Inverse Synthesis of Phase-Shifting Mask for Optical Lithography

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Abstract: We applied an inverse synthesis method to design phase-shifting mask (PSM) via gradient descent optimization under the coherent illumination assumption. The synthesized PSMs have high fidelity and sharp image slope.

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1. Introduction

Optical lithography is the process in which we transfer the circuit patterns from the mask to the silicon wafer by means of physical optics. However, due to diffraction and other nonlinear phenomena, patterns on the mask cannot be transferred to the wafer perfectly. Rule-based optical proximity correction (OPC) and model-based OPC techniques are the two predominant techniques to improve the resolution by prewarping the mask pattern. The former is used for 100nm (and more) technology generation, whereas the latter is used for most advanced technologies. Recently, there are researches on inverse synthesis of mask patterns, where the design problem is considered as an inverse problem. In this paper, we applied an inverse synthesis method to design PSM by means of gradient descent optimization under coherent illumination assumption. We consider the mask pattern as an image so each pixel represents a variable with limited choice of values. We would like to find optimal mask patterns such that the output image on the wafer has minimum error from the desired pattern.

2. Problem Formulation

There are two main elements in optical lithography process, namely the exposure and resist development. The former is the process where pattern on the mask is transferred to the wafer through optics and the latter is the process where the photoresist profile is thresholded according to the intensity level of the aerial image. Let $O(x,y)$ be the object (mask) and $I(x,y)$ be the image (pattern on the wafer). For simplicity we assume that the source is coherent. If the optical transfer function describing the projection optics is given by $h(x,y)$, then the aerial image $A(x,y)$ will be the magnitude square of the convolution between $h(x,y)$ and $O(x,y)$, i.e. $A(x,y) = |h * O(x,y)|^2$ [5]. If we further approximate the resist action as a sigmoid function (i.e. as a continuous thresholding function), then the output binary pattern on the wafer will be $I(x,y)=\text{sig}(A(x,y))$, where $\text{sig}(x) = 1/\{1+\exp[-a(x-t_r)]\}$, a is a large constant and t_r determines the transition position. Our goal is to minimize the error between the output binary pattern $I(x,y)$ and the desired pattern $\hat{I}(x,y)$, i.e. we want to minimize the sum square error $\varepsilon = \sum_{x,y}\left(I(x,y)-\hat{I}(x,y)\right)^2$. However, a point on a chrome-on-glass mask can either be transparent or opaque, the minimization problem is subjected to the constraint that $O(x,y)\in\{0, 1\}$ (similarly, $\{+1, 0, -1\}$ for alternating phase-shifting masks and $\{-1, +1\}$ for 100% transmission phase-shifting mask [6]). Therefore, we can formulate the optimization problem as [5]

$$\text{Minimize} \quad \varepsilon = \sum_{x,y}\left(\frac{1}{1+exp\left\{-a\left[\left|h*O(x,y)\right|^2-t_r\right]\right\}}-\hat{I}(x,y)\right)^2 \qquad (1)$$

$$\text{such that} \quad O(x,y)\in\{0,1\},$$

The problem described in (1) can be solved by relaxing the constraint to $0 \le O(x,y) \le 1$ and adding the penalty term $P(x,y) = O(x,y)[1-O(x,y)]$. So the minimization problem becomes "minimize $F = \varepsilon + \gamma P$, such that $0 \le O(x,y) \le 1$", where $P = \sum_{x,y} P(x,y)$, and γ is the weighting constant. With this formulation, we can solve it by using gradient descent algorithm and a schematic diagram showing this optimization framework is given in Fig.1.

