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Mask Optimization With Minimal Number of Convolutions Using Intensity Difference Map

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Abstract—With the continuous shrinking of minimum feature sizes beyond 193 nm wavelength in optical lithography, more and more computationally expensive algorithms are being developed in the field of Optical Proximity Correction (OPC) to improve pattern fidelity and robustness against process variations. Lithography simulation time and image accuracy are proportional to the number of kernels by which the mask is convoluted to generate the intensity map for each OPC iteration. Typically, there is a trade-off between the accuracy of intensity map and computational time which can be minimized by using only one kernel. Nevertheless, the intensity of each pixel tends to be smaller than its actual value and is not accurate enough resulting in intensity error. However, with considering relaxed Edge Placement Error (EPE) conditions, we observed that the error of pixel intensity is not changed much even if the mask is slightly updated. Therefore, in this paper, we exploit this observation to relax the intensity error by constructing intensity difference map in which the differences between one kernel and multiple kernels intensity maps are stored. For each OPC iteration, one kernel is used to generate intensity map, to which the intensity difference map is added to improve its accuracy. Our experimental results show that the proposed algorithm generates mask solutions within a short computational time with almost the same EPE and process variability band obtained using multiple kernels during optimization.

I. INTRODUCTION

Optical lithography is the process in which an integrated circuit (IC) is patterned layer by layer by projecting the image of a pixelated mask patterns using exposure tool to a silicon wafer which is coated by a photoresist. On the mask, polygons that define electrical structures are carved to be transferred to the wafer. If the exposure dose is greater than a certain threshold level, the exposed region of the resist will be chemically changed and formed the pattern under the development process, and finally etched to transfer to the wafer[1]. As advanced technology nodes are getting smaller and smaller, optical wavelength of the exposure tool had been steadily reduced till 193 nm (ArF excimer laser), and reached its practical limit such as high instability and strong birefringence of lens materials [2]. To obtain more small features printability, immersion lithography was introduced to increase the Numerical Aperture (NA). However, sub-100nm nodes printing suffers from image distortions which badly

impact the proper functionality of the circuit. This gave the birth of Optical Proximity Correction (OPC), in which the mask shape is modified to improve the image quality [3].

Many lithographic models were introduced to simulate the printed image of a mask on the wafer in the field of OPC techniques. Such models are applied so that the geometrical distance between any given point on the target and its corresponding point on the printed image is minimized. This distance is called Edge Placement Error (EPE) which has to be minimized to ensure pattern transfer fidelity. Figure 1 illustrates EPE measurement based on ICCAD 2013 contest. Furthermore, variational OPC algorithms were introduced to improve process window under low-k1 conditions, since lithographic process is susceptible to dose and focus variations, that would badly impact the lithographic yield. Such variations are expressed as the area of XOR between two printed images obtained by two extreme conditions. This metric is called Process Variability Band (PV-band) area which is shown in figure 2.[4].

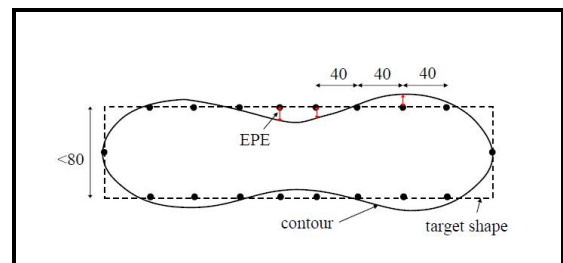


Figure 1: EPE Measurement[4]

An OPC algorithm consists of a number of iterations, in each, mask is modified and its image is simulated and compared with target layout to guide the next iteration mask adjustment. Many previous OPC algorithms are computationally expensive to be used for sub-100 nm features due to the large number of OPC iterations needed to find solution. In realistic industrial test cases, mask data have to be produced in matter of hours to cover the huge number of design shapes needed, therefore, exhaustively searching algorithms are no more applicable to be used. Typically, there is a trade-off between the computational time and the accuracy of the algorithm in finding a good mask solution.

