in the exposure system. We first looked at Semiconductor Wafer Representation (SWR),[2] but SWR is not at all suited to describing the mask in any great detail. We were left with the following choices:

- Use a modeling language used by ray tracers, such as POVRAY. The big drawback is that there is no easy way to extract 2D planes from a 3D geometry.

- Use a full-fledged solid modeler. This is obviously the most general solution, and provides a mechanism to not only describe the system very accurately, but also allows us to extract 1D and 2D slices out the 3D system. There were two strikes against using a solid modeler – the large computational overhead and the lack of freely available robust solid modeling code.

- Create a specialized front-end to describe the topography typical of an exposure system and use Constructive Solid Geometry (CSG) back-end. This turned out to be the most natural solution and this effort subsequently became known as TDM.

3. TDM **DESIGN OVERVIEW**

A primary design goal of TDM way to provide an easy-to-use interface to describe the 3D exposure system, and the result was a set of rules to describe the topography. The initial design goals were:

CAD interface Must be able to interface to multiple CAD database formats, such GDS-II, CIF, simple polygons, etc. at runtime. The CAD interface defines the nominal 2D structure that forms the basis for the 3D topography.

Symbolic material names Users must be able to specify "library" materials (eg., PMMA) or use chemical compositions. The transmission and absorption values are then looked up in one of the available optical constant libraries.

Multiple materials Must be able to put multiple materials on the same mask. This is important for defect simulation, where the defects are of different composition than the mask absorber material.

Grid generator Must be able to produce the transmission masks in multiple grid formats (eg., uniform grids for FFT based engines, FEM grid for stress analysis, triangular grid, etc).

Visualization Must be able to visualize the realized structure using existing software. We chose Virtual Reality Modeling Language (VRML) browser as the visualizer of choice since it is freely available for many different platforms.

In addition to the above, TDM also handles stacked materials (important for phase-shift masks), 2D transformations of the CAD layouts such as biasing and corner rounding, merging multiple CAD databases, windowing simulation on a large mask.

3.1. DATA FLOW

Fig. 1 shows the data flow diagram of the TDM software. The 2D CAD layout is combined with a set of processing rules (eg., slope on the absorber sidewalls, sharp corners in the mask are rounded, mask features are biased, etc) to define the 3D topography of the exposure system. Once the 3D structure is built, the structure is sliced using a solid modeler, and a transmission mask is created from this slice using the appropriate grid generator and optical constants library. The transmission mask is then passed onto the exposure simulator for computing the image. Both the slicer and grid generator are extensible and can be adapted to suit the needs of existing simulators.

3.2. LANGUAGE

The front-end of TDM is a mini-language that lets the user describe the topography using a set of *generation rules*. The 3D topography is built as a set of objects, known as *regions*, each with a nominal 2D planar geometry, and optionally non-uniformity added to it. There is no inherent limit in the number of regions that can be constructed. These generation rules are extendible via C++ virtual inheritance. Currently implemented generators include:

ObjectGenerator	Creates a new TDM object
AppendObjectGenerator	Appends to an existing TDM object
BiasGenerator	Biases the patterns on a given objects
InversionGenerator	Inverts the tone of given objects

