A Fast LUT Based Point Intensity Computation for OPC Algorithm*1

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Abstract – Nanolithography is becoming more challenging with the advancement of technology node. OPC (Optical Proximity Correction) algorithm is becoming more aggressive with an increment of mask complexity. In this research, a simulator is proposed which simulates tap point intensity to guide the OPC algorithm instead of generation of the aerial image of the mask pattern which is time and memory efficient.

I. Introduction

As the advanced technology nodes are continuing to decrease, nanolithography is becoming more challenging[1]. To preserve the acceptable wafer image quality of technology nodes in the lithography simulation, Resolution Enhancement Technique (RET) is adopted[2].

A lithography process is susceptible to various process variations and it affects the wafer image quality on the silicon wafer. When the difference between the target pattern and the wafer image is large, OPE (Optical Proximity Effect) is observed which reduces the wafer image quality[3]. To resolve the problem, OPC (Optical Proximity Correction) algorithms are used. OPC algorithms iteratively adjust the mask pattern till sufficient wafer image quality is achieved.

The purpose of the OPC algorithm is to provide the best mask solution of the given target pattern by utilizing OPE[4]–[6]. The computation time of the OPC algorithm is mostly contributed by aerial image simulation[7].

Simulation of the aerial image is time-consuming. With the increment of the complexity of the mask, the time needed to simulate the aerial image increases. Moreover, computing whole aerial image is not necessary to guide OPC algorithms, although it is needed for the final quality checking of the mask. The behaviour of the OPC algorithm can be guided by some specific points of the target pattern in the layout; such points are the measurement points of the target pattern or tap points. So, calculating the intensity of the whole aerial image to guide the OPC algorithm is redundant.

The purpose of this research is to guide the OPC algorithm without generating the aerial image of the mask pattern in every iteration. So, in this paper, a lithography simulator is proposed which will guide the OPC algorithm using tap points of the mask pattern; such a mechanism ensures faster computation time. In this research, we have used ICCAD 2013 lithography simulator as the benchmark simulator[8].

The proposed lithography simulator comes with a lookup table (LUT) to facilitate faster computation. One of the features of the proposed simulator is that it decomposes any complex mask pattern into simple rectangles. The proposed lithography simulator obtains the intensity of an arbitrary point in the simulation region caused by the decomposed rectangles of the complex mask pattern. Each corner of a decomposed rectangle is represented by four rectangles whose upper left corners are at the origin of the simulation region. The simulator then uses the amplitudes of intensities of four rectangles who have its origin at the origin of the simulation region to calculate the amplitude of intensity of the arbitrary point in the simulation region. These amplitudes of intensities of the four rectangles who have its origin at the origin of the simulation region are precomputed and stored in the LUT. The size of the LUT is proportional to the size of the simulation region.

II. Previous Work

The MEEF (Mask Error Enhancement Factor) matrix help to guide the shifting of edges in OPC algorithms which are based on EPE[9], [10]. The fast intensity-based algorithms do not consider dense mask pattern[11]. Presently, exploration in ILT (Inverse Lithography Technology) has led to developing a robust mathematical model for OPC algorithms. However, the solution of the mask is hard to manufacture because of the pixel-based nature of ILT [12][13]. Similarly, some aggressive OPC algorithms provide complex mask pattern as output which are difficult to manufacture because of the pixel-based nature[14][15]. Rule-based OPC algorithm is a fast method to find a mask solution [16] but it has a lack of scalability than Model-based OPC. MOSAIC, another pixel-based algorithm exploits EPE under each process corner [17]. To reduce the iteration number of OPC algorithms, an algorithm based on the neural network has been proposed which gives significantly better initial guess[18]. Some algorithms consider both EPE and PV band area for process window based OPC (PW-OPC)[19][20]. A fast printability verification method has been proposed which simulates the wafer image of mask pattern with fewer kernels[21] and this accelerates OPC algorithms; because using more kernels will require more iterations. Intensity difference map is another approach to reduce the number of convolutions with kernels[5]. Although around the target boundaries better estimation of intensity is needed.

However, the above mentioned researches are mostly focused on the defects of the previous work and try to find a better way to resolve that defect. This research provides a way to find tap point intensity which is not directly related to the above mentioned researches which use a time-consuming simulator. Similar work has been proposed in [22] where the

*1 A preliminary version of this paper was presented in [23] intensity of a point is calculated with the help of edge-based LUT. However, to calculate a single point several data from LUT is needed; In the proposed research, only four data points from LUT are sufficient enough to calculate point intensity accurately.

