Ultrafast and Accurate Proximity Effect Correction of Large-Scale Electron Beam Lithography based on FMM and SaaS

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***Abstract*—This paper proposes a fast proximity effect correction (PEC) methodology based on fast multipole method (FMM), to simultaneously achieve high calculation speed and accuracy. It is shown that the proposed methodology has both linear computational time complexity, *O*(*N*), where *N* is number of pixels, and linear parallelization speedup on multiple central processing unit (CPU) cores. These linear scaling scenarios are ideal traits for PEC of large-scale electron beam lithography (EBL). The proposed methodology has been implemented using C++ and OpenMP programming tools, and freely available via the Software-as-a-Service (SaaS) mode (http://hnupecsv1.qicp.vip).**

Keywords—device fabrication, proximity effect correction (PEC), electron beam lithography (EBL), fast multipole method (FMM), software as a service (SaaS)

I. INTRODUCTION

Electron beam lithography (EBL) is the most popular choice to manufacture high-resolution nanopatterns, it's widely applied to fabricate optical lithography masks and various important electronic devices [1]. The electron beam is highly focused (nm-scale spot size) to ensure high fabrication resolution through change the solubility of the resist in the incident region. The incident electrons collide with electrons and atoms in the substrate and resists, as a result, their trajectory has changed and back-scatter into the resists far away (e.g. micrometers) from the electron beam center. This effect is often described as the proximity effect, which degrades the fabrication accuracy and pattern quality. So, proximity effect correction (PEC) is necessary to enhance the EBL resolution and accuracy [2, 3].

In this paper, we propose a novel PEC algorithm using fast multipole method (FMM), which reduces the large-scale PEC calculation time complexity from the state-of-the-art $O(N^2)$ to $O(N)$. Then, we further accelerate the PEC calculation using parallelization. As a consequence, the proposed PEC methodology could be 1 to 2 orders of magnitude faster than the existing convolution-based PEC, when $N\approx10^6$. If N further increases, the comparative speed advantage will be even larger. The proposed methodology has been implemented using C++ codes, and freely available via the Software-as-a-Service (SaaS) mode.

II. METHODS

This software consists of Monte Carlo (MC) simulation to get point spread function (PSF). The PSF form commonly is double-Gaussian function (2G), triple Gaussian function (3G) and combination of triple Gaussian with exponential function (3G+E) [4, 6]. The 2G described as follows:

$$\mathrm{PSF}(r)=\frac{1}{\pi(1+\eta)}\left(\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}}+\frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}\right) \tag{1}$$

where $r=\sqrt{x^2+y^2}$, the α parameter defines the forward-scattering (FS) region, the β parameter defines the back-scattering (BS) region, the η parameter defines the radio of the BS to the FS. The 3G described as follows:

$$\mathrm{PSF}(r)=\frac{1}{\pi(1+\eta+\nu)}\left(\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}}+\frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}+\frac{\nu}{\gamma^2}e^{-\frac{r^2}{\gamma^2}}\right) \tag{2}$$

where γ the parameter defines the additional phenomena that the 2G fails to express. The 3G+E described as:

$$\mathrm{PSF}(r)=\frac{1}{\pi(1+\eta+\nu+\nu_2)}\left(\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}}+\frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}+\frac{\nu}{\gamma^2}e^{-\frac{r^2}{\gamma^2}}+\frac{\nu_2}{2\gamma_2{}^2}e^{-\frac{r^2}{\gamma_2}}\right) \tag{3}$$

Since the electron deposition energy:

$$\mathrm{E}(x,y)=\iint \mathrm{D}(x',y')\mathrm{PSF}(x-x',x-y')\mathrm{d}x'\mathrm{d}y' \tag{4}$$

is the convolution between the incident electron dose distribution $\mathrm{D}(x,y)$, and the point spread function (PSF). PEC is accomplished by adjusting D, so that $\mathrm{E}(x,y)=E_0$ matches target fabrication pattern [7]. Here, E_0 is a threshold value up to the resist sensitivity. This involves multiple calculation of convolution whose calculation time complexity is $O(N^2)$ where N is the number of pixels. As shown in Fig. 1(a), PEC of large-scale (N is large) EBL is prohibitively time-consuming.