In this paper, we propose a new algorithm to minimize the

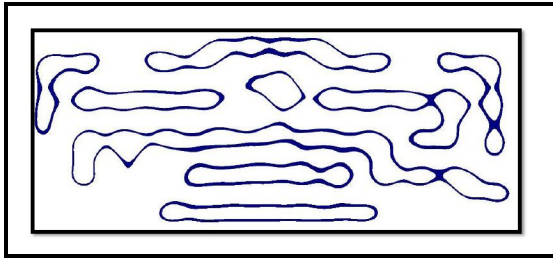


Figure 2: PV-band Area[4]

computational time for any iterative OPC algorithm through minimizing the number of convolutions during mask optimization. This is achieved by improving the accuracy of intensity map generated using only 1 kernel through adding intensity difference map to it so that only one convolution operation is executed per OPC iteration. The contribution of this paper is summarized as follows:

- A new approach is proposed to shorten the time required in lithography simulation. This is achieved by using one kernel to generate an intensity map to which the intensity difference map generated in the initialization stage is added.
- This approach is integrated into an OPC algorithm to show its validity for optimization.

The rest of this paper is organized as following: In section II previous works are presented. The problem is formulated in section III. Intensity map accuracy improvement is described in section IV. In section V, the algorithm is given and experimental results are presented in section VI. Finally, section VII concludes this paper.

II. PREVIOUS WORK

In conventional OPC algorithms, a mask layout is fragmented to divide each polygon edge into freely movable segments that will be shifted outside/inside the polygon to increase/decrease the intensity in testing points till the EPE is minimized [5][6]. However, without defining the best shifting distance, the solution space will be large and thus, computationally expensive. In [7], a variational OPC algorithm is proposed. In this algorithm, segment shifting is modeled as a function of variational EPE and PV-band which needs more iterations to find a best mask solution

Simultaneous Mask and Target Optimization (SMATO) was proposed in [9] with overhead in the computational time. Constructing Mask Error Enhancement Factor (MEEF) matrix to guide segments shifting is one of the proposed approaches to minimize EPE [10]. However, such approach suffers from large computational time as well. 1D design style to decrease mask complexity and layout decomposition for small sized features using double and triple patterning is one of the current available solutions at the cost of using more masks [11][12]. Another linearization approach was introduced to approximate segments shifting, however, this approach does not consider

the number of convolutions needed to generate image per iteration[13].

Finding a good mask solution to minimize EPE and PV-band area within a short computational time is challenging due to the continuous shrinking in features dimensions. In this paper, we propose a new approach to minimize computational time for any OPC algorithm without impacting its performance.

III. PROBLEM FORMULATION

Given an iterative OPC algorithm that finds a mask solution for a target layout defined in layout region with minimal EPE and PV-band area, the main objective is to minimize the computational time needed to generate a mask solution without affecting the algorithm performance in terms of the number of EPE violations and PV-band area.

A. Lithographic Model

In this paper, an optical model is used to generate an aerial image represented by intensity map. This model consists of optical system and projection system expressed by Transmission Cross Coefficient (TCC) which is decomposed into a set of kernels. The aerial image is obtained as shown in eq(1), where I is the aerial image, σ_k and h_k are the eigenvalue and eigenfunction set of TCC, M is the mask function, \otimes denotes the convolution operation, and K is the total number of kernels. This optical model is called sum of coherent systems (SOCS).

$$I = \sum_{k=1}^K \sigma_k |(h_k \otimes M)|^2 \quad (1)$$

The aerial image is represented by an intensity map that stores the intensity value for each pixel. Once this map is obtained, a resist model is applied to simulate photoresist exposure response. Constant Threshold Resist (CTR) is one of models used to represent the resist behavior. In this model, if the intensity is greater than intensity threshold (I_{th}), the resist will be exposed followed by etching. Subsequently, the image on the wafer will be generated. In OPC, both optical and resist models are applied iteratively to generate the image contours that is compared with the target layout.

