Source Optimization and Mask Design to Minimize MEEF in Low k_1 Lithography

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ABSTRACT

Mask Error Enhancement Factor (MEEF) plays an increasingly important role in the DFM flow required to continue shrinking designs in the low-k_1 lithography regime. The ability to understand and minimize MEEF during design optimization and RET application is essential to obtain a usable process window. The traditional limited-cutline approach to analyzing and characterizing MEEF is no longer sufficient to accommodate increasing design complexity. In this paper, we present a new method of edge-based MEEF for analyzing and characterizing MEEF-based hot spots that overcomes the limitations of the traditional cutline approach. Application of the technique to analyze full-field pixel-based two dimensional (2D) MEEF color maps of several different design clips is explained.

Process window (PW) is the most important metric in lithography simulations for evaluating the performance of a given RET solution. Traditionally, process window calculation assumes a perfect mask, with no mask errors or corner rounding. In a low k_1 regime, MEEF increases enough that mask errors can no longer be ignored in PW evaluation. A method of calculating "MEEF-aware" common process windows and creating a MEEF-aware process variation (PV) band, including mask bias, is presented, and wafer image variability is examined under several process variations, including dose, defocus and mask error. Results of MEEF-aware source-mask optimization (SMO) and design rule exploration using inverse lithography technology (ILT) are also presented.

Keywords: MEEF, Design for Manufacturing (DFM), RET, Inverse Lithography Technology (ILT)

1. INTRODUCTION

As lithography moves deeper into the regime of low k_1-factor, co-optimization of design, layout mask, OPC and lithography is critical to deliver a production-worthy patterning solution. The goal of co-optimization is to create a design, along with its corresponding solution of resolution enhancement technologies (RET), that is less sensitive to manufacturing process variations. The most important evaluation metric of the performance of a given RET solution is to characterize its depth of focus (DOF) at certain exposure latitude (EL); this is commonly referred to as the process window, or PW. PW calculation has been traditionally evaluated without considering mask errors. Due to large mask error enhancement factor (MEEF) associated with low k_1 lithography, it becomes increasingly important to consider MEEF and mask error in the total budget of process variations; Consideration of MEEF in design, illumination and mask is crucial to the success of the RET solution.

The extensive use of RET in low k_1 lithography immensely increases the complexity of two dimensional (2D) simulations. Characterization of MEEF using the traditional cutline CD approach may not be sufficient to assure the identification of all lithographically marginal spots in a complex 2D design. In this paper, we will present a new method of edge-based MEEF and its application in several test case studies using inverse lithography technology (ILT) [1]. In section 2, edge-based MEEF and full field edge-based MEEF color bitmap, "MEEF-aware" process window and process variation bands will be introduced. Exploration of MEEF interaction with mask corner rounding and sub-resolution assist feature (SRAF) placement will also be presented in section 2. A case study of MEEF-aware source-mask optimization (SMO) and design rule exploration will be given in section 3.

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2. METHODOLOGY AND MEEF EXPLORATION

2.1 Edge-based MEEF

Mask Error Enhancement Factor (MEEF) is defined as the wafer CD variation as a function of the mask CD variation to wafer level (1X), in which MEEF can be expressed mathematically [2, 3]:

$$MEEF = \frac{\partial CD_{wafer}}{\partial CD_{mask}}$$

When a printed feature is much larger than the Rayleigh resolution limit of projection optics, MEEF is small and close to unity. The changes of left- and right-edge CD in response to mask error are small. MEEF calculated from CD variation provides a reasonable estimate of the sensitivity of either edge to mask variation. At low k_1, MEEF increases substantially and the differing response to mask error of the left and right edges in complex 2D proximity situations cannot be ignored. The asymmetry of edge movement to mask error can no longer be captured by a CD-based MEEF calculation. In order to truly reflect the sensitivity of each edge to mask error, an edge-based MEEF calculation is proposed. It can be written as

$$MEEF_{edge} = \left.\frac{\partial EPE_{wafer}}{\partial EPE_{mask}}\right|_{normal}$$

Where, Edge Placement Error (EPE) is used instead of CD. ∂EPE_{mask} is the mask perturbation per edge, and equals to $\frac{1}{2}\partial CD_{mask}$ of the traditional definition, i.e. the mask is evenly biased. ∂EPE_{wafer} is measured as the distance between the image contour of a perturbed mask and the image contour of a nominal mask along its normal direction, as illustrated in Figure 1. Therefore, the edge-based MEEF can be extracted from the ratio of perturbation from wafer to mask. Along the edge of nominal, two edge-based MEEF numbers can be calculated for positively (+) and negatively (-) biased masks, respectively. The two MEEF numbers are usually slightly different from each other due to asymmetric response to bias-up and bias-down. The magnitude of difference in MEEF of +/- biased mask depends on local environment and is more pronounce for high MEEF area. Since mask error can be either positive or negative in the real world, the average of MEEF from the +/- biased mask should be used.

