



Haojie Zhao

Hunan University October 21, 2022





Contents

Background

- > Theory
- Distributed Parallel Computing Algorithm
- ➤ Simulation
- Software Toolkit HNU-EBL v2.0
- ≻ IP & License
- Conclusion



MA市大学 HUNAN UNIVERSITY

Background



https://doi.org/10.1063/1.3437589

Electron Beam Lithography

https://doi.org/10.1016/j.mee.2007.01.025

(1) proximity effect, (2) fogging effect,(3) loading effect, (4) charging effect, ...

http://www.ebeam.com.cn/



EBL pattern with PEC





Background

"Export Control" to P. R. China

by 《Wassenaar Arrangement》:

https://www.wassenaar.org/control-lists/

<u>3. D. 2.</u> "Software" specially designed for the "use" of equipment specified by 3.B.1.a. to f. or 3.B.2.

<u>3. D. 3.</u> 'Computational lithography' "software" specially designed for the "development" of patterns on EUV-lithography masks or reticles.

<u>**3. B. 1. f. 3.**</u> Equipment specially designed for mask making having all of the following:

a. A deflected focused electron beam, ion beam or "laser" beam; and

b. Having any of the following:

1. A full-width half-maximum (FWHM) spot size smaller than 65 nm and an image placement less than 17 nm (mean +3sigma); or

2. Not used since 2015

3. A second-layer overlay error of less than 23 nm (mean + 3 sigma) on the mask;

"Export Control" to P. R. China

by U.S. federal government:

https://www.govinfo.gov/content/pkg/FR-2020-10-05/pdf/2020-18334.pdf

Destination Control Statement

The technology used in Sentaurus Lithography is strictly controlled for export (under **Export Classification Number 3D003**).

You may not transfer the product or any technical information about the product, or make it available to anyone else, unless you have verified that it is permitted by export laws.

The product may not be exported or re-exported to China, Russia, Armenia, or Vietnam, as well as many other countries, without a valid export license issued by a government agency. Foreign nationals of these and other countries are restricted from receiving this technology unless they are documentedpermanent residents of countries where export is permitted.





Background

Software Toolkit – HNU-EBL v1.0

PC: small memory, slow speed Difficult to PEC for large-scale layouts



Software Toolkit – HNU-EBL v2.0 Supercomputer: large memory, fast speed, multi-nodes Easy to PEC for large-scale layouts



http://www.ebeam.com.cn/

Parallelization





2022 Theory

• Point Spread Function (PSF)

$$P(r) = \frac{K}{\pi(1+\eta)} \left(\frac{1}{\alpha^2} \exp(-\frac{r^2}{\alpha^2}) + \frac{\eta}{\beta^2} \exp(-\frac{r^2}{\beta^2})\right)$$

- Energy Deposition $E(r) = \iint P(|r-r'|)\sigma(r')dr'$
- Threshold development $H(r) = \begin{cases} 0, E(r) < E_{\text{thr}} \\ 1, E(r) \ge E_{\text{thr}} \end{cases}$ • Mean Square Error (MSE) $MSE = \frac{\sum_{i=1}^{N} (H(r_i) - D(r_i))^2}{N}$ • Dose correction $\sigma_k(r) = \frac{D_T \sigma_{k-1}(r)}{F(r)}$ http://www.ebeam.com







2022 Theory

1

• Energy deposition in range $[-d, d] \times [-d, d]$

$$E_d = \frac{K}{\pi(1+\eta)} \left(\int_{-d}^{d} \int_{-d}^{d} \frac{1}{\alpha^2} \exp\left(-\frac{x^2+y^2}{\alpha^2}\right) \sigma(x, y) \, dx \, dy \right)$$
$$+\eta \int_{-d}^{d} \int_{-d}^{d} \frac{1}{\beta^2} \exp\left(-\frac{x^2+y^2}{\beta^2}\right) \sigma(x, y) \, dx \, dy$$

• Energy deposition error

$$e = \frac{4K\sigma_{max}}{1+\eta} \left(\left(1 - \Phi\left(\frac{\sqrt{2}d}{\alpha}\right)\right)^2 + \eta \left(1 - \Phi\left(\frac{\sqrt{2}d}{\beta}\right)\right)^2 \right)$$







Distributed Parallel Computing Algorithm

1. Read GDSII layout on each computing node and splits the exposure layout into multiple sub-layouts







Distributed Parallel Computing Algorithm

2. Exchanging the edge information of adjacent sub-layout for calculating energy deposition





Scaling Test



(a) In the case of several different nodes, the calculation time consumption is with the change curve of the number of pixels. (b) For a test benchmark layout, the speedup ratios under different node cases are analyzed.

