

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

Haojie Zhao

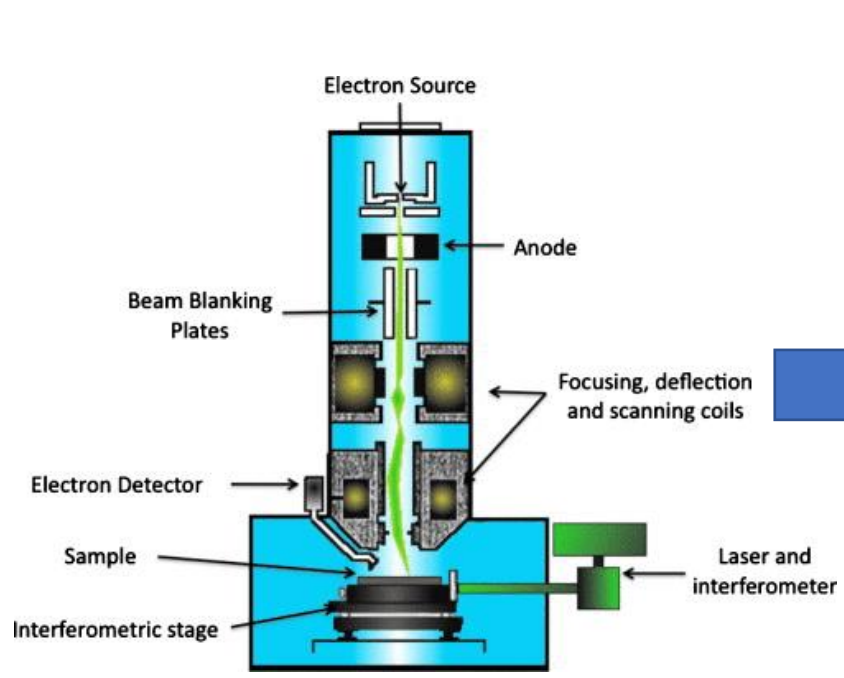
Hunan University

October 21, 2022

Contents

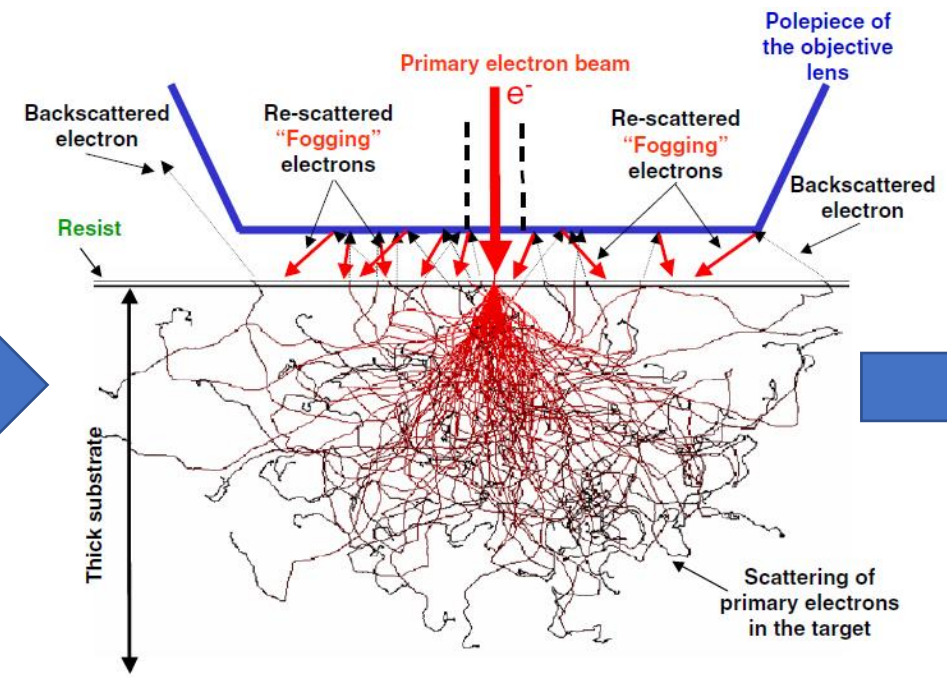
- Background
- Theory
- Distributed Parallel Computing Algorithm
- Simulation
- Software Toolkit – HNU-EBL v2.0
- IP & License
- Conclusion

Background



<https://doi.org/10.1063/1.3437589>

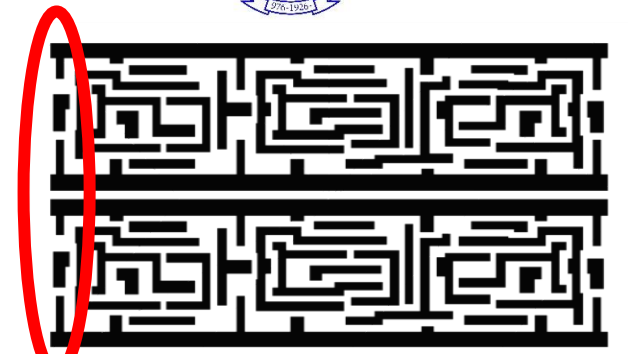
Electron Beam Lithography



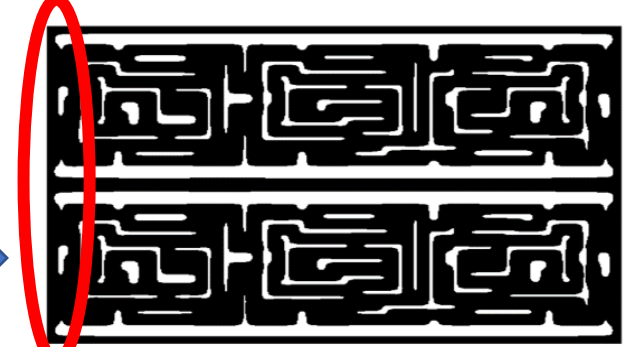
<https://doi.org/10.1016/j.mee.2007.01.025>

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

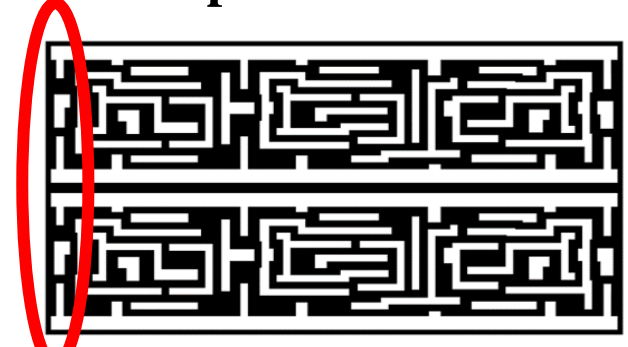
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EBL target pattern



EBL pattern w/o PEC



EBL pattern with PEC

Background

“Export Control” to P. R. China

by 《Wassenaar Arrangement》 :

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

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

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

3. B. 1. f. 3. 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 documented permanent residents of countries where export is permitted.

