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

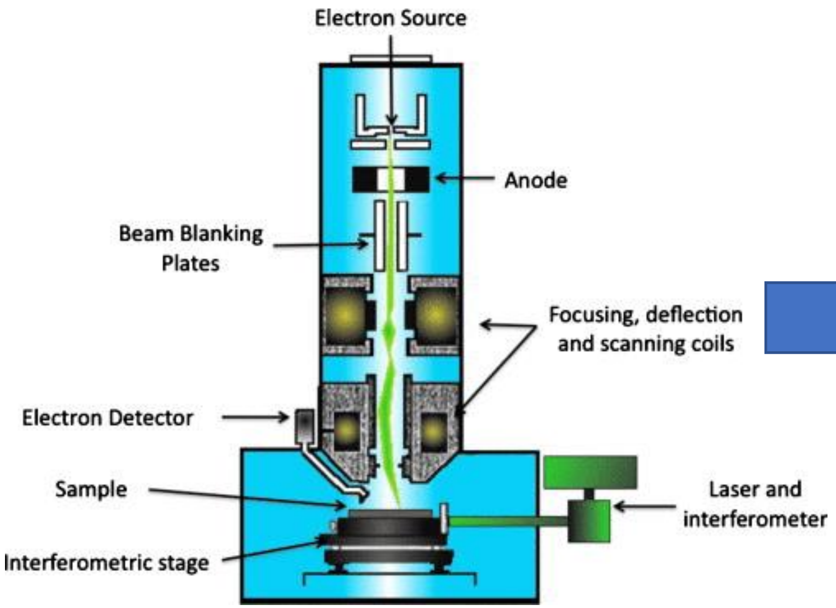
Haojie Zhao

Hunan University

October 21, 2022

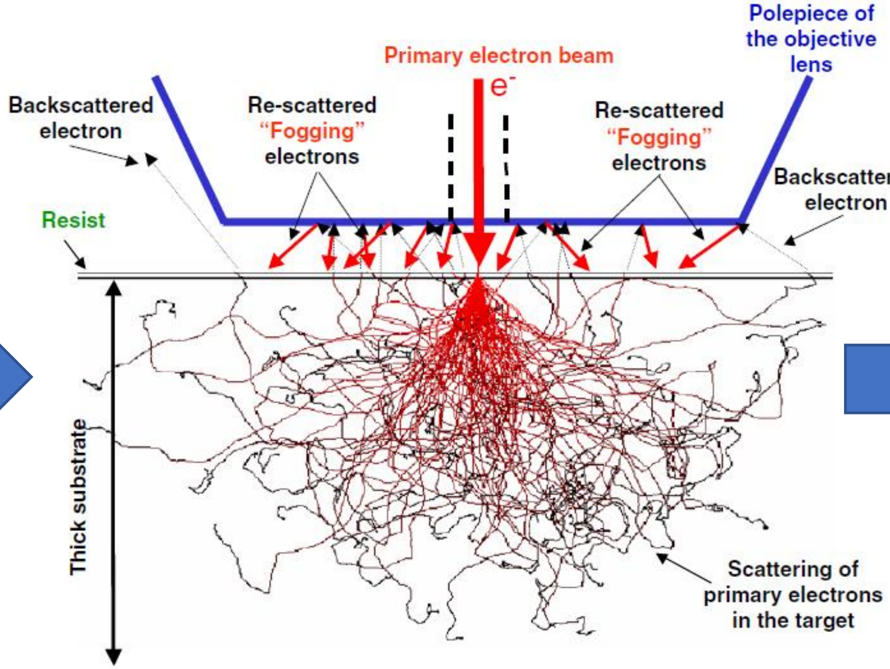
Contents

Background



https://doi.org/10.1063/1.3437589

Electron Beam Lithography

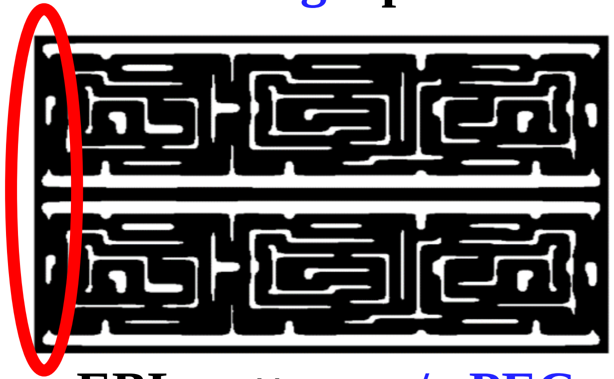


https://doi.org/10.1016/j.mee.2007.01.025

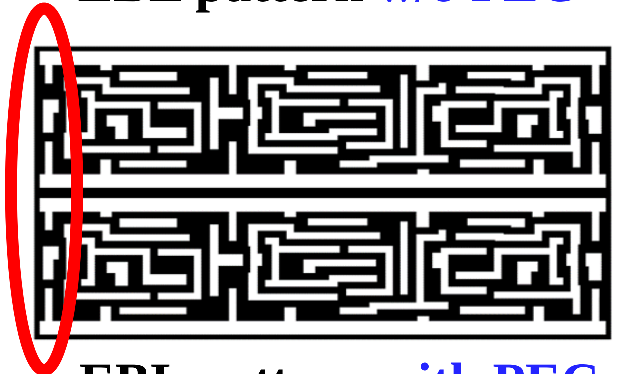
(1) proximity effect, (2) fogging effect, (3) loading effect, (4) charging effect, …

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

EBL 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 documentedpermanent residents of countries where export is permitted.

Background

Software Toolkit – HNU-EBL v1.0

PC: small memory, slow speed

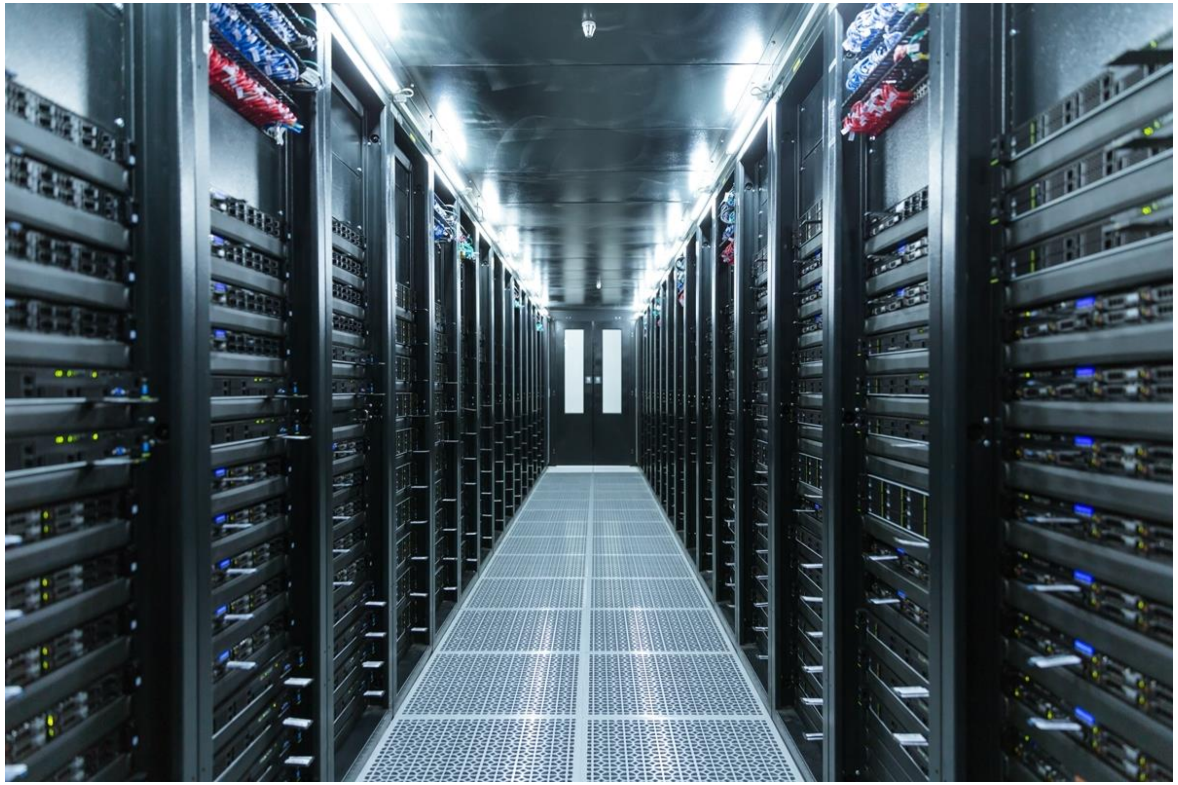
Difficult to PEC for large-scale layouts

