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Various Effective Resist Diffusion Lengths Methodology for OPC Model Calibration

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Abstract: A various effective resist diffusion lengths methodology for OPC model calibration is proposed, which considers the discrepancy of effective resist diffusion lengths between 1D and 2D patterns. An important step of this methodology is to set up a new calibration flow that lets 1D and 2D patterns have the same optical parameters but different effective diffusion lengths. Furthermore, a design for manufacturing (DFM) interaction is suggested in the calibration flow of the proposed model. From the CD errors of fitting results and the comparison between simulated contours and SEM images, it is found that the various effective resist diffusion lengths model calibration methodology results in a more accurate and stable model.

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1 Introduction

As feature sizes continue to shrink, to accurately predict critical dimensions (CD) during the patterning process becomes more important, and the errors that were once perceived insignificant can easily consume the majority of the CD budget of the lithography process. Typically, lithography models attempt to describe the physical phenomena as accurately as possible. However, more accurate simulations of the complicated lithography process often require greatly increased computational resources. For a chemically amplified resist (CAR), simulations of the resist process consist of three steps: resist exposure, post exposure bake reaction and diffusion, and development. In the past few years, there are detailed researches on the first principle resist models [1], all of which suffer computational problems. On the other hand, large area simulators, as used in optical proximity correction (OPC) tools, use the empirical models to take into account the impact of process conditions on the resist performance. The simplest resist model considers the aerial image only. Cobb and Zakhor introduced the concept of variable threshold resist model, in which the threshold intensity is viewed as a function of the local image intensity parameters [2]. However, the resulting parameters have little physical meanings. Despite there are also several groups attempting to merge specific physics into aerial image resist models, the commonly used resist model by some OPC tools is the simplified diffused aerial image model (DAIM)[3,4], which considers the aerial image as a diffusible quantity. The effective diffusion length then becomes a model parameter for calibration. The resist edges are placed using the diffused aerial image and a threshold value.

On one hand, the current OPC modeling methodology treats 1D and 2D patterns equally with the same effective diffusion length. On the other hand, recently, Wu *et al*. suggested that the effective diffusion length varies for different pitches and complex line end patterns [5~7]. As a result, conflicts arise in the fitting results between 1D and 2D patterns. In this paper, we aim to present the feasibility of the various effective resist diffusion lengths methodology for OPC model calibration. A simplified DAIM model is discussed. A classical OPC model calibration flow in the industry is reported. The design for manufacturing (DFM) based OPC model calibration flow that we use to test the various effective resist diffusion lengths methodology is presented. Results of the proposed model calibration methodology are concluded. Further studies for more effective pattern recognition during the correction stage will be discussed elsewhere.

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2 Simplified diffused aerial image model

The combined reaction and diffusion of acid and base species is represented by the coupled differential equation given in Eqs.(1) and (2)：

$$\frac{\mathrm{d}U_{\mathrm{A}}(x,t)}{\mathrm{d}t} = -k_{\mathrm{Q}}U_{\mathrm{A}}(x,t)U_{\mathrm{Q}}(x,t) + D_{\mathrm{A}}\nabla^{2}U_{\mathrm{A}}(x,t) \tag{1}$$

$$\frac{\mathrm{d}U_{\mathrm{Q}}(x,t)}{\mathrm{d}t} = -k_{\mathrm{Q}}U_{\mathrm{A}}(x,t)U_{\mathrm{Q}}(x,t) + D_{\mathrm{Q}}\nabla^{2}U_{\mathrm{Q}}(x,t) \tag{2}$$

$U_{\mathrm{A}}(x,t)$ is the photo-acid density function while $U_{\mathrm{Q}}(x,t)$ is the base components density function. D_{A} and D_{Q} represent the diffusion constants for acid and base, respectively. k_{Q} is the acid-base quenching constant.