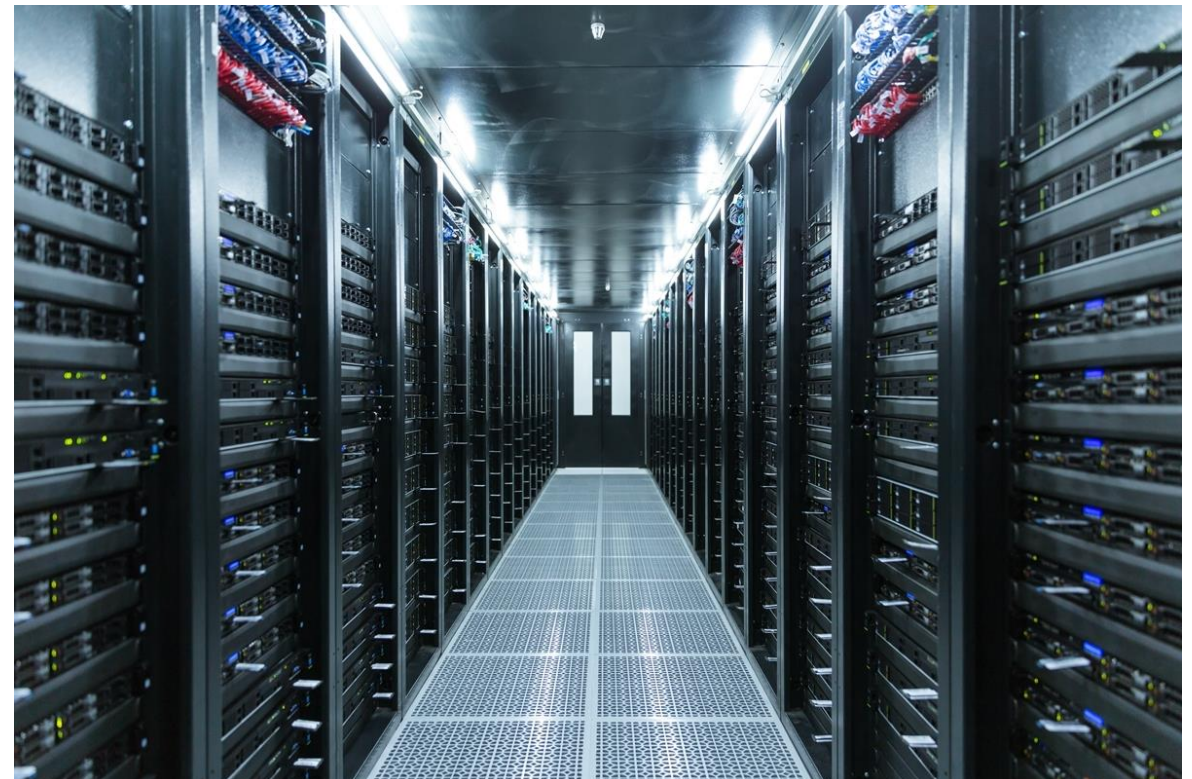
Background

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



Theory

- Point Spread Function (PSF)

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

- Energy Deposition

$$E(r) = \iint P(|r-r'|) \sigma(r') dr'$$

- Threshold development

$$H(r) = \begin{cases} 0, & E(r) < E_{thr} \\ 1, & E(r) \geq E_{thr} \end{cases}$$

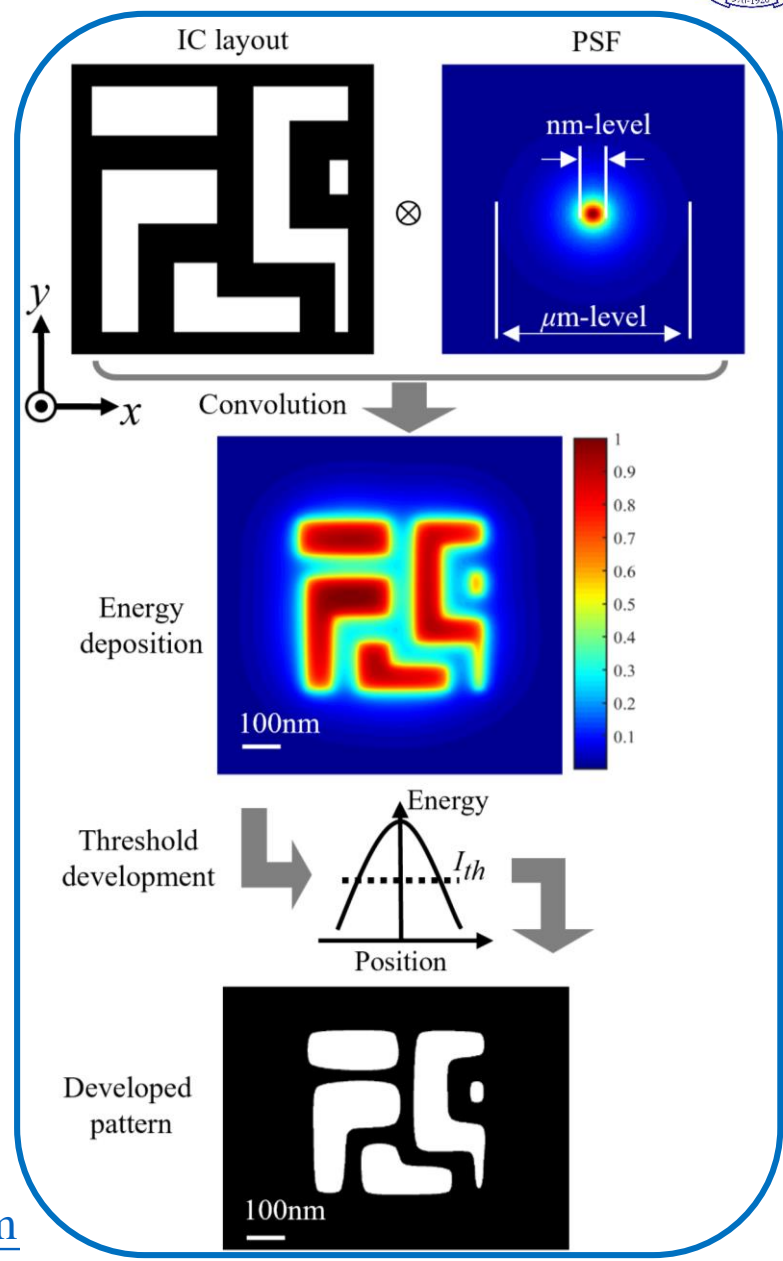
- Mean Square Error (MSE)

$$MSE = \frac{\sum_{i=1}^N (H(r_i) - D(r_i))^2}{N}$$

- Dose correction

$$\sigma_k(r) = \frac{D_T \sigma_{k-1}(r)}{E(r)}$$

<http://www.ebeam.com>



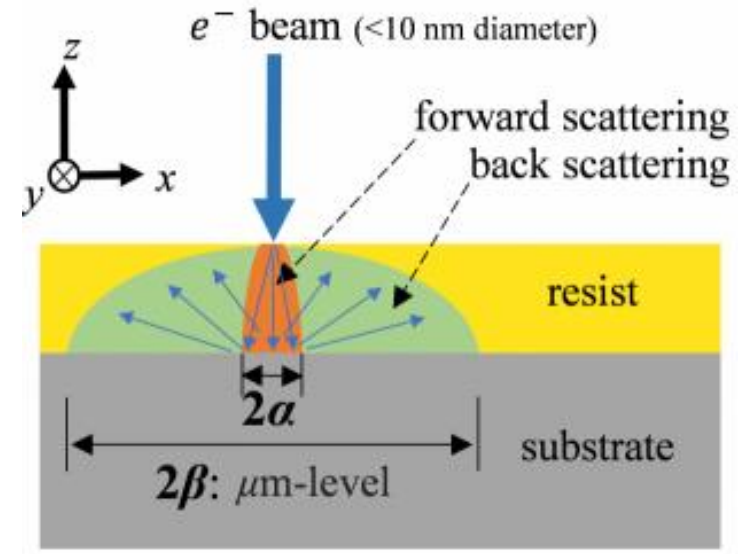
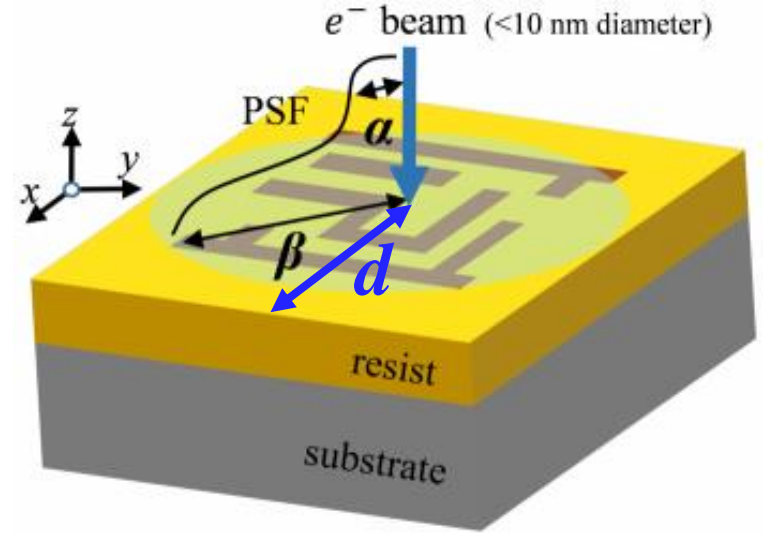
Theory

