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# Using rule-based shot dose assignment in model-based MPC applications

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## ABSTRACT

Shrinking feature sizes and the need for tighter CD (Critical Dimension) control require the introduction of new technologies in mask making processes. One of those methods is the dose assignment of individual shots on VSB (Variable Shaped Beam) mask writers to compensate CD non-linearity effects and improve dose edge slope. Using increased dose levels only for most critical features, generally only for the smallest CDs on a mask, the change in mask write time is minimal while the increase in image quality can be significant.

This paper describes a method combining rule-based shot dose assignment with model-based shot size correction. This combination proves to be very efficient in correcting mask linearity errors while also improving dose edge slope of small features.

Shot dose assignment is based on tables assigning certain dose levels to a range of feature sizes. The dose to feature size assignment is derived from mask measurements in such a way that shape corrections are kept to a minimum. For example, if a 50nm drawn line on mask results in a 45nm chrome line using nominal dose, a dose level is chosen which is closest to getting the line back on target. Since CD non-linearity is different for lines, line-ends and contacts, different tables are generated for the different shape categories.

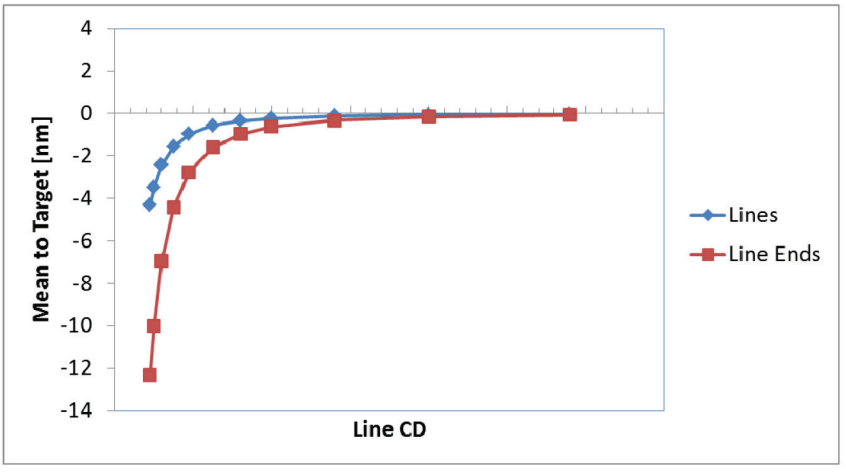


*Figure 1. CD linearity curves of lines (blue) and line ends (red) shown as mean to target errors. Drawn line CD is decreasing from right to left resulting in increasing deviation between drawn and measured CD.*

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# EDITORIAL

## EUV Lithography - A View of History

**Glenn Dickey,** Shin-Etsu MicroSi, Inc.

I would like to start by saying that I am not a history expert, however, I have been an avid reader of the many articles and comments on the subject. While there are proponents of EUV, there are some who still believe the technical challenges will not be solved in time to make EUV viable for prime time production.

In 2002 SPIE's OE magazine, an article reported major EUVL technology development beginning in 1997, with the goal of supporting the 100nm process, with beta tools by 2003. The article went on to say that all elements of EUVL technology have been successfully demonstrated in a full-field "proof of concept" lithography tool.

Also in 2002, the Lithography Roadmap Acceleration and Wavelength Generations required this progress to keep up with Moore's Law (Table 1):

| Year | Node | Lithography |
|---|---|---|
| 1981 | 2000nm | i/g-line Steppers |
| 1984 | 1500nm | i/g-line Stepper |
| 1987 | 1000nm | i/g-line Stepper |
| 1990 | 800nm | i/g-line Stepper |
| 1993 | 500nm | i/g-line Stepper |
| 1995 | 350nm | i-line DUV |
| 1997 | 250nm | DUV |
| 1999 | 180nm | DUV |
| 2001 | 130nm | DUV |
| 2003 | 90nm | 193nm |
| 2005 | 65nm | 193nm –> 157nm |
| 2007 | 45nm | 157nm -> EUV |
| 2009 | 32nm and below | EUV |

**Table 1: Wavelength "Generations"**

It was stated that two factors have contributed to the accelerated rate of change in Lithography:

1. Transition to sub-wavelength patterning
2. The finite limit on the Numerical Aperture (NA) of optical systems which sets a limit on the minimum possible resolution at a particular wavelength.