Software Toolkit – HNU-EBL v2.0

Supercomputer: large memory, fast speed, multi-nodes

Easy to PEC for large-scale layouts

Parallelization



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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

$$E(\mathbf{r})=\iint P(|\mathbf{r}-\mathbf{r}'|)\sigma(\mathbf{r}')\mathrm{d}\mathbf{r}'$$

- Threshold development

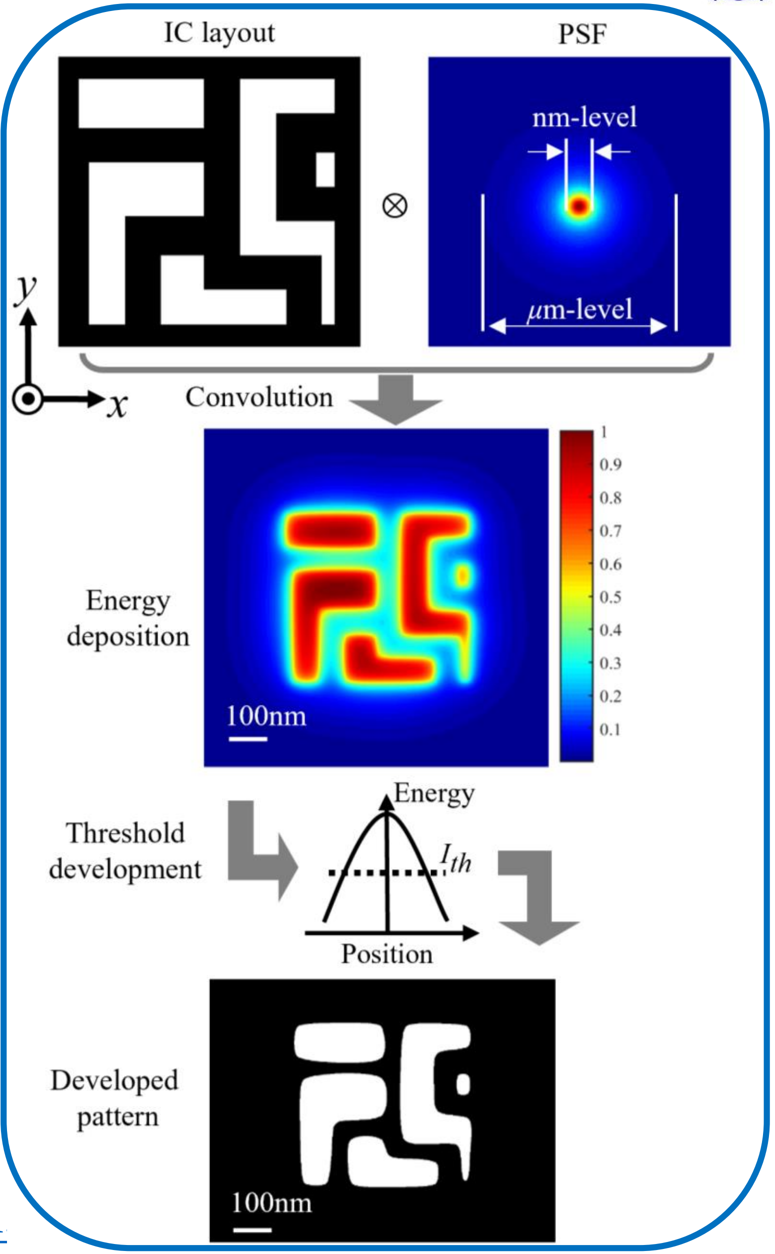
$$H(\mathbf{r})=\begin{cases}0, & E(\mathbf{r})<E_{\mathrm{thr}}\\ 1, & E(\mathbf{r})\geq E_{\mathrm{thr}}\end{cases}$$

- Mean Square Error (MSE)

$$\mathrm{MSE}=\frac{\sum_{i=1}^{N}\left(H(\mathbf{r}_i)-D(\mathbf{r}_i)\right)^2}{N}$$

- Dose correction

$$\sigma_k(\mathbf{r})=\frac{D_{\mathrm{T}}\sigma_{k-1}(\mathbf{r})}{E(\mathbf{r})}$$



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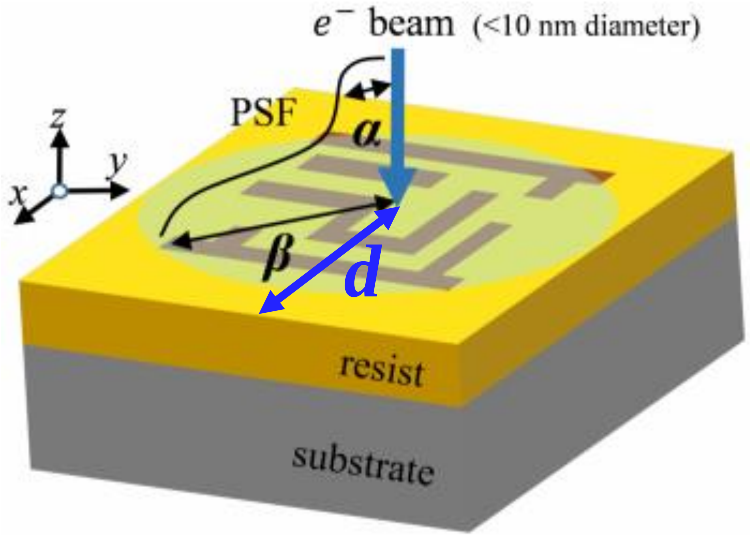
Theory