III. Preliminaries

A. *Optical Proximity Correction*

Optical lithography simulation is a process through which wafer image is formed on silicon wafer when monochromatic light is passed through and diffracted by mask pattern. The process is affected by various process variations which cause a difference between the target pattern and the projected pattern on the silicon wafer.

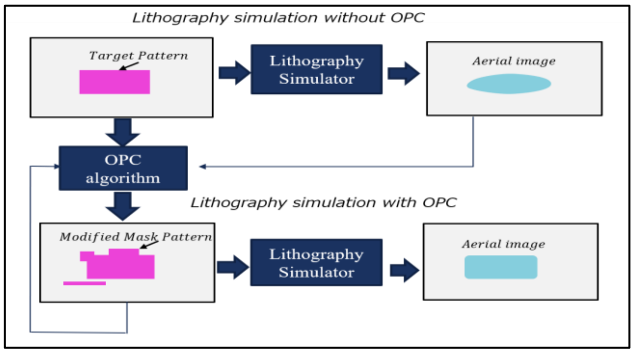

Figure 1: Lithography Simulation with and without OPC

OPC algorithm takes the target pattern as input and provides a modified mask pattern as output by the iteration process by using OPE (Fig 1). So, lithography simulation with OPC algorithm gives a viable aerial image.

B. *Sum of Coherent System Model (SOCS model)*

SOCS Model is the mathematical model of lithography simulation. SOCS Model gives the aerial image intensity $I(M)$ as output by evaluating the square of the sum of convolution of kernels (ϕ_k) having weight (w_k) and the mask pattern M [23].

$$I(M) = \sum_k w_k |M \otimes \phi_k|^2 = \sum_k w_k I_k(M) \qquad (1)$$

The convolution of mask M and kernel ϕ_k gives the amplitude $A_k(M)$ of the mask pattern M. So, from Eq (1),

$$I(M) = \sum_k w_k I_k(M) = \sum_k w_k |A_k(M)|^2 \qquad (2)$$

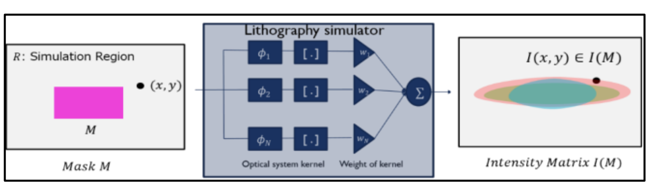

Figure 2: SOCS Model

Let, $I_k(x,y,M) \in I_k(M)$ be the intensity of a point (x,y) in the simulation region R (Fig 2). By following the SOCS Model of Eq (1) and (2), the intensity of the point (x,y) caused by the mask pattern M can be written as:

$$I(x,y,M) = \sum_k w_k |A_k(x,y,M)|^2$$

The amplitude in the lithography process is a complex number. So, the above equation can be written as:

$$I(x,y,M) = \sum_k w_k \left|A_k^{\mathrm{Re}}(x,y,M) + jA_k^{\mathrm{Im}}(x,y,M)\right|^2 \qquad (3)$$

C. *Tap point Intensity*

Tap points are the measurement points in the target pattern where intensity is checked to evaluate the wafer image quality. By evaluating the intensity at tap points, we can know, whether the target pattern is properly transferred to silicon wafer or not.

Let, in the simulation region R, there are three tap points p_1, p_2 and p_3 of mask M (Fig 3). The intensities at these points of the aerial image are evaluated to assess the quality of the wafer image by filtering the intensities with a threshold intensity I_{th}. Let I_{p1} be the intensity at p_1. At p_1, $I_{p1} \geq |I_{th}|$ might be expected in good mask, but the wafer quality might not be protected.