In 2003, International Sematech and Schott Lithotec signed an agreement on EUV Mask Blanks, in which Schott Lithotec would provide advanced mask blanks for use in EUV Lithography. Under the agreement, Schott Lithotec was to follow a defined roadmap for quality improvement of the blanks.

In that same year, SEMATECH launched the EUV Mask Blank Development Center (MBDC) in Albany, New York, with the mission to determine the risk associated with manufacturing EUV mask blanks. Much of the current knowledge about EUV defects including their formulation, printability, characterization and removability, was derived from work by scientists and engineers at SEMATECH. Still, achieving zero defect density on the whole quality area of the mask blank (142 x 142mm2), was back then and remains to this day, the greatest hurdle.

Another challenge for SEMATECH engineers was how to remove particles on top of EUV masks and those resulting from patterning. SEMATECH engineers learned that repetitive cleanings create more pits and compromise reflectivity so to reduce cleaning, a familiar method used for optical reticles was proposed, the use of a pellicle.

Research to find a suitable EUV pellicle was started and is ongoing today with pellicle suppliers.

In 2004, Electronic News Jeff Chappell wrote in his article "EUVL on Track for 32nm Node", and presenters at International Sematech Lithography forum were confident, that the technology will be ready to jump into production in 2009 at the 32nm node. There were challenges to be overcome and the question at the time was, will the Masks and Sources be ready in 5 years?

*continues on page 7*

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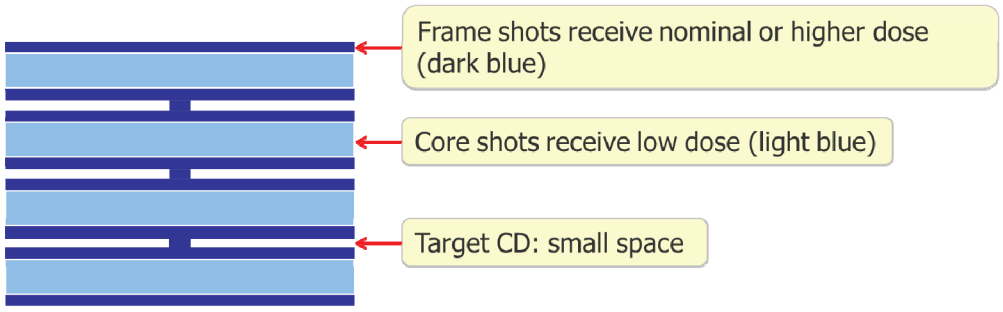


*Figure 2. Example of a test structure demonstrating reduced dose of core shots inside large exposed areas. While the core area is written at a dose below the nominal dose level, a 30 nm to 50 nm collar is written at or above nominal dose to maintain high edge slope around the narrow spaces.*

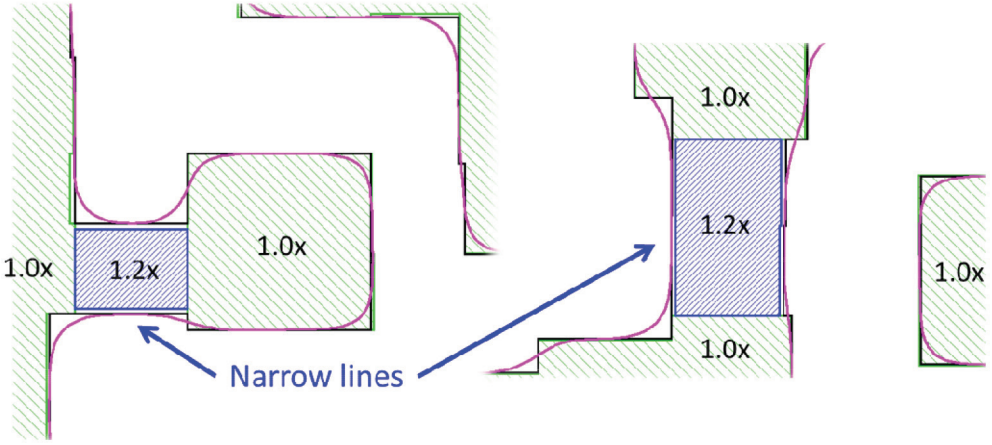


*Figure 3. Example of dose assignment (blue polygons) of narrow lines on a metal layer. Narrow lines are exposed at 1.2x nominal dose while larger CDs are exposed at nominal dose. After dose assignment all shapes are corrected during MPC to get the simulated contour (pink) close to target (black polygons).*

The actual dose assignment is done via DRC rules in a pre-processing step before executing the shape correction in the MPC engine. Dose assignment to line ends can be restricted to critical line/space dimensions since it might not be required for all line ends. In addition, adding dose assignment to a wide range of line ends might increase shot count which is undesirable. The dose assignment algorithm is very flexible and can be adjusted based on the type of layer and the best balance between accuracy and shot count. These methods can be optimized for the number of dose levels available for specific mask writers.