The two image-in-resist terms $U_{\mathrm{A}}(x,t)$ and $U_{\mathrm{Q}}(x,t)$ are allowed to diffuse and quench each other. The acid component of the image-in-resist is integrated through time to determine the final soluble image at each position. A simplified solution method for obtaining $U_{\mathrm{A}}(x,t)$ arises when one considers the base with zero quencher.

In the case of zero quencher, Equation (1) can be written as

$$\frac{\mathrm{d}U_{\mathrm{A}}(x,t)}{\mathrm{d}t} = D_{\mathrm{A}}\nabla^{2}U_{\mathrm{A}}(x,t) \tag{3}$$

with the boundary condition：

$$U_{\mathrm{A}}(x,t=0) = I_{0}(x) \tag{4}$$

$I_{0}(x)$ stands for the aerial image generated by the optical system.

A solution with the separable variant law and Fourier series law to the above equations can be written as

$$U_{\mathrm{A}}(x,t) = \int_{-\infty}^{+\infty} I_{0}(x')\frac{1}{2\sqrt{\pi D_{\mathrm{A}}t}}\mathrm{e}^{-\frac{(x-x')^{2}}{4D_{\mathrm{A}}t}}\mathrm{d}x' \tag{5}$$

If we let the effective diffusion length $a=\sqrt{2D_{\mathrm{A}}t}$, Equation (5) can also be written as

$$U_{\mathrm{A}}(x,t) = \int_{-\infty}^{+\infty} I_{0}(x')\frac{1}{a\sqrt{2\pi}}\mathrm{e}^{-\frac{(x-x')^{2}}{2a^{2}}}\mathrm{d}x' \tag{6}$$

Equation (6) can be regarded as a convolution of the aerial image and the Gaussian function：

$$U_{\mathrm{A}}(x) = I_{0}(x)\otimes G(x) \tag{7}$$

$$G(x) = \frac{1}{a\sqrt{2\pi}}\mathrm{e}^{-\frac{x^{2}}{2a^{2}}} \tag{8}$$

This is the simplified DAIM resist model that is commonly used in some OPC model calibration tools. The effective diffusion length is an important parameter that will be regressed.

In recent years, there are some papers discussing the pattern dependent photo-acid diffusion. The effective diffusion length can be extracted from some image contrast parameters such as the exposure latitude (EL) or mask error factor (MEF). The general equation that describes such relationship can be written as[5]

$$U(x) = f_{1}(\delta,p,\sigma) - f_{2}(\delta,p,\sigma,a)\cos\frac{2\pi x}{p} \tag{9}$$

$$\mathrm{MEF} = \frac{\dfrac{p}{\pi}\times\dfrac{1}{\sin\dfrac{\pi CD}{p}}\displaystyle\int_{\sigma_{\mathrm{in}}}^{\sigma_{\mathrm{out}}}\sigma\mathrm{d}\sigma\left[\frac{\frac{\partial f_{1}(\delta,p,\sigma)}{\partial\delta}}{f_{2}(\delta,p,\sigma,a)} \mp \frac{\frac{\partial f_{2}(\delta,p,\sigma,a)}{\partial\delta}}{f_{2}(\delta,p,\sigma,a)}\cos\frac{\pi CD}{p}\right]}{\displaystyle\int_{\sigma_{\mathrm{in}}}^{\sigma_{\mathrm{out}}}\sigma\mathrm{d}\sigma} \tag{10}$$

where $U(x)$ represents the intensity of the diffused aerial image as a function of spatial coordinate x, $f_{1}(\delta)$ and $f_{2}(\delta)$ are the coefficients that are closely related to the scattering efficiency of illumination light into the zeroth and the first orders, respectively. δ represents the mask CD and p represents the pitch. The "−" and "+" signs demonstrate results for the line and space, respectively. By setting Eq.(10) to the measured MEF value, the effective diffusion length "a" can be obtained. Consequently, the pattern dependent resist diffusion lengths can be found. Instead of being involved in the complex calculation, the simplified DAIM model provided by the first principle simulation tools can be used for the parameter regression. The detail will be presented in section 4.