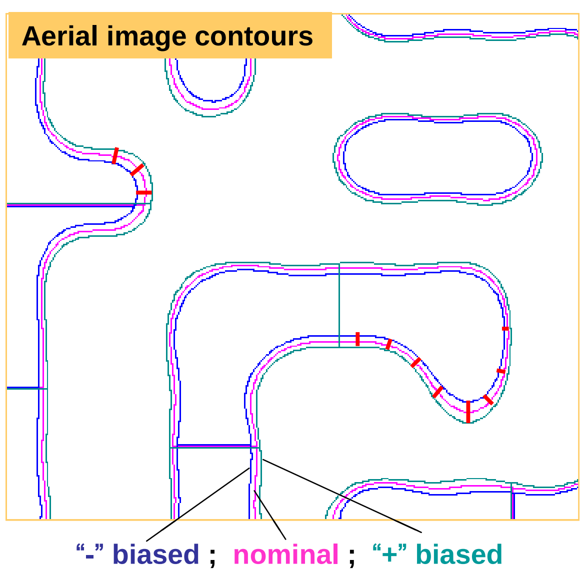


Figure 1. An example of aerial image contours from regular and biased masks. EPE based MEEF is calculated from the delta between positively (+) and negatively (-) biased masks along normal direction of nominal image contour.

2.2 Full field pixel-based MEEF map

Traditionally, MEEF is calculated by measuring CD change across a cut-line. Multiple cut-lines are placed across potentially challenging locations. This method is often sufficient for relative simple pattern. For a complex two dimensional pattern, however, due to the strong proximity effect among neighboring features and high inter-correlation among illumination conditions, mask, and OPC at low-k_1, it becomes more challenging to pre-identify all of the weak points. Since the number of cut-lines is practically limited, the cut-line approach may not measure all critical locations. A full-field instead of limited cut-line analysis of MEEF is therefore important to assure the capture of all critical information needed for a complex 2-dimensional design.

From the definition of edge-based MEEF given in the previous section, one can derive the MEEF of every segment along an aerial image contour. Due to the variation of MEEF, the aerial image contour must be divided into small segments in order to accurately calculate MEEF everywhere along the contour. The native implementation of ILT in pixel-based space makes it ideal to render edge-based MEEF into a full field MEEF bitmap. As shown in Figure 2, a full field color MEEF map generated from Luminizer^{TM} LE displays the color coded MEEF value of each pixel along the aerial image contour. MEEF hotspots are visually apparent on the map. In the previous section, we mentioned asymmetry of MEEF across a pair of edges due to the different proximity environment. It is evident from the MEEF map that at these highly non-uniform locations, two sides of a contour do not display the same colors. Traditional CD cut-line based MEEF will average out the two sides of a contour, underestimating MEEF. This can potentially hide a serious design problem.

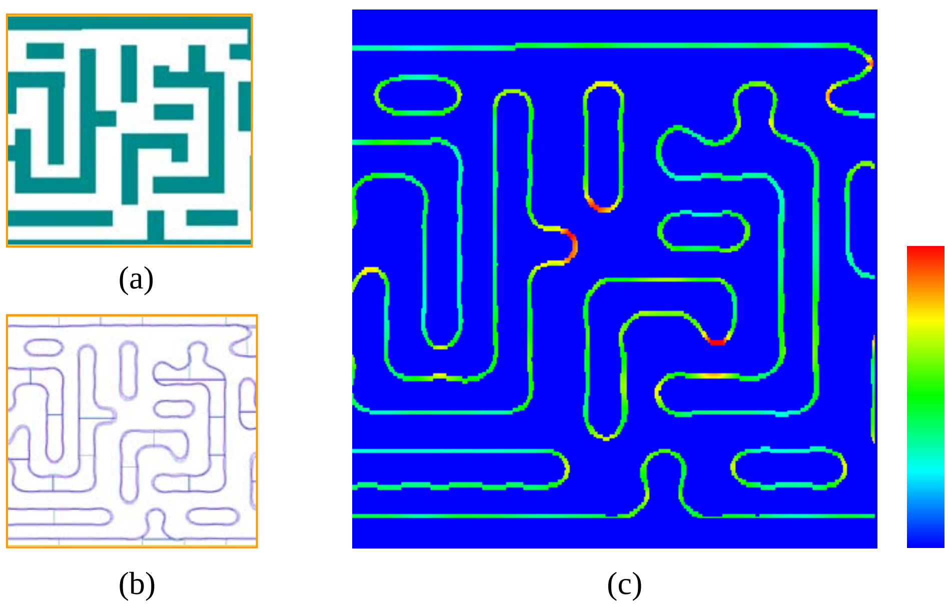
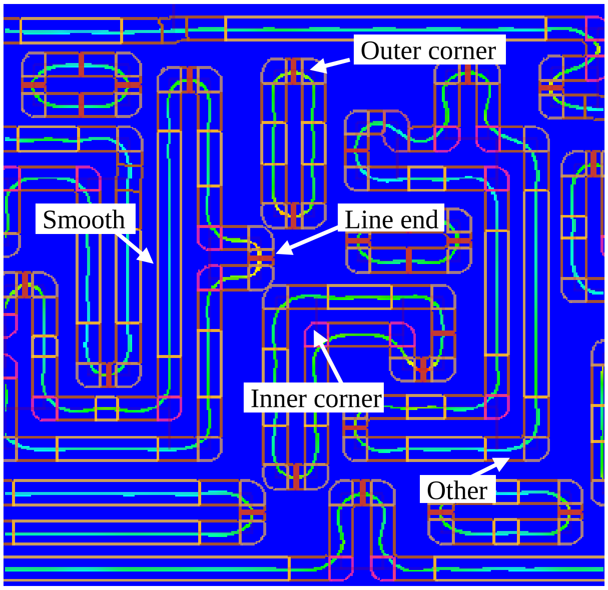


Figure 2. (a) Design target clip; (b) Aerial image contours of +/- biased masks; (c) full field edge-based MEEF bitmap showing MEEF distribution and hotspots. Red color represents high MEEF and cool color represents low MEEF value. Each pixel along the contour represents the edge-based MEEF of the edge segment inside the pixel.