The MPC engine now needs to be able to handle different dose levels and requires a model which accurately predicts mask shapes at all dose levels used. The calibration of such a model is described in a separate paper.[1]

In summary this paper presents an efficient method for combining rule-based VSB shot dose assignment with modelbased shape corrections in MPC. This method expands the printability of small features sizes without the need for increasing the base dose of the e-beam writer which reduces backscattering and increases the lifetime of the electron gun of the writer.

## 1. Introduction

When adding variable dose to a conventional MPC solution, one can consider various implementation options. The approach taken in this paper is based on well-established techniques already used for many years in the design tape-out flow, namely DRC rules and shape based proximity correction as it is applied in conventional OPC and MPC.

Principally, dose assignment of individual VSB shots could be part of the optimization performed during MPC and could be fully model based. Such an approach, however, has some practical limitations which lead to the method of rule-based dose assignment presented in this work.

First, for shape correction only, well designed optimization engines exist in the OPC domain and can be applied to MPC without significant modifications. Introducing shot dose as an additional optimization variable would require substantial changes to the underlying engine, specific to MPC.

Second, some of today's high-end e-beam writers support a total of eight dose levels only. Such a small number of levels does not allow for a continuous variation of dose, when a maximum relative dose of 150% or more is required. The resulting discontinuities in dose levels would make a concurrent optimization of dose and

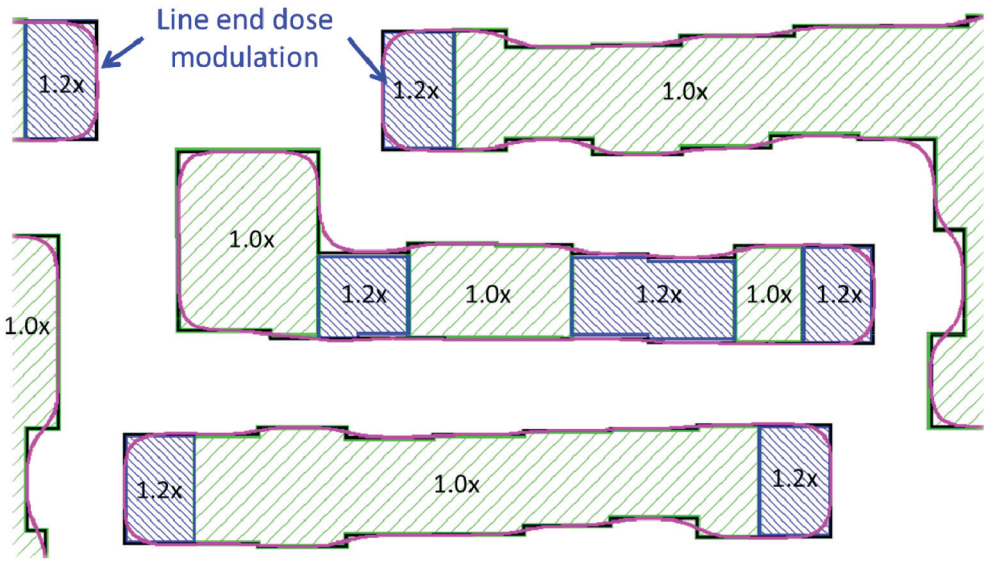


*Figure 4. Dose assignment examples demonstrating dose assignment of lines and line ends. It should be noted that line ends are dosed up at CD values where embedded line segments are not dosed up yet as shown in Table 2.*

*Table 1. Dose levels are chosen based on the dose range the mask process can tolerate and are encoded as layers or data types in an OASIS output.*

| Layer # | Dose Factor |
|---|---|
| 0 | 1 |
| 1 | 0.75 |
| 2 | 0.85 |
| 3 | 1.1 |
| 4 | 1.2 |
| 5 | 1.3 |
| 6 | 1.4 |
| 7 | 1.5 |