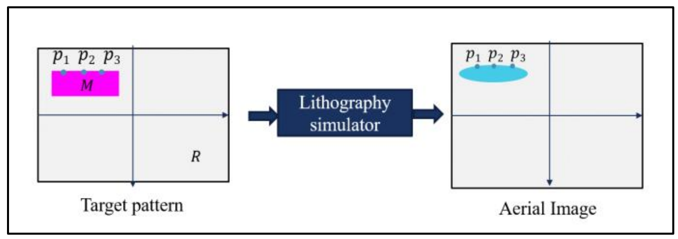

Figure 3: Tap points of mask M

In typical OPC algorithm, the positions of tap points are determined in the following way: Any edge of a target pattern is divided into some segments. If the edge of the target pattern is a multiple of L_{seg} which is predefined by OPC algorithm, the edge is divided into equal segments each of length L_{seg}. Otherwise, the residual segment $l < L_{seg}$ is equally concatenated with neighbouring segments. The centre point of each newly bounded segment is called a tap point or a point of measurement (Fig:4).

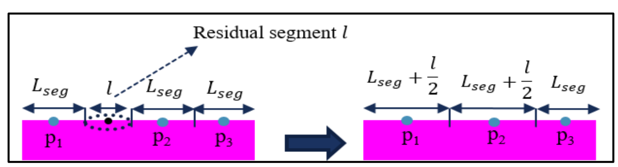

Figure 4 Tap point site determination

D. *Periodic Boundary condition*

In this research, simulation is conducted under periodic boundary condition which states that:

- Mask pattern M in simulation region R is repeated infinitely in a two-dimensional plane.
- The size of simulation region R is set large enough to obtain intensity of the center region of R accurately as independent of outside of R.

If R has a peripheral area which is at least as wide as the optical radius of the source of lithography simulation then this assumption is practically correct even if actual outside is different from the assumption.

E. Parallel Shift

Parallel shift operation reduces the size of LUT and makes the process of generation of LUT faster. Let, R be the simulation region whose height and width are L_x and L_y respectively and the centre of R is (x_c, y_c). The upper left corner of R is at (0,0). In R, there are two masks M_1 and M_2. M_1 has a tap point p at (x_1, y_1) and M_2 has its upper left corner at (x_2, y_2) (Fig 5).

Under the periodic boundary condition, parallel shift gives any impact on the intensity of a tap point. The tap point under evaluation is moved to the centre (x_c, y_c) of R. To bring p of M_1 at the centre of R, M_1 is parallel shifted by the amount (d_x, d_y) in X and Y direction respectively. This shift is applied to all other patterns existing in R such as M_2. So, the relative position of M_1 and M_2 before and after the shift is maintained.

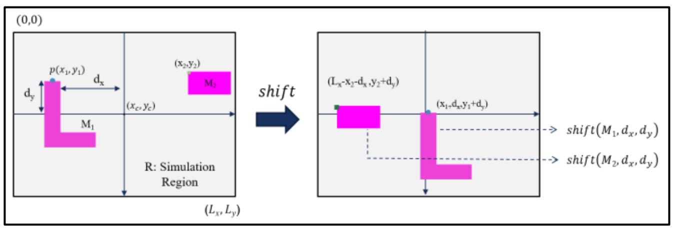

Figure 5: Parallel shift operation demonstration

So, the new position of p becomes $(x_1 + d_x, y_1 + d_y)$. Also, the new position of (x_2, y_2) becomes: $(L_x - x_2 - d_x, y_2 + d_y)$ by parallel shift. As the relative position of M_1 and M_2 is maintained under the periodic boundary condition, the amplitude caused by $M_1 \cup M_2$ at the tap point, $p(x, y)$ is the same as the amplitude caused by $\mathrm{shift}(M_1, d_x, d_y) \cup \mathrm{shift}(M_2, d_x, d_y)$ at the new location of p which is at $(x_1 + d_x, y_1 + d_y)$. So,

$$A_k\left(x_1 + d_x, y_1 + d_y, \mathrm{shift}(\mathrm{M}_1, d_x, d_y) \cup \mathrm{shift}(\mathrm{M}_2, d_x, d_y)\right) = A_k(x_1, y_1, M_1 \cup M_2) \qquad (4)$$

IV. Problem Description

The target pattern in the lithography simulation can be any complex pattern. In this research, any complex pattern is decomposed into simple rectangles having four corners. The target of this research is to evaluate the intensities at the tap points of the decomposed rectangles which form the complex mask layout.

To evaluate a tap point intensity, the tap point is located at the centre position of R by parallel shift. As intensity is the square of amplitude (Eq 2), the final target is to find the amplitude of the tap point at the centre of R caused by all patterns existing in R by the proposed amplitude decomposition (described in section V) in a time efficient way.