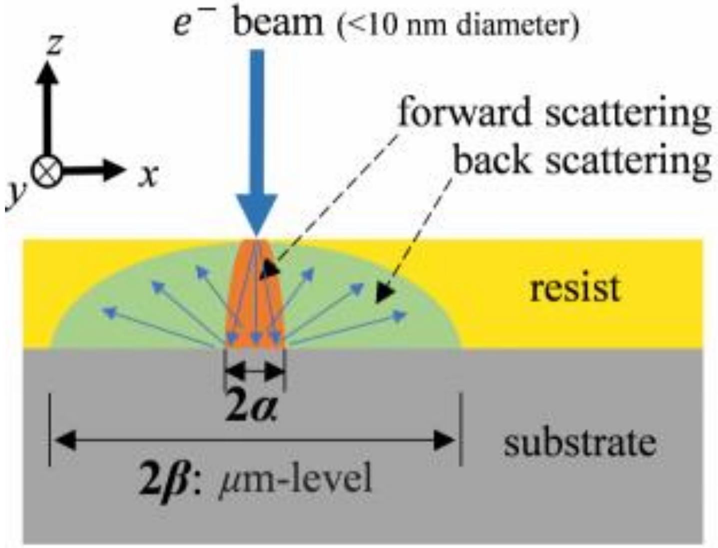
- Energy deposition in range $[-d, d]\times[-d, d]$

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

- Energy deposition error

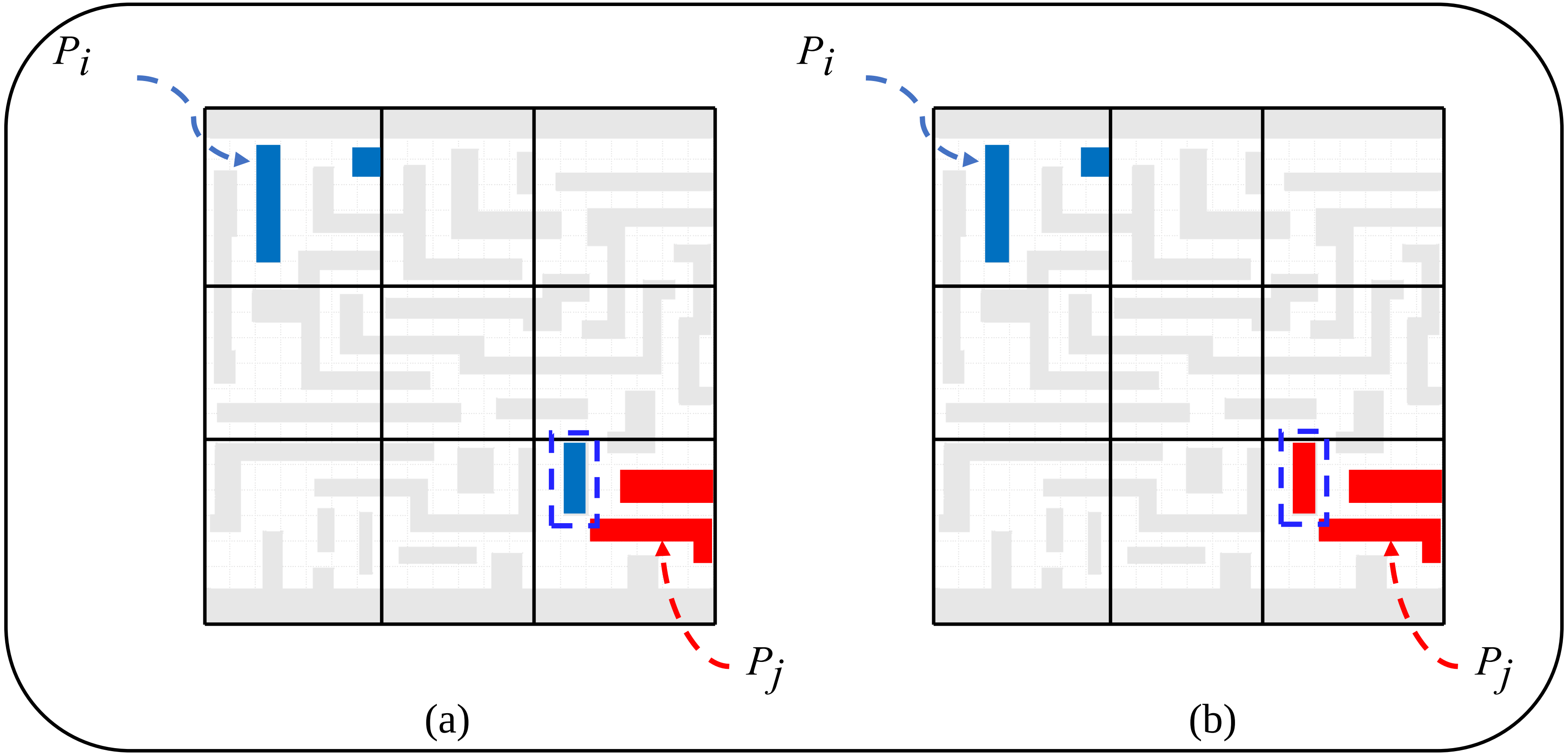
$$e=\frac{4K\sigma_{max}}{1+\eta}\left(\left(1-\Phi\left(\frac{\sqrt{2}d}{\alpha}\right)\right)^2+\eta\left(1-\Phi\left(\frac{\sqrt{2}d}{\beta}\right)\right)^2\right)$$





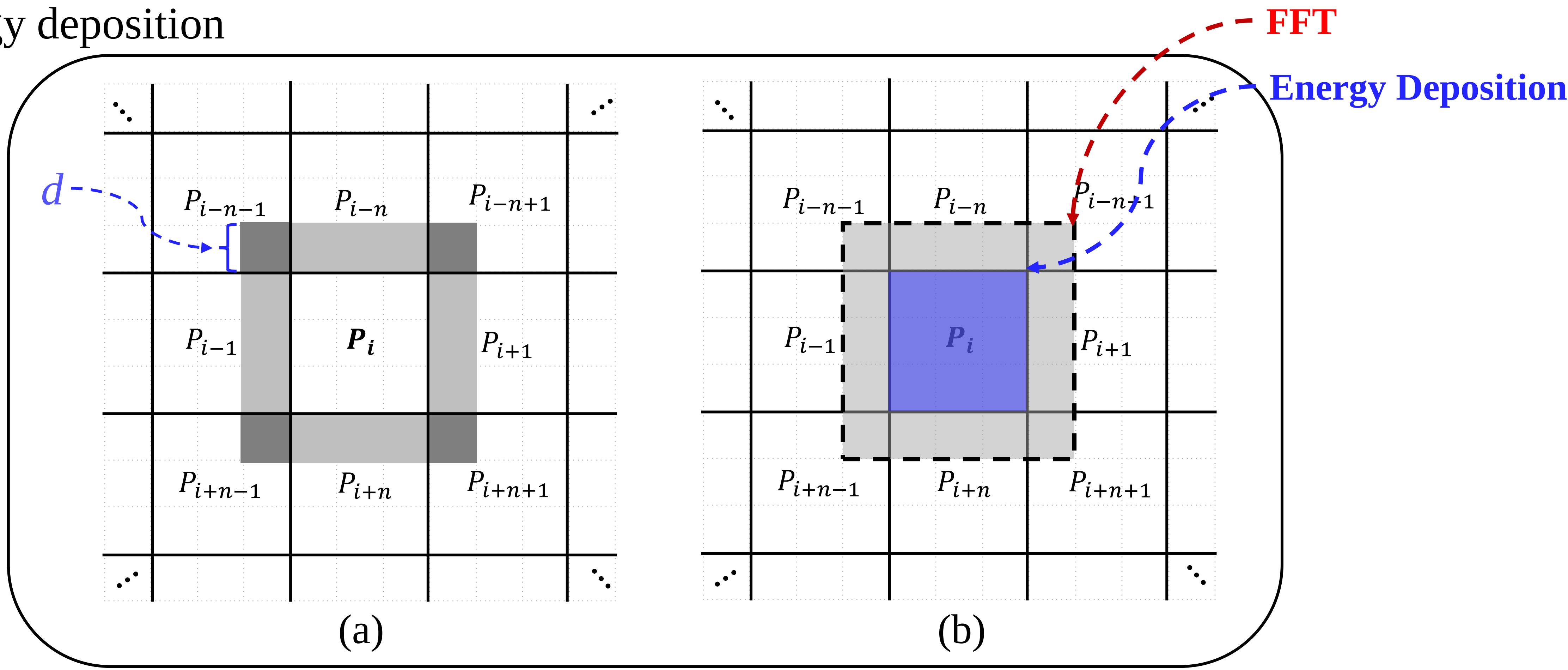
Distributed Parallel Computing Algorithm