*Table 2. Dose assignment intervals for embedded line segments and line ends are generally different due to the different signatures in non-linearity (see Figure 1). As with the choice of dose levels, the range of CD intervals largely depends on the mask process to be corrected.*

| Line Width CD [nm] | Line End Width CD [nm] | OASIS Layer # |
|---|---|---|
| > 160 | > 200 | 0 |
| 160 ≥ CD ≥ 120 | 200 ≥ CD ≥ 160 | 3 |
| 120 ≥ CD ≥ 90 | 160 ≥ CD ≥ 120 | 4 |
| 90 ≥ CD ≥ 70 | 120 ≥ CD ≥ 90 | 5 |
| 70 ≥ CD ≥ 55 | 90 ≥ CD ≥ 70 | 6 |
| ≤ 55 | ≤ 70 | 7 |

shape a challenging task.

In this situation rule-based dose assignment seems to be most efficient since the dose levels required can be extracted from mask measurements and can easily be implemented in DRC code.

## 2. Dose Assignment Rules

Dose assignment is required only for certain shapes on a mask and rules have to be developed and then applied in a preprocessing step to MPC. Due to the processing sequence chosen here, dose assignment is not performed on a per-shot basis but on a per-polygon basis. During fracturing larger polygons with the same dose assignment might be divided into several VSB shots. In this section the development of rules is explained in detail and examples for dose assignments are discussed.

### 2.1 Dose assignment complexity

The complexity of dose assignment rules is governed by a combination of mask non-linearity and design rules. With shrinking feature sizes rules become more complex if the mask process is unchanged. For example, when only SRAFs are significantly affected by mask non-linearity, the entire SRAF layer can be exposed at a higher dose while all other features can remain on the nominal dose level. When main features get into a CD range where they are affected by nonlinearity significantly, rules become more complex and need to take into account specific segments of polygons.

Taking a metal layer as an example, the following complexity levels for dose assignment rules can be defined.

a) SRAFs only

b) SRAFs and line-ends

c) SRAFs, line-ends, and small lines

d) Large exposed area dose reduction, possibly combined with levels a) to c)

Dose assignment rules become more complex with decreasing minimum feature sizes for a given mask process. After the simple rule of dosing up SRAFs only, the next more complex set of rules includes dose assignment of line-ends. Line-ends are treated separately since they are more strongly affected by non-linearity effects then the CD loss of line width. This is illustrated schemati-

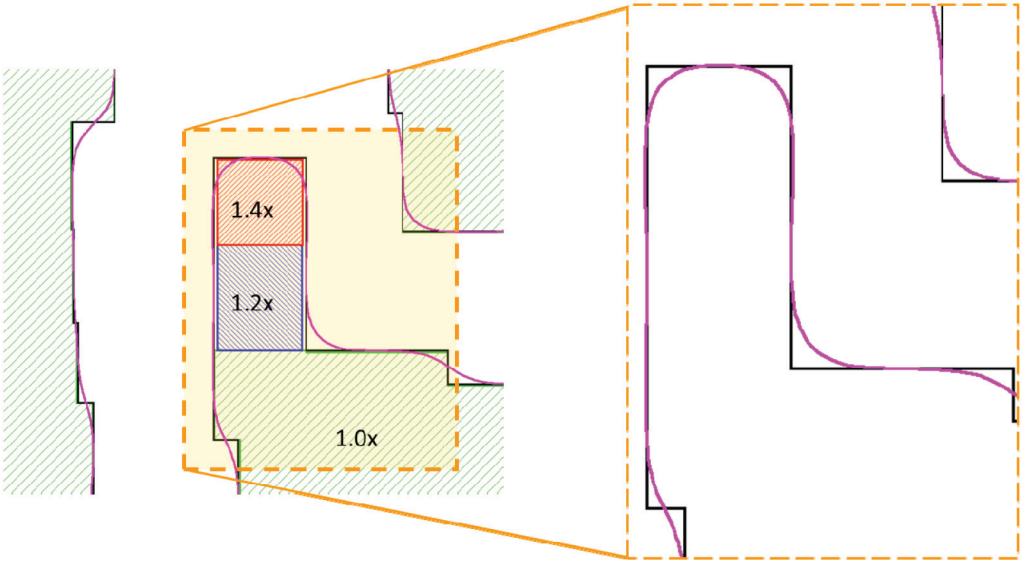


*Figure 5. Dose assignment as it could appear in an EUV design where main features are in a CD range where they are heavily affected by mask non-linearity. Besides nominal dose, two additional dose levels are assigned, 1.2x for the embedded narrow line segment and 1.4x for the narrow line end. The close-up shows the simulated contour (pink) after correction compared to the design target (black).*

cally in Figure 1.