3 Classical OPC model calibration methodology

Figure 1 shows the classical OPC model calibration methodology. Once the calibration data measurement has finished, the model calibration procedure looks like a black box that is totally separated from the manufacturing process. Figure 2 is the classical OPC model calibration flow.

Previously, it is the industry practice that a parametric OPC model is calibrated by the proximity and linearity curves, coupled with complex 2D structures such as dense and isolated end-to-end (ETE) features with a lower cost function. In the classical model calibration methodology, both 1D and 2D patterns share

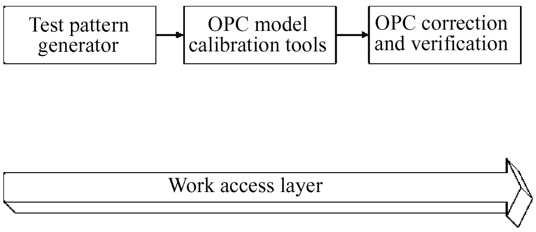

Fig.1 Classical OPC model calibration methodology

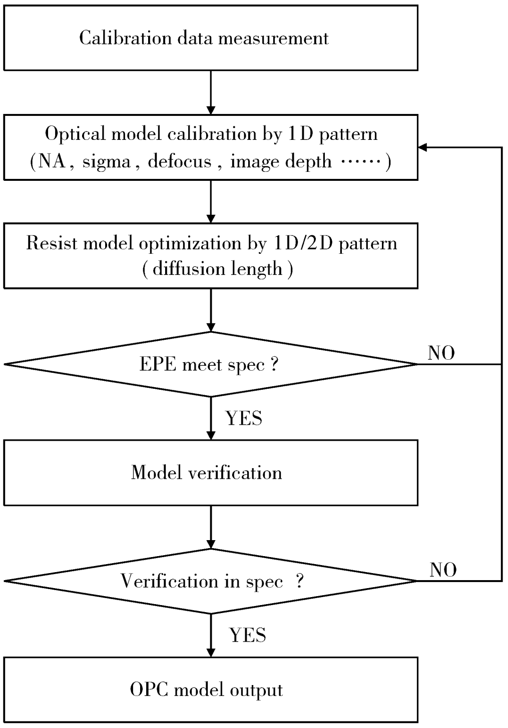

Fig.2 Classical OPC model calibration flow

the same effective diffusion length, which has been found to be structure dependent. Therefore, conflicts arise between the fitting results of 1D feature and 2D line end test patterns. Figures 3 to 5 show the fitting results for proximity, linearity and ETE test patterns, respectively. The abbreviation of “ED120” stands for dense ETE with a gap of 120nm, while “EI120” means isolated ETE with a gap of 120nm. One could hardly fit both 1D and 2D patterns well simultaneously. As shown in Figs.3 to 5, the CD errors for proximity and linearity patterns remain within ±5nm, while the fitting result for ETE test patterns is not satisfactory. One solution to this problem is applying mathematical kernels to compensate these errors, which has little physical background. Another way is ensuring the pitch and linearity curves of a low edge placement error (EPE) while giving line end patterns a rule-based bias during the correction stage, which is commonly used in our routine jobs. By this approach, there are also some problems. First, there must be a tight distribution of the line end EPE to meet the global bias. Second, it is difficult to write the rule for complex 2D patterns that cannot be defined as the line end.