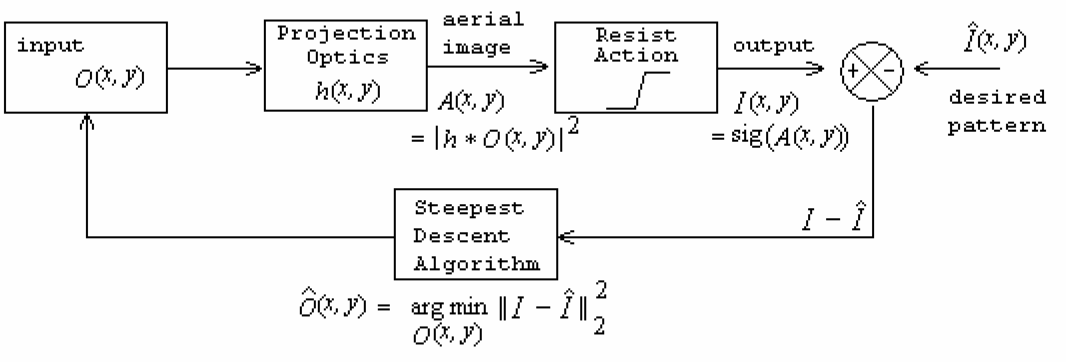

Fig. 1 Optimization framework

3. Experimental Results and Discussion

We use the methodology described above to generate several 100% transmission phase-shifting masks (PSM). These PSMs can take values either -1 or 1. Accordingly, we relax the constraint to $-1 \le O(x,y) \le 1$, and let $P(x,y) = 1 - O(x,y)^2$. Here, we demonstrate two common circuit patterns, namely SRAM and XOR gate. For coherent source, the optical transfer function $h(x,y)$ can be found as $h(x,y) = J_1(2\pi r\, NA/\lambda)/\,(2\pi r\, NA/\lambda)$, where $J_1(.)$ is Bessel function of first kind, $r = (x^2 + y^2)^{1/2}$. We use $NA = 0.85$ and $\lambda = 193$nm, which are typical values for an optical lithography system. The size of $h(x,y)$ is 151×151pixels, where the resolution is 10nm/pixel. For the sigmoid function, we set $a = 25$ and $t_r = 1$.

The results are shown in Fig.2. The figures on the left column are the target patterns. If we do not perform any OPC and use the target pattern as the mask, the aerial image are shown in the middle column and we can see that lines are shortened and narrowed, corners are rounded, and some parts even disappear. Figures on the right column are the output aerial image using optimal PSM. We can see that the lines are thicker, contrast is higher, and shapes are closer to the target. In general, the image fidelity of using optimal PSM is significantly better than using the original mask.

Target Pattern | Aerial Image Using target pattern as mask | Aerial Image Using optimal masks

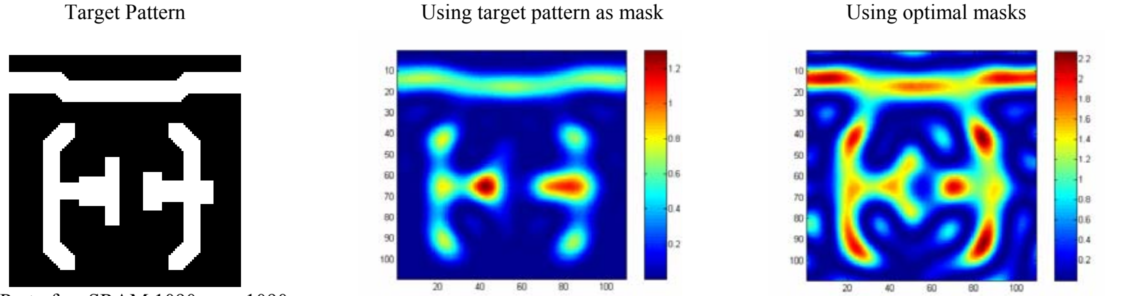

Fig.2a. Part of an SRAM 1090nm × 1090nm

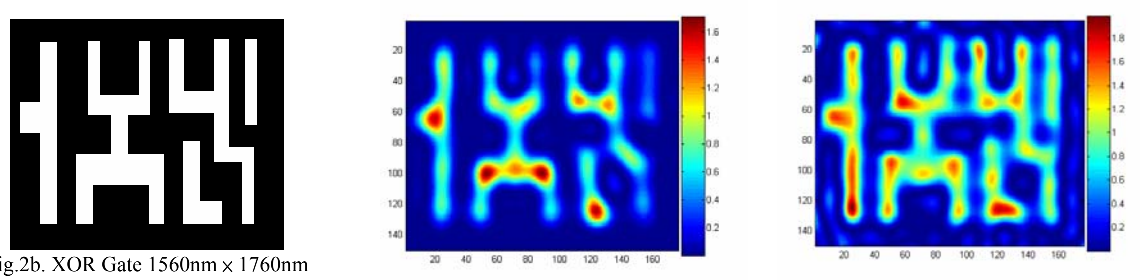

Fig.2b. XOR Gate 1560nm × 1760nm

Fig. 2. Left: Target patterns of several circuits. Middle: The aerial image we have using the target pattern as the mask. Right: The aerial image we have using the optimal designed 100% transmission phase-shifting mask. The resolution is 10nm/pixel.