When the minimum CD of main features on a mask decrease even further, additional dose assignment of small lines can be added to the rule set in order to improve resolution of those line segments.

If the mask contains large exposed areas, a different type of rules can be introduced as well.[2] In this case large exposed areas can be dosed down, reducing the amount of backscattering and therefore increasing the ability to resolve small spaces. Since dosing down a feature near its edge would decrease its edge slope of the dose profile, dose reduction is applied only inside the feature leaving a 30nm to 50nm collar of nominal or higher dose around the edge as illustrated in Figure 2.

### 2.2 Dose assignment examples

Figure 3 shows an example for dose assignment of narrow line segments. In this case the rule applies 20% more dose to line segments below a certain threshold CD (blue line segments). Subsequent model based shape correction brings the simulated CD (pink contour) on target (black polygons). The correction of the narrow line segment on the left of Figure 3 can be seen clearly while the correction of other line segments requires only minimal edge movement.

Dose assignment to line ends is performed by searching for two adjacent convex corners where the enclosing line segment is smaller than a specified threshold and the line segments on both sides are longer than a specified threshold. This makes sure only narrow lines qualify for line end treatment but small bulges introduced by OPC are not selected.

Ideally, dose assignment is done in such a way that consequent shape corrections are kept minimal. However, since only eight dose levels are used here, some shape correction may be required even on segments receiving dose assignment. The selection of dose levels and strategy for dose assignment used in this work is described in section 3.

## 3. Dose Assignment Strategy

### 3.1 Determination of dose levels

Dose levels are pre-defined by the range of possible dose levels the process can tolerate. For example, using a positive tone resist, the lowest dose used in large exposed areas needs to be well above the dose to clear the resist. Otherwise patches of resist could be left in those areas. On the high side, the dose is limited by heating and thermal resist stability.

The dose levels used in this work are shown in Table 1. Dose levels are increased in 10% points up to 150% and reduced in two steps down to 75% of nominal dose. This choice of dose levels is just an example and the best dose range should be identified experimentally.

### 3.2 Dose assignment tables

Dose assignment of certain features like lines and line ends is performed in intervals of features sizes. Since line end shortening and CD loss have different signatures (see Figure 1), different dose assignment intervals might be chosen for lines and line ends.

CD intervals and dose levels should be determined experimentally or they can be derived from a mask model if an accurate, dose sensitive mask model is available. A summary of dose assignment conditions is given in Table 2. In this example dose assignment of line ends starts below 200 nm line CD while entire line segments are dosed up only below a CD of 160 nm. As a reminder, the absolute values depend on the mask process and the table is given only to demonstrate the principle.

## 4. Analysis of Correction Results

When following the guidelines for dose assignment tables and rules outlined in section 2 and 3, the correction results achieved after MPC are extremely good and show the expected improvement in edge slope for small features.

As an example a design clip is shown in Figure 5 as it could appear in an EUV design. The structure in the center is defined

