Reducing shot count through Optimization based fracture

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1.0 ABSTRACT

The increasing complexity of RET solutions with each new process node has increased the shot count of advanced photomasks. In particular, the introduction of inverse lithography masks represents a significant increase in mask complexity. Although shot count reduction can be achieved through careful management of the upstream OPC strategy and improvement of fracture algorithms, it is also important to consider more dramatic departures from traditional fracture techniques. Optimization based fracture allows for overlapping shots to be placed in a manner that allows the mask intent to be realized while achieving significant savings in shot count relative to traditional fracture based methods. We investigate the application of Optimization based fracture to reduce the shot count of inverse lithography masks, provide an assessment of the potential shot count savings, and assess its impact on lithography process window performance.

Keywords: optimization based fracture, fracture, e-beam, inverse lithography

2.0 INTRODUCTION

2.1 Problem Statement

Optimization based fracture is motivated by the increasing application of aggressive resolution enhancement (RET) solutions. Methods such as model based assist features and inverse lithography technology produce complex masks that do not naturally have rectilinear shapes. The basic approach to delivering manufacturable ILT masks is to represent curvilinear shapes by Manhattan segments[1]. These Manhattan masks still employ a large number of shots, but are manufacturable.

Researchers have previously proposed a method to further reduce shot count by relaxing traditional mask fracturing restrictions that require shapes to be abutting and non-overlapping. It has also been proposed that preserving curved shapes that are naturally output from inverse lithography solutions improves the lithography process window relative to their Manhattan counterparts[2]. This paper explores both of those assertions.

2.2 Characteristics of Optimization based fracture

Optimization based fracture represents a significant departure from traditional fracture. In traditional fracture, primitive shapes are created to exactly cover the input polygons submitted to the fracture algorithm; shots are abutting and non-overlapping. Also, the primitive shape is typically a trapezoid. The post-OPC layout must be represented by combining these trapezoids of various sizes and configurations (again, in abutting and non-overlapped configurations). These factors lead to the following consequences. First, highly fragmented layouts from aggressive OPC treatments increase the total shot count for advanced photomasks. Additionally, curvilinear or “raw” masks that are sometimes output from inverse lithography OPC solutions are not practically writeable using single-beam vector shaped beam writers as the number of trapezoids needed to approximate a curve is too large. To date, practical implementations of ILT solutions require a Manhattanization step prior to the fracture step.

Optimization based fracture has been suggested as one method to enable writing of curvilinear masks within a reasonable shot count. Optimization based fracture allows for the input layout to be represented by overlapping and non-abutting shapes. It incorporates an e-beam blur to simulate the expected mask contour from these overlapping and non-abutting shapes. A natural consequence of using e-beam blur is that smooth contours are achievable. Rectangles or trapezoids produced rounded corners when convolved with Gaussian kernels. The placement of overlapping and

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non-abutting shots combined with a band-limited simulation model allows for some ability to represent curved shapes on the mask. In all but limiting cases where the curvature present in the incoming mask target exactly represents the curvature resulting from the blur induced by the mask making process, it will not be possible to achieve arbitrary fidelity between the Optimization based fracture result and the incoming mask target without increasing the number of shapes. In other words, there will always be tradeoff between mask pattern fidelity and achievable shot count savings.

E-beam blur has also been used to rationalize smoothing the target of a Manhattan input for the purposes of providing a smooth contour. However, this approach implies that the mask maker is allowed some liberty to interpret the lithography intent. For example, applying a blur value that results in the elimination of a jog implies that jog was not important to the OPC result. However, it is generally not possible for the mask manufacturer to properly assess this impact without knowledge of the wafer (optical and resist) models used to create the OPC solution. In other words, by applying target smoothing of Manhattan mask, the mask manufacturer is modifying the mask target. Doing so without proper lithography characterization is not recommended.

2.3 Optimization algorithms

Optimization based fracture includes a global optimization step that places a reduced number of shots and a refinement step that adjusts the size and position of each of the shots in order to minimize the mask error.

In this paper three global optimization algorithms are evaluated. The first is a simple approximation that sets the minimum size for a shot. The second method includes applying heuristic algorithms that opportunistically combine shots in order to reduce shot count. The third approach evaluated involves techniques to select shots based on basis pursuit algorithms. A detailed discussion of optimization algorithms and techniques is beyond this paper's intended scope. The reader is directed to the references at the end of the paper for more detailed discussion of compressive algorithms[3,4].

3.0 EXPERIMENTAL

3.1 Impact on fracture shot count and lithography process window

The application of Optimization based fracture to a curvilinear mask target results in residual mask error. The objective of this experiment is to investigate the wafer lithography impact of these errors using a case-based analysis. Two 32 nm node contact patterns are prepared using inverse lithography technology (ILT). The resulting ILT patterns are characteristically complex with sub-resolution assist features (SRAFs) occupying a large fraction of the pattern area.

For each pattern, five different methods for Optimization based fracture are used to produce a fracture result. The shot count for each of these methods is compared to a baseline fracture flow. The baseline fracture flow comprises a conventional fracture algorithm applied to a Manhattanized ILT result.