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

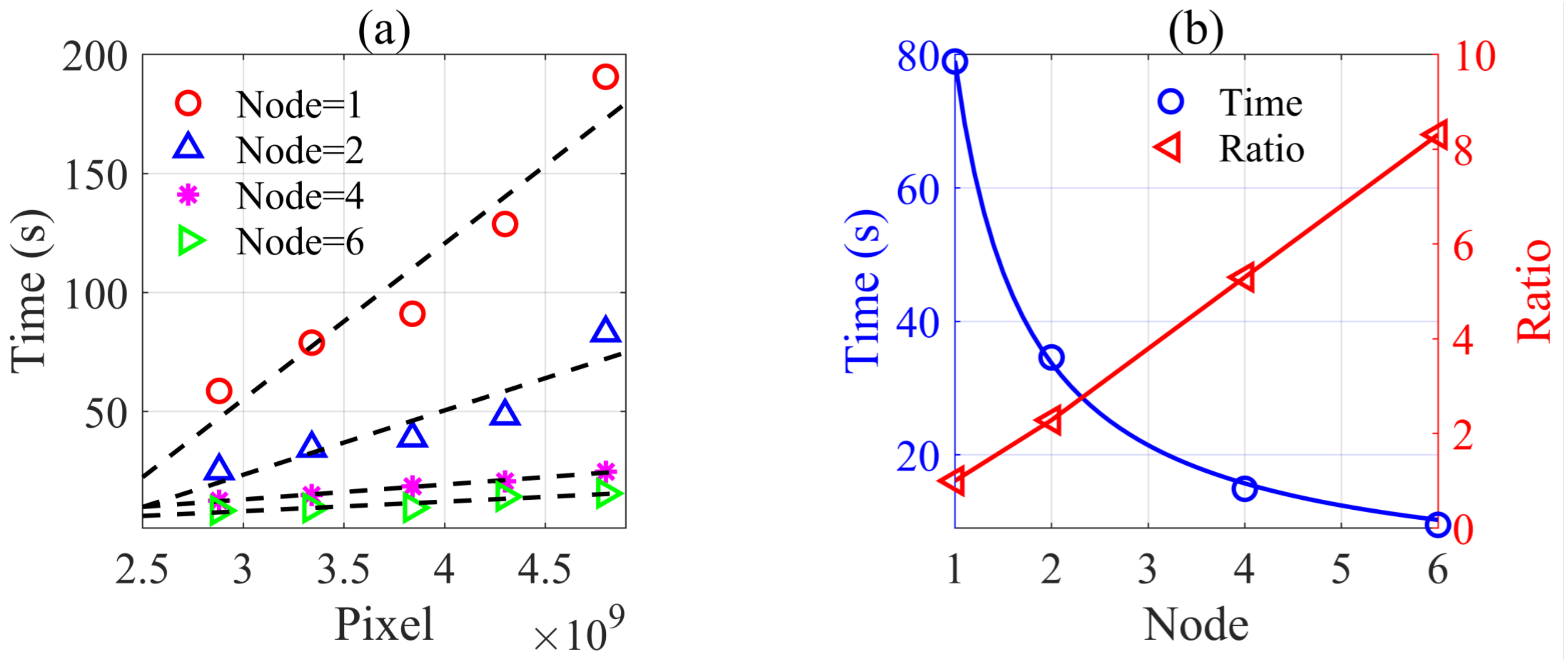


Distributed Parallel Computing Algorithm

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

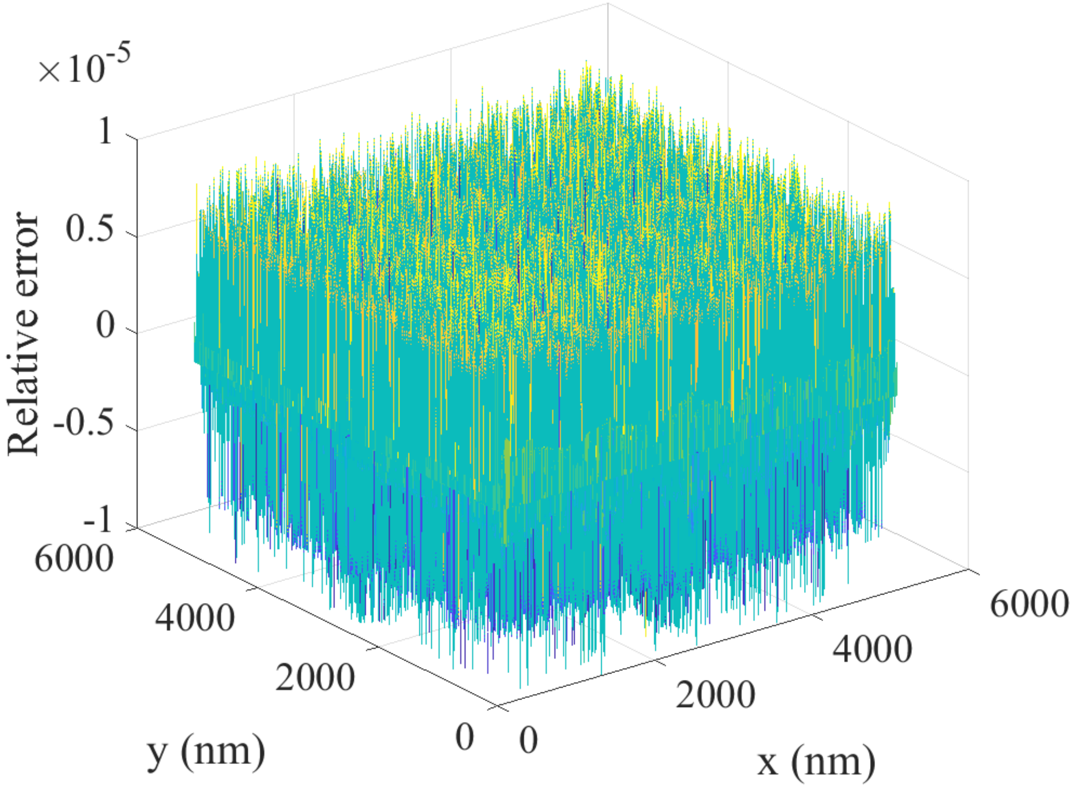


Scaling Test

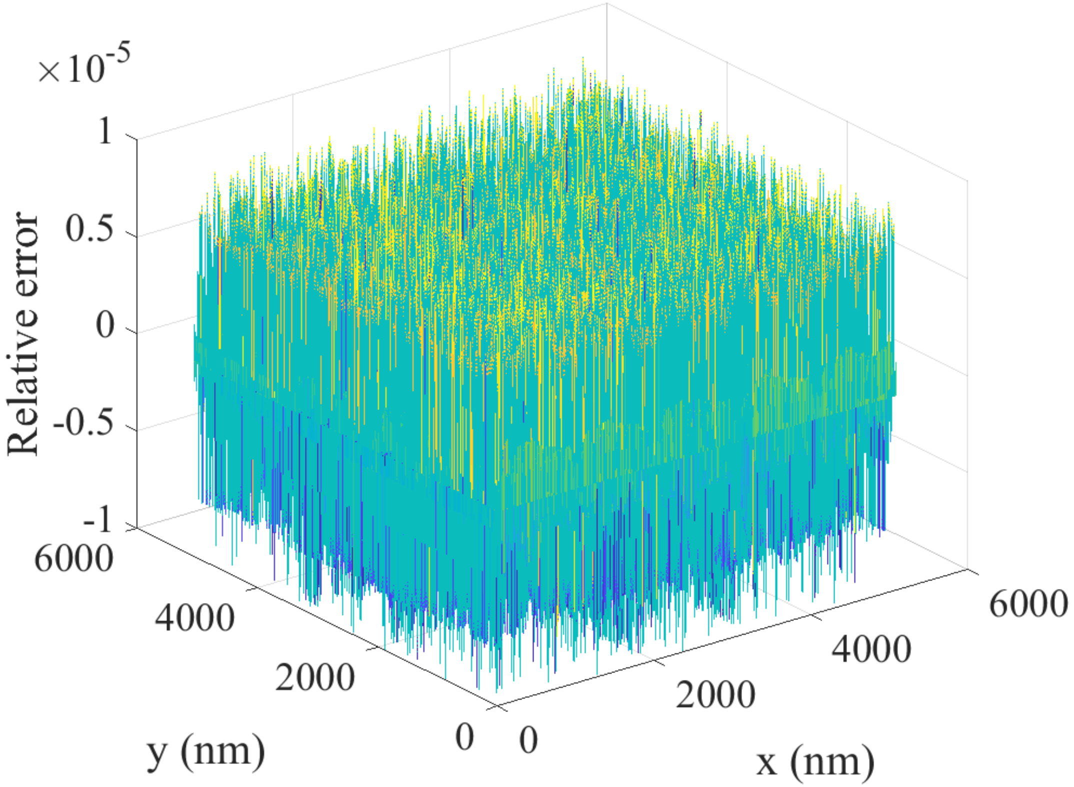


(a) In the case of several different nodes, the calculation time consumption is with the change curve of the number of