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A Kernel-Based Convolution Method to Calculate Sparse Aerial Image Intensity for Lithography Simulation*

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Abstract: Optical proximity correction (OPC) systems require an accurate and fast way to predict how patterns will be transferred to the wafer. Based on Gabor's "reduction to principal waves", a partially coherent imaging system can be represented as a superposition of coherent imaging systems, so an accurate and fast sparse aerial image intensity calculation algorithm for lithography simulation is presented based on convolution kernels, which also include simulating the lateral diffusion and some mask processing effects via Gaussian filter. The simplicity of this model leads to substantial computational and analytical benefits. Efficiency of this method is also shown through simulation results.

Key words: lithography simulation; optical proximity correction; convolution kernels
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1 Introduction

Recently along with the advance in semiconductor manufacturing technology, the critical dimensions (CD) have become shorter than the wavelength used for optical lithography. Thus, when layout patterns on a mask are transferred to a wafer, more noticeable deformations are introduced through optical proximity effects (OPE). OPE, as a technical terminology, usually refers to all of the undesired pattern versus layout distortions caused by mask making, optical lithography, and etching. To compensate OPE for better manufacturability, various resolution enhancement technology (RET) methods based on layout correction and mask phase assigning have emerged. Optical proximity correction (OPC), phase-shifting masks (PSM), and scattering bars insertion (SBI) are three basic categories of them. In state of the art IC designs, these RETs are used in concert to maximally improve the quality of pattern transferring under environment with OPE. The ever increasing complexity of RET design methodology brings about a dramatic increase in final layout complexity and mask making expense. This reality demands an accurate and fast way to ensure the correctness of post-RET layouts[1~4].

In fact, methods of dense aerial imaging were studied intensively before the emergence of spare

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points imaging methods. The implementations in space domain or frequency domain can be found in simulators such as SPLAT[2]. Based on Gabor's "reduction to principal waves"[1], a partially coherent imaging system could be represented as a superposition of coherent imaging system. This method is directly applicable to optical modeling with the convolution form. The sum of the products of these kernels is an approximation to the 4-D transferring function of the bi-linear system. The intensity of one spatial point is calculated by square sum the convolutions of mask and these kernels. The kernel-based convolution method can compute aerial image fairly fast compared with the rigorous solution of the Hopkins equation. Especially it is effective for large area calculation.

2 Simulation algorithm

2.1 Kernel-based convolution method

The imaging mechanism of a stepper can be modeled by Hopkins formulas (1) and (2)[2].

$$I(f,g) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} T(f'+f, g'+g, f', g') \times F(f'+f, g'+g) F^*(f', g') \mathrm{d}f'\mathrm{d}g' \quad (1)$$

$$I(x,y) = F^{-1}\{I(f,g)\} \quad (2)$$

where $I(f,g)$ is the Fourier transform of the output image intensity $I(x,y)$, $F(f,g)$ is the Fourier transform of mask transmission function $F(x,y)$, and $T(f',g';f'',g'')$ is transmission cross-coefficient (TCC) of the optical system, which summarizes all the information about the imaging system and illumination. The TCC function is given by the formula (3).

$$T(f',g';f'',g'') = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} J(f,g) K(f+f', g+g') \times K^*(f+f'', g+g'') \mathrm{d}f\mathrm{d}g \quad (3)$$

where $J(f,g)$ is mutual intensity function, which describes coherence properties of the illumination, and $K(f,g)$ is coherent point spread function, which describes properties of the imaging system.

So, in order to model intensity of an input pattern projected through an optical system, we first used the formula (3) to calculate TCC, then use the formula (1) to calculate intensity at any point in frequency domain, finally attain intensity at any point in spatial domain through the inverse Fourier transform. This computation process apparently costs too much time. Since most of the time is spent in aerial image simulation, so if we use an accurate and fast calculation algorithm to calculate the aerial image intensity for lithography simulation, the calculating time of lithography simulation will be greatly decreased.

Recently, all kinds of mathematical ways are formulated precisely to approximate the Hopkins formulas[1,3], so that some fast and effective intensity calculation algorithms for lithography simulation are hopefully developed. The approximations that we consider here are based on representations of partially coherent imaging systems as weighted superposition of coherent imaging systems. There are a number of possibilities for such representations. Pati *et al.*[3] presented optimal coherent approximations. If the imaging model is represented as follows:

$$\mathrm{TCC}(f_1, g_1; f_2, g_2) = \sum_i c_i \Phi_i(f_1, g_1) \Phi_i^*(f_2, g_2) \quad (4)$$