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

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

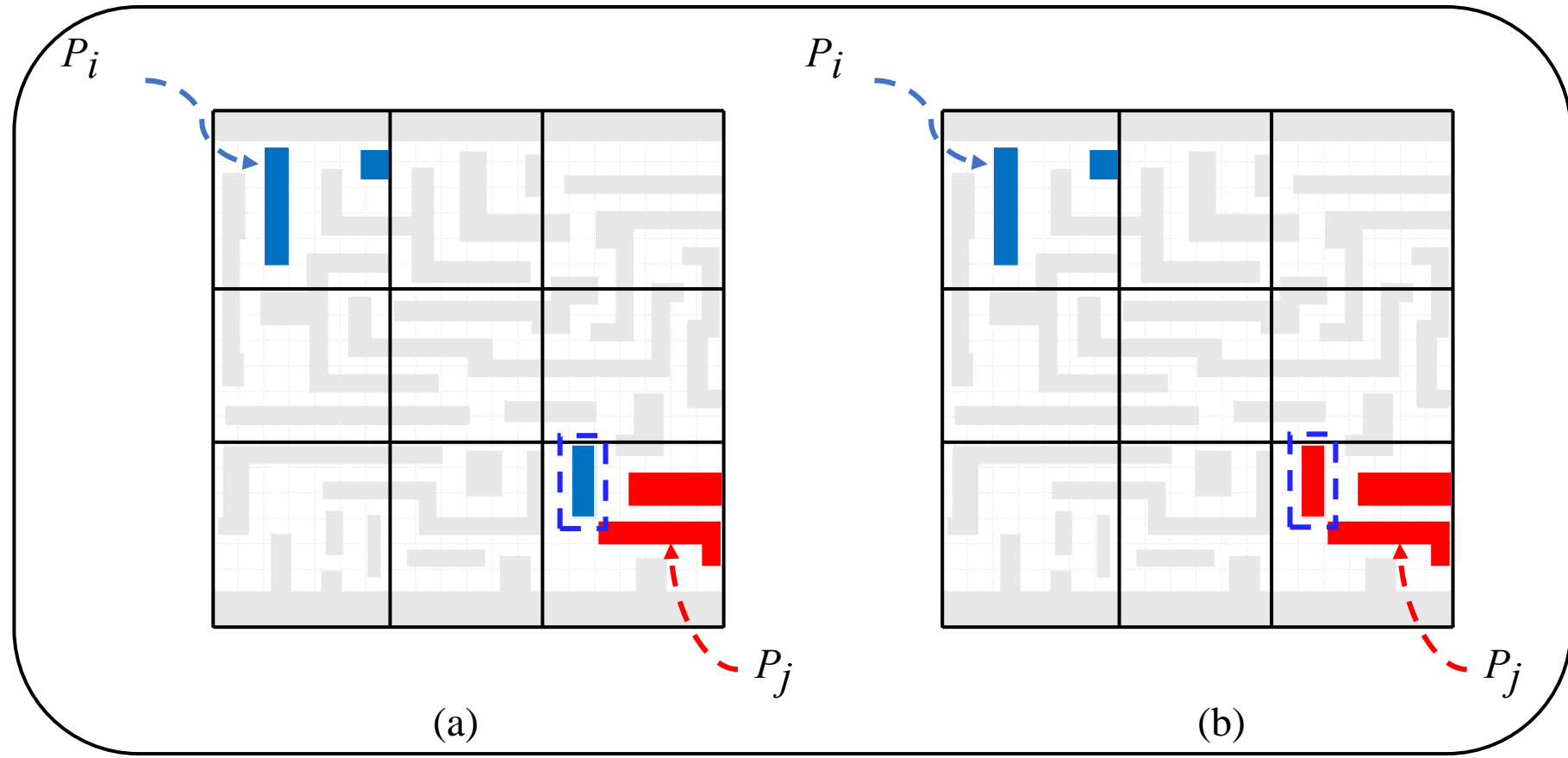
- Energy deposition error

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



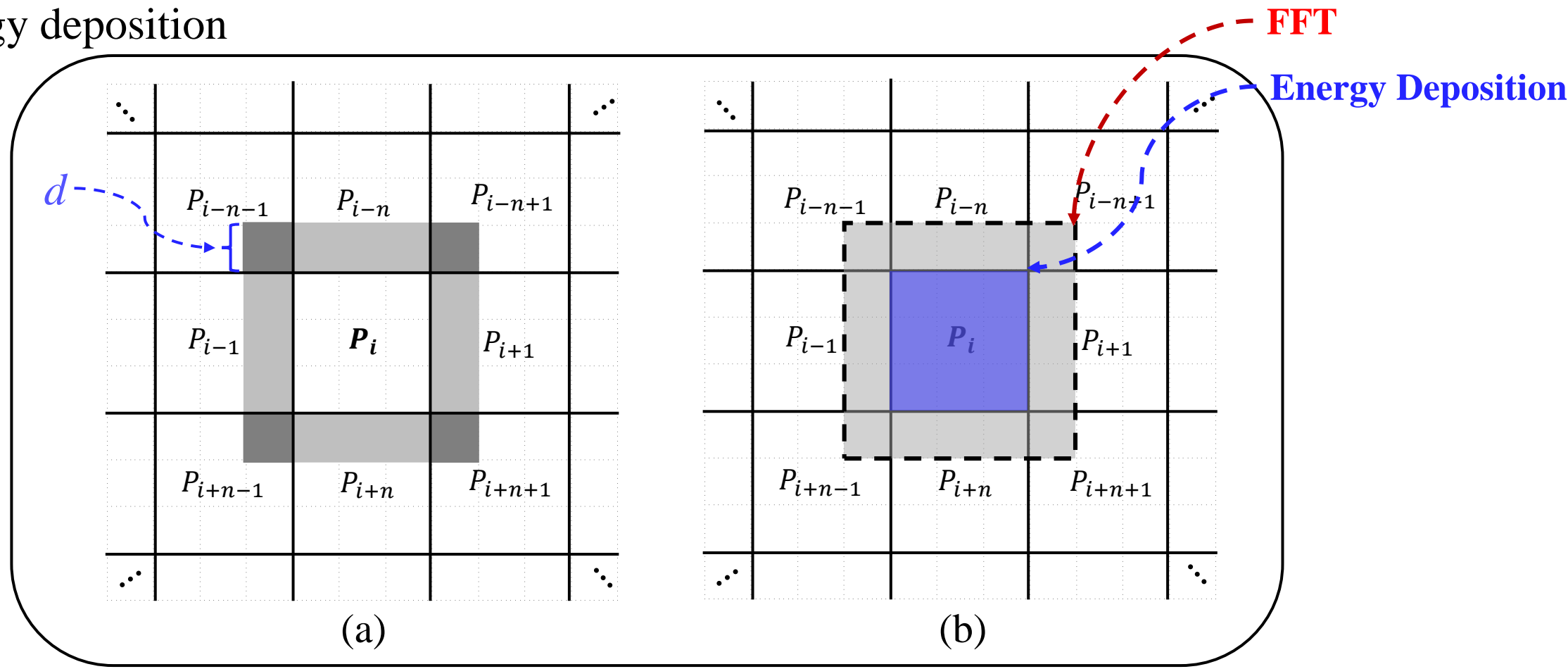
Distributed Parallel Computing Algorithm