pixels. (b) For a test benchmark layout, the speedup ratios under different node cases are analyzed.

Accuracy Test



(a) Nodes = 4



(b) Nodes = 9

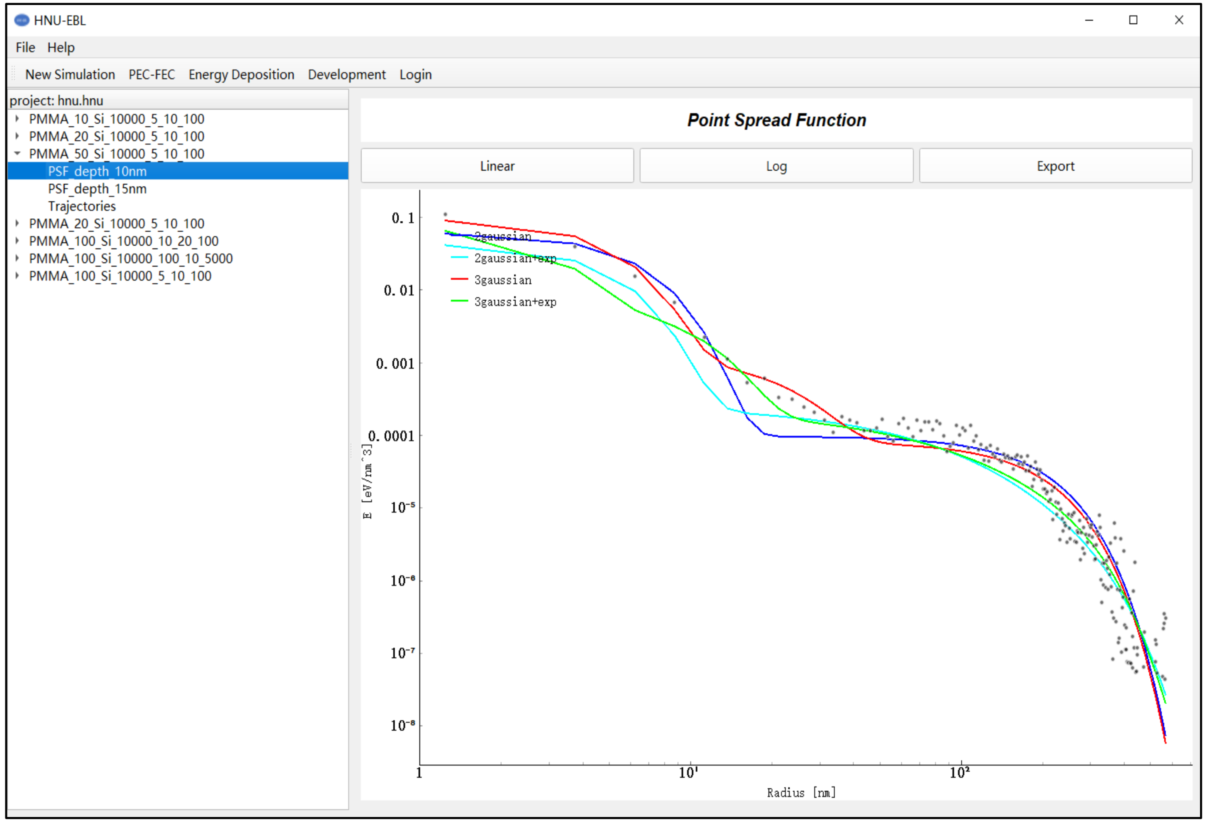
The relative error distribution between the multi-computing node and the single-computing node PEC results. (a) and (b) represent the relative errors of 4 and 9 computing nodes on the PEC of the same layout, respectively.