Wafer lithography for each Optimization based fracture method is assessed by simulating the expected mask contour that results from the Optimization based fracture solution and then inputting the mask contour into a wafer simulation (Figure 1). Wafer process simulation is performed through dose, focus, and mask bias in order to generate edge placemen t error (EPE) and process variation band (PVB) distributions. EPE measures the error from the simulated contour at nominal process conditions and the target edge. The PVB indicates the expected range of wafer contours when the given mask used to print wafers in a wafer process subject to systematic and random variation. A smaller band width is more desirable as it indicates less sensitivity to process variation.[5] For process window analysis a comparison against the "raw mask" is also included. The raw mask has curvilinear shapes and is not practically manufacturable. However, it is included as a benchmark for the wafer lithography process window. Experimental details are summarized in Table 1 below.

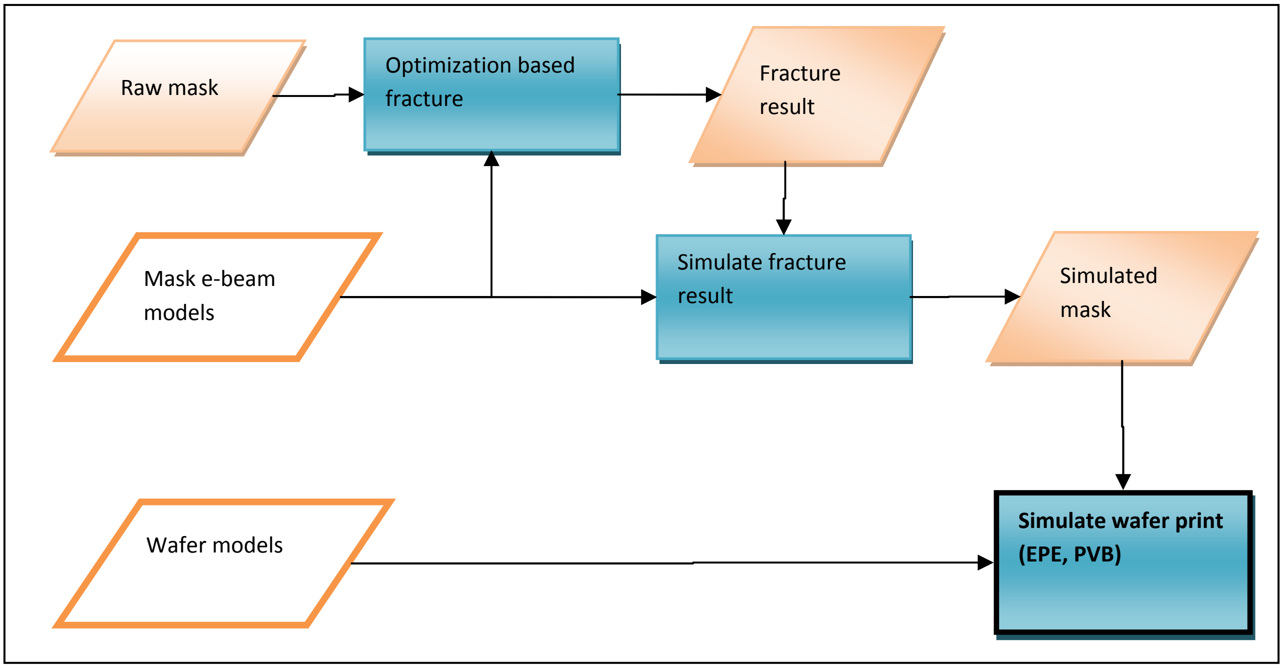

Figure 1. Wafer simulation flow for Optimization based fracture. With the raw mask as the target, an optimization based fracture solution is generated. The solution is simulated with a e-beam forward scatter model. Wafer print simulation uses the simulated mask and wafer process models to generate EPE and PVB results.

The treatment options for Optimization based fracture include five global solution algorithms. Exp1 uses a simple approximation which limits the minimum size of a given shot. Additional heuristics can be applied to further reduce shot count. These are Exp2 and Exp3. Finally, basis pursuit algorithms are also investigated. These are labeled Exp4 and Exp5.

Layout	Layout 1: Contact layer, curvilinear mask (min CD = 66 nm, 1X) Layout 2: Contact, curvilinear mask (min CD = 60 nm, 1X)
Treatment	Baseline: Manhattan mask Optimization based fracture (mask model, σ = 25nm) - **Exp1**: Simple approximation - **Exp2**: Heuristic 1 - **Exp3**: Heuristic 1 (less aggressive) - **Exp4**: Basis pursuit - **Exp5**: Basis pursuit with additional simplification Original curved mask (Raw mask)
Response	Mask shot count Wafer EPE distribution Wafer process variation band Assist feature printing

Table 1. Experimental conditions and responses

Layout 1	**Optical model:** λ = 193 nm NA = 1.35 Illumination: Optimized (custom) **Process window conditions:** Focus: +/- 52 nm Dose : +/- 3.3% Mask size: +/- 0.5 nm
Layout 2	**Optical model:** λ = 193 nm NA = 1.35 Illumination: Optimized (custom) **Process window conditions:** Focus: +/- 57 nm Dose : +/- 3.8% Mask size: +/- 0.5 nm

Table 2. Wafer simulation conditions for EPE and PVB analysis

4.0 RESULTS AND DISCUSSION

4.1 Layout 1

An example of the Optimization based fracture solution applied to Layout 1 is shown in Figure 2. In this layout window, only the center contact is a printed feature. The other features are sub-resolution assist features (SRAFs). Using the smooth contour as its target, Optimization based fracture places rectangular shots and adjusts their size and position through a refinement step.