The MEEF map is visually useful for identifying hotspots. In addition to the MEEF map, Luminizer^{TM} LE also generates MEEF statistics. The tolerance for process variation can be different for different parts of a design. For example, the tolerance for the inner corner of a metal line can be much higher than for line-end. To provide a better assessment of MEEF, automatically categorized MEEF reports are generated for each type of topology, such as line-ends, outer corners, inner corners, etc. Figure 3 shows different types of geometry-based topology markers and reported MEEF statistics for each topology, with maximum and average MEEF values. Aside from automatically generated topology markers, customized user defined markers can also be added to the design for further customized analysis. Additional MEEF reports can be generated for each type of user defined topology regions.



Topology MEEF Statistics:

	Maximum	Average
Line end:	6.80	3.59
Smooth :	4.82	2.38
Outer corner:	5.71	3.39
Inner corner:	4.22	2.88
Others:	6.79	2.75

Overall MEEF Statistics:

Maximum MEEF	:	6.80
Average MEEF	:	2.66
Standard deviation	:	0.71

Figure 3. Automatically generated geometry based topology markers overlay with MEEF map. MEEF statistics of each topology type as well as overall combined of all topology types are generated for detailed analysis.

2.3 MEEF aware process window and process variation band

Process window (PW) is the most important metric in lithography simulations for evaluating the performance of a given RET solution. Achieving a certain minimum depth of focus (DOF) at a given exposure latitude (EL) is the paramount goal. Process window calculation traditionally is based on a perfect mask, assuming no mask errors, no corner rounding, etc. In reality, process variation always leaves residual mask errors which affect process window for on-wafer printing. When MEEF is low, the impact of mask error is small compared to the total budget of process variation. In a low k_1 regime, MEEF increases substantially to the level of 4~6, or even higher. Mask errors are magnified several-fold and have a much more pronounced impact at wafer level. DOF predictions that do not consider MEEF are usually unrealistically optimistic.

To obtain a more realistic view of whole process variations, mask error must be factored into process window calculations. Given mask bias, *m*, inferred from mask targeting specifications, MEEF aware process window is calculated as the common process window of unbiased and +/-*m* biased masks. As shown in Figure 4, when MEEF and a 1nm mask bias were included in the computation, DOF at 5%EL was reduced from ~220nm (Figure 4(a)) to ~145nm (Figure 4(c)).

In addition to process window, another useful way to study the predicted quality of printed image is by analyzing process variation (PV) bands. The band is generated by calculating wafer aerial image at the various process conditions and combining the resulting images into a band. The width of the band represents the range within which a feature will print as the process conditions vary. Typically the conditions used to generated PV bands are %EL and defocus, as shown in Figure 4(b). If MEEF and mask error is also included in the process variation conditions, a much larger band area is generated as seen in Figure 4(d), which suggests a much worse aerial image variation than would result from a perfect-mask assumption. Figure 4(b) and 4(d) represent the best- and worst-case scenarios from mask variations, respectively. Actual variation would be expected to fall between the two extreme scenarios.