The following set of rules creates a simple exposure system consisting of carrier, absorber, gap and resist.
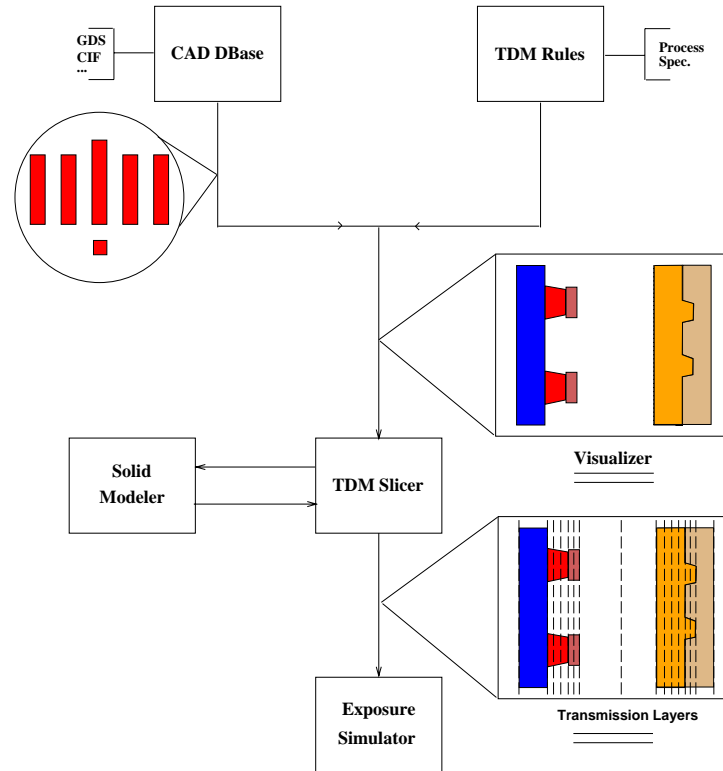
Figure 1. TDM data flow

```
# set the width (y) and height (x) of the final matrix. All units in nm.
set xrm width 2250 height 1800;
# create carrier. No pattern, so defaults to flat.
create region 1 name carrier composition "Si1 N1" density 2.7
    thickness 2000;
#
# create absorber patterns. Sidewall slope is 4 degrees.
create region 2 name absorber composition Au density 18.85
    thickness 450 slope 4
    pattern box 759 90 900 180
    pattern box 759 1530 900 180;
#
# and create gap and resist. No Pattern, so defaults to flat topography.
#
create region 3 name gap composition He density 1.0e-4 thickness 20000;
create region 4 name resist1 composition "C5 H8 O2" density 1.11
    thickness 500;
```
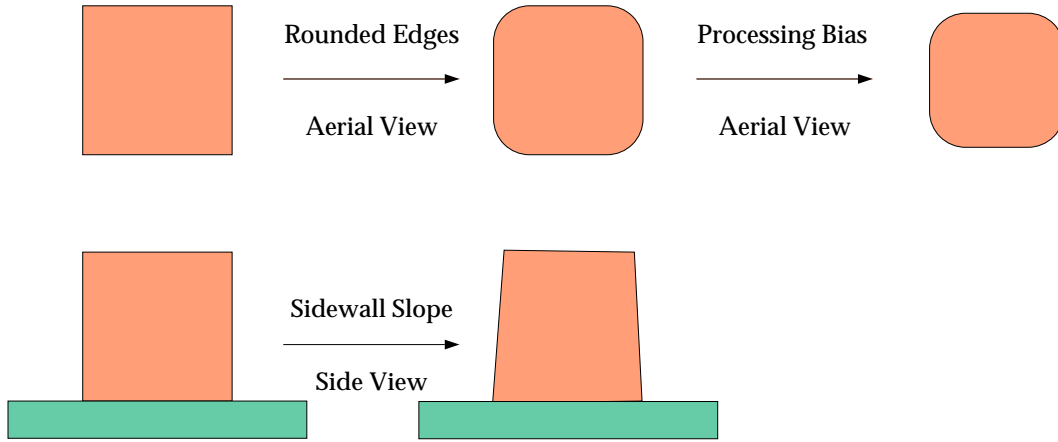
If we now wanted to bias the mask features by 20 nanometers and also invert the mask, we would simple add the following rules.
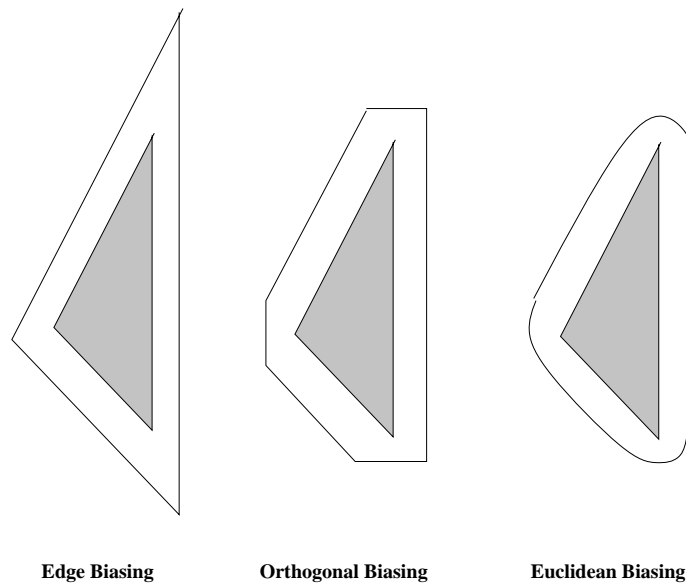
```
bias absorber 10;
invert absorber;
```