V. Amplitude Decomposition

Amplitude decomposition is based on SOCS Model. Amplitude decomposition is used to find intensity at an arbitrary point in the simulation region caused by more than one rectangle. Let, $M_P \subset R$ and $M_Q \subset R$ be two mutually exclusive and independent rectangles. The intensity caused by M_P and M_Q at a point $(x, y) \in R$:

$$I_k(x, y, M_P \cup M_Q) = \left|A_k(x, y, M_P \cup M_Q)\right|^2$$

Note that, the amplitude is obtained by convolution of mask and kernel and convolution operation has associative property. So, the amplitude $\mathrm{A_k}(M_P \cup M_Q)$ caused by two independent rectangles is the sum of amplitude caused by the two rectangles individually.

$$A_k(M_P \cup M_Q) = (M_p + M_Q) \otimes \phi_k$$
$$= (\mathrm{M_P} \otimes \phi_k) + (\mathrm{M_Q} \otimes \phi_k) = A_k(M_P) + A_k(M_Q) \qquad (5)$$

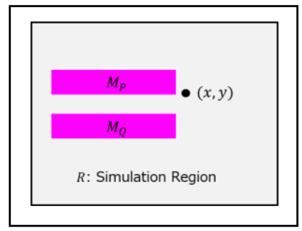

Figure 6: Amplitude decomposition of two masks

So, from Eq (5) the intensity caused by $M_P \cup M_Q$ at (x, y):

$$I_k(x, y, M_P \cup M_Q) = \left|A_k(x, y, M_P \cup M_Q)\right|^2$$
$$= \left|A_k(x, y, M_P) + A_k(x, y, M_Q)\right|^2$$
$$= \left(A_k^{\mathrm{Re}}(x, y, M_P) + A_k^{\mathrm{Re}}(x, y, M_Q)\right)^2 + \left(A_k^{\mathrm{Im}}(x, y, M_P) + A_k^{\mathrm{Im}}(x, y, M_Q)\right)^2$$
$$\neq A_k^{\mathrm{Re}}(x, y, M_P)^2 + A_k^{\mathrm{Re}}(x, y, M_Q)^2 + A_k^{\mathrm{Im}}(x, y, M_P)^2 + A_k^{\mathrm{Im}}(x, y, M_Q)^2$$
$$= |A_k(x, y, M_P)|^2 + \left|A_k(x, y, M_Q)\right|^2$$
$$= I_k(x, y, M_P) + I_k(x, y, M_Q)$$

So, it is to be noted that,

$$\mathrm{I_k}(x, y, M_P \cup M_Q) \neq I_k(x, y, M_P) + I_k(x, y, M_Q) \qquad (6)$$

Amplitude decomposition is also used to find tap point intensity of a mask when the mask pattern is represented by other patterns by superimposition principle. For example: let, in the simulation region R, a rectangle $M(w, h)$ is placed in such a way that the tap point $p(x, y)$ is located at the centre of R. Here w is the width and h is the height of rectangle $M(w, h)$. Amplitude is evaluated at the tap point $p(x, y)$. The four corners of the rectangle $M(w, h)$ are highlighted with small green rectangles (Fig 7). The upper left corner of M is (x_1, y_1) and the lower right corner is $(x_1 + w, y_1 + h)$.

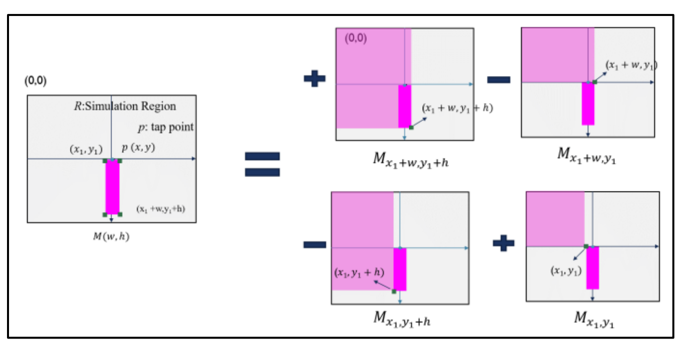

Figure 7: Finding tap point intensity by amplitude decomposition

The four corners of $M(w, h)$ are then represented by four rectangles $(M_{x_1,y_1}, M_{x_1,y_1+h}, M_{x1+w,y1}, M_{x_1+w,y_1+h})$ whose upper left corners reside in the origin of simulation region R (0,0) and the lower right corners coincide with that of each corner of $M(w, h)$. For example, $M_{x_1y_1}$ has its upper left corner at (0,0) and lower right corner at (x_1, y_1) which is the upper left corner of $M(w, h)$. By superimposition principle and following Eq (5),

$$A_k(p, M) = A_k(p, M_{x_1y_1}) - A_k(p, M_{x_1y_1+h}) - A_k(p, M_{x_1+w,y_1}) + A_k(p, M_{x_1+w,y_1+h}) \quad (7)$$