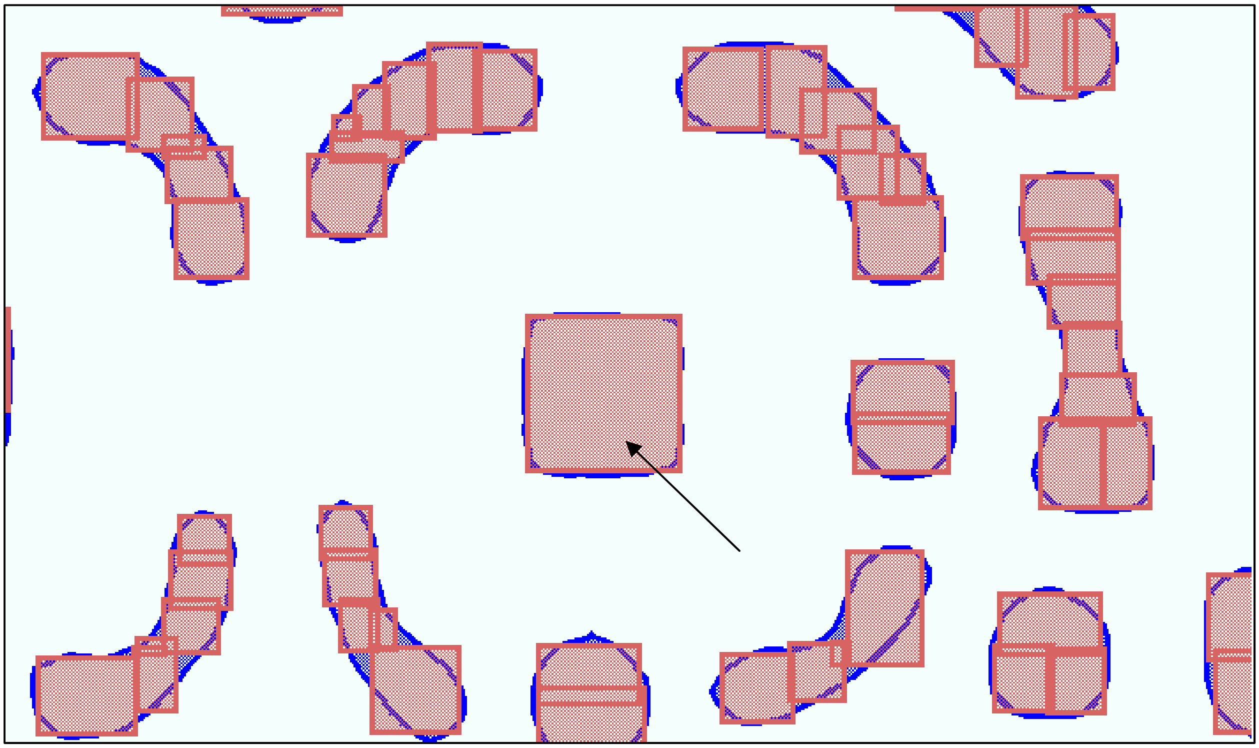

Figure 2. Layout example from Optimization based fracture applied to Layout 1. The smooth contour (blue) represents the target mask contour as output by ILT solution. The rectangular figures (red) indicate the shot placement solution from Optimization based fracture. The main feature is indicated by the arrow. The remaining shapes are SRAFs. The minimum wafer target CD for the contact is 66 nm (1X).

Table 3 summarizes the reduction in shot count that can be achieved through various fracture treatments applied to Layout 1. Depending on the optimization method chosen, a shot count reduction of 17% to 28% is observed. This particular layout also shows no degradation to the wafer lithography pattern fidelity and process window as indicated by Max EPE and Max PVB. The corresponding EPE and PVB distributions shown in Figure 3 and Figure 4 also indicate that wafer lithography quality is preserved throughout these fracture treatments.

Treatment	**Shot count**	**Reduction**	**Max EPE (nm)**	**Max PVB (nm)**
Baseline	2769	0%	14.7	23.9
Exp1	2291	17%	13.2	22.9
Exp2	2147	22%	12.8	22.9
Exp3	2055	26%	12.8	22.9
Exp4	2070	25%	14.2	23.4
Exp5	1997	28%	14.4	22.6
Raw mask			12.9	22.6

Table 3. Summary results for Layout 1. Shot count reduction and wafer simulation results are reported.