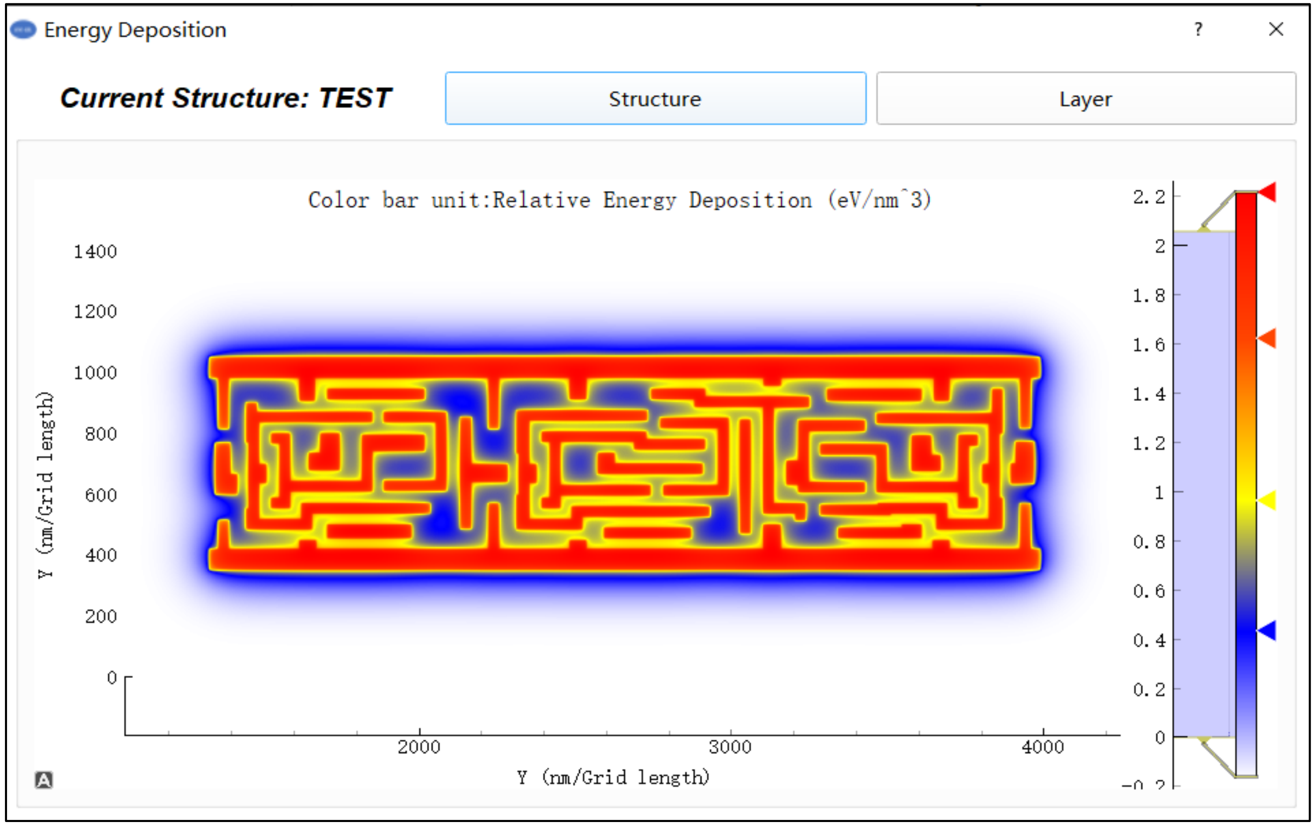
Software Toolkit – HNU-EBL v2.0

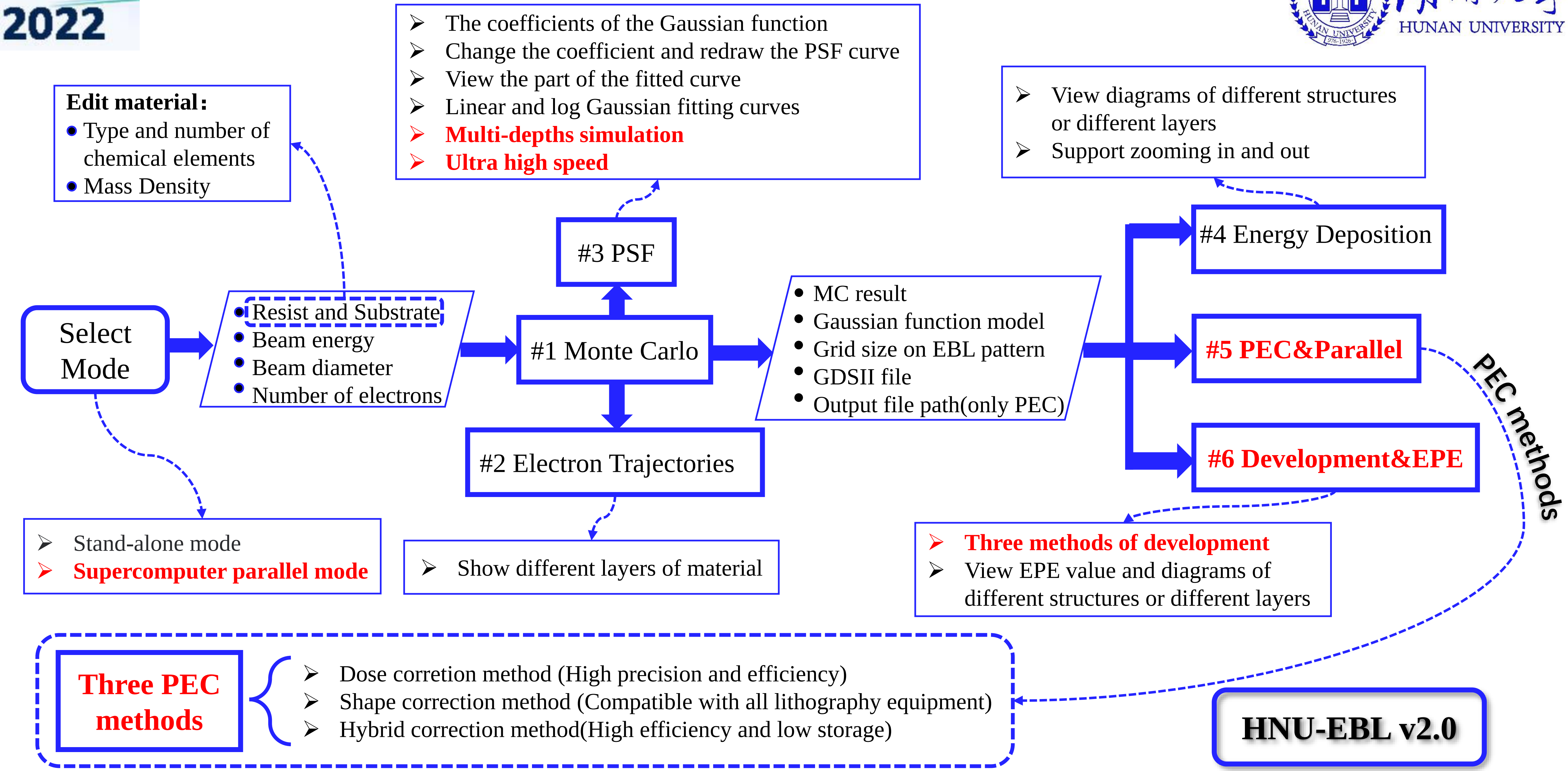
Developed from scratch at Hunan University in China