When the tap point of a mask of interest is located at the centre of R, Eq (7) evaluates the amplitude of the tap point. Hence, the intensity at p is evaluated.

$$I_k(p, M) = |A_k(p, M)|^2$$

Therefore, if the amplitude of intensity caused by rectangles $M_{x_1,y_1}, M_{x_1,y_1+h}, M_{x1+w,y1}, M_{x_1+w,y_1+h}$ at the centre of R can be known, Eq (7) is used to find $A_k(p, M)$.

VI. Lithography Simulation Engine Framework

The proposed lithography simulation engine evaluates the intensity of tap point using the pre-calculated amplitude of intensity data stored in LUT. Eq (7) is the backbone of the lithography simulation engine framework.

A. Generation of LUT

The purpose of LUT is to facilitate faster calculation of the proposed simulation engine. The LUT stores the complex value of amplitude caused by each of the rectangles inside the simulation region at the centre point of the simulation region whose upper left corner resides at the origin of the simulation region. In the proposed research, dynamic programming is used to find the amplitude of intensity of such rectangles at the centre point of the simulation region.

Let, R be the simulation whose length $= L_x$ and breadth $= L_y$ and whose origin is at $(0,0)$. Let, $M(w, h)$ be the rectangle in R which has its origin at (0,0) and the w and h are the width and height of M. Let, (x_c, y_c) be the centre point of R and $s =$ unit length $=$ unit width $=$ step size. For LUT T, we need to evaluate the amplitude of $M(w, h)$ for a fixed kernel k at the centre of R, $A_k(x_c, y_c, M(w, h))$.

By, superimposition principle, $M(w, h)$ can be represented by three rectangles $M(w - s, h - s), M(w, h - s), M(w - s, h)$ and a parallel shifted unit tile (Fig 8). A unit tile $M(s, s)$ is a square mask pattern of unit length (s) whose upper left corner is at (0,0).

So, the amplitude of intensity caused by $M(w, h)$ at the centre of R, can be obtained by equation (7) using superimposition principle.

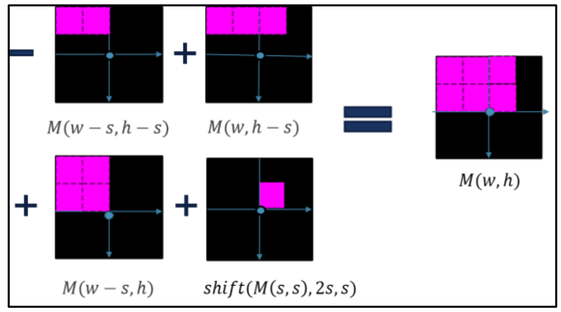

Figure 8: Dynamic Programming Approach to generate LUT

$$\begin{aligned} A_k(x_c, y_c, M(w, h)) &= -A_k(x_c, y_c, M(w - s, h - s)) \\ &+ A_k(x_c, y_c, M(w, h - s)) \\ &+ A_k(x_c, y_c, M(w - s, h)) \\ &+ A_k(x_c, y_c, \text{shift}(M(s, s), 2s, s)) \end{aligned}$$

This equation is just a variation of Eq (7). Note that, the values $A_k(x_c, y_c, M(w - s, h - s)), A_k(x_c, y_c, M(w, h - s)), A_k(x_c, y_c, M(w - s, h)) \in T$ and can be accessed while calculating the above equation. It is necessary to know the centre point amplitude of shifted unit tile $\text{shift}(M(s, s), 2s, s)$.

Any arbitrarily shifted unit tile is obtained by shifting the unit tile $M(s, s)$ following periodic boundary condition. So, the shifted unit tile $\text{shift}(M(s, s), 2s, s)$ is obtained by shifting the unit tile $2s$ in the X direction and s in the Y direction following periodic boundary condition (Fig 9). Similarly, the complex amplitude of unit tile $M(s, s)$ is also shifted by the same amount which gives the amplitude of intensity caused by $\text{shift}(M(s, s), 2s, s)$.