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

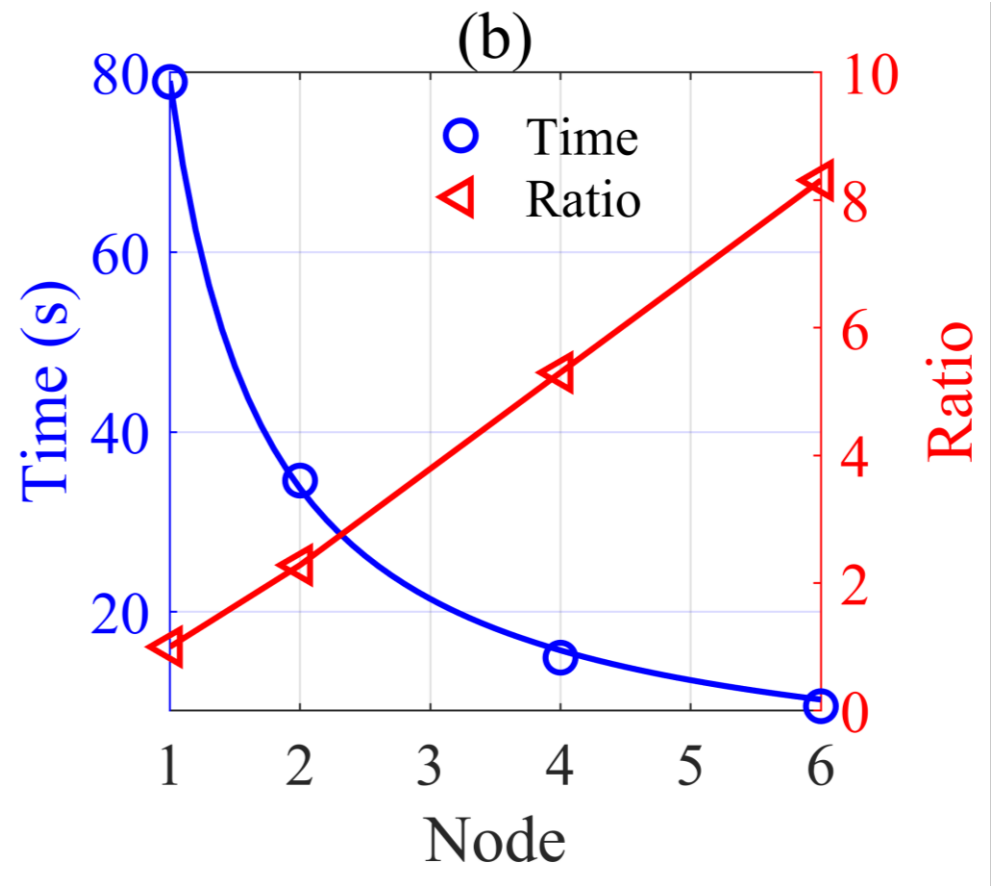
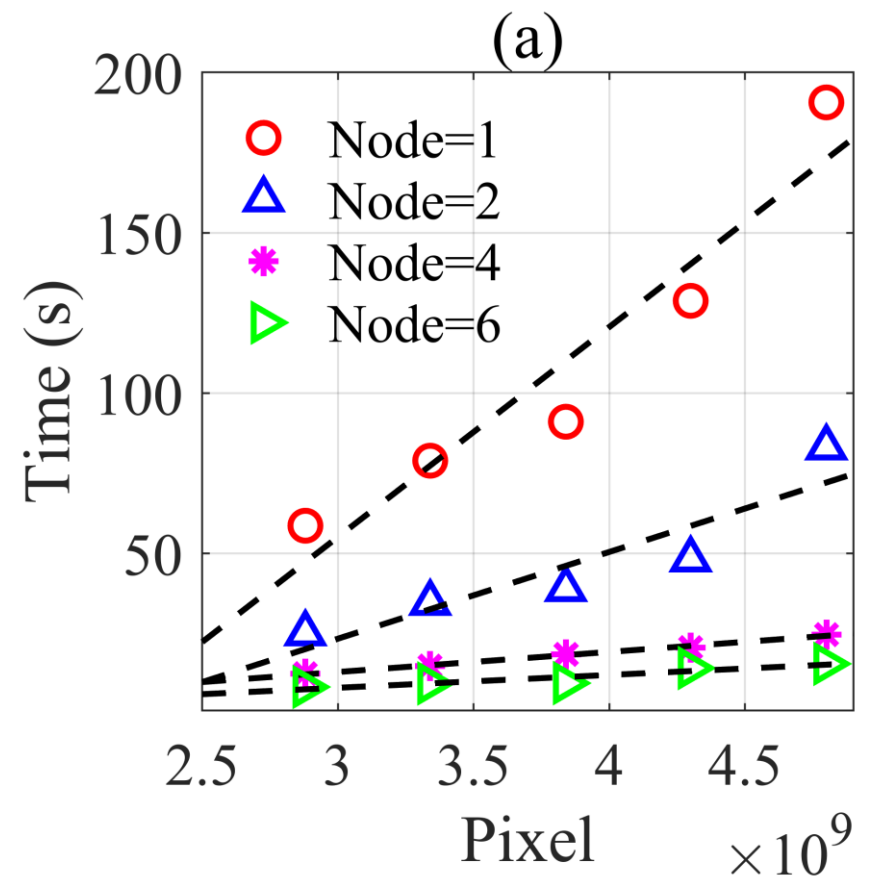