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

≈50,000 lines of C++/Python codes







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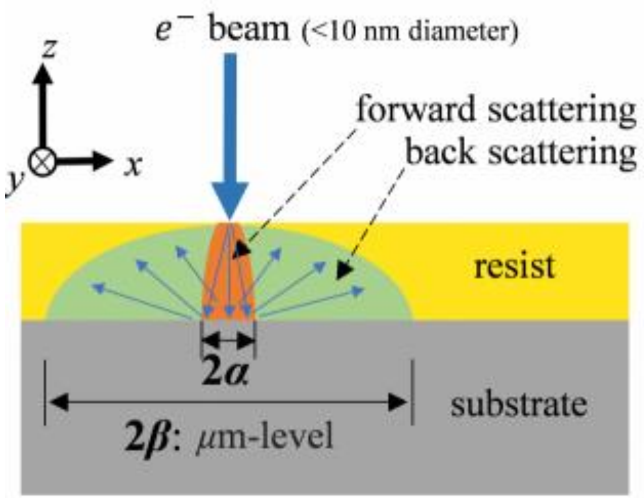
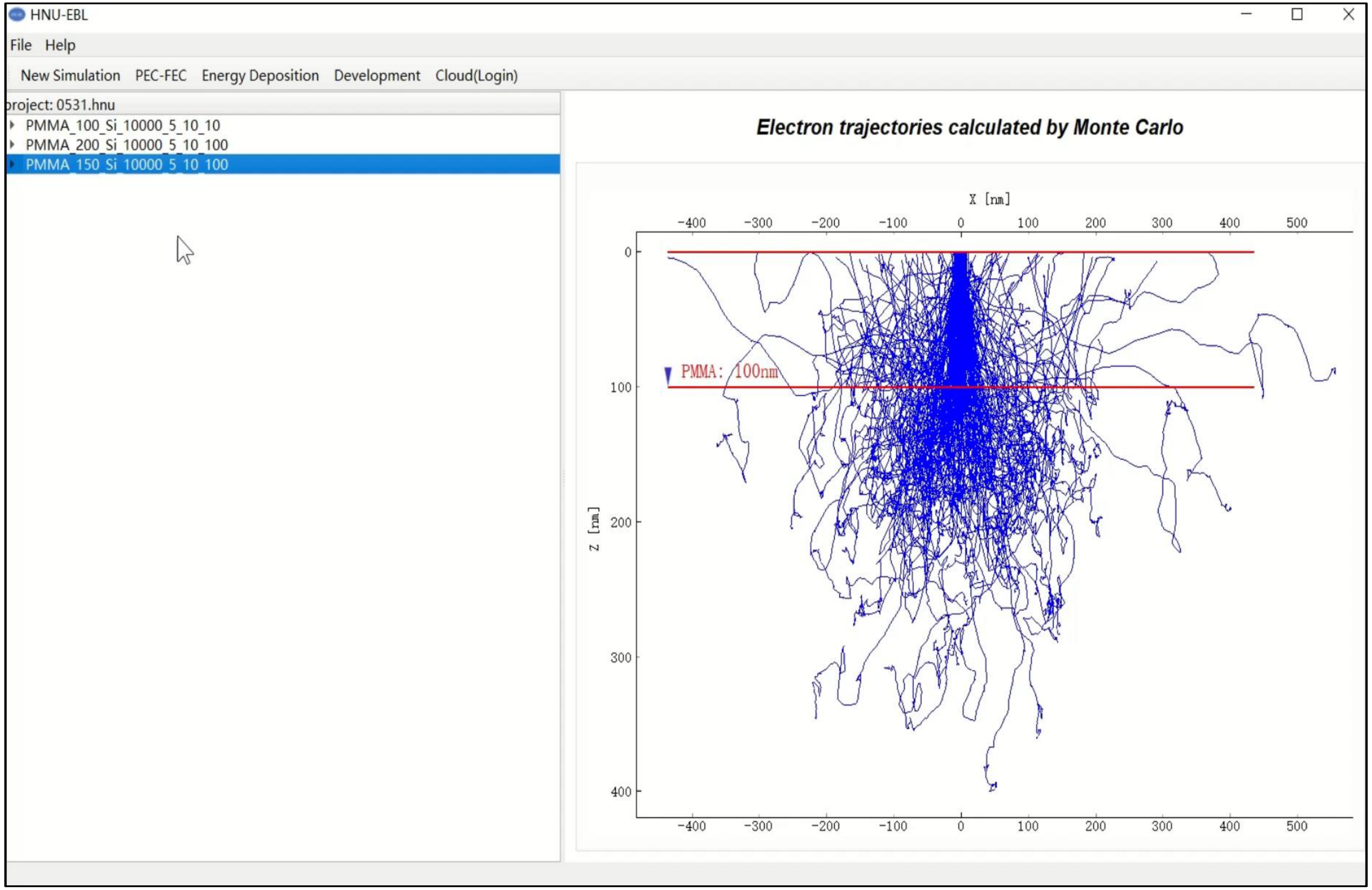
HNU-EBL v2.0

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

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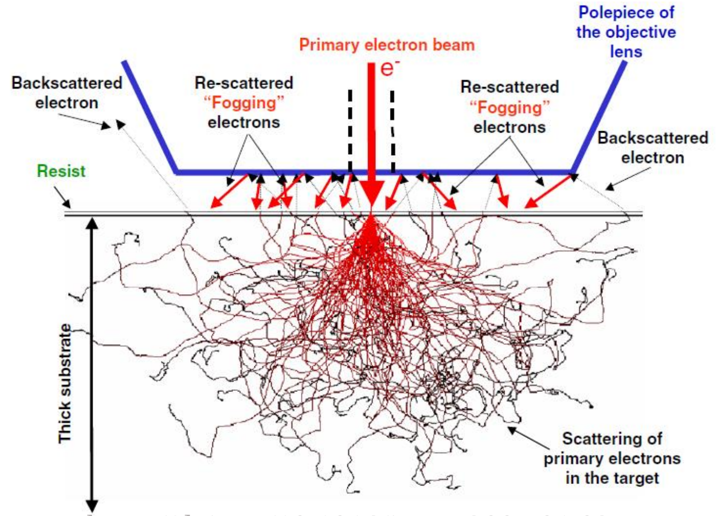
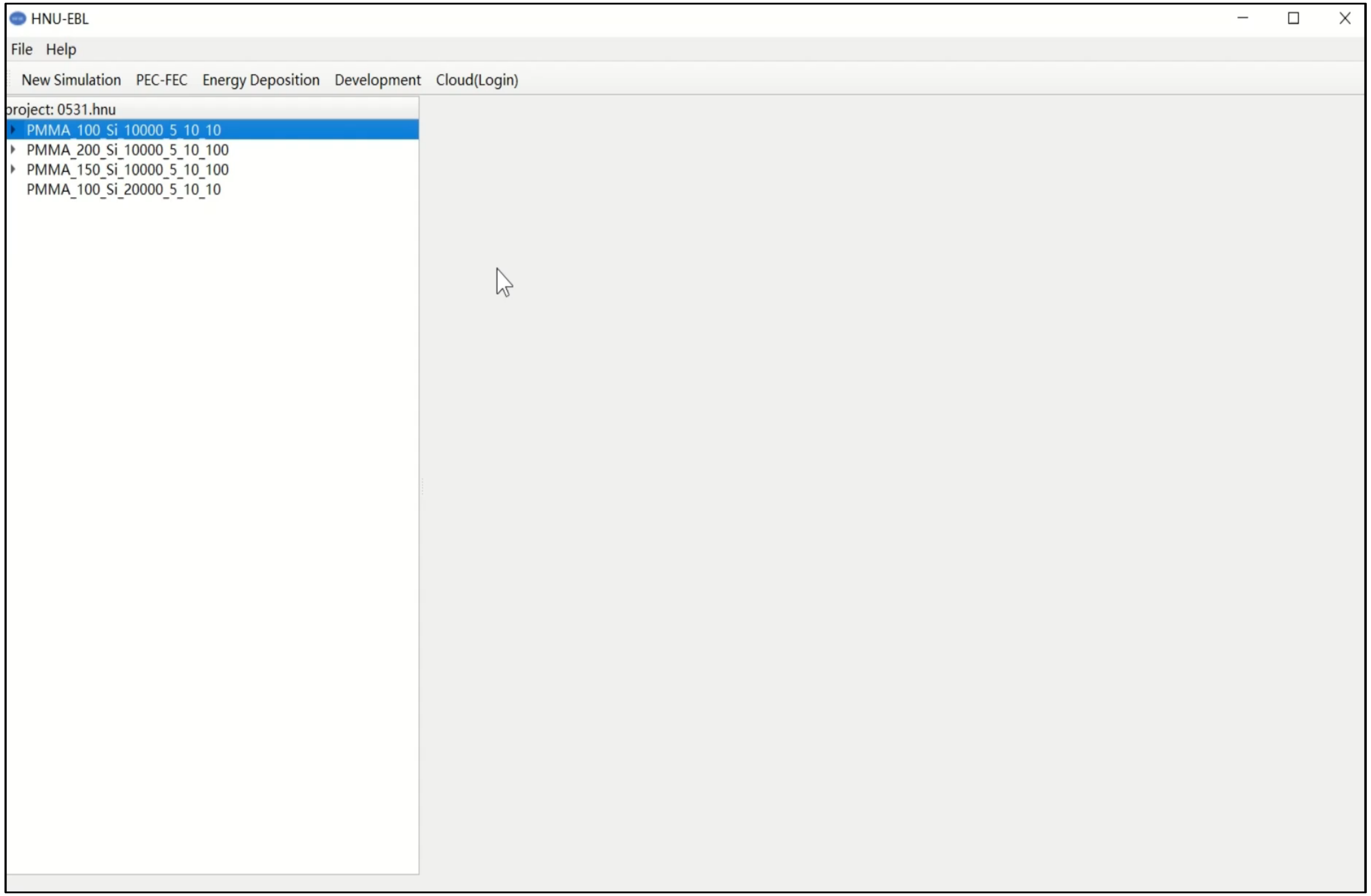
HNU-EBL v2.0