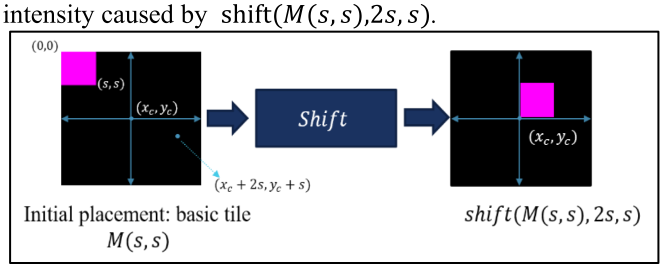

Figure 9: Shifted unit tile obtained from unit tile

By periodic boundary condition,

$$\begin{aligned} A_k(x_c, y_c, \text{shift}(M(s, s), 2s, s)) &= A_k(x_c + 2s, y_c + s, M(s, s)) \\ &= \text{shift}(A_k(M(s, s)), 2s, s) \end{aligned}$$

That is, the amplitude of $M(s, s)$ at $(x_c + 2s, y_c + s)$ is the same as amplitude caused by $\text{shift}(M(s, s), 2s, s)$ at the centre of R. Note that, $A_k(M(s, s))$ is obtained by lithography simulation of benchmark simulator (Fig 9). This is the only time when the benchmark simulator is used.

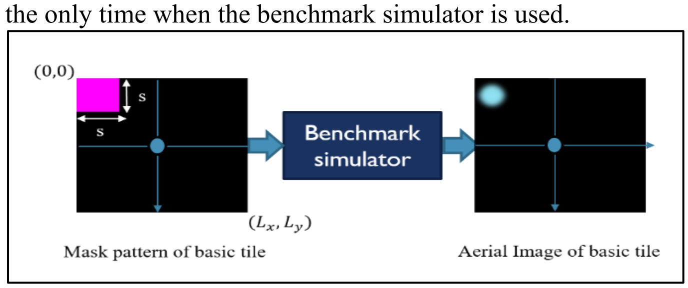

Figure 10: Generation of basic tile by benchmark simulator

In this way, the amplitude of intensity caused by rectangle $M(n,m)$ whose upper left corner are positioned at the origin (0,0) of simulation region R and the lower right corner at (n,m) are obtained where $n = s, 2s, \dots, L_x$ and $m = s, 2s, \dots, L_y$). The number of such type of rectangle is $\frac{L_x L_y}{s^2}$.

B. *Finding the intensity of tap points*

Let, R be the simulation region whose length is L_y and width is L_x and the centre position is (x_c, y_c). Let, in simulation region R, there are 2 masks M_1 and M_2. Let, the point of evaluation is tap point $p(x,y)$ located in the mask M_1. M_1 is a polygon which is decomposed into rectangles $M_{1,a}$ and $M_{1,b}$ each having 4 corners (Fig 11).

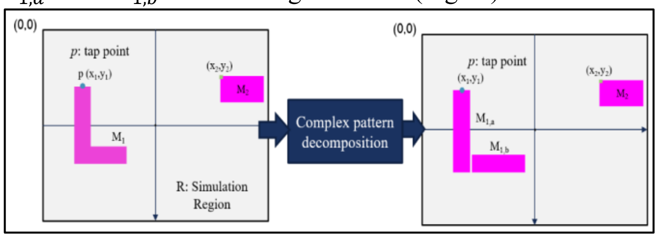

Figure 11: Complex pattern decomposition

Then, the layout is parallel shifted d_x in X direction and d_y in the Y direction following periodic boundary condition in such a way that the tap point $p(x,y)$ is located at the centre (x_c, y_c) (Fig 12). Let the new position of shifted rectangles are $M'_{1,a}$, $M'_{1,b}$, M'_2 and the new position of tap point is p'

$$\text{shift}(M_{1,a}, d_x, d_y) \equiv M'_{1,a}$$
$$\text{shift}(M_{1,b}, d_x, d_y) \equiv M'_{1,b}$$
$$\text{shift}(M_2, d_x, d_y) \equiv M'_2$$