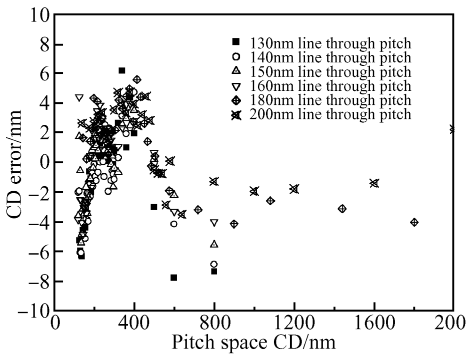

Fig.3 Proximity fitting result of the classical OPC model calibration methodology

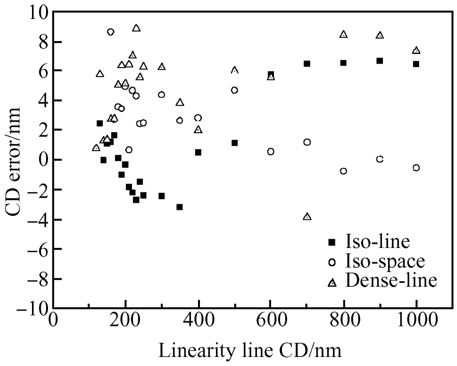

Fig.4 Linearity fitting result of the classical OPC model calibration methodology

4 Various effective resist diffusion lengths model calibration methodology

Figure 6 is the various effective resist diffusion lengths model calibration methodology and Figure 7 shows the calibration flow.

There is a DFM interaction between the calibration data measurement and the model calibration stage. As mentioned in section 2, some process parameters are evaluated in the first principle simulation

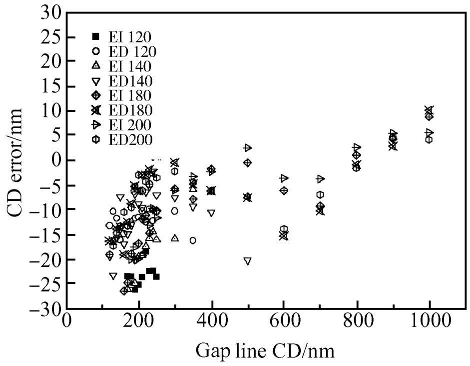

Fig.5 Gap fitting result of the classical OPC model calibration methodology ED: dense end-to-end; EI: isolated end-to-end