Distributed Parallel Computing Algorithm

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

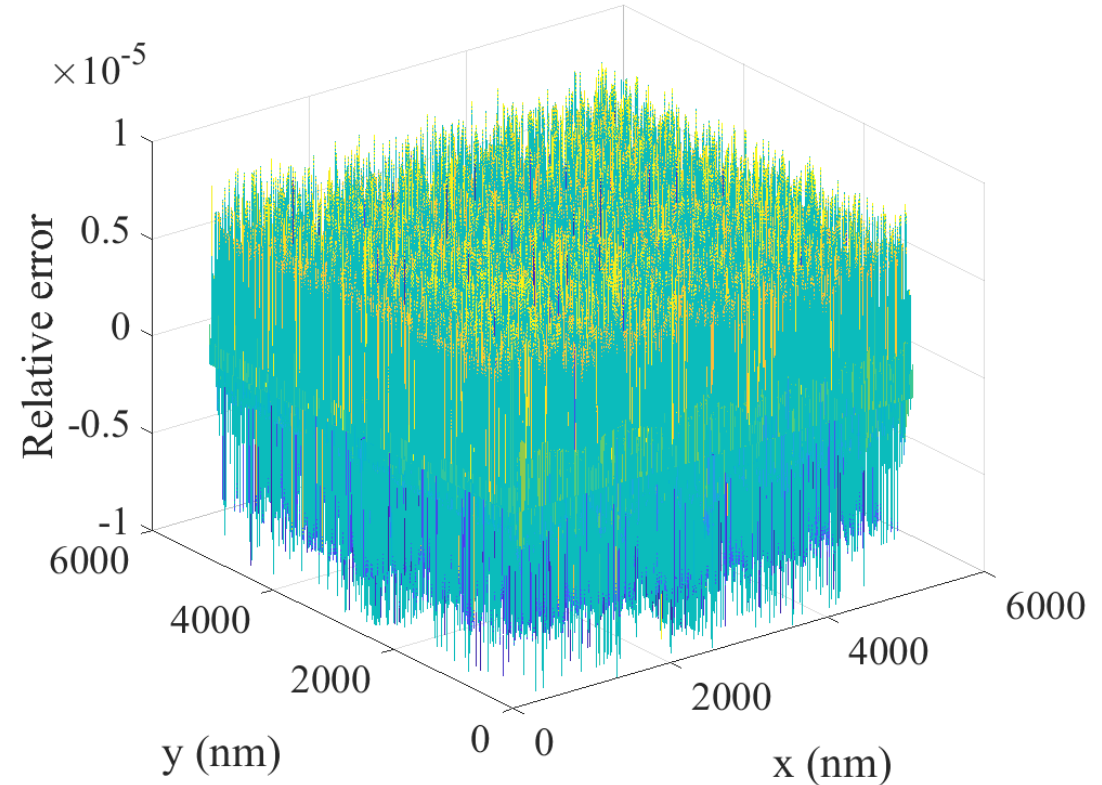


Scaling Test

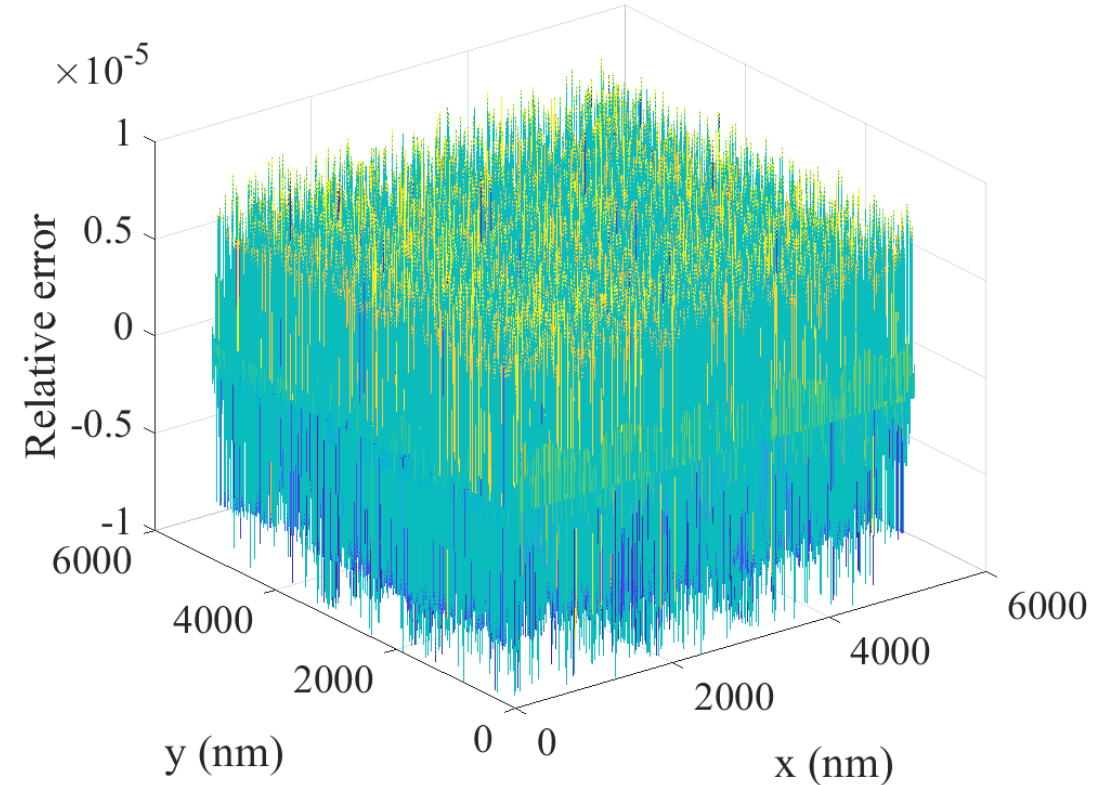


(a) In the case of several different nodes, the calculation time consumption is with the change curve of the number of pixels. (b) For a test benchmark layout, the speedup ratios under different node cases are analyzed.

Accuracy Test



(a) Nodes = 4



(b) Nodes = 9

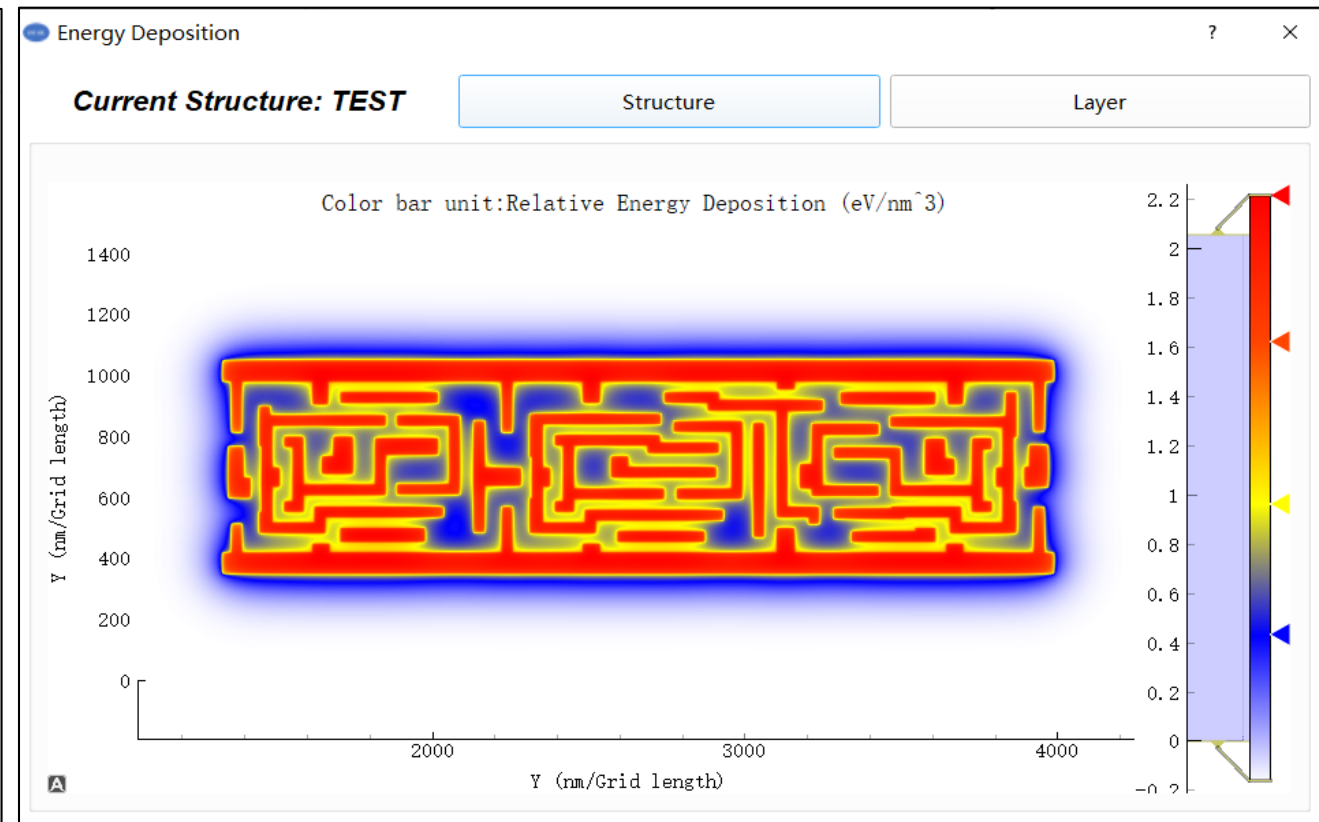
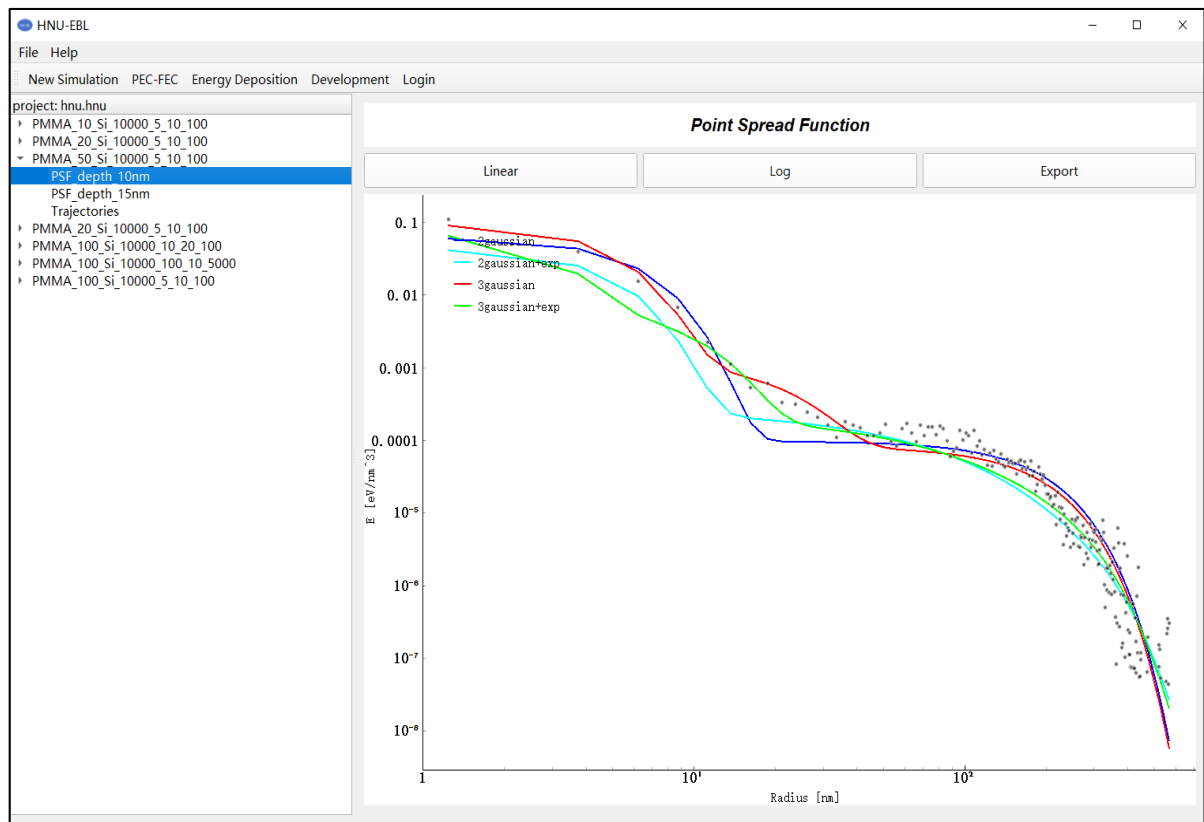
The relative error distribution between the multi-computing node and the single-computing node PEC results. (a) and (b) represent the relative errors of 4 and 9 computing nodes on the PEC of the same layout, respectively.