IWAPS 2022

Accurate and Efficient Proximity Effect Correction for Electron Beam Lithography Based on Distributed Parallel Comp



Accuracy Test



The relative error distribution between the multi-computing node and the single-computing node PEC results. (a) and (b) represent the relative errors of 4 and 9 computing nodes on the PEC of the same layout, respectively.





≈50,000 lines of

C++/Python codes

Software Toolkit – HNU-EBL v2.0

Developed from scratch at Hunan University in China

Website: http://www.ebeam.com.cn/

HNU-EBL Energy Deposition ? X File Help New Simulation PEC-FEC Energy Deposition Development Login Current Structure: TEST Structure Layer roiect: hnu.hnu PMMA 10 Si 10000 5 10 100 Point Spread Function PMMA 20 Si 10000 5 10 100 PMMA 50 Si 10000 5 10 100 Linear Log Export PSF depth 15n 2.2 Color bar unit:Relative Energy Deposition (eV/nm³) Traiectories 0.1 PMMA 20 Si 10000 5 10 100 PMMA 100 Si 10000 10 20 100 1400PMMA 100 Si 10000 100 10 5000 2gaussi: PMMA 100 Si 10000 5 10 100 — 3gaussian 0.01 1.8 3gaussian+exp 1200 1.60.001 1000 1.4length) 800 0.0001 1.2 5 [eV/nm[°] (rum/Grid 600 1 10-5 0.8 400 ⊳ 10-8 0.6 200 0.4 10-7 0. 0.2 10-8 2000 3000 4000 Y (nm/Grid length) А -0.21 Radius [nm]







2022 HNU-EBL v2.0



Features:

- Monte Carlo based on Rutherford, Mott, etc.
- Point Spread Function curve fitting
- Multi-depths simulationUltra high speed



Step 1. Monte Carlo simulations & PSF





HNU-EBL v2.0



https://doi.org/10.1016/j.mee.2007.01.025 Features:

- \succ CD down to 1.0 nm
- Efficient codes (C++, FFT, MPI, OpenMP)
- Proximity/Fogging effect...
- Supercomputing platform

Step 2. PEC & parallel

			_	\sim
		-		^
ие нер				
New Simulation PEC-FEC Energy Deposition Development C	Cloud(Login)			
oject: 0531.hnu				
РММА 200 Ši 10000 5 10 100 РММА 150 Ši 10000 5 10 100 РММА 150 Ši 10000 5 10 100 РММА_100_Si 20000 5 10 10				
	\searrow			





HNU-EBL v2.0

Development model
 > Threshold

Mack

> Notch



Banerjee et.al, "Electrically driven optical proximity correction," Proc of SPIE, 2008.



Step 3. Development & EPE evaluation

File Help New Simulation PEC-FEC Energy Deposition Development Cloud(Login) ropet:r0311hm PMMAA_105_5110005_510_100 PMMAA_05_510_100 PMMAA_159_5110000_510_100 PMMAA_05_10_100 PMMAA_05_100 PMMA
New Simulation PEC-FEC Energy Deposition Development Cloud(Login) roject: 0531.hmu PMMA_105_10000_5_10_100 PMMA_205_5_10000_5_10_100 PMMA_150_5_101000_5_10_100 PMMA_150_5_101000 PMMA_150_5_10100 PMMA_150_5_101000 PMMA_150_5_10100 PMMA_150_5_101000 PMMA_150_5_10100 PMMA_150_5_1000 PMMA_150_5_100 PMMA_150_5_1000 PMMA_150_5_1000 PMMA_150_5_100 PMMA_150_5 PMMA_150_5_100 PMMA_150_5 PM
roject: 031.hpu > PMMAA_205 \$1,1000 \$10,10 > MMAA_150_\$1,10000_\$_10_100





R&D Team of HNU-EBL







Conclusion

- ➢PEC based on Distributed Parallel Computing
- ≻To break the limitation of computing and memory
- ≻Suitable for large-scale layouts
- ➢Dose-correction, Shape-correction, Hybrid-correction
- ➢GUI-based EDA with 50,000 lines of C++, Python codes for EBL (EUV/optical mask)
- ≻IP by Hunan University (4 papers + 8 patents + 5 software copyrights)

Limitations:

- >Version: second-release (under improvement)
- **Functionalities**: 2D correction
- >Verification: limited experimental verification





Thanks!