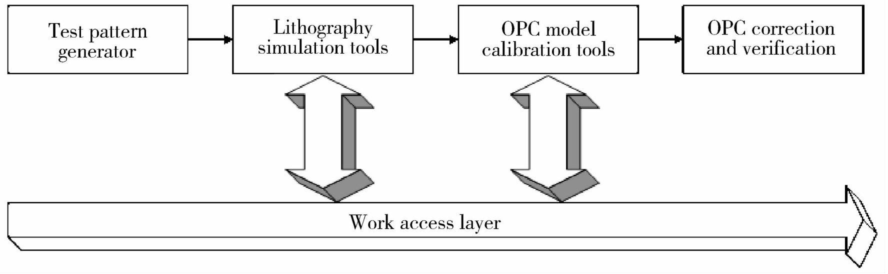

Fig. 6 Various effective resist diffusion lengths model calibration methodology

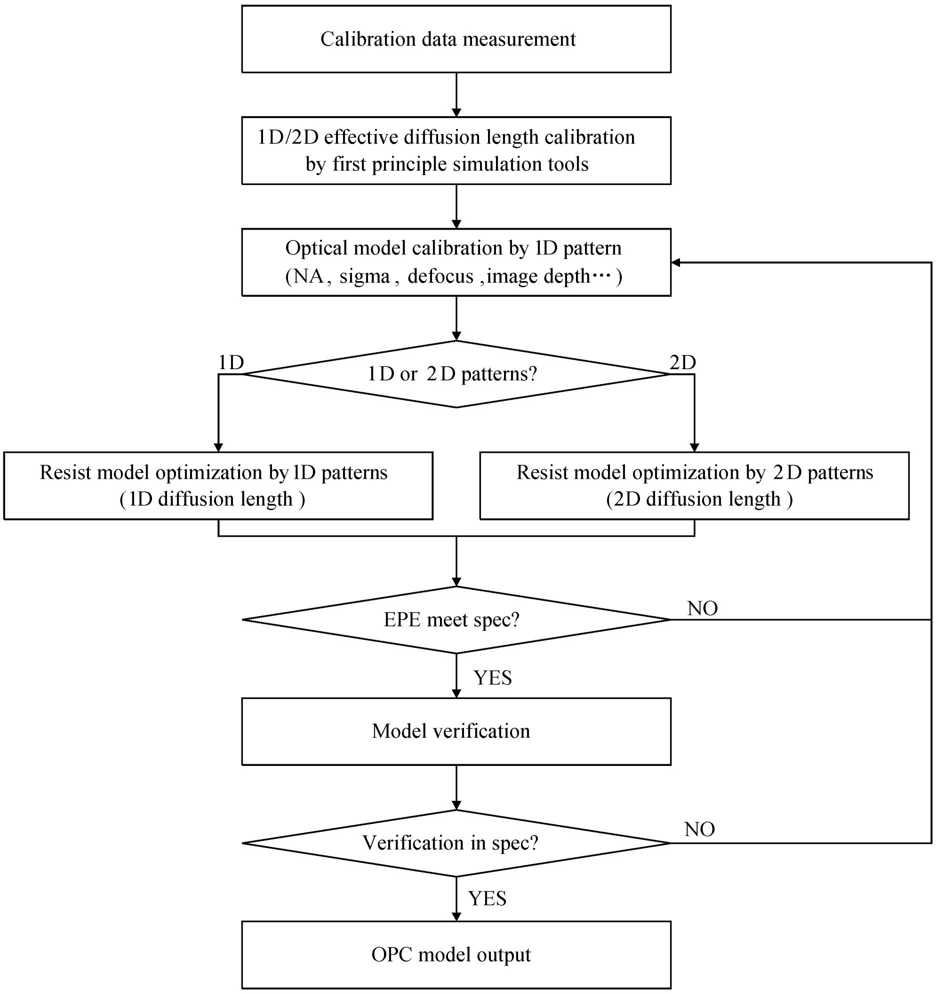

Fig. 7 Various effective resist diffusion lengths model calibration flow

tools and extracted to the OPC model calibration tools for regression reference. The complete data sheet is split into two parts: 1D patterns and 2D patterns. The effective diffusion lengths are evaluated respectively. Table 1 demonstrates the output of the first principle simulation tool. The reason for the larger effect of diffusion on the line end can be traced to the three-directional nature of the diffusion process: at the line end, chemical species from the exposed areas can diffuse from all three sides of the line end, as opposed to one direction for the line or space edge.

Table 1 Effective diffusion lengths output by the first principle simulation tool

	1D	2D
The effective diffusion length/nm	29	35

In the proposed calibration flow, there is another difference from the classical one. Instead of treating 1D and 2D patterns equally with the same effective diffusion length, a judgment is done before the resist model optimization is carried out. It is realized by setting up a new calibration script in the OPC model calibration tool. In such a way, the discrepancies of effective diffusion lengths between 1D and 2D structures no longer exist. When the model calibration is finished, there will be two models to be output: the 1D

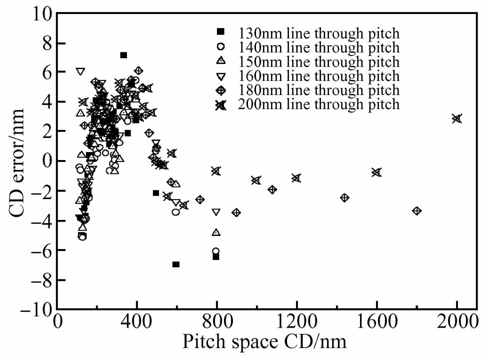

Fig. 8 Proximity fitting result of the various diffusion lengths OPC model calibration methodology

model and the 2D model. The two models share the same optical components but different effective diffusion lengths.

In a full OPC flow that consists of the model calibration, full chip correction and verification, there are two stages that require the pattern recognition. The first time is in the model calibration flow. As the gauge name is pre-defined when the test patterns are generated, this judgment does not seem to be difficult. Consequently, the second time is in the full chip correction stage. The definition of the patterns will be found in the edge based OPC correction recipe, which is beyond the discussion of this paper.