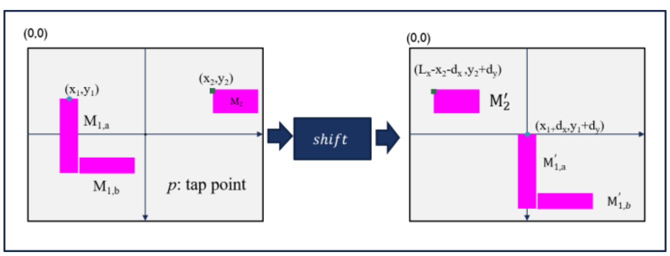

Figure 12: Parallel shift of mask

Now, the target is to know the effect of amplitudes of each of these shifted rectangles $M'_{1,a}$, $M'_{1,b}$ and M'_2 at the tap point p'. Using Eq (7) for k^{th} kernel,

$$A_k(p', M'_{1,a} \cup M'_{1,b} \cup M'_2) = A_k(p', M'_{1,a}) + A_k(p', M'_{1,b}) + A_k(p', M'_2)$$

Using the 4 corners of each of these shifted rectangles in R, appropriate rectangles $M^i_{n,m}$ for i^{th} shifted rectangle are accessed from LUT and using (6) and (7) the tap point intensity is found out.

VII. Experimental Results

In this research, ICCAD 2013 lithography simulator is used as benchmark simulator. The speed and accuracy of the proposed simulator to calculate the tap point intensity of the proposed simulator is compared with this simulator. The simulation region R has area 2048 x 2048 nm^2.

For the generation of LUT, knowing the step size is important because step size determines the number of data in LUT. From the limitation of ICCAD 2013 simulator, it was observed that within 2 nm distance, the intensity caused by mask pattern at the centre point does not change. So, step size, s = 2nm and # of data point of LUT with this step size $= \frac{L_x L_y}{s^2} = \frac{2048^2}{2^2} = 1048576$ which is stored in a binary file of size 8 MB for use in simulator unit and this requires only 15 sec to prepare. The time to prepare the LUT depends linearly only on the area of simulation region.

With this LUT and with the help of proposed simulator, the intensity of the centre point (x_c, y_c) of the simulation region caused by the following test cases (Fig 13) is evaluated for the first kernel of the benchmark simulator. These intensities are then compared with the benchmark simulator in Table 1.

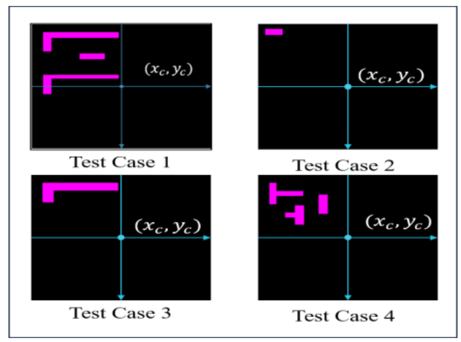

Figure 13: Test Cases

Table 1: Comparison of accuracy

Test Cases	Simulator	
	Benchmark	Proposed
	Intensity($I_1(x_c, y_c) \times 10^{-5}$)	
1	67.50	67.50
2	0.01	0.01
3	0.02	0.02
4	0.05	0.05

In this research, L_{seg}= 20 nm in both X and Y direction and this is predefined by the benchmark simulator. With this L_{seg}, the tap points of the test cases in both X and Y directions are calculated. The time needed to calculate these tap points is evaluated. The preparation of LUT is a one-time approach for one particular system of kernel of the lithography system. So, the time needed to prepare LUT is not included in the evaluation of the time of proposed simulator. In Table 2, the time to calculate 36 time points by the proposed simulator is 0.30 ms and these tap points are sufficient to evaluate the wafer image quality of testcase 1. The time needed to generate the aerial image to guide the OPC algorithm by the benchmark simulator varies from 7000 to 9000 ms.

Table 2 Computation Time

Test Cases	# of tap points	Time to calculate tap points by proposed simulator(ms)	Time to generate aerial image by benchmark simulator(ms)
1	36	0.30	7000~9000
2	30	0.25	
3	84	0.92	
4	40	0.29	

Although, the parameter L_{seg} is predefined by benchmark simulator, any change in L_{seg} will change the number of tap points of the mask pattern; If the number of tap point increases, the runtime increases linearly; but there is no change in the accuracy of the simulator.

VIII. Conclusion

In this paper, a lithography simulator is presented which provides an innovative solution to calculating the amplitude of tap point in a mask. Such simulator has immense usage in guiding the OPC algorithm and will make the OPC algorithm much faster.

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