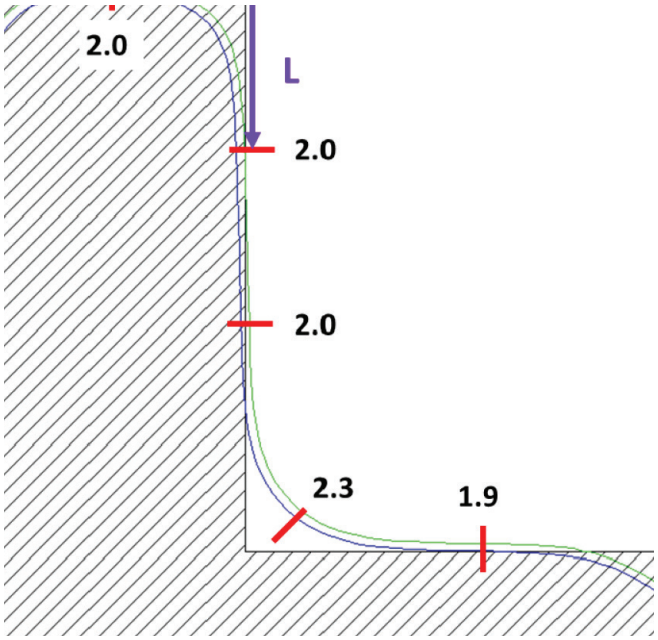


*Figure 6. A close-up of the structure shown in Figure 5 showing contours at -5% and +5% of nominal dose and without any shape correction. Edge slope can be measured indirectly by measuring the gap between both contours which varies here between 1.9 nm for a large CD and 2.3 nm for the concave corner. Combined line end pull back and corner rounding (L) measured as the distance from the corner to the contour intersection with the target is 74 nm.*

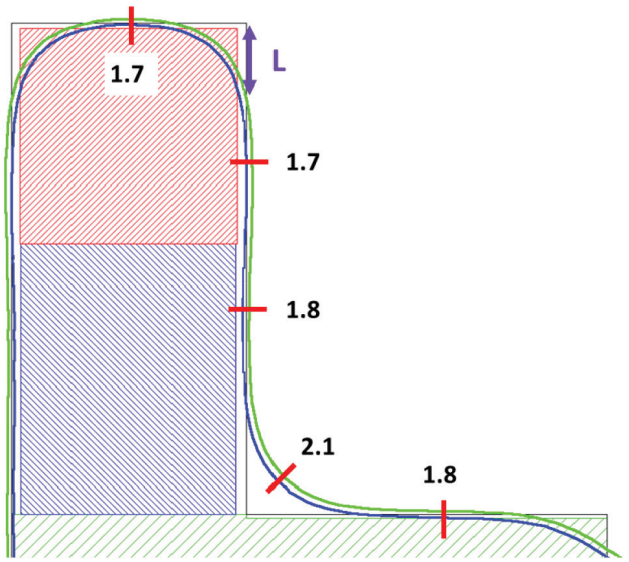


*Figure 7. A close-up of the structure shown in Figure 5 showing contours at -5% and +5% of nominal dose after dose assignment and shape correction. Line end dose (red) is 1.4x nominal dose, narrow line segment (blue) is 1.2x nominal dose, and bottom line (green) is on nominal dose level. The combination of dose assignment and shape correction reduces the distance L from 74 nm to 27 nm and reduces contour edge movement for the ±5% dose variation from 2.0 nm to 1.7 nm at the line end.*

by three different dose levels, nominal dose for the large CD area, 20% dose increase for the narrow line segment and 40% dose increase at the end of the narrow line.

When assigning different dose levels to different line segments it is important not to introduce additional CD errors in the transition from one dose level to the next. We achieve this by carefully assembling the dose assignment table from measurements to keep shape corrections minimal and by choosing the line end shot size close to the amount of corner rounding observed for this mask process.

When correcting line end shortening the best solution depends on the design intent. In many cases it is desirable to reduce line end shortening even on the expense of slightly increasing the CD close to the line end. Such a solution is shown in Figure 5, where the CD is slightly over-corrected in the 1.4x dose area to push the intersection of the contour with the design target (distance L shown in Figure 6 and Figure 7) closer to the corner. Line end shortening, measured as distance L of the intersection between contour and target, is reduced here from 74 nm in the uncorrected case to 27 nm for the corrected case. If over-correction as shown here is not allowed and CD needs to be kept strictly at or below the target CD, correction parameters can be tuned accordingly resulting in a slightly larger distance L.

Figure 6 shows a close-up of uncorrected contours for a dose variation of ±5% around the nominal dose. The numbers besides the red gauges show the contour difference between -5% and +5% dose in nanometers at this location. As expected, the worst edge slope, i.e. largest contour difference of 2.3 nm, is observed in the concave corner followed by a contour difference of 2.0 nm around the line end and smallest difference of 1.9 nm for a large line segment.

After dose assignment and shape correction edge slope is improved at all locations measured here (see Figure 7). The edge slope at the line end is even better than the edge slope of the nominally dosed large CD. The contour difference at the line end is 1.7 nm only while the uncorrected contour difference at the largest CD is 1.9 nm.