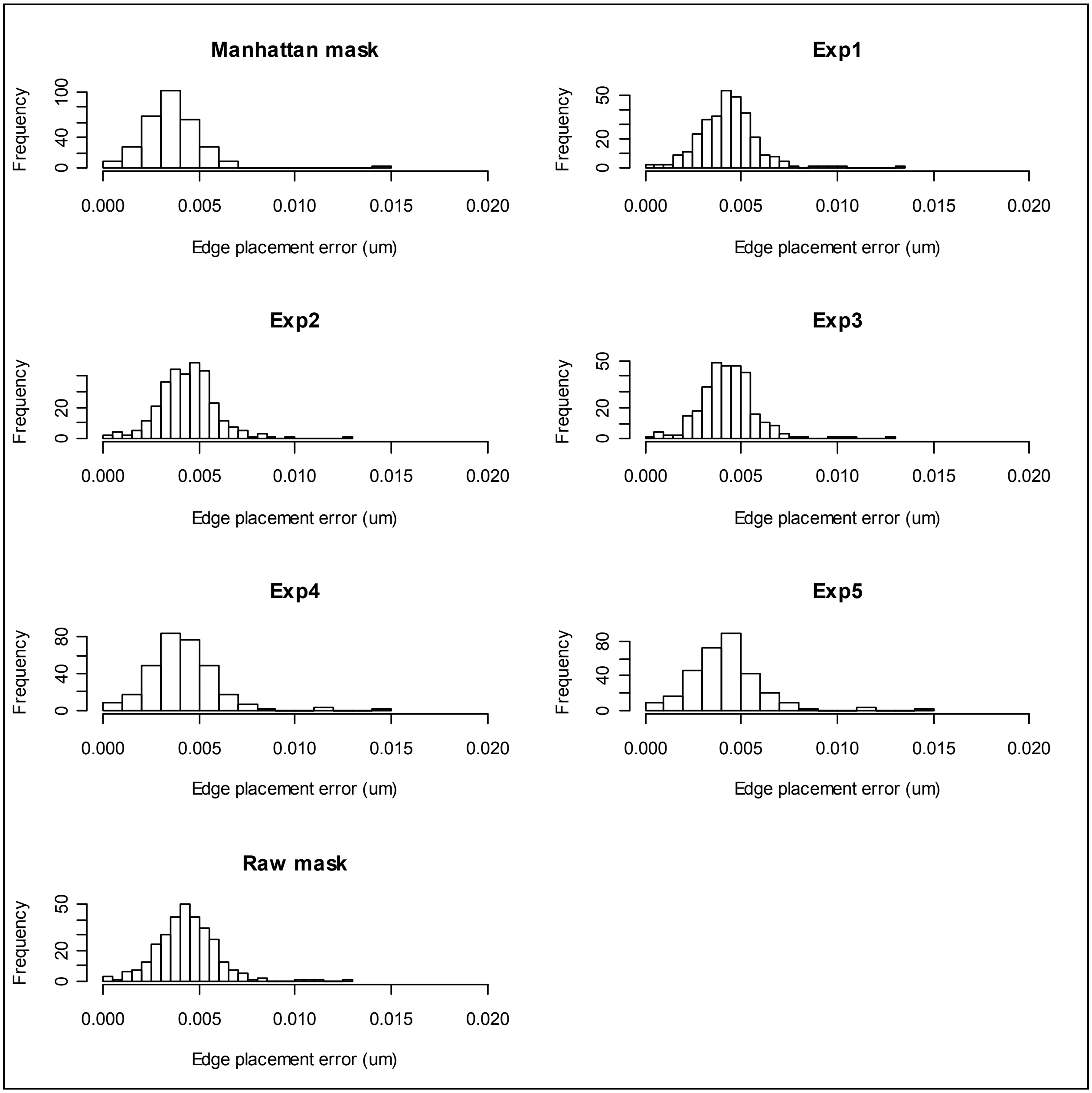

Figure 3. Histogram of edge placement errors (EPE) for Layout 1

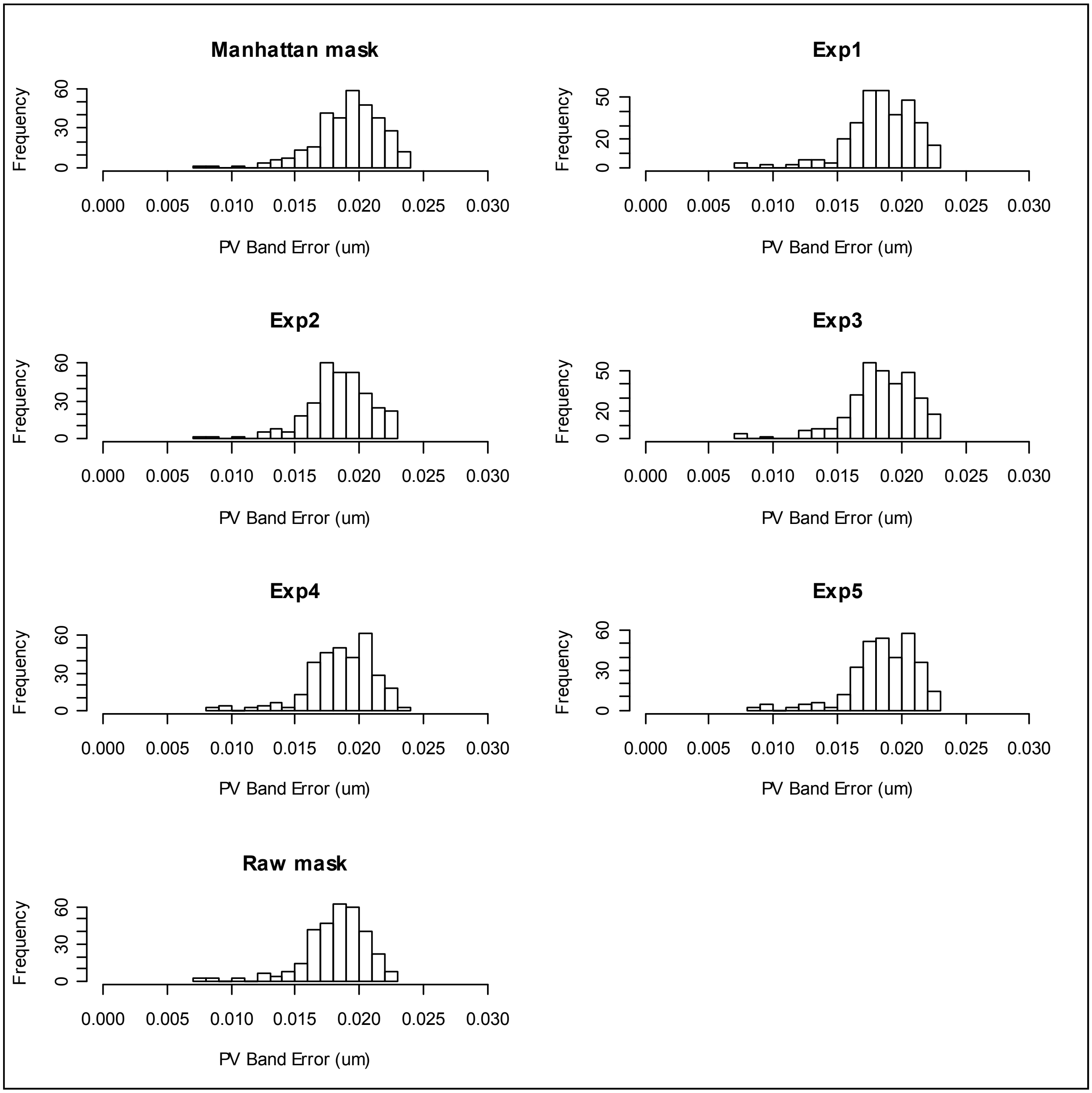

Figure 4. Histogram of process variation band (PVB) widths for Layout 1

4.2 Layout 2

An example of the Optimization based fracture result for Layout 2 is shown below in Figure 5. Layout 2 has a slightly more difficult layout due to the presence of a jog feature in addition to the conventional contact.