B. Lithographic System Terminology

Let R be a layout region which consists of pixels. Let T be a target layout in R , that is, $T \subset R$. T contains a number of polygons. A polygon $S \in T$ consists of pixels. If a pixel $p \in R$ is contained in polygon S , then we denote $p \in S$. In the following, if $p \in S \in T$, then we simply denote $p \in T$. A mask M in R which consists of pixels determines the intensity of each pixel in R under certain lithographic process conditions. The intensity of pixel $p \in R$ by mask M is denoted by $I(M, p)$. Generally, let $I(M)$ be the intensity map of R derived by M under nominal conditions. That is, $I(M)$ is a list that contains the intensity value for each pixel.

Let $G(M)$ denotes the printed image of mask M on

the wafer. Typically, $G(M)$ is obtained by applying a resist model. In our algorithm CTR is the model used to obtain the image. In this model, if the intensity in any pixel p is greater than or equal intensity threshold I_{th} , it will be exposed and resist will be removed. Otherwise, resist will remain. In other words, $G(M, I) = \{p \in R \mid I(M, p) \geq I_{th}\}$. In this paper, both EPE violation number and PV-band area are measured based on ICCAD 2013 contest formulation [4].

C. OPC Computational Time

Image generation is the most expensive computation during mask optimization process. Generally, OPC computational time is the total time required to generate the mask solution. As shown in eq(1), the mask M has to be convoluted with all kernels to obtain an aerial image. Typically, a convolution operation is computationally expensive compared to other operations. Therefore, in this paper, we model the OPC computational time as the number of convolutions (NOC) performed during optimization.

IV. INTENSITY MAP ACCURACY IMPROVEMENT

The intensity map is typically estimated by using a transmission cross coefficient method in which convolution operation between kernel and mask is executed, and the computation time is proportional to the number of kernels used. There is a trade-off between the accuracy of intensity map estimation and the computation time. Although a rough intensity map is obtained by using higher weight kernels in short time, the intensity of each pixel in the map tends to be smaller than the actual value and it is not accurate enough. In this section, we discuss the possible approaches to minimize NOC per iteration with almost same OPC algorithm performance as using all kernels. It is important to refer that relaxed EPE conditions defined in ICCAD contest [4] are considered in this paper. The main objective is to minimize the K-band area with minimum number of convolutions.

A. Pixels Error Model

To evaluate the pixels error, we will define a new parameter called kernel band (K-band) area. K-band area is the XOR area between two mask images obtained from different intensity maps. For K kernels lithographic system, let $I_g(M)$ be the golden intensity map obtained by convoluting the mask with all kernels while $I_n(M)$ be an intensity map obtained using different approach. The K-band area is given in eq(2) where $G_g(M)$ and $G_n(M)$ represent the mask image obtained from $I_g(M)$ and $I_n(M)$, respectively.

$$KBandArea(M) = \sum_{p \in R} kband(M, p)$$

$$kband(M, p) = \begin{cases} 1; & G_g(M, p) \oplus G_n(M, p) \\ 0; & \text{Otherwise} \end{cases} \quad (2)$$

With considering relaxed EPE definition, using only high weight kernels for optimization would be enough. Let M_k denotes the minimum number of kernels needed per each OPC iteration to generate a mask solution with almost the same EPE violations number as using all K kernels in a lithographic system. However, using multiple kernels per iteration is still computationally expensive. To obtain a significant time reduction, using one kernel per iteration is a good solution. Nevertheless, high inaccuracy is expected which might result in generating inappropriate mask solutions. Therefore, some workaround is needed.

B. Offset Approach

The inaccuracy is relaxed by adding average intensity error for each pixel. Let $I_{mk}(M)$ and $I_1(M)$ denote the intensity maps generated using 1 kernel and M_k kernels, respectively. $I_1(M)$ is modified by adding average error value E for each pixel p as shown in eq(3), where E is given in region R . However, our experiments show that such approach does not achieve good accuracy for complex layouts.

$$I_{offset}(M, p) = I_1(M, p) + E$$

$$E = \sum_{p \in R} \frac{I_{mk}(M, p) - I_1(M, p)}{|R|} \quad (3)$$

C. Intensity Difference Map

Under relaxed EPE conditions, we observed that the error of intensity varies in each pixel in map, but the error of intensity of a pixel is not changed much even if a mask is slightly modified. Therefore, the intensity difference map is constructed for each target layout to improve the accuracy of intensity map estimation without increasing computational time.