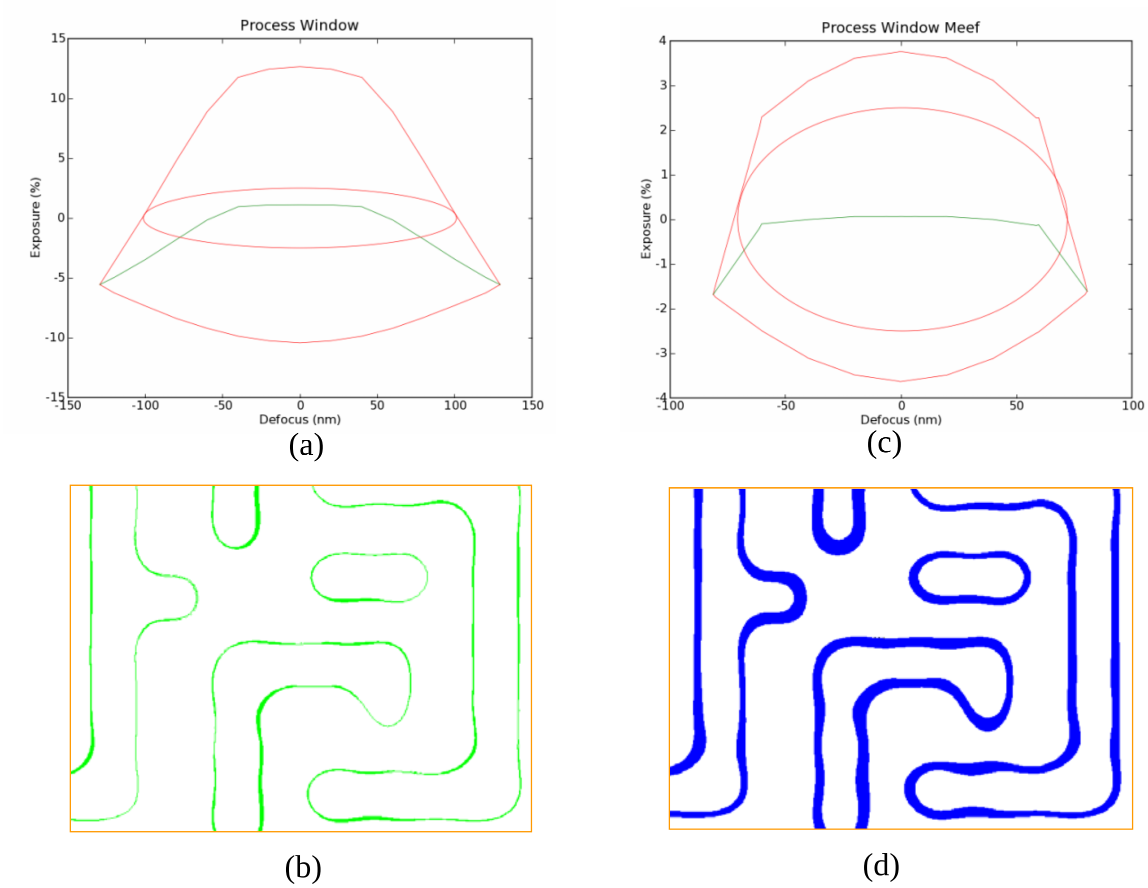


Figure 4. Process window and PV band with and without MEEF term included. (a) Regular process window plot; (b) PV bands with no mask error in account; (c) Common process window plot with awareness of mask error. It is a common process window of three masks, unbiased and +/- biased. (d) PV bands with mask errors included in process variation conditions.

2.4 Mask corner rounding affect on MEEF calculation

With today's state-of-the-art mask process incorporating the most advanced variable shaped e-beam mask writers, high contrast chemically amplified resist, and low-etch bias process, pattern fidelity on reticle has reached an unprecedented level of performance. However, some corner rounding is always present. Therefore, when running a simulation of an RET mask, mask-corner rounding must be considered. Since MEEF is sensitive to mask shape and size, it is important to understand the impact of mask corner rounding in simulation. Mask corner rounding is part of Luminizer™ LE mask geometry and 3D model. It works seamlessly with ILT inversion, forward imaging and resist model calibration engines.

Figure 5(a) and 5(b) are two MEEF maps generated without and with 15nm mask corner rounding. Without mask corner rounding, maximum MEEF and average MEEF are reported as 7.29 and 2.88, respectively. When mask corner rounding is applied, both maximum and average MEEF numbers are reduced, maximum MEEF becomes 6.82 and average MEEF is lowered to 2.84. The results suggest that MEEF tends to be over-estimated in simulations when mask corner rounding is not considered. The question then arises as to where mask corner rounding most impacts the calculation of MEEF. From the two maps, it is hard to see the subtle difference between the two cases. In order to see its impacts more clearly, an XOR operation was done on the image contours (for MEEF calculation) of masks with and without corner rounding, as shown in figure 5(c). It is clear from the figure that mask corner rounding has a significant impact on corners and line-ends, while having little effect on long straight edges.

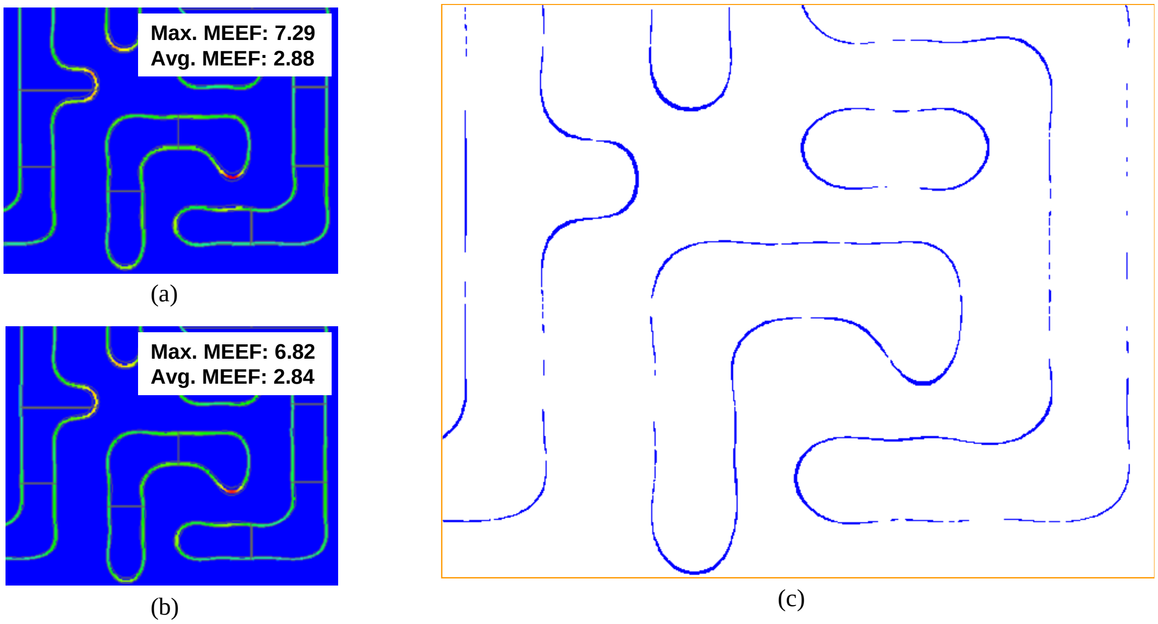


Figure 5. MEEF maps with and without mask corner rounding. (a) MEEF map of mask without corner rounding. (b) MEEF map of mask with corner rounding. (c) The difference of the MEEF image contours. The width of residual difference is proportional to the impact of mask corner rounding effect. It shows mask corner rounding has more effect on corners and line-ends, and little effect on long straight edges.