The *append region* rule can be used to add multiple materials to the same *region*, and is typically used to add defects to a mask.

Figure 2. Process-induced transformations

Edge Biasing   Orthogonal Biasing   Euclidean Biasing

Figure 3. Biasing algorithms

4. TDM **ALGORITHMS AND IMPLEMENTATION**

The algorithms in TDM are roughly divided into two categories – algorithms that typically operate on CAD layouts to model process-induced transformations, and algorithms that implement generalized slicing operations using Constructive Solid Geometry (CSG). TDM is written mostly in C++ with an embedded Tcl interpreter to interact with CSG back-end.

4.1. Process-induced 2D and 3D transformations

TDM allows the user to specify the various 2D and 3D transformations that are typical of most processes, such as processing bias, corner rounding of sharp corners, sloping absorber side-wall, etc. Fig. 2 shows the various transformations that TDM currently implements. Biasing is implemented using 3 different algorithms – Edge biasing, Orthogonal biasing and Euclidean biasing.[3] Fig. 3 shows the three different algorithms pictorially.

4.2. Slicing

TDM slicer is implemented as a front-end to a CSG engine[4] as well as a an intelligent grid-generator. It accepts a 3D description of the system, slices the system using the solid modeler and then generates transmission masks by
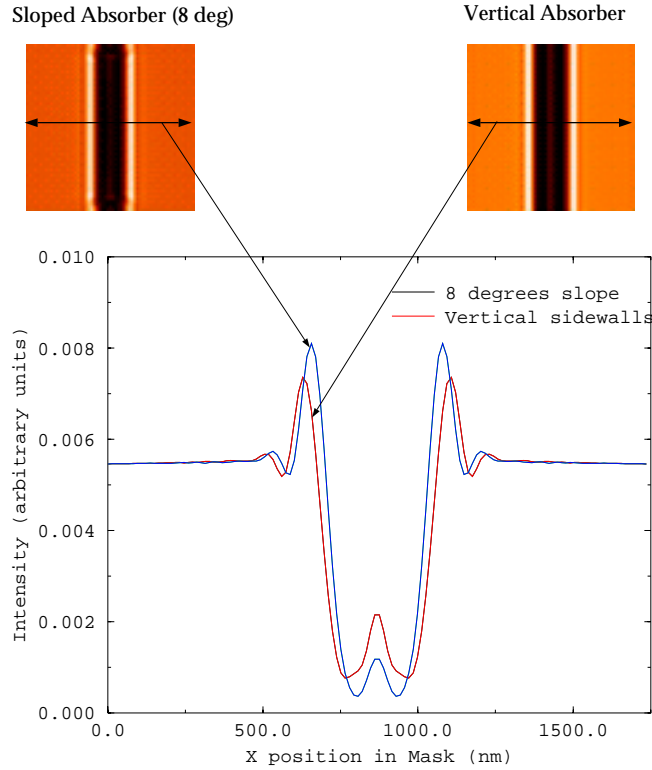
Figure 4. Effect of side-wall slope

scan-converting the slices into specified grid format. The scan conversion process uses a algorithm that can produce "grey" pixels to avoid pixel aliasing in the simulations.