So,

$$\begin{aligned} I\{x,y\} = F^{-1}\{I(f,g)\} &= \sum_i c_i \iiiint \Phi_i(f_1+f, g_1+g) \Phi_i^*(f_1,g_1) F(f_1+f, g_1+g) F^*(f_1,g_1) \mathrm{e}^{\mathrm{j}2\pi(fx+gy)} \mathrm{d}f_1\mathrm{d}g_1\mathrm{d}f\mathrm{d}g \\ &= \sum_i c_i \iiiint \Phi_i(f_2,g_2) \Phi_i^*(f_1,g_1) F(f_2,g_2) F^*(f_1,g_1) \mathrm{e}^{\mathrm{j}2\pi((f_2-f_1)x+(g_2-g_1)y)} \mathrm{d}f_1\mathrm{d}g_1\mathrm{d}f_2\mathrm{d}g_2 \\ &= \sum_i c_i \iint \Phi_i(f_2,g_2) F(f_2,g_2) \mathrm{e}^{\mathrm{j}2\pi(f_2x+g_2y)} \mathrm{d}f_2\mathrm{d}g_2 \iint \Phi_i^*(f_1,g_1) F^*(f_1,g_1) \mathrm{e}^{-\mathrm{j}2\pi(f_1x+g_1y)} \mathrm{d}f_1\mathrm{d}g_1 \\ &= \sum_i c_i \left| (F \otimes \Phi_i)(x,y) \right|^2 \end{aligned} \quad (5)$$

That is to say, a symmetric separable representation of TCC is a series representation of the convolution kernels (also called the principal waves according to Gabor's theory). Usually, only the first few convolution kernels are required to meet the accuracy requirements. Granik *et al.*[4] discussed the number of kernels to be used and the range of ambit. This point is closely relative to the accuracy of model.

2.2 Modified optical model

In fact, the modification to the aerial image simulation can include convolving the aerial image with a Gaussian filter to smear the image in a manner analogous to photo acid generator diffusion. Studies[5~8] show how to extend convolution kernels to model the chemically amplified resist processing. The computation process is derived as follows:

$$I_{eff}(f,g) = I(f,g)G(f,g) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} T(f'+f, g'+g; f', g') \times F(f'+f, g'+g)F^*(f', g')\,df'dg' \quad (6)$$

$$T(f',g';f'',g'') = T(f',g';f'',g'') \times G(f'-f'', g'-g'') \quad (7)$$

The profile function is described by the convolution formula of image intensity $I(f,g)$ and the Gaussian filter $G(f,g)$, the diffusion length is adjusted to experimental data for the diffusion reaction of a chemically amplified resist. The diffusion reaction in a chemically amplified resist is incorporated with the kernel function in advance as follows:

$$I(x,y) = \sum_i c_i \left| (F \otimes \Psi_i)(x,y) \right|^2 \quad (8)$$

where c_i and Ψ_i are obtained as the result of decomposing $T(f',g';f'',g'')$ in the formula (7) by solving the eigenvalues problem. Ψ_i are the new convolution kernels which are incorporated with the Guassian filter.

This method is very efficient since the new TCC computed once throughout the lateral diffusion and some mask processing effects are computed in the frequency domain. The intensity cutline comparison of the different diffusion length of the Gaussian filter is shown in Fig. 1. The diffusion length of the solid line is 0, and the diffusion length of the dashed line is 0.1μm.

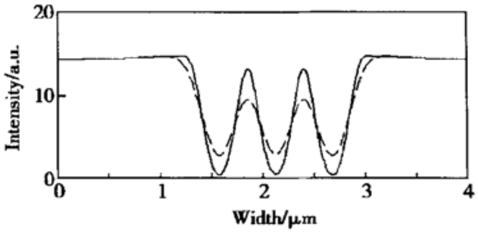

Fig. 1 Intensity cutline comparison of the different diffusion length of Gaussian filter

3 Results and analysis

The computation process of the convolution form of optical model is shown in Fig. 2. The model form consists of two filtering operations: the optical filter which results in an aerial image, the Gaussian filter which results in a diffused aerial image. We work with these two filters independently. But for the final correction model we are interested in the total system filter. The total system filter can be derived by simply switching the order of convolution. The system filter here is the convolution between the optical and Gaussian filters.

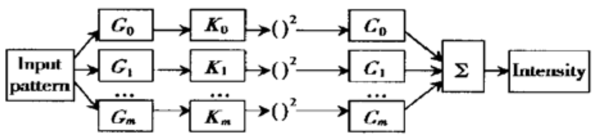

Fig. 2 Kernel-based convolution method of optical model with the Gaussian filter

In Fig. 2, the K filters denote the optical model kernels (derived from the TCC), the G filters denote Gaussian kernels that convolve with the optical kernels. Now we use an implementation issues, showing performance results of the method, and take a look at this method by comparing to SPLAT (SPLAT is a FORTRAN program, based on the

Hopkins' theory of partially coherent imaging, that simulates two-dimensional projection-printing with partial coherence).