In many cases it might not be desirable to optimize the edge slope of line ends beyond the slope observed at large lines exposed at nominal dose. Instead, the dose level might be chosen such that the edge slope of line ends is similar to the slope of nominally dosed large lines. Here, the high dose level is chosen for demonstration purposes showing that slope improvement in hot spot areas can be accomplished to a level which even exceeds nominal edge slope of large CDs.

## 5. Conclusions

The method described in this paper combines rule-based shot dose assignment available on state of the art e-beam writers with conventional model based MPC correction. A major advantage of rule-based dose correction with model based shape correction is the availability of all components required for realizing the flow. Dose assignment is achieved through DRC rules in a pre-processing step to MPC while only minor changes have to be made to a conventional, single dose MPC engine. Results show substantial improvement in edge placement error and edge slope of the dose profile for small features after applying an increased dose of 1.4x of the nominal dose level to the line end followed by a model based shape correction in MPC. This method has been tested on various designs and proves to be versatile and robust so that it can be used in a production tape-out flow.

## 6. Acknowledgments

The authors thank Tom Donnelly and Gordon Russell of Mentor Graphics for their valuable discussions and input regarding efficient DRC code implementations.

## 7. References

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[2] R. Galler, K.-H. Choi, M. Gutsch, C. Hohle, M. Krueger, L. E. Ramos, M. Suelzle, and U. Weidenmueller, "Geometrically Induced Dose Correction Method for e-Beam Lithography Applications," **Proc. SPIE 7823,** Photomask Technology 2010 (2010).

# EDITORIAL *(continued from page 2)*

## EUV Lithography - A View of History

However, it had to be reiterated that, unlike optical masks, EUV reticles won't have a protective pellicle, and would have to have extremely low defectivity, a big challenge for the industry.

After much progress and industry co*nsolidation in the 2004 – 2006 timeframe, resulting in a few large merchant mask makers and captive shops, when work on producing low-defect masks and source improvements continued, we jump ahead to 2012. EUV Mask Defects: What Can We DO About Them? was a question raised by Abbas Rastegar, a SEMATECH Fellow and BACUS Steering Committee Member.

In his article, he points out the complexity of producing defect free mask blanks starting with the EUV substrate, defects on top of as well as inside and under the multi-layer films. He notes the size and shape of particles and pit defects on the substrate change when the multilayers are deposited. Many substrate defects including scratches, pits, and embedded particles are created by mechanical polishing of the substrate.

Pattern shifting is a method currently used to build optical masks including EUV masks. The locations of the defects are determined by inspection of the blank so the pattern can be positioned to cover as many of the blank defects as possible. As reported by this author in a previous BACUS editorial, mask blank inspection is still a major concern for the pattern shift method.

One of the past editorial comments has suggested optical mask blank inspection has had somewhat of a holiday, meaning that future inspection R&D investments were going to EUV. Now Optical lithography is being asked to fill in the gaps while EUV blank inspection finds a way to detect 40nm – 20nm defects. Is there a path forward to fill in the inspection gap for optical lithography at 50nm – 40nm and even 30nm while EUV inspection continues to develop? Artur Balasinski has written in this newsletter about the EUV Inspection roadblocks and the increasing complexity of the mask. This complexity will continue for optical lithography at 14nm and 10nm as well. However, the current gap is still the blank inspection. Inadequate blank inspection will result in poor mask yield and high repair costs. One would hope the technology being developed for EUV detection of small defects can be applied to the current optical technology inspection tools, which will help to sustain Moore's Law when EUV production is ready for prime time.

At the 2012 BACUS, I recalled the editorial comments by Frank Abboud (BACUS President) on innovation and how solutions we once thought impossible are now generally accepted and are the norm rather than the exception. As Frank stated "Innovation, Innovation, Innovation is the engine that keeps our mask industry going". From a supplier's point of view, it is Innovation and competitive pressure that allows for a timely organized transition to the next node.

Despite all of these obstacles, deposition, blank inspection, pellicle, post pellicle inspection and ever increasing cost plus technical challenges for source improvement, progress has been made. ASML and IBM reported a breakthrough in source development. As Mark Lapedus posted: could the lowly pellicle become the Achilles heel for the technology".