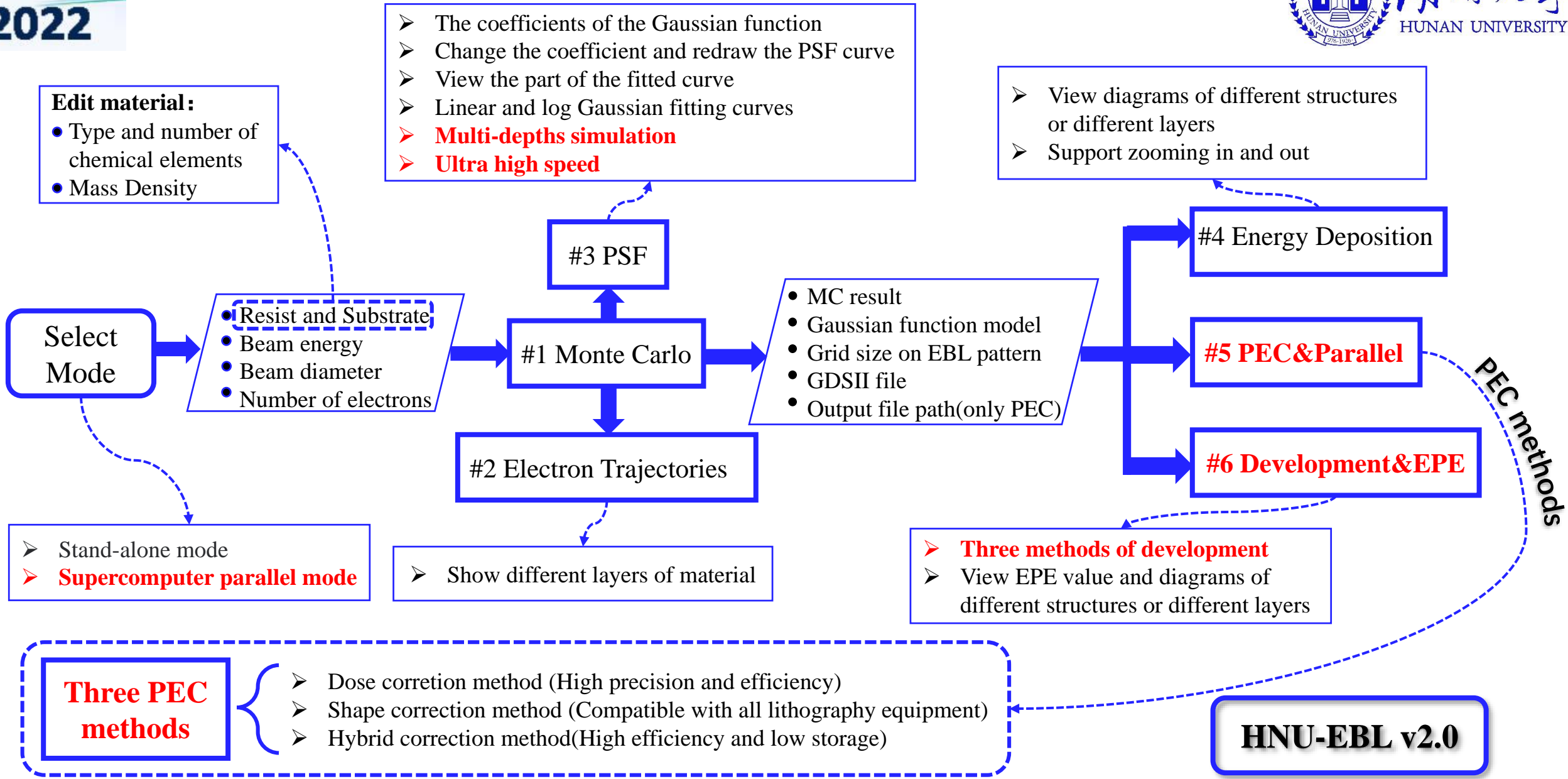
Software Toolkit – HNU-EBL v2.0

Developed from scratch at Hunan University in China

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

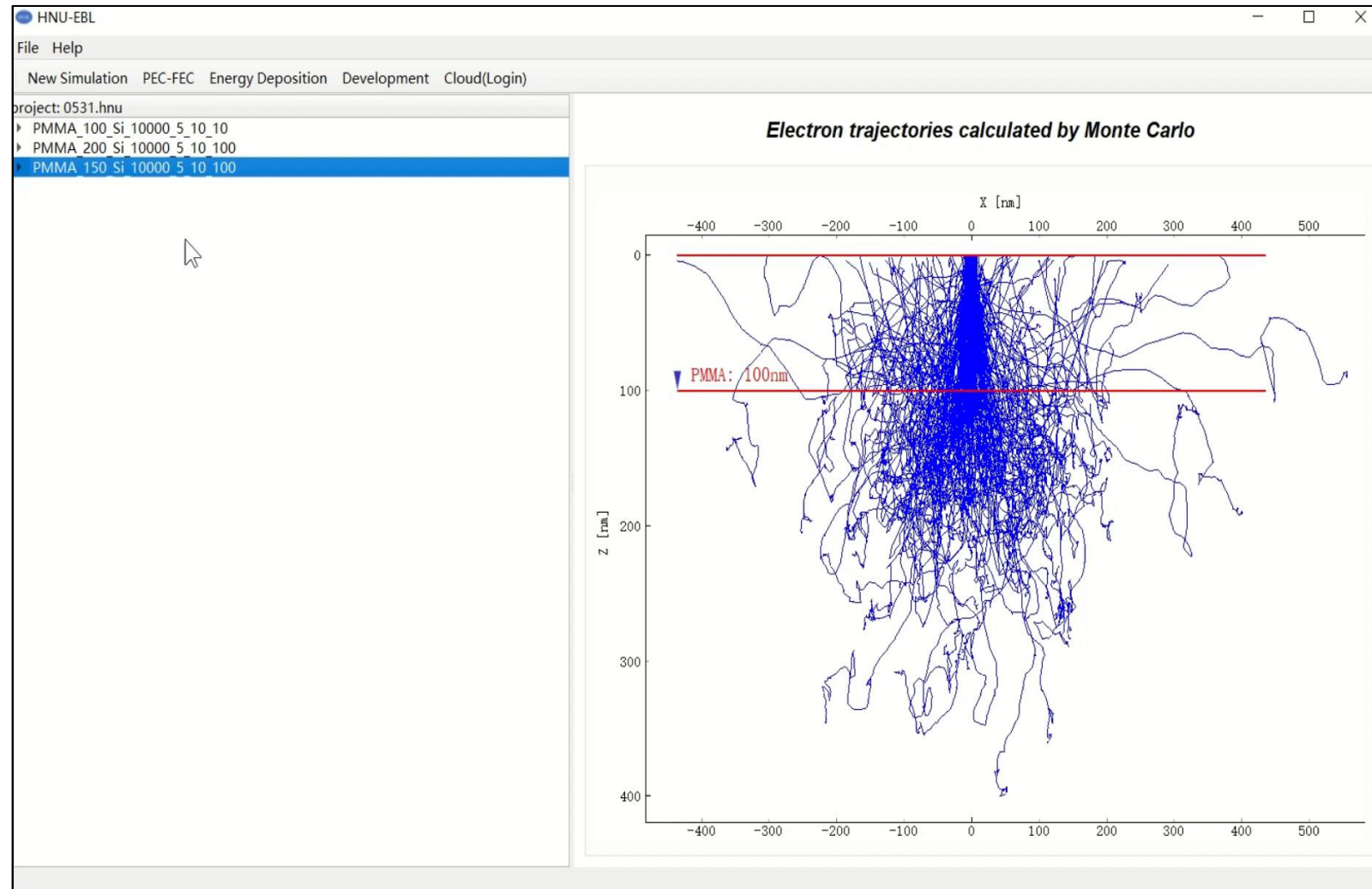
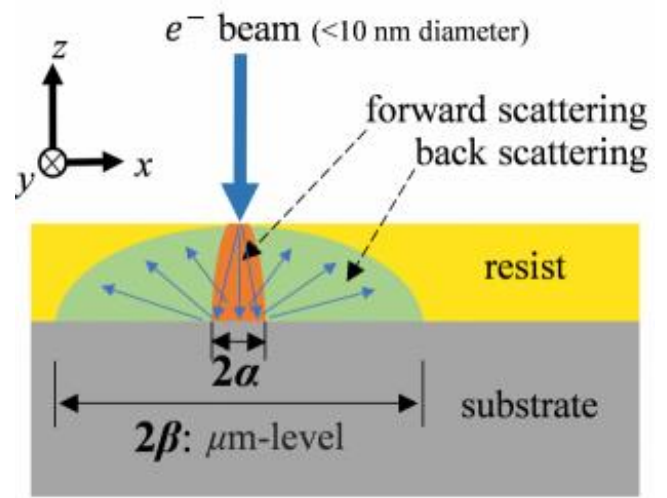
≈50,000 lines of
C++/Python codes