The intensity difference map ($I_{diff}(M)$) is defined as the difference of the intensity map of a large number of kernels and the intensity map of a small number of kernels. In this paper, we construct the intensity difference map from M_k kernels map and 1 kernel map. Then, the 1K map is enhanced during each OPC iteration by adding the intensity difference map to it as illustrated in figure 3. For a pixel p , the intensity value is modified as shown in eq(4) where I_{eval} is the new intensity map. Note that M represents the current mask while M_{org} represents the initial mask which is set to be same as the target.

$$I_{eval}(M, p) = I_1(M, p) + (I_{mk}(M_{org}, p) - I_1(M_{org}, p)) \quad (4)$$

D. Approaches Comparison

Let $G_1(M)$, $G_{offset}(M)$, and $G_{eval}(M)$ denote the images obtained from $I_1(M)$, $I_{offset}(M)$, and $I_{eval}(M)$, respectively. In the following experiments, we evaluated the K-band area using lithosim simulator from ICCAD contest with $I_{th} = 0.225$, $K = 24$ kernels, and $M_k = 5$ kernels. The K-band area was calculated using the following three approaches:

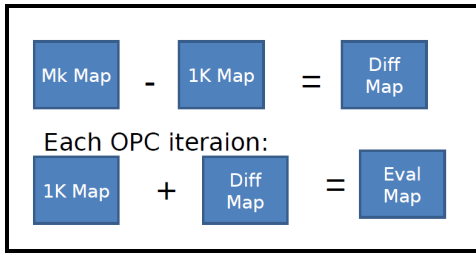


Figure 3: Intensity Difference Map Usage

- 1) 1K approach: $G_g(M) \oplus G_1(M)$
- 2) Offset approach: $G_g(M) \oplus G_{offset}(M)$
- 3) I_{diff} approach: $G_g(M) \oplus G_{eval}(M)$

Given the mask layout shown in figure 4-a, the K-band area was calculated for this mask using the three previously mentioned approaches. When only the highest weight kernel is used, K-band area is 69914 nm^2 (figure 4-b). When trying to modify 1 kernel map by adding average error, the K-band area is reduced to 59316 nm^2 (figure 4-c). Finally, when adding intensity difference for each pixel using intensity difference map, the resultant K-band area is 12676 nm^2 (figure 4-d). This area is the smallest one among the others and it is equivalent to the K-band area when using 5 kernels since both $I_1(M)$ and $I_5(M)$ were obtained from the same target.

To ensure the usability of intensity difference map approach, K-band was calculated for the OPCed mask shown in 5-a using the same mentioned approaches. Note that E and I_{diff} values are the ones obtained from the target layout of this mask (figure 5-a). The K-band values are 82641, 67760, 48828, 13692 nm^2 using 1K, offset, I_{diff} , and M_k kernels, respectively (figures 5-(b-e)). Although using M_k kernels results in the least K-band area, it results in large computation time. I_{diff} approach K-band area is acceptable if compared with other approaches. Furthermore, the K-band area line width is few pixels in several regions which might not cause EPE violations (15 pixels is the allowable EPE distance for ICCAD contest). Therefore, using intensity difference map during mask optimization is recommended as long as no EPE violations occur as shown in section VI.

V. PROPOSED FAST OPC ALGORITHM

For a K kernels lithographic system with N OPC iterations needed to minimize EPE and PV-band area, the number of convolutions is given in eq(5).

$$NOC = K * N \quad (5)$$

In our fast intensity map estimation, an improved accuracy intensity map is obtained by combining the intensity map by the first kernel and the intensity difference map. Given K kernels lithographic system, we use the largest weight M_k kernels from K to construct the intensity difference map, then, only one kernel (largest weight kernel) is used to obtain the intensity map for each iteration. Hence, the number of