5. APPLICATION TO X-RAY LITHOGRPAPHY

The case studies shown here have been conducted using the CXrL Toolset, a software package to simulate x-ray lithography process.

5.1. Absorber side-wall slope effects

This particular case study was conducted to see how much effect a slight slope in the absorber side-wall would have on the resulting image. In the complete study, we computed the images at slopes from 0 deg to 8 deg at steps of 0.5 deg. Fig. 4 shows the result for 2 such slopes.

5.2. Exposure over topography

One very important feature of TDM is that it allows exposure over existing topography. In this example, we used two different wafers – one with existing topography and one bare – and simulated the exposure on both the wafers. Fig. 5 shows the difference in the image between the two cases.

5.3. Novel fresnel zone plate

This example shows a novel application of TDM in designing a Fresnel Zone Plate with stair-stepped absorber pattern.[5] Fig. 6 shows the zone plate mask design as well as the simulated intensity profiles at various slices within the mask and at $f/1$ and $f/5$.
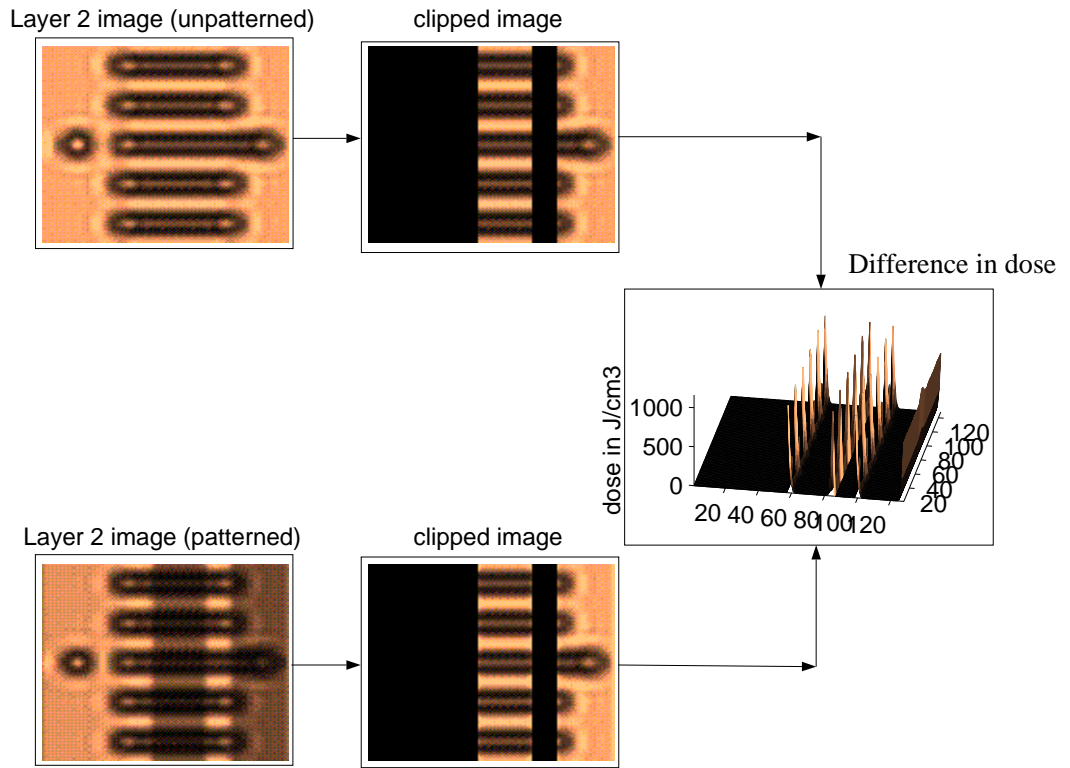
Layer 2 image (unpatterned) clipped image