5 Results

Figures 8 to 10 illustrate the fitting results of the proposed methodology. The CD errors for proximity and linearity test patterns are kept within ± 5nm, which are comparable with the classical calibration methodology. And the CD error for ETE test patterns is distributed between ± 10nm, which has a better performance than the classical calibration methodology. It is shown that 2D fitting results are improved without sacrificing the 1D accuracy.

Furthermore, Figures 11 and 12 show the GDS file, SEM image and simulation contours of poly layer in the SRAM area. The gray contour is generated by the proposed methodology while the black one by the classical methodology. By comparing the gap CD with the wafer data, it is found that the various effective resist diffusion lengths methodology better predicts the final gap CD of 216.8nm.

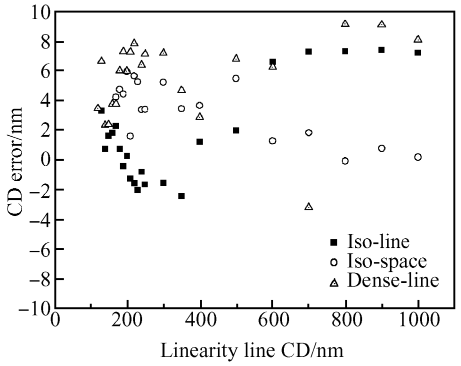

Fig. 9 Linearity fitting result of the various diffusion lengths OPC model calibration methodology

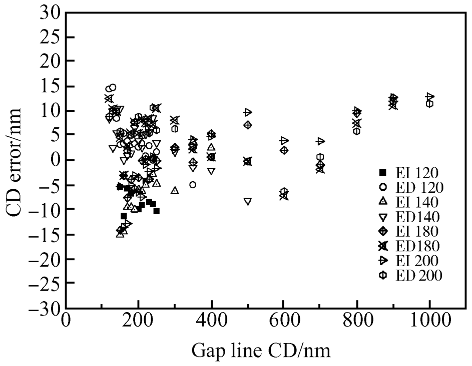

Fig. 10 Fitting result of the various diffusion lengths OPC model calibration methodology

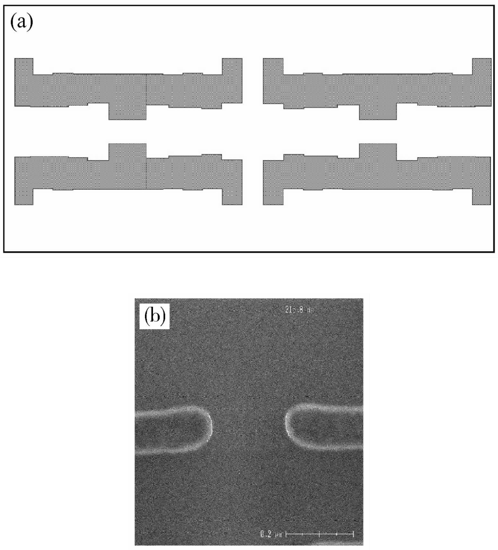

Fig. 11 GDS file and SEM image of poly layer in the SRAM area The gap CD is 216.8nm.

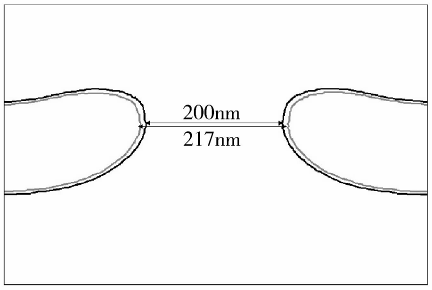

Fig. 12 Simulation contours generated by the two methodologies Black contour: the classical methodology, with the gap CD of 200nm; Gray contour: the proposed methodology, with the gap CD of 217nm.