For the two-dimensional convolution process (Eq. (4)), a new type of FMM [8] is used in the N-body problem of PEC to speed up the calculation of convolution. For an interpolation structure of the low-rank approximation, the first-kind Chebyshev polynomials have been proved to be the stability interpolation method and the uniform error distribution of Chebyshev interpolation use fewer interpolation nodes to achieve higher accuracy, which is almost optimal in most interpolation schemes [9]. As shown in Fig. 1 (a), the computational complexity of FMM is $O(N)$ compared with convolution $O(N^2)$. In additional, FMM algorithm can be further accelerated by parallelization shown in Fig. 1 (b), which is 1 to 2 orders of magnitude faster than the existing convolution-based PEC.

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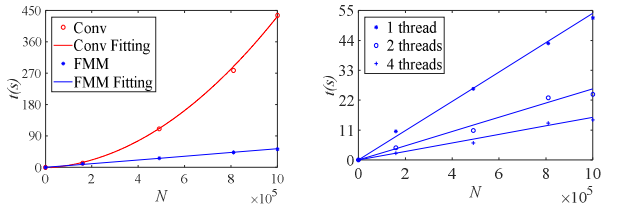


(a) (b)

Fig. 1. (a) Comparison between the calculation time, t, of the proximity effect correction (PEC) using the proposed fast multipole method (FMM), and the conventional convolution algorithm (Conv), based on 1 central processing unit (CPU) core. (b) Calculation time, t, of the proposed FMM using multiple CPU cores. Here, N is the number of pixels in the electron beam lithography.

III. Software

The proposed FMM-based PEC methodology has been implemented into freely available via Software-as-a-Service (SaaS) mode (http://hnupecsv1.qicp.vip/) [10]. In this mode, all maintenance and management about the software are the sole responsibility of software providers, which can save financial expenses and reduce unnecessary for users from the aspects of hardware, maintenance and so on.

The process of software mainly consists of 4 steps shown in Fig. 2 (a):

Step1, user registration and login. For the first time to use the software, users download protocols and guidelines to get account and password, and download the step by step instruction.

Step2, input of parameters. After a selection of the number of simulation layer, user inputs simulation parameters about materials and thickness of resist and substrate, diameter and number of electron beam, and correction parameter about the size of mesh and the file (.gds) of the layout to be corrected. Then, start Monte Carlo simulation.

Step3, select the PSF. After the calculation of PSF based on Monte Carlo, user selects PSF through the display of a variety of PSF. Then, start PEC calculation.

Step4, FMM-based PEC calculation. The process of calculation is display. Users download the corrected result after PEC calculation.

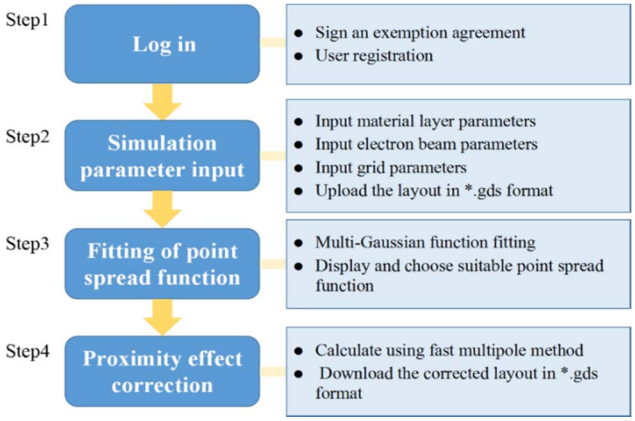
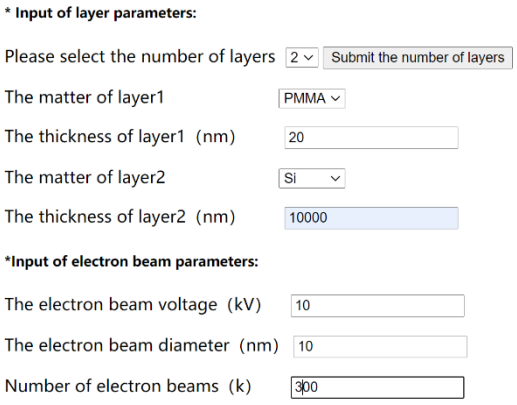


Fig. 2. The schematic flowchart of PEC software via Software-as-a-Service (SaaS) mode.