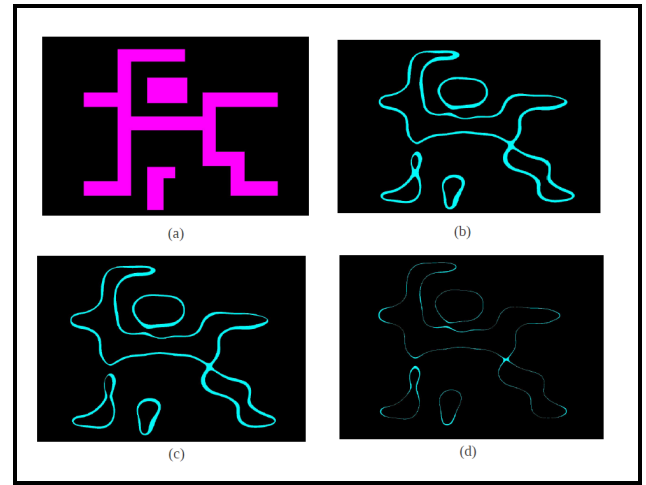


Figure 4: (a) Mask. (b) K-band area for only 1 kernel. (c) K-band area for 1 kernel+offset. (d) K-band area for 1 kernel+ intensity difference.

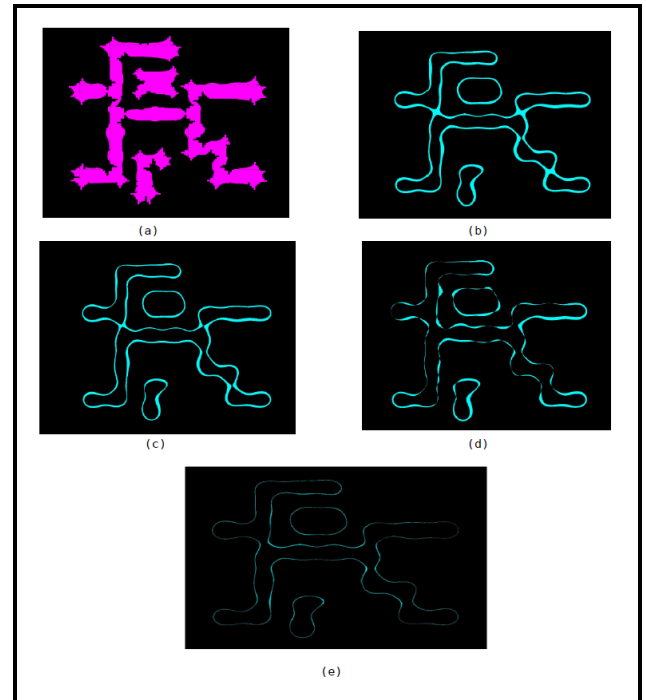


Figure 5: (a) OPCedMask. (b) K-band area for only 1 kernel. (c) K-band area for 1 kernel+offset. (d) K-band area for 1 kernel+ intensity difference. (e) K-band area for 5 kernels

convolutions with our enhanced approach is reduced as shown in eq(6).

$$NOC_{enhanced} = M_k + N \quad (6)$$

Figure 6 illustrates the general flow chart of our proposed fast OPC algorithm. First, we choose the highest weight M_k kernels from K kernels. M_k is the minimum number of kernels needed to generate a mask solution with almost the same number of EPE violations and PV-band area (with assuming relaxed conditions). Then, the mask M is set to be same as target T . Two intensity difference maps are generated, the first one using M_k kernels, denoted by $I_{mk}(M)$ and the second one using only highest weight kernel, denoted by $I_1(M)$.

Table 1: Results for Public Benchmarks

Benchmark	$M_k = 5$ Kernels				Proposed Algorithm				
	#EPEV	PVBand	Time(sec)	Cost	#EPEV	PVBand	Time(sec)	Cost	Time Reduction(%)
M1-test1	4	78922	230	335688	5	79801	125	344204	45.6
M1-test2	4	65860	217	283440	5	61900	109	272600	49.7
M1-test3	34	126690	237	676760	31	126447	157	660788	33.7
M1-test4	0	32278	204	129112	0	31353	70	125412	65.7
M1-test5	0	64955	201	259820	0	63485	110	253940	45.3
M1-test6	0	64393	201	257572	3	65190	95	275760	52.7
M1-test7	0	48724	293	194896	0	47123	72	188492	75.4
M1-test8	0	23618	151	94472	0	23679	67	94716	55.6
M1-test9	0	66557	207	266228	0	67909	70	271636	66.2
M1-test10	0	18569	72	74276	0	17884	47	73640	34.7
Average				257226.4				256118.8	52.2

