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Regularization in Inverse Lithography: Enhancing Manufacturability and Robustness to Process Variations

Edmund Y. Lam

Imaging Systems Laboratory, Department of Electrical and Electronic Engineering,
The University of Hong Kong, Pokfulam Road, Hong Kong

Abstract

Inverse lithography, as a mask design tool, has the capability of producing unintuitive patterns with topologies much different from those obtained from either rule-based or model-based optical proximity correction (OPC). These mask patterns may have the advantage of producing circuit patterns that are otherwise very difficult to achieve; on the other hand, the mask may be too complicated that renders it impossible to manufacture, or that the cost of producing it would be astronomical. There is also good likelihood that the resulting circuit patterns may be severely affected when there are process variations, such as in focus or dose. In this work, we discuss how various regularization techniques may be employed to tackle these two problems: simplifying the mask pattern in an inverse lithography process, and incorporating robustness explicitly in the design algorithm.

1 Introduction

Optical lithography is a critical step in the fabrication of integrated circuits, involving the use of a photomask as a template to print identical circuit patterns repeatedly on a wafer. Unfortunately, the reduction of feature size in the circuit elements reaches the limits in the imaging system, causing severe distortion in the printed images. Optical Proximity Correction (OPC) is a technique for predistorting the mask patterns so that the resultant circuits are close to the desired shapes. However, variations in imaging parameters, process fluctuations, and the increasing use of phase-shifting masks (PSMs) make it difficult to determine the appropriate level of predistortion, particularly as circuit elements continue to shrink.

There are primarily two approaches in predistorting the circuit patterns: rule-based and model-based. For the former, a number of rules are devised to regulate the correction [1]. For the latter, one models the imaging system and employs image processing techniques to make adjustments to the mask patterns that counteract the inevitable distortion [2]. Hybrid approaches combining the two methodologies are also used.

For complicated circuits, the number of parameters under consideration for rule-based methods is huge, making model-based approaches more preferable. The last decade saw some of the earlier works that treated the problem of OPC mask design. In [3], Hopkins equations are used in modeling the imaging mechanism and a single cost functional is defined to facilitate the use of optimization techniques. However, because of its complexity, a simulated annealing algorithm is needed, which is computationally intensive and difficult to track. Subsequent work has sped up the process through formulating it as a feedback control problem with an iterative solution [4]. In [5], attention is given to provide a computationally efficient algorithm especially for phase-shifting masks. With several approximations the mask design problem is converted to the classical phase-retrieval problem in optics, for which the Gerchberg-Saxton method is a fast iterative scheme [6]. However, the resulting mask design is only suboptimal, and several issues such as depth of focus had not been addressed. Meanwhile, [7] treats only the problem of binary mask design under incoherent imaging, and approaches it as an instance of image synthesis. A mixed linear integer programming formulation is given, which is then solved with the branch-and-bound method. Yet, the resultant images are seen to contain many isolated pixels, making the mask difficult to manufacture.

In recent years, advances in image processing have provided new tools that can be applied to the OPC design problem. In particular, the use of total variation in image restoration produces images with sharp edges and fewer transitions [8]. This can be used to maintain good manufacturability for the photomask pattern, and in fact has been applied for a simple case of binary mask design [9]. Developments in optimization methods have also made solving large-scale problems more feasible [10]. Meanwhile, current OPC methods need significant improvement as circuit critical dimensions (CD) drop to sub-90nm level [11, 12]. Better models of the imaging system are needed [13], and more stringent requirements emerge, such as the need for a more robust process window to withstand variations during production.

In what follows, we treat the OPC design problem as an inverse imaging problem, which is commonly known as inverse lithography technology (ILT) [14, 15]. We focus in particular on how regularization in solving the inverse problem can be used to simplify the mask pattern, and how we can incorporate robustness explicitly in the design algorithm. More elaborate discussions and results can be obtained from [16, 17], as well as from [18, 19, 20].

2 Inverse lithography technology and regularization

2.1 Imaging system modeling

For simplicity, consider binary masks in a coherent imaging system. We use $M(x, y)$, $I(x, y)$, and $\hat{I}(x, y)$ to represent the mask, the on-wafer pattern (aerial image), and the target pattern, respectively. For binary masks, the pixel values can only be either 0 or 1. The ideal optical transfer function (OTF), denoted by $\tilde{H}(f, g)$, is given by [21, 6]

$$\tilde{H}(f,g) = \begin{cases} 1 & \text{when } \sqrt{f^2+g^2} \leq \mathrm{NA}/\lambda \\ 0 & \text{otherwise} \end{cases}, \tag{1}$$

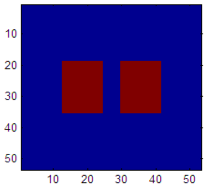
where NA is the numerical aperture, and λ the wavelength. The actual OTF, which may incorporate defocus parameterized by β [16], is

$$H(f, g; \beta) = \tilde{H}(f, g)\mathrm{e}^{-j\pi(f^2+g^2)\beta}. \tag{2}$$

The aerial image is then calculated by convolving the mask transmittance with the inverse Fourier transform of the OTF defined in Equation 2, denoted as $h(x, y; \beta)$. The resist effect is modeled by a sigmoid function, with a the contrast adjustment parameter and t the threshold. The on-wafer pattern I is then given by

$$I(x, y) = \left[1 + \mathrm{e}^{-a(|M(x,y)*h(x,y;\beta)|^2-t)}\right]^{-1}. \tag{3}$$