2.5 SRAF insertion and MEEF

Due to the high contrast of photoresist, many mask patterns can produce identical contours, as long as their images are dark enough and bright enough in the interior and exterior regions defined by the contours. This provides additional degrees of freedom to optimize more than just the desired contours. Contours obtained with different masks may be identical under nominal conditions, yet exhibit different sensitivity to errors in dose, defocus, or errors in sizes of mask patterns. In general, minimizing sensitivity of the contours to each of these variables yields a different solution of the inverse problem. Because sensitivity of patterns to these sources of error varies, the ideal inverse solution permits optimization under a weighted average of their effects. We define an objective cost function based on a weighted sum of pattern edge placement errors. In addition to covering a selected set of dose, defocus, and mask error conditions, the cost function also includes weights based on the relative importance of controlling dimensions of different types of features, such as long straight edges, line ends, jogs, and corners. The objective of inverse lithography is to find a mask pattern that minimizes the cost function using gradient-descent methods over vector spaces [1]. To have a solution with high EL, large DOF, and low sensitivity to mask errors is the goal of any lithography. Unfortunately most of time, a trade-off must be made from among these goals. One example which illustrates this problem is a through pitch study of SRAF insertions in which MEEF exhibits sharp increase when SRAFs are first inserted [4]. In this case, SRAFs are placed in order to achieve required minimum DOF, but barely fit in to meet MRC requirements for minimum width and spacing. Due to the tight space between inserted SRAF and main contacts, any perturbation of the size of features on the mask would result in a pronounced effect on image, hence DOF and MEEF.

To explore this trade-off space, a number of ILT solutions are generated with different mask sizes of SRAF and main contact. DOF and MEEF are plotted against the size of SRAFs as shown in Figure 6. The results show that larger SRAFs tend to produce a larger DOF, but higher MEEF as well. When SRAF size decreases, the DOF also decreases, but at the same time MEEF is reduced. SRAF size can only be reduced either to the minimum SRAF width or until the minimum DOF is reached. Increasing the SRAF size will eventually result in either sidelobe printing, or violation of the minimum spacing requirement of mask rules. However, within these constraints, DOF and MEEF can be traded off to give the optimal combination of conditions.

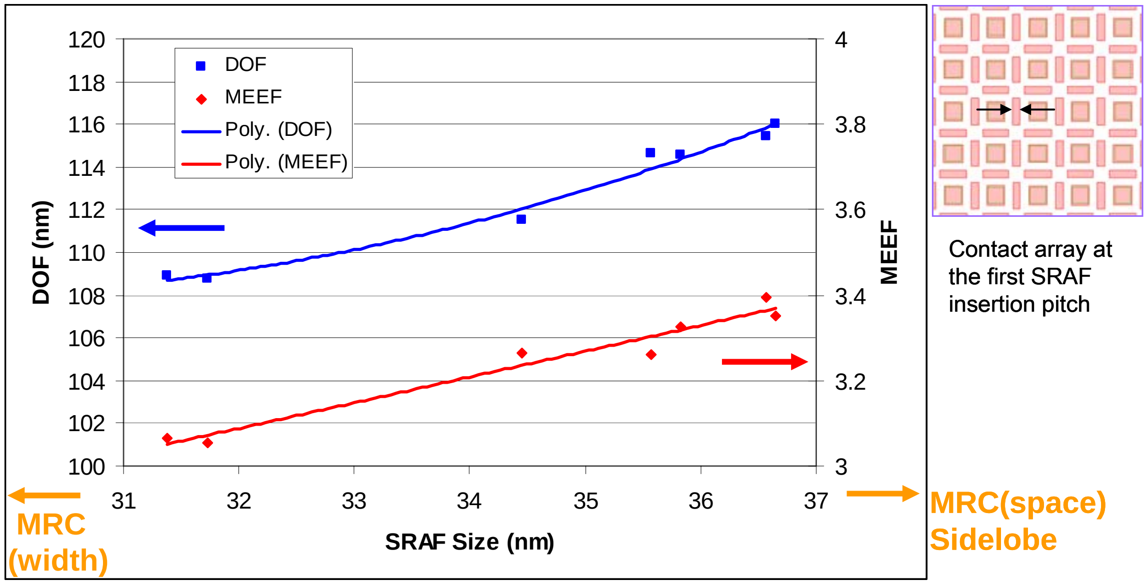


Figure 6. DOF and MEEF response to SRAF size at the first SRAF insertion pitch of contact array.