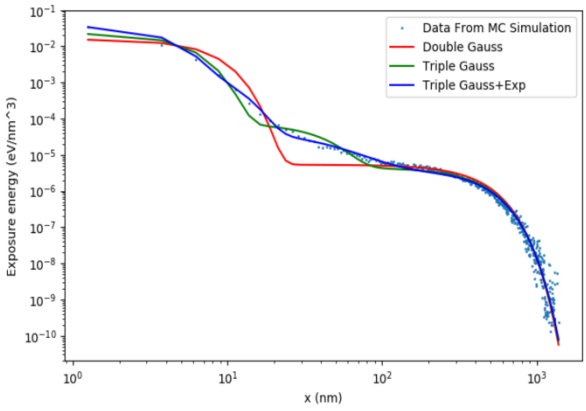
IV. Result

Using this software to perform PEC on an integrated circuit layout, the minimum critical dimension (CD) length is 5nm and the number of grid points reaches 10^6. For input parameters of MC simulation, 50nm thick PMMA on SiO_2 is set, the electron beam diameter is 10nm, the number of electron beam is 100K. After log in and register the software, the specific parameter input interface is shown in Fig.3 (a). MC simulation result and the fitting result is shown in Fig.3 (b) and the fitting coefficients of different PSF form is shown in Table.1. For 2G fitting function, PSF is divided into forward scattering range (α) and back scattering range (β). So the fitting in the mid-range part is not accurate enough. For 3G fitting function, mid-range scattering range (γ) is introduced to optimize the PSF in the mid-range range. For 3G+E fitting function, an exponential shift further optimizes the accuracy of PSF fitting.

After choosing a best optimized PSF function, this software starts the PEC calculation steps. As shown in Fig. 4 (a), uniform exposure dose may lead to proximity effect, where the edge energy deposition of the graphic is much smaller than the densely exposed area in the middle of the graphic. These non-uniform energy deposition causes pattern distortion in the final development process shown in Fig. 4 (b). By the process of MC simulation and PEC calculation based on FMM, the exposure dose is optimized to get uniform absorbed energy in resist shown in Fig. 4 (c) and developing contour is shown in Fig. 4 (d).



(a)



(b)

Fig. 3. (a) The software interface of parameters input. (b) The display of the result of MC simulation and fitting by 2G, 3G and 3G+E function.

TABLE I. FITTING COEFFICIENTS OF DIFFERENT PSF FORM

PSF form	Fitting coefficients						
	α	β	η	γ	v	γ_2	v_2
2G	7.85	408.81	0.93	—	—	—	—
3G	5.60	416.61	1.06	39.88	0.15	—	—
3G+E	4.16	420.54	1.18	9.70	0.37	32.31	0.20

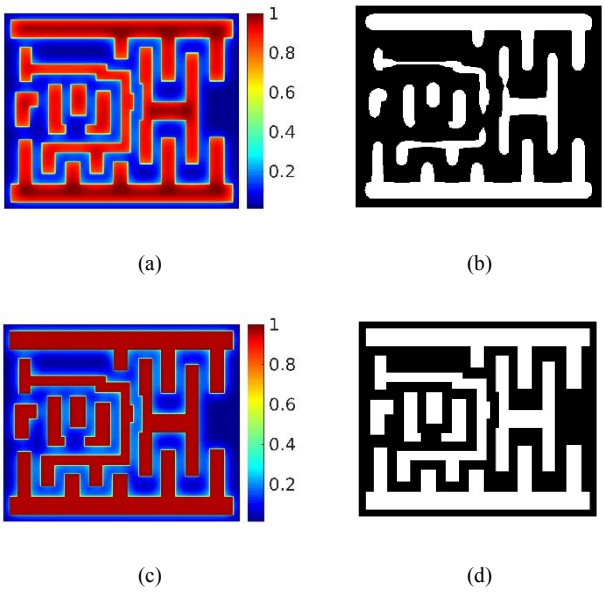


Fig. 4. (a) The Absorbed Energy without PEC. (b) Developing contour without PEC by the threshold model. (c) The Absorbed Energy with FMM PEC. (d) Developing contour with FMM PEC by the threshold model.

V. CONCLUSION

This article proposes a fast and efficient proximity effect correction method based on fast multipole method (FMM) and publish a free PEC parallelized calculation software for researcher use. The proposed methodology has both linear computational time complexity, and effectively reduce the computational complexity of convolution when simulating energy exposure.

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