In ILT, we calculate the optimal mask by minimizing the error between what would be imaged with $M(x, y)$ (that is, $I(x, y)$) and the ideal output pattern $\hat{I}(x, y)$. This is



(a) Target pattern

(b) Mask designed with nominal focus

(c) Mask designed with focus variations

(d) Output pattern of (b) at nominal focus

(e) Output pattern of (c) at nominal focus

(f) Output pattern of (b) at 160nm defocus

(g) Output pattern of (c) at 160nm defocus

Figure 1: Experimental results of a two-rectangle pattern [16].

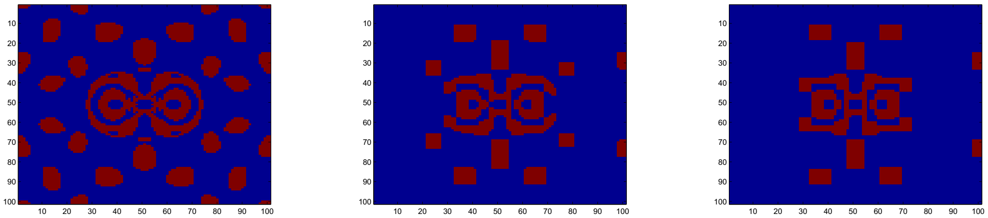
an inverse problem because we are trying to derive $M(x, y)$ from its output $I(x, y)$. It is common to use mean square error (MSE) as the metric, in which case the optimization problem can be written as

$$M_{\text{opt}} = \underset{M(x,y)\in\{0,1\}}{\arg\ \min}\ \mathcal{E}_{\beta}\left\{\sum_{x,y}\left[I(x, y) - \hat{I}(x, y)\right]^2\right\}, \tag{4}$$

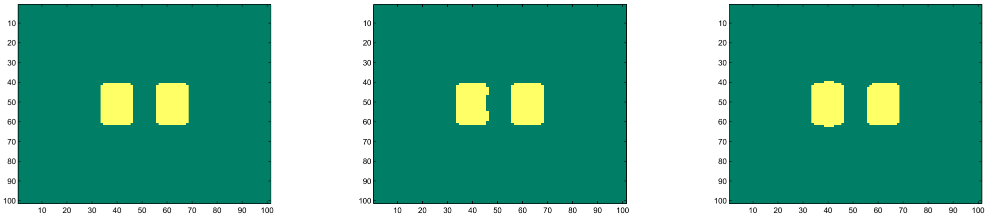
where $\mathcal{E}_\beta$ denotes expectation over random variable β.

2.2 Robustness

Many ILT optimization routines target a nominal focus point, i.e., with $\beta = 0$. We have shown in [16] that it is in fact possible to compute the optimization with the expectation in place at a moderate computational cost. There we assume a Gaussian distribution of this defocus parameter, although other distributions can also be used in practice. A representative set of images are shown in Figure 1 [16]. This example involves a target pattern with two rectangles. Two masks are designed with ILT, one aiming at the nominal focus point only using the algorithm in [22] and one using the robust design in [16]. We can



(a) Unregularized mask (b) TV regularization (c) Edge regularization



(d) Output of (a) (e) Output of (b) (f) Output of (c)

Figure 2: Experimental results of another two-rectangle pattern [17].

observe that both give good circuit patterns at the nominal focus, but at 160nm defocus, the latter remains good but the former is not.

2.3 Regularization

Equation 3 represents an ILT optimization without manufacturability constraints. It is quite possible that the resulting mask pattern has many small features, making it very costly to manufacture. It is possible to add regularization to the optimization framework, resulting in

$$\tilde{M}_{\text{opt}} = \underset{M(x,y)\in\{0,1\}}{\arg\min}\ \mathcal{E}_\beta \left\{ \sum_{x,y} \left[I(x,y) - \hat{I}(x,y) \right]^2 \right\} + \mu \mathcal{R}\{M(x,y)\}, \tag{5}$$

where μ is the Lagrange multiplier controlling the level of regularization, and $\mathcal{R}\{M(x,y)\}$ represents the fact that the regularization is performed on the mask under design. The form of $\mathcal{R}\{\cdot\}$ is under much study; possibilities include using a total variation (TV) norm, and a regularization on the image edges [17]. Figure 2 shows a representative result on another two-rectangle pattern. We can compare the three masks generated by three different schemes, which vary in complexity, but produce equally good circuit patterns.

3 Conclusion

In this paper we have given an overview of two techniques in ILT to cope with process variations and mask pattern simplification. They show that the generic ILT framework is general enough that we can incorporate additional constraints to shape the solutions. Further research will look further into the computational issues and explore ways to speed up the calculations, while also using more realistic imaging models.

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