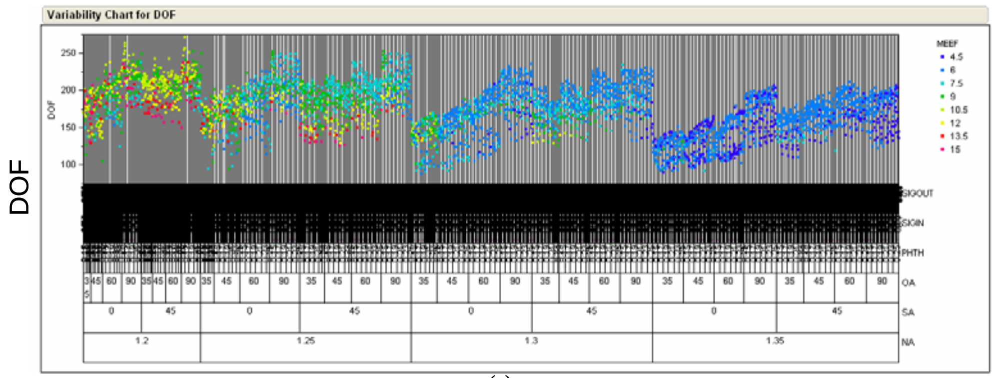
3. TEST CASE STUDY WITH MEEF AWARENESS AND RESULTS

3.1 Source mask optimization (SMO)

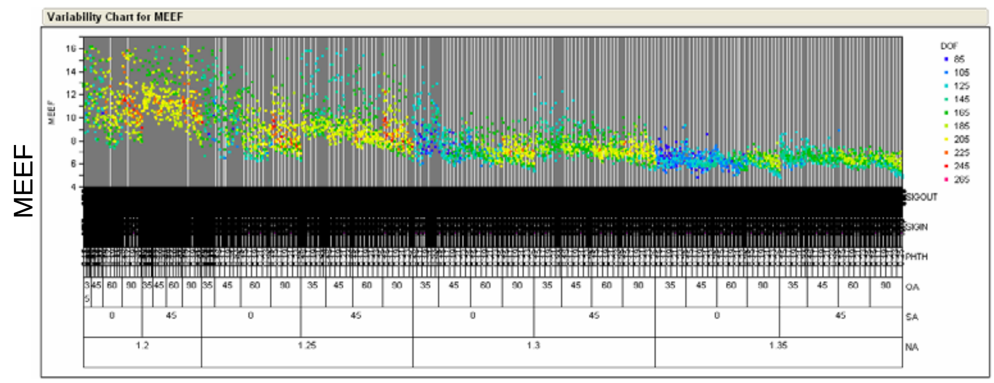
As k_1 is pushed to lower and lower values for 32nm node and beyond, one key objective is to improve final image contrast to enhance printing performance of critical features for manufacturing. Model based RET masks, in combination with hyper-NA and illumination optimization, are the optical extensions which enable lithographic manufacturing in a very low k_1 regime. For a given design pattern, the SMO process sweeps through various conditions such as illumination, NA, sigma, polarization, mask type and resist threshold to identify the right combination of source-mask which maximizes the image quality and process latitude.

As a test case study, a contact clip is used for SMO. A parameterized space is selected with variables of numeric aperture (NA), inner (SIN) and outer (SOUT) illuminator diameters, illuminator position (SA) and fan open angles (OA), photoresist threshold (PHTH). A total number of about 6000 variations were created for optimization. All simulation jobs were submitted automatically to Luminizer^{TM} LE for parallel computation. Total runtime of all 6000 jobs was about 8 hours on a standard Luminizer^{TM} system. Figure 7 shows variability plots of DOF and MEEF with all sweep conditions. If only looking at DOF as in figure 7(a), it suggests that the largest DOF conditions are in lower NA region. However, the corresponding MEEF values of these conditions are mostly above 9 or 10 as shown in figure 7(b). Configurations of illumination and mask with MEEF of such high values are practically not desirable. Any predicted DOF from simulation without considering MEEF may not yield in a real manufacturing process. MEEF awareness in SMO is necessary in the low k_1 regime to ensure a manufacturable RET solution.

To narrow down the potential solutions from sweep results, data pruning is an important step to enable “cherry picking” among a manageable number of conditions. The criteria of data pruning can be quite objective depending on certain types of application, design, and user requirements. In this example, the data pruning condition of MEEF<6.5 and DOF>150nm is set. There are total of 97 conditions that satisfy the criteria, as shown in Figure 8. With the additional MEEF constraints, the conditions with large DOF at lower NA of 1.2 and 1.25 are pruned away. A balanced solution with reasonable MEEF and DOF should be among those conditions on the higher NA side.

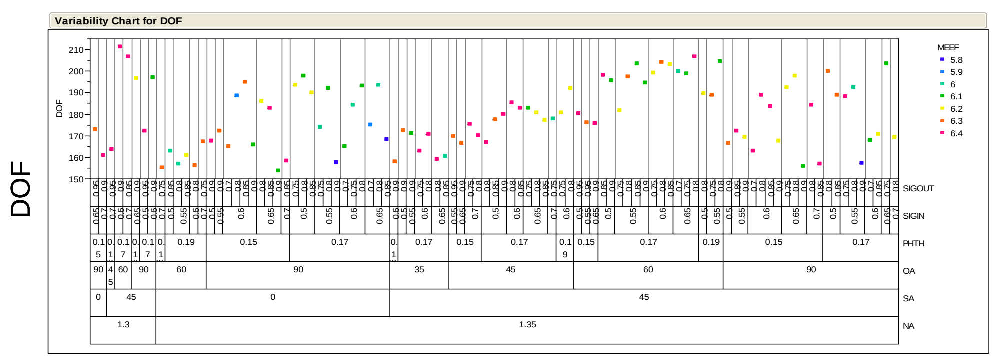


(a)