The relative optical parameters are included as follows: $\lambda = 0.248$, $NA = 0.5$, defocus $= 0$, and $\sigma = 0.5$. For simplicity, we set the standard diffused length of the Gaussian filter as 0, i.e., we does not use the Gaussian filter. According to the computation flow listed in Fig. 2, we firstly calculate the TCC according to the formula (3), then decompose the TCC matrix, assuming that the eigenvalues and eigenfunctions have been ordered such that $\lambda_1 \geqslant \lambda_2 \geqslant \cdots$, these top three convolution kernels are truncated in Fig. 3. The input pattern is shown as Fig. 4(a). The minimum feature dimensions and spacings are all 0.18μm. The constant threshold model and a new algorithm for 2D contour extraction of shaped silicon areas based on intensity simulation of spare aerial points are used[9]. The result is shown as Fig. 4(b) using the kernel-based convolution method (only six kernels are used), it spent about 3s, and Fig. 4(c) using the SPLAT, it spent about 42s. The machine we used is SUN Ultra-Sparc 60 (2CPU, 2G memory).

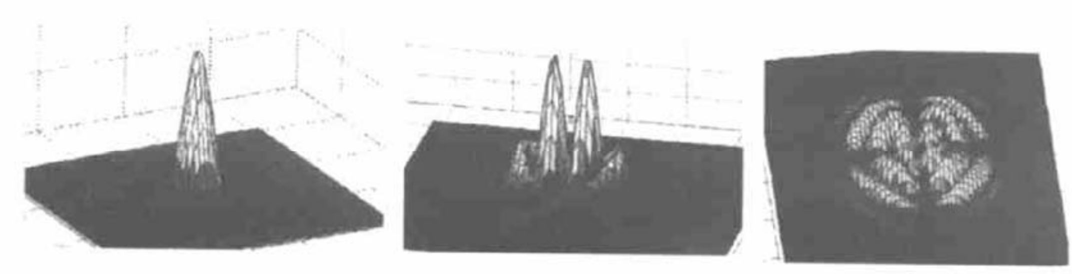

Fig. 3 Convolution kernels

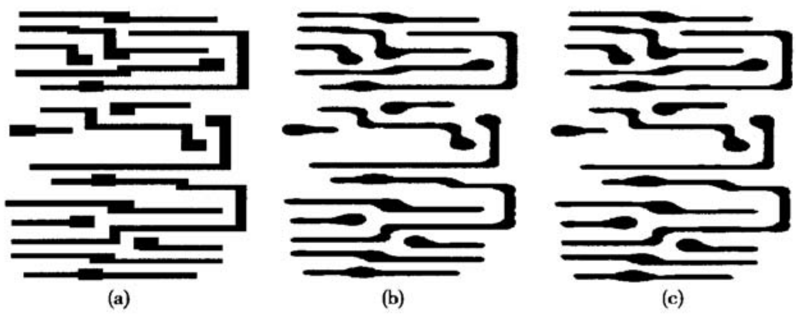

Fig. 4 Result comparison of kernel-based convolution method with SPLAT (a) Original design; (b) Simulation result by kernel-based convolution method; (c) Simulation result by SPLAT

4 Conclusion

An accurate and fast sparse aerial image intensity calculation algorithm based on convolution kernels has been derived. The modification to the aerial image simulation can include convolving the aerial image with a Gaussian filter to smear the image in a manner analogous to photo acid generator diffusion. The new TCC computed once throughout the lateral diffusion and some mask processing effects are computed in the frequency domain. As we will see, the simplicity of the coherent imaging model leads to substantial computational and analytical benefits. This method is often used to practical OPC tools for edge-based simulation and manipulation.

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一种基于卷积核用于光刻模拟的计算稀疏空间点光强的方法*

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摘要: 光学邻近校正(OPC)系统要求一种精确、快速的方法来预测掩模图形转移到硅圆片的成像结果. 基于 Gabor 的"降解为主波"方法, 一个部分相干成像系统可以用相干成像系统的叠加来近似, 并用高斯过滤器来模拟光刻胶横向扩散和一些掩模工艺效应, 由此提出了一种基于卷积核的精确、快速地用于光刻模拟的稀疏空间点光强计算方法. 这种模型的简单性从本质上给计算和分析带来了好处. 仿真结果说明这种方法是有效的.

关键词: 光刻仿真; 光学邻近校正; 卷积核

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