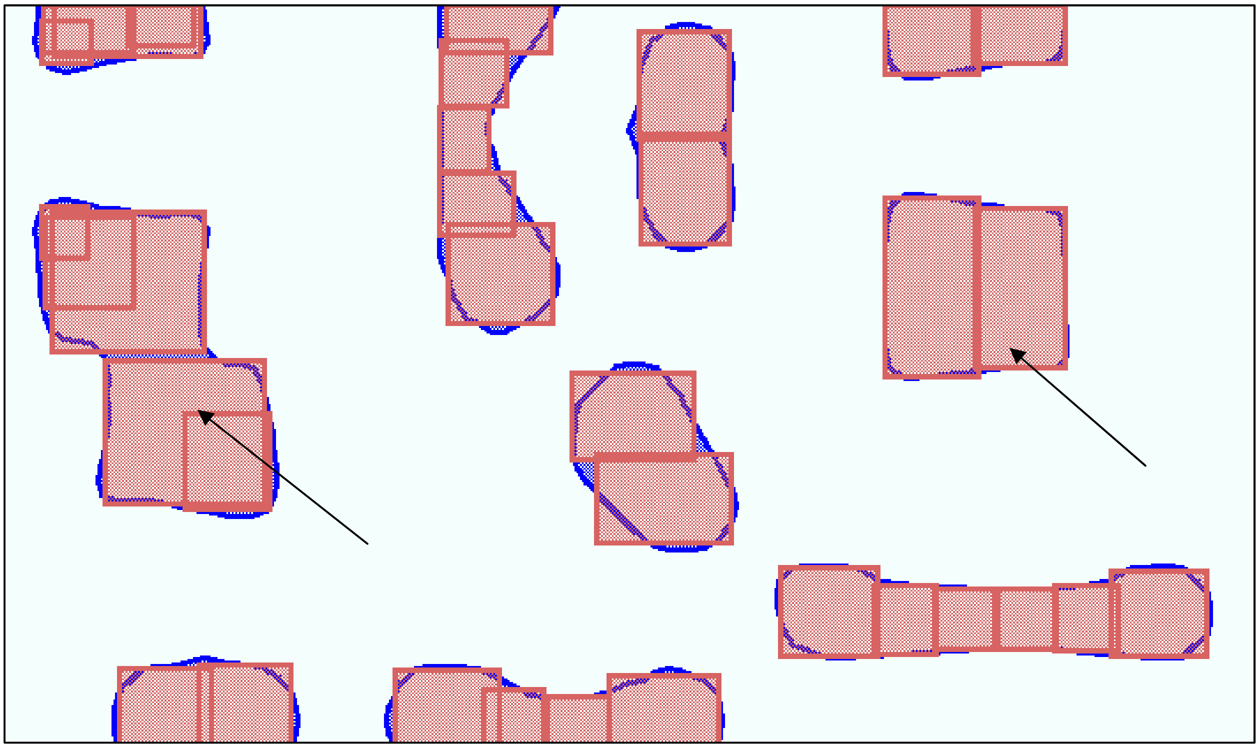

Figure 5. Layout example from Optimization based fracture applied to Layout 2. The smooth contour (blue) represents the target mask contour as output by ILT solution. The rectangular figures (red) indicate the shot placement solution from Optimization based fracture. The main feature is indicated by the arrow. The remaining shapes are SRAFs. The minimum target wafer CD is 60 nm (1X). The second mode of errors in EPE distribution is caused by larger errors near the convex corners of the left feature.

Table 4 summarizes the reduction in shot count that can be achieved through various fracture treatments applied to Layout 2. The wafer EPE and PVB histograms are also shown in Figure 6 and Figure 7. In contrast to Layout 1, the maximum wafer EPE for the experimental Optimization based fracture treatments is higher than what is observed for the baseline Manhattan mask and raw mask. This is a result of residual mask errors translating transferring to wafer print. Depending on the layout, optical configuration, and RET solution, mask errors are amplified upon wafer print. For Layout 1, there was no observed impact. However, for Layout 2, the residual errors present on the mask manifest in degraded pattern image fidelity and assist feature printing (Figure 8).

Treatment	Shot count	Reduction	Max EPE (nm)	Max PVB (nm)
Baseline	11822	0%	17.0	14.8
Exp1	11091	6%	23.6	14.7
Exp2	10575	11%	21.8	14.8
Exp3	10770	9%	23.5	14.9
Exp4	10645	10%	22.0	14.8
Exp5	10391	12%	22.5	14.8
Raw mask			17.0	14.2

Table 4. Summary results for Layout 2. Shot count reduction and wafer simulation results are reported.