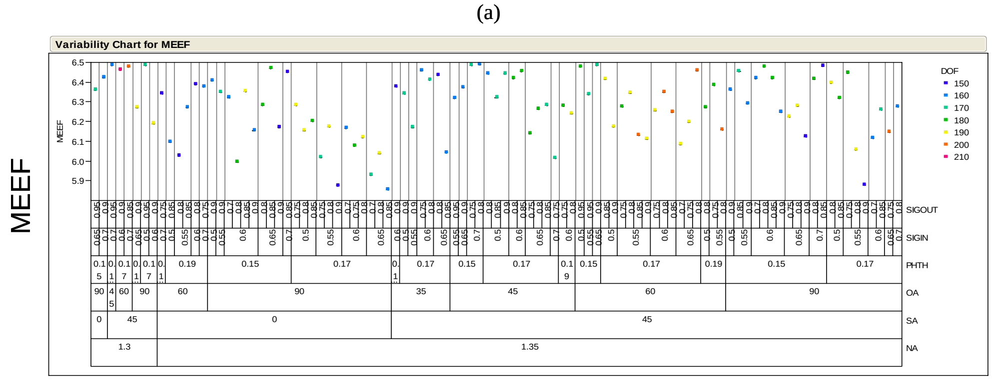


(b)

Figure 7. Sweep results of DOF and MEEF in parameterized space.



(a)



(b)

Figure 8. DOF and MEEF plots of pruned data with conditions satisfy DOF>170nm and MEEF < 6.5. There are total of 97 conditions left after data pruning.

3.2 Design rule exploration

Design rule complexity has increased immensely due to much smaller k_1 factors and subsequent extensive use of resolution enhancement technologies [4]. Extensive two dimensional (2D) simulations with parameterized structures are paramount for exploration of restrictive design rules. The ability to generate design rule sets that encode all lithographic constraints allows designers to identify and correct problematic structures well before tape-out.

For parameterized structures, it is often necessary to deal with a large GDS design with various module blocks, each with a unique set of parameters/conditions. To set up the experiment of studying parameterized structures, the information on location of each design module is fed into automation scripts on Luminizer™ LE system. Distributed computation of all design modules in parallel ensures a fast turnaround. Figure 9 illustrates a simulation flow of design rule exploration.

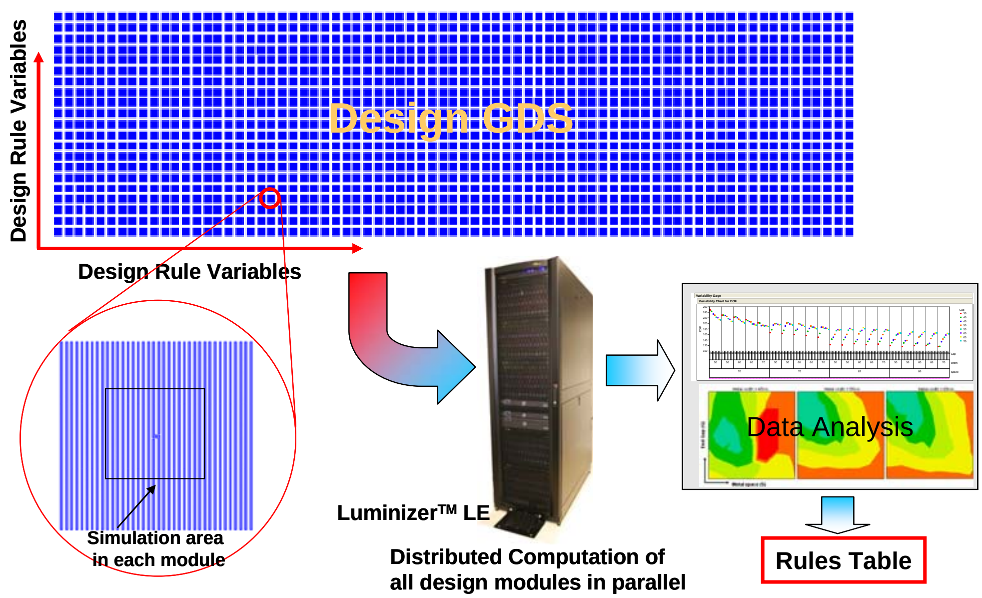


Figure 9. Simulation flow of design rule exploration with parameterized structures.

For this work, a poly cross gate design rule exploration is demonstrated with a pre-defined illumination configuration. Parameterized space includes poly line width (L) and space (S), cross gate width (W) and gate line end gap width (G) (Figure 10). Full inversion results with all pertinent information including DOF and MEEF are saved for each condition of the parameter space. Offline analysis was carried out to generate the restrictive design rule with full lithography awareness of dose, defocus and mask errors. An example is given in Figure 10 to illustrate the process of MEEF awareness in design rule exploration. For a set of gate line and space conditions, contour plots were generated with cross gate width and line end gap for DOF, MEEF and MEEF aware common DOF. If focusing the DOF plot alone, it is not necessary to apply restrictive rule for covered simulation space of cross poly gate width and gate line end gap. DOFs of condition (a), 45nm end gap, and condition (b), 60nm end gap are almost the same. However, as shown in the MEEF plot, MEEF values of the two points (a) and (b) are quite different. Condition (a) exhibits high MEEF value of 5.1. Color MEEF map clearly shows that the tipping point of gate line end is where it causes highest MEEF in the design. Potential bridging may occur between the line end and cross poly corner as depicted in the PV band contours of condition (a). Once MEEF is factored into the calculation of common process window, sharply different DOF values are yield for conditions (a) and (b). Condition (a) has no process window while condition (b) has 145nm common DOF. Therefore, after MEEF consideration, different sets of rules for gate line end gap might have to be created.