► IIPR: 4 papers + 8 patents + 5 software copyrights

➤ "setup.exe" of GUI-based EBL software

> 70+ pages of software user guide

									HNU	Ultraf	> REPLA
				BIDAC				第 巻 第 2021年	L	01 La	E
							10000	文章编号。			Mı
					证书	证书	UE 75		1^{κ}		
									College of Electi Eng		
		1	t	i					Hanan Chang		v
								14.5.10	liuw@		
	23							姚文泽	4th Hor	Abstract—1h correction (PEC)	Abstraci effect serie
10 44 DL	1 the 14 A	the phy a	1 校供名	数件 3				(L. 4119)	College of Electi Eng	(FMM), to simul accuracy. It is st	conditions
教 件 3	· · · · · · · · · · · · · · · · · · ·	A 11 4	2 2 1 2						Hunan Chang	linear computati- of pixels, and line	FFT) calc
					爱 1	12 1	92 II	子来。	hongcheng	processing unit (suffer from uneventy d
	22						Contraction of the second	"自	7 ⁶ Ht	(EB1). The prop	spaced grid
著作;	著作 名	著作も	著作 あ	著作 老	发	宠	发	件实	College of Mech Eng	the Softy	the exposu
								SDS S	Hunan Chang	(http://hnupecsvi	equally spa based on 2
	22	22			4	10	4	于卷	duanhgi	Keywords-da (PEC), electron 1	current fa density is
				T (D ab al				关键	Abstract-Th	(FMM), software	the 10-th
开发完成	开发完成	于 开发完成	一 开发完成	計 并发完成	专利	专利	专利	聚甲	optimize electroi		FMM is w
		E	The second second	AL MARKE AD AN		1.0	10.1	艺过	of three consecut EBL resist and	choice to man	paper has (SaaS) m
首次发表	首次发表	百 百次发表	自伏反表	目伏反农	专 1	セオ	专习	的计 -	Carlo (MC), an fitting the electr	widely applied	optimizatio
		and the set of the set	一一一一	2 初刊初名		1.		秋件 約日	dose distribution	highly focused (available a
2 权利取得	日 权利取得	1 权利取得	2 权利取得	权利权得	地	地	地		fogging effect th	resolution throu incident region.	Index 1 fabrication
			副教	如 利 利 利		2.0	10.10	1030	and pattern qua dose distribution	and atoms in t trajectory has d	method (F
1 秋利 1	权利者		1X 11 12		授权	授权	投权	14/6	based on metric HNU-EBL toolk	away (e.g. micro	
E 28 13	Et #2	5 8 7	四 務 记	· · · · · · · · · · · · · · · · · · ·				ic.uc.	successfully appl	degrades the fa	
THE REAL REAL					证书	证书	证书	HNU-	Keywords—e (MC) fort Family	EBL resolution a	
				10 40 40	中请	中请	中语	8	proximity effect c	In this paper,	Va
- 根据	~ 极据	11 根据	12 秋坊	110.30				Wenze Yao		multipole metho calculation time	[5], micro devices [7
				四 如今 9	利权	利权	利权	(1.1	Electron bea and mask fabri	O(N). Then, we	and cost-
规定,意	规定, 腔	烈龙, 型	烈龙, 经	MAR, 4				and	resolution and f	methodology co	while opti
		j				1.100			resist at one lo	the existing conv increases, the cor	needed for
22	22					10000	1000	ADS the menufact	undesirable exp locations $\mathbf{r} = 0$	The proposed m	researcher
								Design Auto	proximity effect	(SaaS) mode.	lithograph
		E 6		E G				have been in	fidelity of EBL		further sa
		3			局十	局十	局+	and substrate	It is desirable	This softwar	lithograph
						100	eta l	beam scatter	and pattern fide	double-Gaussiar	layout.
					(# 3	е т т	6 44 1	and fogging	in the lithograp	(3G+E) [4, 6], T	
No.	No. 0	No.	No. (No.	20	32	22	convolution	very sophisticat		This work of China un
B CSC					Hor	Too	Cor	收稿目期。	to run (*).		for the Centr Gathering Pr
2 2000	8 20 20	E POR	E TOPON		200	200		基金項目: 6			Developmen part by the
IS NO C		H Le G	H LOCA		1000 Call	4000000	3000000	"通信联系》	978-1-6654-2079-2	978-1-7281-7577-56	
อีอออออออออออออออออออออออออออออออออออออ	Jereserere	annananana an	Persenance	(Second second s							
Section Section									Authorized I	Authorized Iv	



ACE THIS LINE WITH YOUR PAPER IDENTIFICATION NUMBER (DOUBLE-CLICK HERE TO EDIT) < 1

Efficient Proximity Effect Correction Using Fast Iultipole Method with Unequally Spaced Grid for Electron Beam Lithography