From those maps, the intensity difference map $I_{diff}(M)$ is constructed by storing the difference in intensity values stored in $I_{mk}(M)$ and $I_1(M)$ for each pixel. Finally, OPC algorithm starts, and for each iteration, only highest weight kernel is used to obtain the evaluation intensity map, for which, intensity difference map is added. Algorithm 1 illustrates our proposed algorithm in details. If $M_k = K$, more accurate results can be obtained at the cost of more computational time.

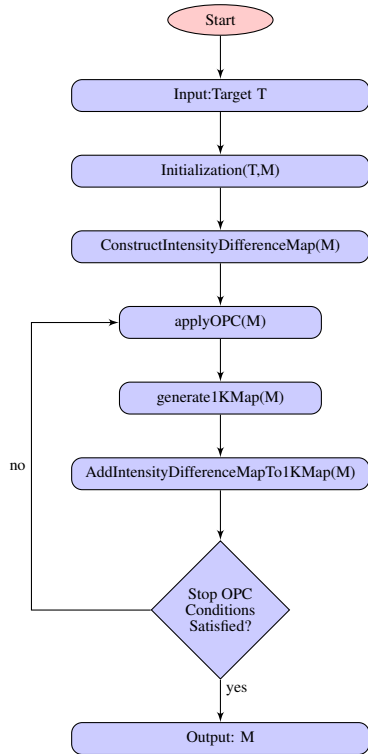


Figure 6: OPC Algorithm Flow chart

VI. EXPERIMENTAL RESULTS

All experiments were executed on lithosim simulator from ICCAD contest [15]. In this simulator, T is defined in 1024×1024 pixels region where each pixel represents $1 \text{ nm} \times 1 \text{ nm}$ with $I_{th} = 0.225$. The segments shifting OPC algorithm defined in [14] is used to generate the optimized mask. Both EPE and PV-band area are measured using EPE checker tool and PV-band area calculation tool from ICCAD contest. We used ICCAD cost function as shown in 7 with $\alpha = 5000$ and

Algorithm1: Intensity Difference Map Integration with OPC Algorithm

```

***** Initialization*****
M ← T // largest weight kernels
M_k ← chooseMKernelsFromAll(K) // largest weight kernels
I_Mk(T) ← findIntensityMapUsingMKernel(T, nominalDose, inFocus)
I_1(T) ← findIntensityMapUsing1Kernels(T, nominalDose, inFocus)
I_diff(T) ← I_Mk(T) - I_1(T)
iteration ← 0
***** OPC*****
while epe Stop conditions are not satisfied. do
  M ← applyOPC(M) //using any algorithm like the one described in [14]
  I(M) ← findIntensityMapUsing1Kernels(M)
  I(M) ← I(M) + I_diff(T)
  G_n(M) ← applyResistModel(I(M), I_th)
  epe ← calculateEPE(G_n(M), T)
  iteration ← iteration + 1
end while
  
```

$$\beta = 4.$$

$$Cost = \alpha * EPEV + \beta * PVBandArea \quad (7)$$

Table 1 shows the EPE, PV-band area and execution time for applying OPC algorithm on ICCAD contest public benchmarks using 5 kernels and using intensity difference map approach. As shown in the table, it is obvious that the OPC computational time was reduce effectively using intensity difference map concept with almost the same average cost as using 5 kernels per iteration.

VII. CONCLUSIONS

In this paper, we proposed a new algorithm to minimize the number of convolutions during mask optimization process. Consequently, the OPC computational time is reduced. Our experimental results on the public benchmarks show that the proposed algorithm reduces the computational time effectively without affecting OPC algorithm performance in terms of the number of EPE violations and PV-band area.

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