Apart from having high fidelity, the aerial images can achieve high contrast, low dose sensitivity, and low focus sensitivity. We use the pattern shown in Fig.3a as a demonstration. Using our methodology, we generate the optimal PSM and obtain the aerial image using this PSM (Fig.3b). We make a cross section along in the middle row and plot the intensity curve (Fig.3c). We also plot the target pattern and the aerial image intensity without OPC. Note that we will only focus on the intensity level of Fig.3c from pixel 37 to pixel 64, because it is the separation between the two rectangles and we consider it the most critical feature for the image.

To compare contrast, we can calculate the visibility of the aerial image using PSM and without using any OPC. Visibility is defined as $V = (I_{max}\text{-}I_{min})/(I_{max}\text{-}I_{min}) \times 100\%$, where I_{max} and I_{min} are the max and min image intensity level respectively. For the one using PSM, we find that V = 45.5% whereas for the one that does not use any OPC, the visibility is V = 0%. Therefore, our PSM can generate aerial images with sharp image slope. Dose sensitivity can be compared using normalized image log slope (NILS) [7]. The higher the value NILS is, the larger the tolerable dose variation we have. For the one using PSM, NILS is 1.135 whereas for the one that does not use any OPC, NILS is only 0.655. Hence, our PSM is able to generate aerial images that tolerate large range of dose variation. Focus sensitivity can be measured by observing the pattern error as the focal length changes and such change in focal length can be modeled by a phase-shifting element [8]. In our case, we would like to see to what extent will the rectangles be merged together as we adjust the focal length. We observe that when the nominal focal length is 500nm, the tolerable focal length ranges from 317nm to 1196nm. This shows that our PSM can tolerate a large range of focus deviation.

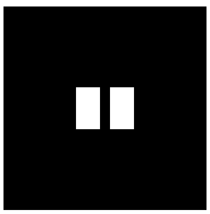

Fig.3a. Target image. 1000nm × 1000nm. White = 1, black = 0

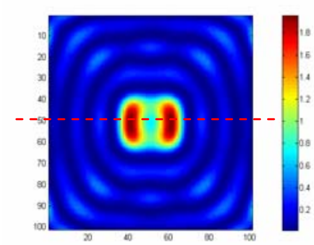

Fig.3b. Intensity of output aerial image using optimal mask.

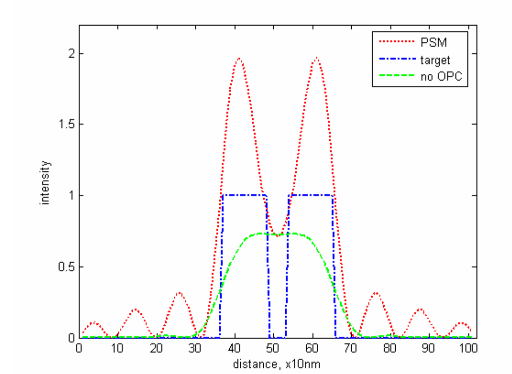

Fig.3c. Intensity curves of target image, aerial image got using original mask without any OPC, and aerial image got using optimal PSM. Cross section cut at Row 50 of Fig.3b.

Here, we would like to point out that the "optimal" PSM obtained is never the unique global optimum [9]. This is because the search space of the problem (1) is governed by the sigmoid function. The sigmoid function is nonlinear and the problem becomes ill-posed. Besides, the method we use to solve the problem is iterative and is a local search algorithm. Therefore, it is not surprising that we can obtain many "good" local minima but not a unique global minimum. Although local minimal masks may cause pattern errors to the output image, obtaining a unique global minimum is not necessary. We can always set criteria to find the most acceptable local minimum.

4. Conclusion

We have demonstrated the principle of applying inverse lithography in designing phase-shifting masks. The design problem can be solved by an optimization framework. The objective function is set to be the error between the desired pattern and the binarized output image. We solved the problem by relaxing the constraint and adding penalty terms. The algorithm is tested for SRAM and XOR gate patterns. In general the mask generated by the algorithm can produce image patterns with high fidelity, high contrast, low dose sensitivity and low focus sensitivity.

5. Reference

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