Similarly, the same methodology described above with ILT can be applied in identifying "weak" spots in a layout cell/block libraries so that they can be updated with a more lithography-compliant and manufacturable design style. Catching these "weak" spots at the cell creation step will reduce the number of re-spins for post-tapeout tweaks and post-layout design fixes, hence reduce the time to market.

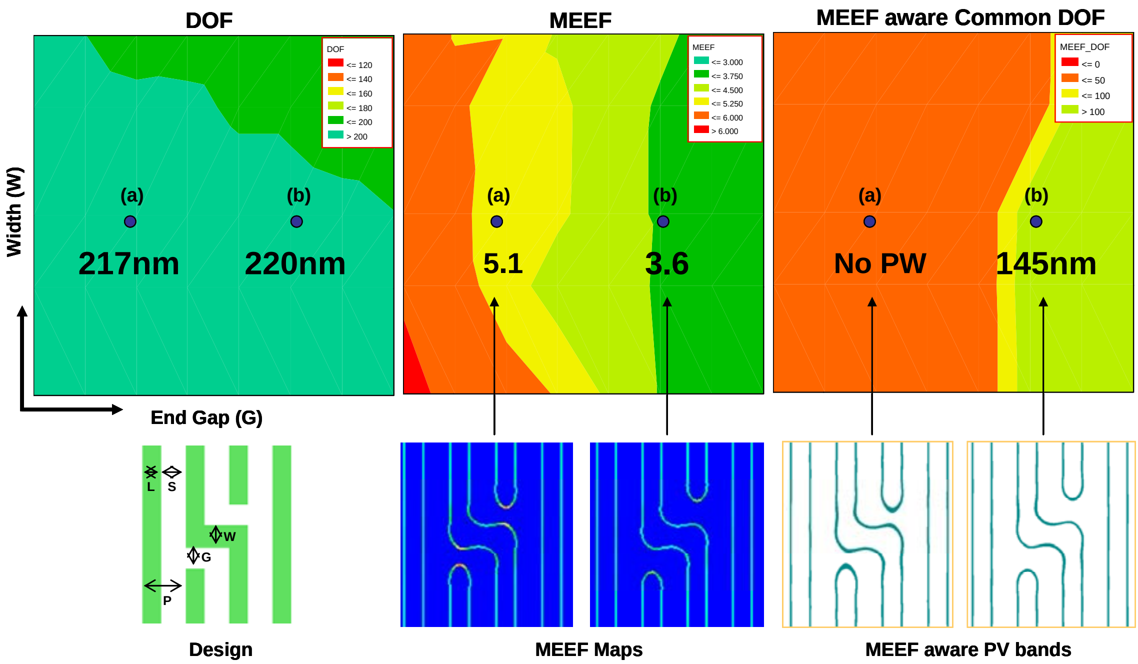


Figure 10. Data analysis of cross gate design rule exploration. DOF and MEEF contour plots as well as MEEF map and PV band plots are generated for detailed analysis.

4. SUMMARY AND CONCLUSIONS

MEEF is a big factor that cannot be ignored in low k_1 lithography. It must be included in mask pattern correction and source mask optimizations. An edge-based MEEF calculation is proposed to address the need for more detailed analysis of MEEF in a complex 2D environment in a low k_1 regime. A full-field MEEF color bitmap using edge-based MEEF definition is presented to provide easy visual identification of hotspots. The automated placement of topology markers to cover all pattern feature types ensures that all marginal lithographic spots will be identified. A categorized MEEF report associated with each topology type allows users to evaluate MEEF at different proximity environment.

Traditional process window evaluation without considering MEEF and mask error can undermine resolution enhancements due to the increased impact from mask errors in low-k_1 lithography. A third dimension (MEEF) in process window assessment is introduced to provide a more realistic litho simulation in the DFM flow. The method of creating a MEEF-aware PV band, including mask bias, is presented to show wafer image variability under all process variations from dose, defocus and mask error. It provides a more realistic of view of image quality against process variations.

DOF and MEEF are often competing factors in a RET solution. For a given illumination condition, a trade-off between MEEF and DOF can be made with different variation of mask pattern. This has been demonstrated in the first SRAF insertion pitch of a contact array, by varying the size of SRAF, a tradeoff can be made between DOF and MEEF.

MEEF and DOF should be considered simultaneously in illumination source mask optimization and design rule development. Model based SRAF placement and automated topology based MEEF and DOF calculations in lithography simulation allow experiments requiring huge numbers of random logic simulations to be performed in a reasonable time. ILT and Luminizer™ LE provide enabling tools for lithographers and designers, and reduce time-to-market for advanced semiconductor products.

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