Difference in dose

dose in J/cm3

1000
500
0

20 40 60 80 100 120

120
100
80
60
40
20

Layer 2 image (patterned) clipped image

Figure 5. Effect of exposure over topography

f/5   f/1
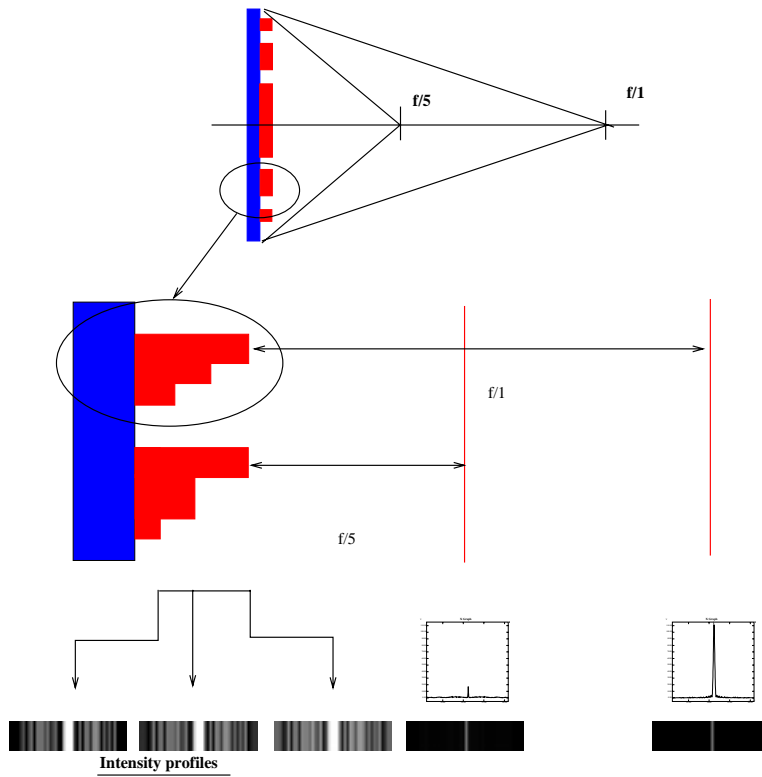
f/1

f/5

Intensity profiles

Figure 6. Fresnel Zone Plate application

6. SUMMARY AND CONCLUSION

We have designed and implemented a software package to describe the topography of an exposure system and interface it to exposure simulators. TDM allows the modeling of realistic structures and enables the user to study the effects of irregularities in the mask, substrate topography and non-uniform (both vertical and lateral) systems. TDM comes with interfaces for multiple CAD database formats, such as GDS-II and CIF, and for optical constants libraries. Integration with EXCON[6] allows the automated exploration of process parameter space (eg., *bias, slope, rounding* etc.).

ACKNOWLEDGEMENTS

REFERENCES

1. J. Xiao, M. Khan, R. Nachman, J. Wallace, Z. Chen and F. Cerrina, J. Vac. Sci. Technol., **B12**, 4038 (1994)
2. SEMATECH and Technology Modeling Associates, *SEMATECH TCAD Workbench Review*, April, 1995
3. T. G. Szymanski and C. J. Van Wyk, *Space efficient algorithms for VLSI artwork analysis*, IEEE Design and Test of Computers, vol. 2, no. 3, (1985)
4. Martti Mantyla, *Solid Modeling*, Computer Science Press (1988)
5. Zheng Chen, Private communications.
6. M. Khan, P. Anderson and F. Cerrina, Proc. SPIE, **1465**, 315(1991).