Wenze Yao, Haojie Zhao, Chengyang Hou, Wei Liu, Hongcheng Xu, Xin Zhang, Jing Xiao, Jie Liu

—In electron beam lithography (EBL), the proximity usly influences pattern resolution under high-precision Mainstream proximity effect correction (PEC) sed on two-dimensional fast Fourier transform (2D-As shown in Fig. 1(a), the incident electron beam penetrate brough resist, where electrons are scattered by resist material (forward scattering). And certain portion of incident electrons is contrared back into maint by the substrate (back scattering dimensional fast Fourier transform (2D-umber of unexposed points, thus it may cy especially when the exposure layout is is paper proposes an efficient unequally of Dr EBL based on fast multipole method ust calculates the interaction between all d thus it gets rid of the limitation of the While forward scattering is useful to write target pattern by polymer chain scission of resist only few nanometers (a) aroun the highly-focused electron beam, back scattering undermine fabrication accuracy by undesirably influencing resist regions wints, and have it gets of af the limitations of the get Compared in the interface of the limit of the limit of the proximity of the limit of the limit of the limit of the proximity of the limit of the limit of the proximity of the limit of the limit of the proximity of the limit of the limit of the proximity of the limit nicrometers (β) away (Fig. 1(b)), which is referred to as "proximity effect". The double Gaussian point spread function (PSF) [13, 14] is commonly used to model the electron beam Although EBL is the nanometer-level precision maskles hography technology, the proximity effect may severely reduce the resolution of the exposure layout without proximity effect correction (PEC) for large-scale dense layout, e.g., large-scale graphics array, and integrated circuit (IC) mask layout [15]. Taking an Exclusive-OR (XOR) mask layout as an example, electron deposition energy without PEC (Fig. 1(c)) and, hence, development contour with threshold development model [16] (Fig. 1(d)) significantly deviates from expects pattern. Correspondingly, electron deposition energy with PEG (Fig. 1(e)) leads to development contour (Fig. 1(f)) accurately meeting the desired pattern. Therefore, PEC can be I. INTRODUCTION indispensable to ensure reliable fabrication in FBL. tron beam lithography (EBL) is a nanoscale direct Optical proximity correction (OPC) in photolithography is achieved by mask shape modulation [17, 18]. On the other hand rious devices, e.g., sensors [1-4], electronic devices PEC in EBL can be implemented by dose modulation [17, 18]. On the other hand PEC in EBL can be implemented by dose modulation at each o-electro-mechanical systems (MEMS) [6], optical exposure point. Currently, the mainstream PEC with dose 7, 8], nanostructures [9] etc. EBL is more convenient correction method uses 2D-FFT convolution [19] with Fective for prototype research and development, calculation time $t \propto O(Nlog(N))$. And PEC with shape ical lithography such as Extreme Ultra-violet (EUV) correction method via filtering and projection [20] also uses the st-effective for mass production. Furthermore, EBL is 2D-FFT method for convolution iteration. 2D-FFT method iseffective for mass production. Furthermore, EBL is 2D-FFT method for convolution netration, 2D-FT1 method for the expanse lpaced (a, two-investigation) and the size of the PSF two-dimensional method with an expanse lpaced to an expanse lpaced method. The pSF two-dimensional method with the size of the PSF two-dimensional method with the size of the PSF two-dimensional statistical by MFERDW libeopart. The demand for targe-scale exposure is the same are the location statistical by MFERDW libeopart. The demand for targe-scale exposure is the same are the location method with the different statistical by MFERDW libeopart. The demand for the different different statistical by MFERDW libeopart. The demand for the different different statistical by MFERDW libeopart. The demand for the different method based on EBL for large-scale lithography algorithms. 2D-FFT convolution algorithm calculates energy deposition in a large number of unexposed areas rovince, China, under Grant 2019GK5029, and in part by the Fund fi

we was appendix in party by Rolicol Natural Scence Foundation — Province, Chine, and G Gant 2016/SEO29, and in part by the Fandard Research Funda Distribution of Chapel stand Crattal Research Funda Distribution of Chape Land Crattal Research Funda Distribution of Chape Land Crattal Research Funda Distribution of Research Research Party Distribution of Research Research Research Party Distribution of Research Research Research Party Distribution of Research R

Welcome to contact us!!!

License to all EBL Users from Academia/Industry <u>http://www.ebeam.com.cn/</u> support@ebeam.com.cn jie_liu@hnu.edu.cn