While not being part of the EUVL development, I have had the good fortune to be involved in the early Lithographic progress in 1973, as a process engineer with early proximity printing on 1" wafers, i-line and DUV lithography and in sales today providing the alternate optical blanks for advanced lithographic nodes at 45nm, 32nm, 22nm 14nm and 10nm. It has been a rewarding and innovative experience.

The question remains, when will EUVL be ready for production? When Innovation, and the competitive pressures overcome the remaining obstacles and technical challenges to make it cost effective.

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# Industry Briefs

## Deno Macricostas Bestows $3 Million To WestConn

*By* **Daily Voice Schools**
**Full story at http://goo.gl/qmp029**
**October 17, 2014**

Danbury Connecticut businessman and philanthropist Constantine "Deno" Macricostas has given a gift of $3 million from the Macricostas Family Fund to Western Connecticut State University in Danbury, the largest donation in WestConn's history.

"With this gift, Deno Macricostas and his family become, by far, the largest philanthropic supporters of our university," WCSU President James W. Schmotter said in a statement.

"Our gratitude to them is unbounded, and it is made even more special because of Deno's personal experiences. His is the classic American immigrant success story, and it provides an inspiration to all on our campus.

Macricostas explained why he and his family decided to support WCSU with this gift.

"Education is important to the success of our children and our community," Macricostas said. "We live in a competitive and challenging world that requires growing our knowledge and increasing exposure from each generation. Our family takes pride in helping to support the great work of Western Connecticut State University in preparing students for active participation in our global society."

Deno Macricostas emigrated from Greece in search of a better life. While attending college he earned extra money as a fry cook at a local diner on weekends. He saved enough money to start his own company in 1969, Photronics Inc., which manufactures photomasks.

## EUV and Mask Complexity

*By* **Jeff Dorsch,** Contributing Editor, Solid State Technology
**Full story at http://goo.gl/79aMNL**
**October, 2014**

EUV and mask complexity were the hot topics at this year's SPIE Photomask Technology conference in Monterey, Calif.

Giving the keynote presentation, Martin offered a lengthy update on his company's progress with EUV technology.

ASML's overarching goal is providing "affordable scaling," Martin asserted, through what he called "holistic lithography." This involves both immersion litho scanners and EUV machines, he said.

Martin offered a product roadmap over the next four years, concluding with manufacturing of semiconductors with 7nm features in 2018.

The ASML president acknowledged that the development of EUV has been halting over the years, while asserting that his company has made "major progress" with EUV. He said the EUV program represented "a grinding project, going on for 10 years."

For all of EUV's complications and travails, "nothing is impossible," Martin told a packed auditorium at the Monterey Conference Center. With many producers of photomasks in attendance at the conference, Martin promised, "We are not planning to make a significant change in mask infrastructure" for EUV. He added, "What you are investing today will be useful next year, and the year after that."

### SPIE panel tackles mask complexity

Photomasks that take two-and-a-half days to write. Mask data preparation that enters into Big Data territory. And what happens when extreme-ultraviolet lithography really, truly arrives?

These were among the issues addressed by eight panelists in a session "Mask Complexity: How to Solve the Issues?" The panelists were generally optimistic on prospects for resolving the various issues in question. Dong-Hoon Chung of Samsung Electronics said solutions to the thorny challenges in designing, preparing, and manufacturing masks were "not impossible."

Several panelists took the long-term view and looked beyond the coming era of EUV lithography to when multiple-beam mask writers and actinic inspection of masks will be required. EUV and actinic technology, it was generally agreed, will arrive at the 7-nanometer process node, possibly in 2017 or 2018.

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## About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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**SPIE Advanced Lithography**
22-26 February 2015
San Jose Convention Center
and San Jose Marriott
San Jose, California, USA
**www.spie.org/al**

**SPIE Photomask Technology**
*Co-located with*
**SPIE Scanning Microscopies**
29 September-1 October 2015
Monterey Marriott and
Monterey Conference Center
Monterey, California, USA

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SPIE is the international society for optics and photonics, a not-for-profit organization founded in 1955 to advance light-based technologies. The Society serves nearly 225,000 constituents from approximately 150 countries, offering conferences, continuing education, books, journals, and a digital library in support of interdisciplinary information exchange, professional growth, and patent precedent. SPIE provided over $3.2 million in support of education and outreach programs in 2013.

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You are invited to submit events of interest for this calendar. Please send to lindad@spie.org; alternatively, email or fax to SPIE.