Step 2. PEC & parallel

$$E(\boldsymbol{r}) = \iint P(|\boldsymbol{r} - \boldsymbol{r}'|)\sigma(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}'$$



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

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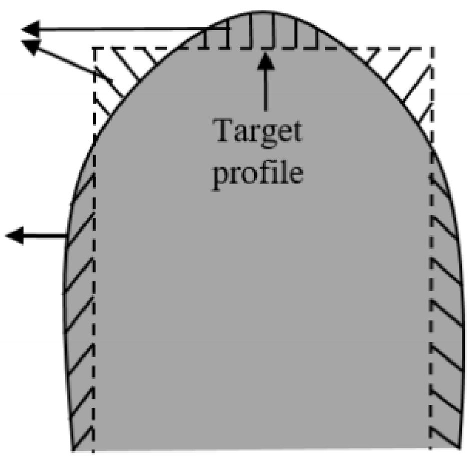
HNU-EBL v2.0

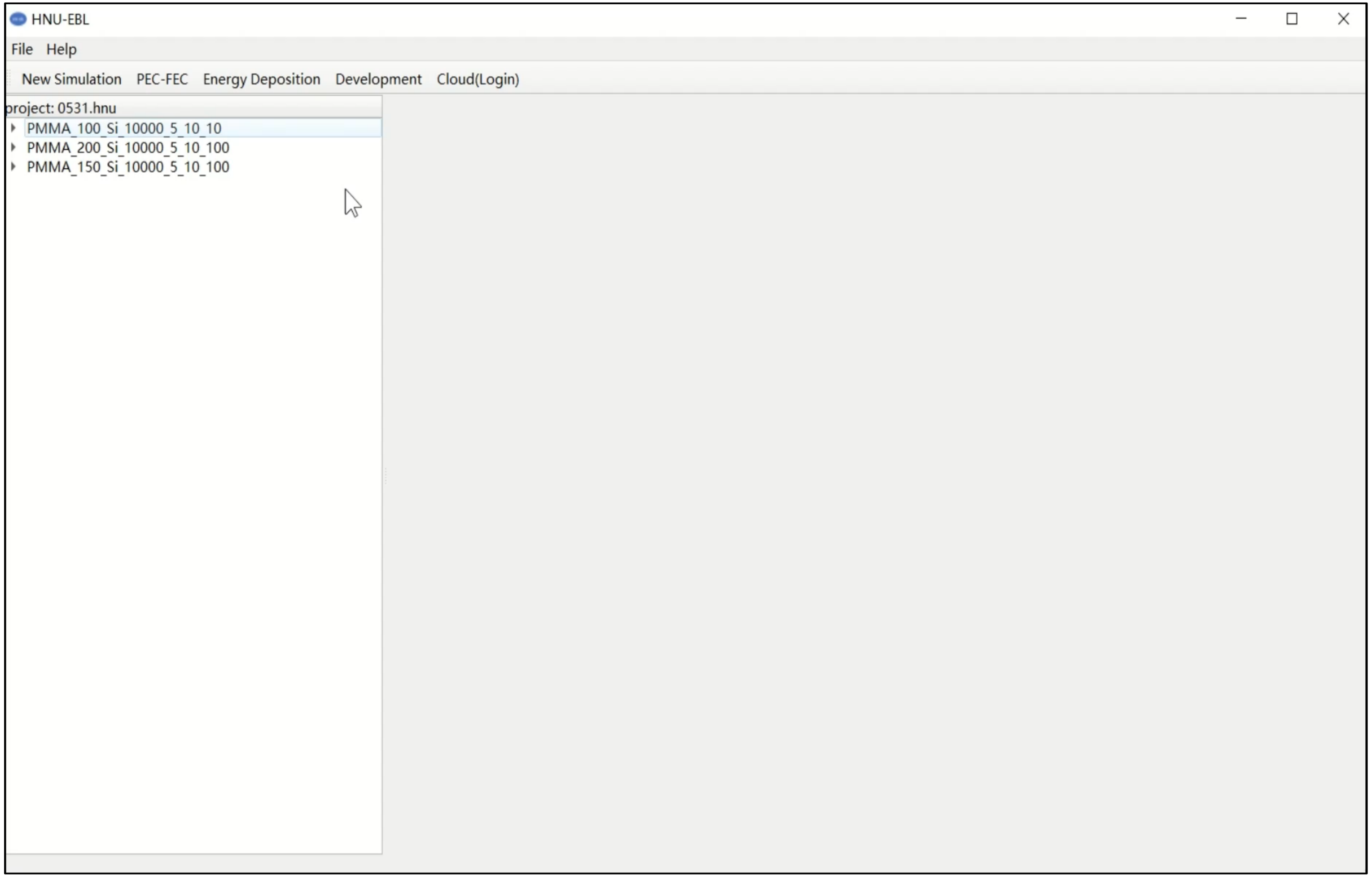
Step 3. Development & EPE evaluation

- Development model
  - **Threshold**
  - **Mack**
  - **Notch**



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

- Edge Placement Error (EPE)



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R&D Team of HNU-EBL

HNU-EBL

Role:

Software Development

Experimental Verification


Jie Liu


Huigao Duan

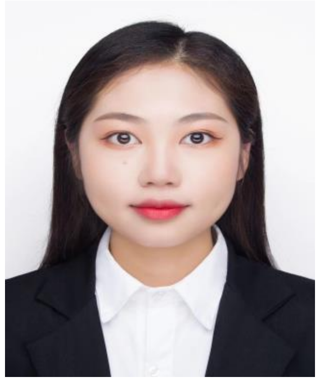

Yiqin Chen


Haojie Zhao


Wenze Yao


Hongcheng Xu


Siyuan Zhang


Yujie Yang

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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
- ……

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Thanks!

- IIPR: 4 papers + 8 patents + 5 software copyrights
- “setup.exe” of GUI-based EBL software
- 70+ pages of software user guide

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

support@ebeam.com.cn

jie_liu@hnu.edu.cn