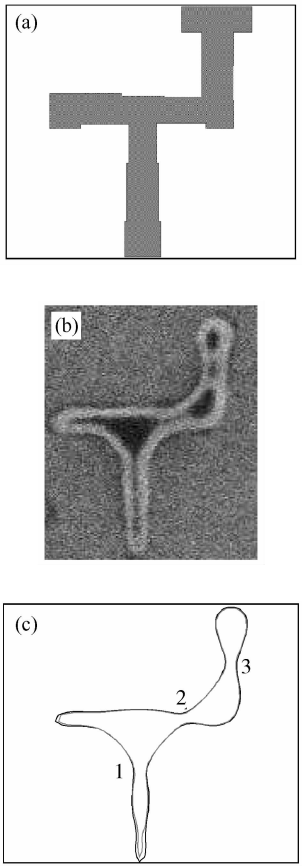

Fig. 13　GDS file, SEM image and simulation contours of a complex 2D pattern　Black contour: the classical methodology; Gray contour: the proposed methodology.

Consequently, another case of a complex 2D pattern is shown in Fig. 13. Three segments of the contours marked in Fig. 13(c) are presented in a relatively larger scale in Fig. 14 to illustrate the differences. Similar to the last case, the various effective resist diffusion lengths methodology also succeeds in predicting the potential pinching risk.

6　Summary

In this paper, the various effective resist diffusion lengths methodology for OPC model calibration is proposed from its physical background. A DFM interaction is carried out before the OPC model calibration procedure. An important step of this methodology is to set up a new calibration flow that lets 1D and 2D patterns have the same optical parameters but different effective diffusion lengths. Consequently, a judgment is done before the resist parameters' regression is carried through. Considering the physical discrepancies of effective diffusion lengths between 1D and 2D patterns, the improved EPE fitting results are achieved. From the verification step after the calibration stage, it is shown that the proposed methodology better predicts the CD and the potential pinching risk of the defined 2D patterns. Our study may just serve as a beginning for a more detailed study of the various effective resist diffusion lengths methodology for OPC model calibration, which can help with more accurate OPC modeling and better process control. Further improvements can be achieved by applying a more effective pattern recognition methodology in the full chip correction stage.

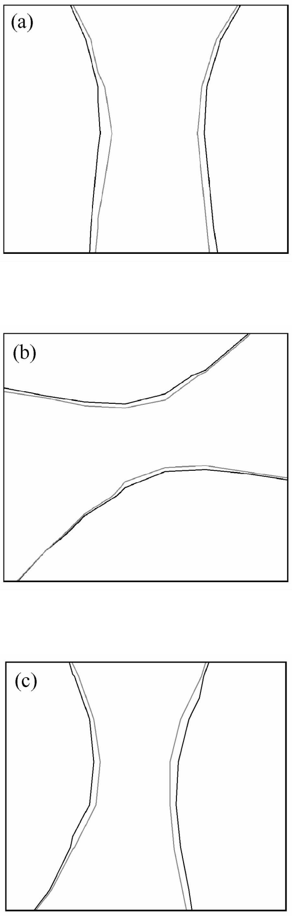

Fig. 14　Contours in a relatively larger scale for sites 1, 2, 3 in Fig. 13(c)

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基于多光刻胶有效扩散长度的光学临近效应修正模型校准方法

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摘要： 提出了基于多光刻胶有效扩散长度的光学临近效应修正模型校准方法，其考虑了一维和二维图形之间光刻胶有效扩散长度的不同.该方法的一个重要步骤在于建立起全新的校准流程，使得一维图形和二维图形具有相同的光学参数和不同的光刻胶有效扩散长度.另外，在该模型校准流程中提出了一种基于可制造性设计理念的交互.从校准结果的关键尺寸误差及仿真轮廓和扫描电子显微镜图像的对比来看，基于多光刻胶有效扩散长度的光学临近效应修正模型校准方法的输出模型更加精确和稳定.

关键词： 光学临近效应修正；可制造性设计；扩散光学影像模型；边缘位置误差；化学放大光刻胶；掩膜误差因子
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