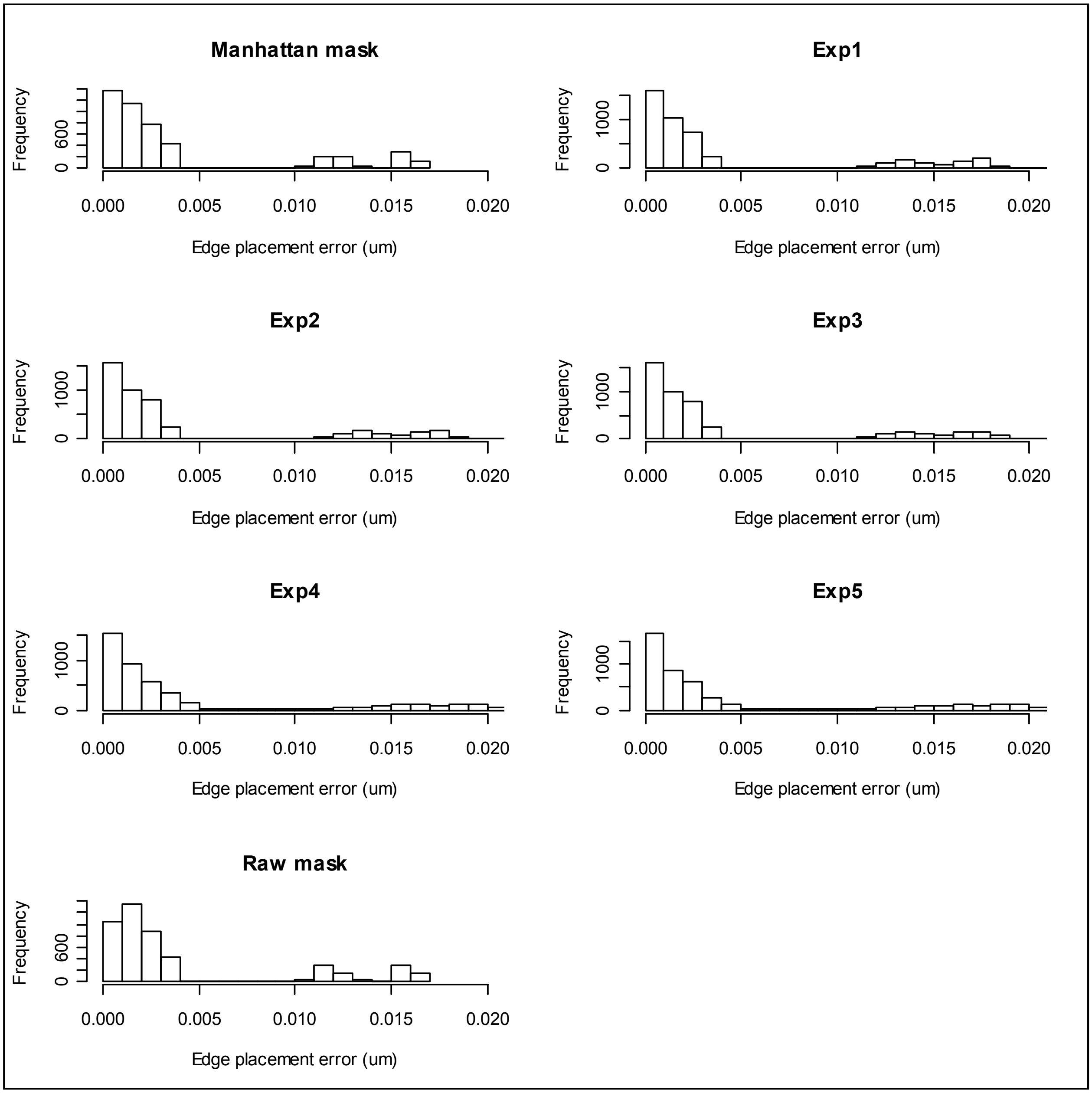

Figure 6. Histogram of edge placement errors (EPE) for Layout 2

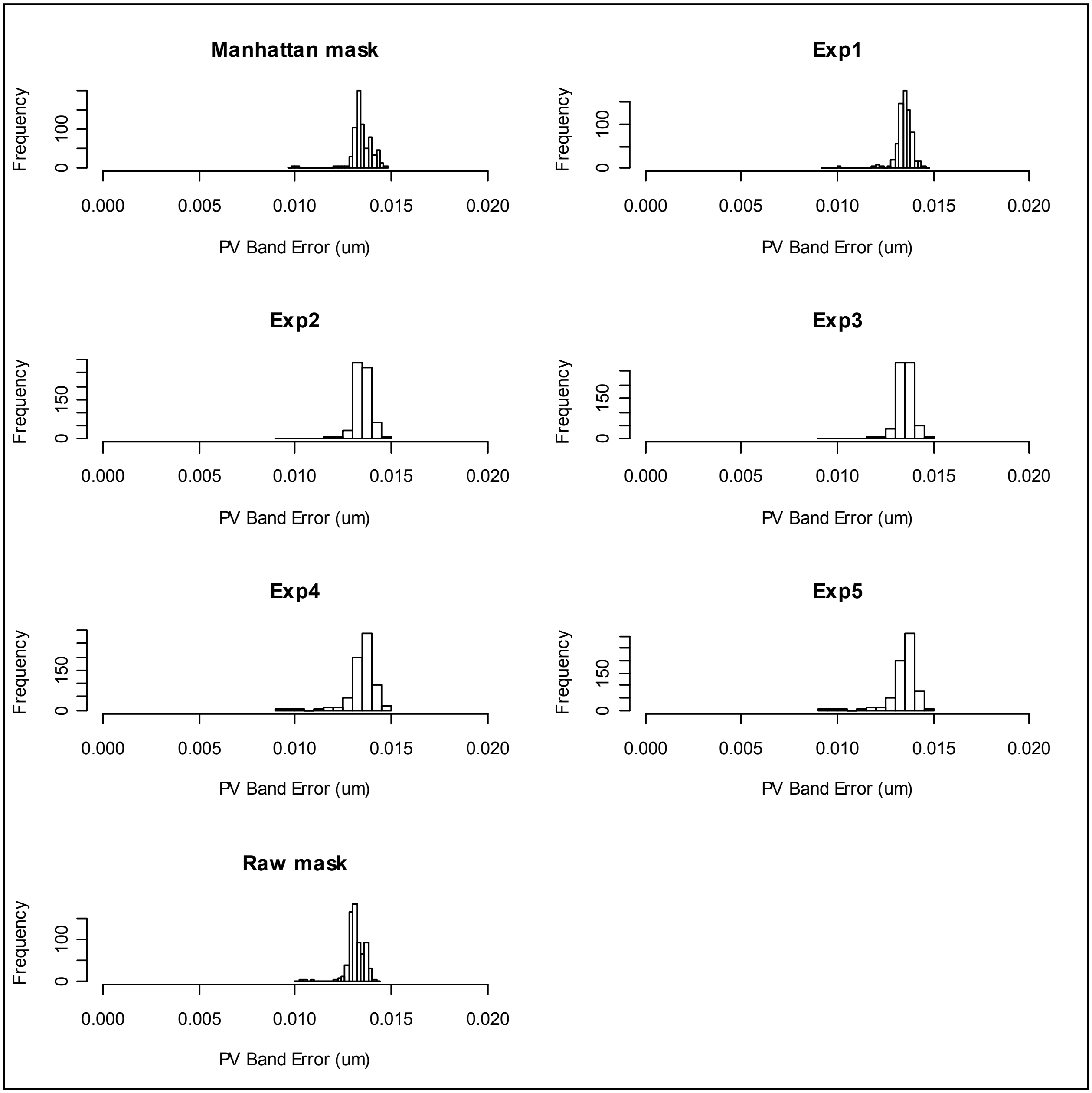

Figure 7. Histogram of process variation band (PVB) widths for Layout 2

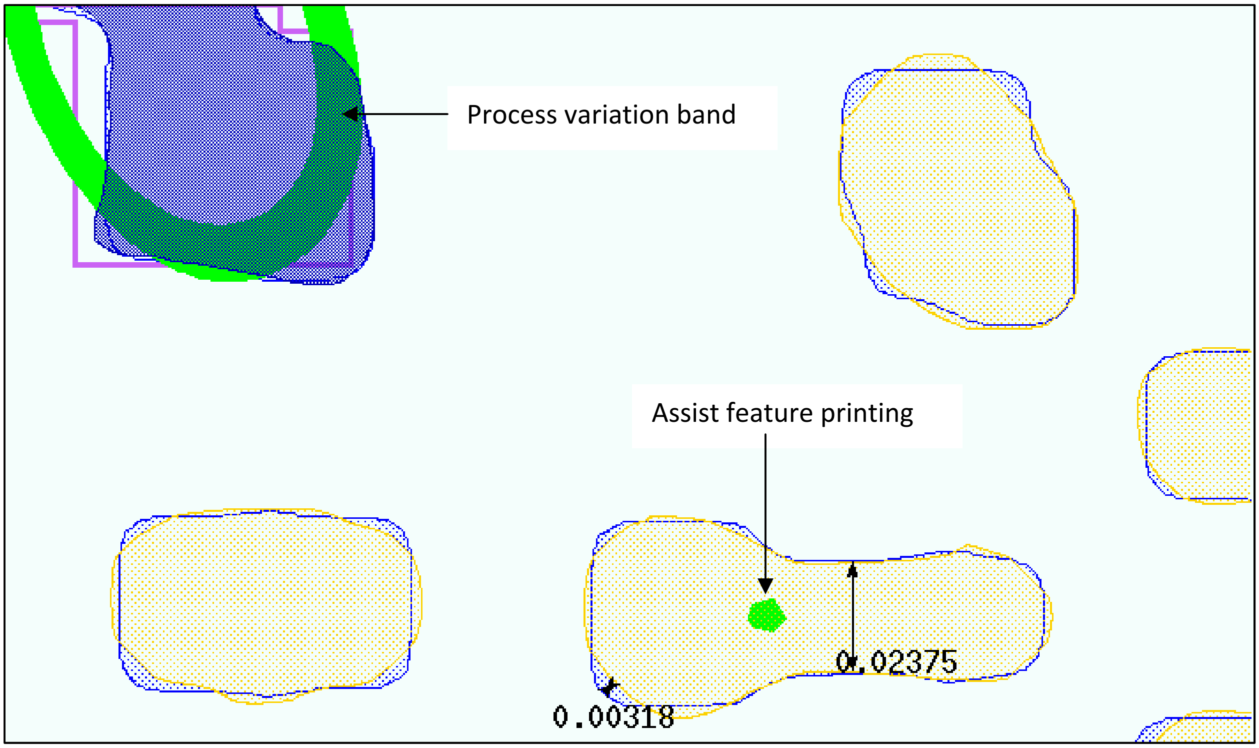

Figure 8. Layout window for Layout 2 showing assist feature printing for a mask generated with Exp 5. The process variation band indicated above shows a band of expected wafer print contours through process variation. The assist feature printing is undesired.

The results from Layout 2 indicate one problem when applying Optimization based fracture to mask layouts. Since algorithms to simplify layouts result in residual mask errors, there exists a risk that these mask errors will lead to large errors at wafer print. Furthermore, for any given layout and RET solution, the sensitivity of the wafer print to mask errors cannot be predicted without information about the optical configuration that will be used to print the wafer. Also, wafer error sensitivity to mask error is expected to vary widely enough across the layout as to preclude the application of a single guard band specification. Note that the Manhattanized mask benefits from being an integrated part of the OPC step. As such, its error distribution is comparable to that of the raw mask.

A key outcome from this discussion is that Optimization based fracture should be coupled with the RET solution that generates the original mask. The optimization for shot reduction must be conducted with information concerning the sensitivity of the wafer print to mask errors.

Another result (though not exhaustively demonstrated) of this study, is that wafer lithography quality as measured by EPE and PVB width is not significantly impacted by the Manhattan simplification of the raw mask.

5.0 CONCLUSIONS

Optimization based fracture can reduce the shot count of complex masks relative to Manhattan simplification. The amount of the reduction depends on layout specifics, the choice of global solution, and sensitivity of wafer lithography to residual mask errors. The results from the experiments conducted in this paper demonstrate the importance of integrating Optimization based fracture with the wafer lithography and RET solution.

A manufacturing flow that utilizes this technique increases the complexity of the flow. Optimization based fracture induces changes to manufacturing rule check and mask inspection procedures. It also requires tighter integration between the wafer fab and mask shops. Such implementation costs should be evaluated against the potential gains.

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