HNU-EBL v2.0

Step 1. Monte Carlo simulations & PSF



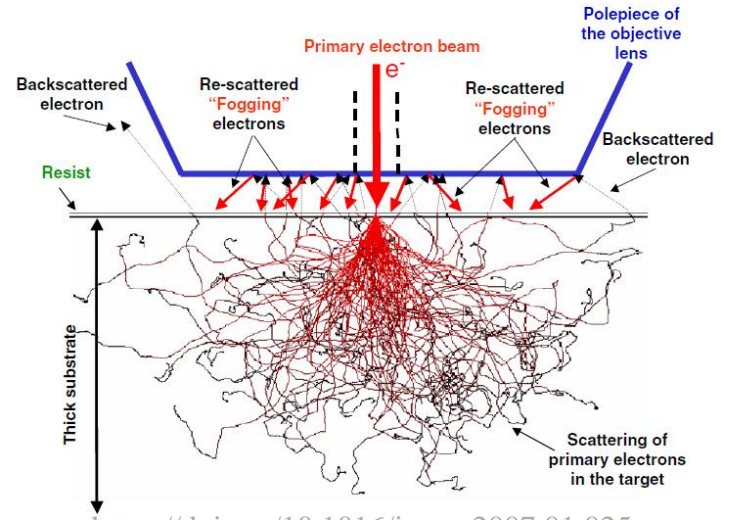
Features:

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

HNU-EBL v2.0

Step 2. PEC & parallel

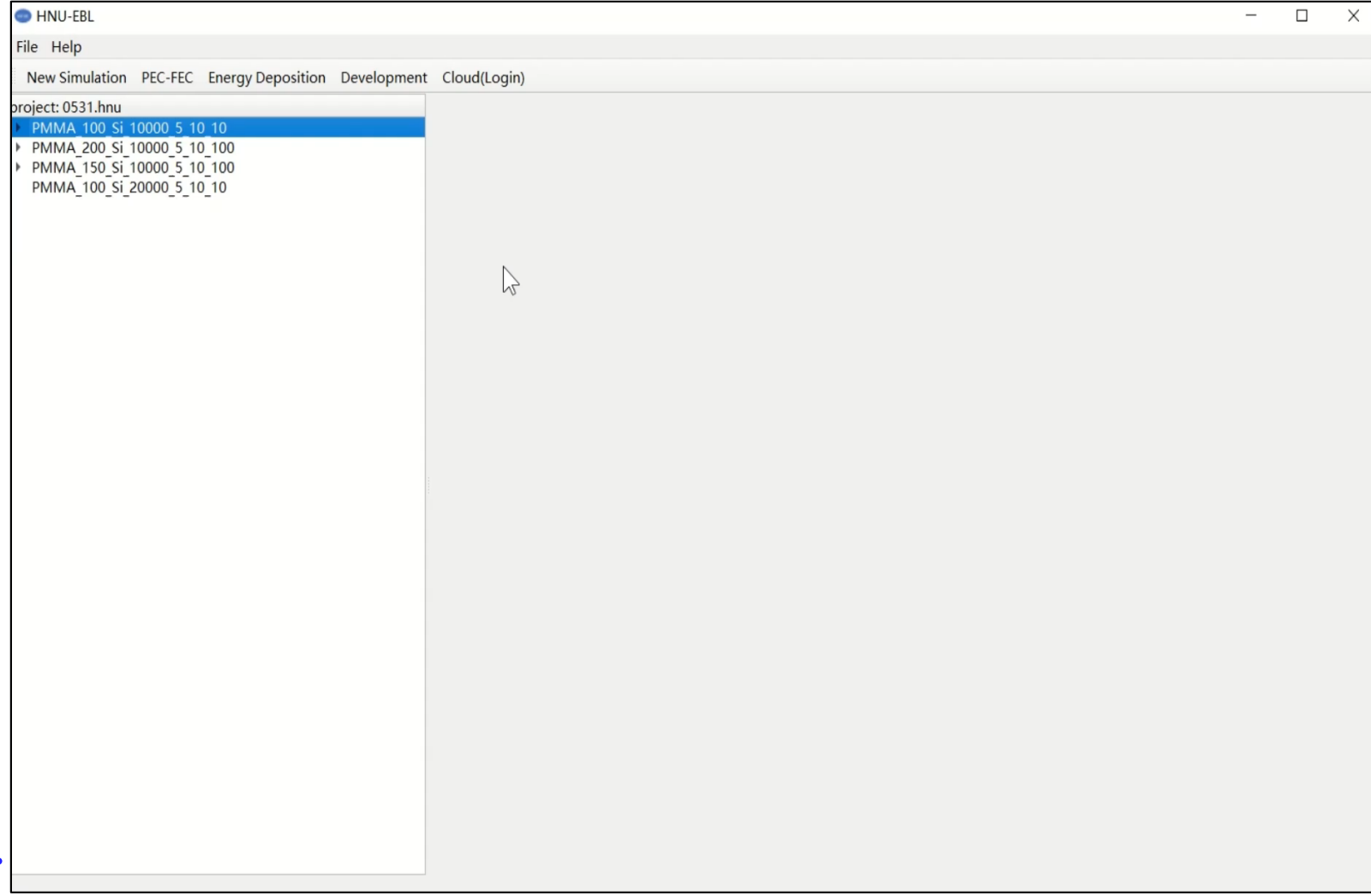
$$E(r) = \iint P(|r-r'|) \sigma(r') dr'$$



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

Features:

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



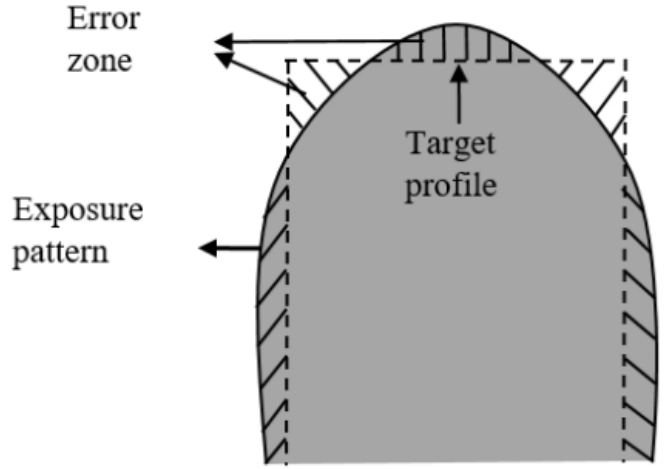
<http://www.ebeam.com.cn/>

HNU-EBL v2.0

Step 3. Development & EPE evaluation

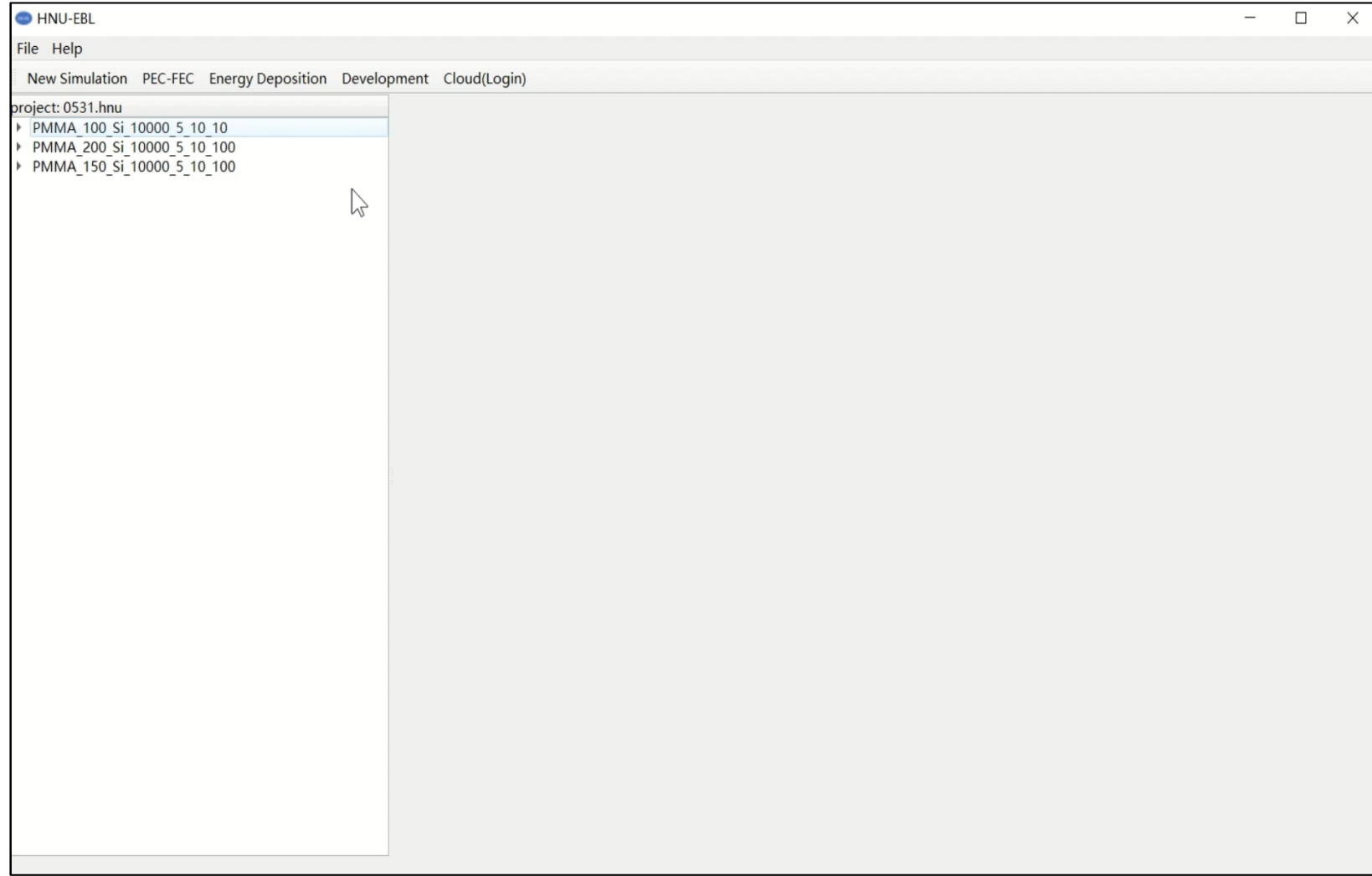
- Development model

- **Threshold**
- **Mack**
- **Notch**



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

- Edge Placement Error (EPE)



R&D Team of HNU-EBL



Jie Liu



Huigao Duan



Yiqin Chen



Haojie Zhao

Role:

Software Development

Experimental Verification



Wenze Yao



Hongcheng Xu



Siyuan Zhang



Yujie Yang

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

Welcome to contact us!!!

License to all EBL Users from Academia/Industry

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

support@ebeam.com.cn

jie_liu@hnu.edu.cn

软件名称	软件名	软件名	软件名	软件名
开发完成	开发完成	开发完成	开发完成	开发完成
首次发表	首次发表	首次发表	首次发表	首次发表
权利取得	权利取得	权利取得	权利取得	权利取得
登记	登记	登记	登记	登记
根据规定, 经	根据规定, 经	根据规定, 经	根据规定, 经	根据规定, 经

证书	证书	证书
发	发	发
发	发	发
专	专	专
专	专	专
地	地	地
授	授	授
证	证	证
中	中	中
权	权	权
局	局	局
申	申	申

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Abstract—In electron beam lithography (EBL), the proximity effect seriously influences pattern resolution under high-precision conditions. Mainstream proximity effect correction (PEC) methods based on two-dimensional fast Fourier transform (2D-FFT) calculate a large number of use spaced points, thus it may suffer from low efficiency especially when the exposure layout is unevenly distributed. This paper proposes an efficient unequally spaced grid PEC method for EBL based on fast multipole method (FMM). FMM in PEC just calculates the interaction between all the exposure points, and thus it gets rid of the limitation of the equally spaced grid. Compared to the state-of-the-art PEC method based on 2D-FFT, the calculation speed of FMM will exceed the current fastest 2D-FFT convolution when the layout exposure density is below a certain proportion (approximately 80% under the standard CPU parallel computing conditions). For the application of integrated circuit (IC) mask industry, the error of FMM is within the acceptable range of PEC. PEC method in this paper has been applied to a free software via Software as a Service (SaaS) mode, and a Windows-based EBL simulation and optimization software named “HNU-EBL” which is freely available at <http://www.ebeam.com.cn>.

Index Terms—electron beam lithography (EBL), IC mask fabrication, proximity effect correction (PEC), fast multipole method (FMM).

I. INTRODUCTION

Electron beam lithography (EBL) is a nanoscale direct writing maskless lithography, widely used to fabricate various devices, e.g., sensors [1–4], electronic devices [5], micro-electro-mechanical systems (MEMS) [6], optical devices [7, 8], nanostructures [9] etc. EBL is more convenient and cost-effective for prototype research and development, while optical lithography such as Extreme Ultra-violet (EUV) [10] is cost-effective for mass production. Furthermore, EBL is needed for photomask writing. In recent years, more and more researchers focus on massively parallel electron beam direct write (MPEDW) lithography [11, 12] in order to improve lithography throughput. The demand for large-scale exposure is further satisfied by MPEB/DW technology. Therefore, it is necessary to further study more efficient computational lithography method based on EBL. For large-scale lithography

This work was supported in part by the National Natural Science Foundation of China under Grant 61804009, in part by the Fundamental Research Funds for the Central University of China, in part by the Hubei Provincial High Level Talent Cultivating Project under Grant 2019CZ0301, in part by the Academic Research and Development Project of Hunan Province, China, under Grant 2019JJ20017, in part by the Technology Innovation and Entrepreneurship Funds of Hunan

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Province, China, under Grant 2019JJ20020, and in part by the Fund for Distinguished Young Scholars of Changsha under Grant 190401, and in part by the China Postdoctoral Science Foundation under Grant 2020M68252, and in part by the College of Electrical and Information Engineering, Hunan University, Changsha, P.R. China. Corresponding authors are Jie Liu (jie_liu@hnu.edu.cn, <http://www.ebeam.com.cn>) and Jing-Yan Guo (jyguo@hnu.edu.cn).

