Satoshi Shimizu
March 11th 2022

Laser Lithography

レーザーグレースケール露光及びバイナリ露光のため描画データ最適化のご紹介

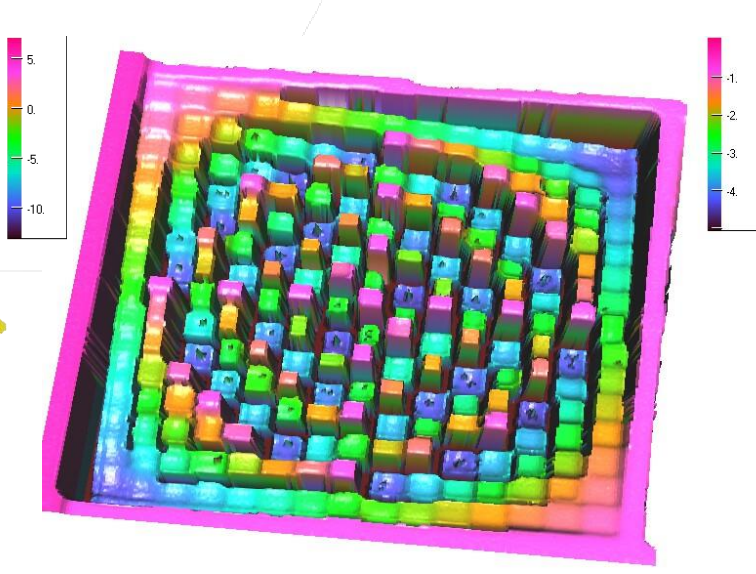
GenISys株式会社 清水 諭

Agenda

・三次元構造物の作製やバイナリマスク描画などを念頭においてレーザー描画が昨今活用されています。

・描画においては、ガウス分布するレーザー光の重なりとその光量の強弱によって、現像後のレジストパターンのサイズやコーナー出し、あるいは三次元の場合には高さも含めて制御を行う手法は、時に多くの技術的知見や経験を要します。

・本講演では、データ準備の観点から所望の設計構造物を念頭においた描画データ最適化の手法をご紹介します。

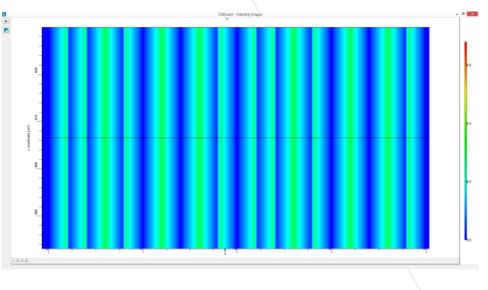


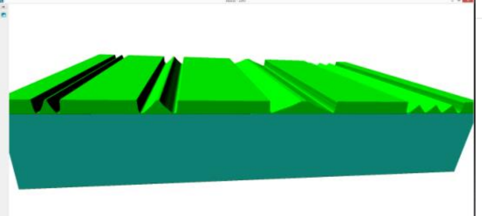
Heidelberg Instruments and GenISys Announce Cooperation on Maskless Laser Lithography

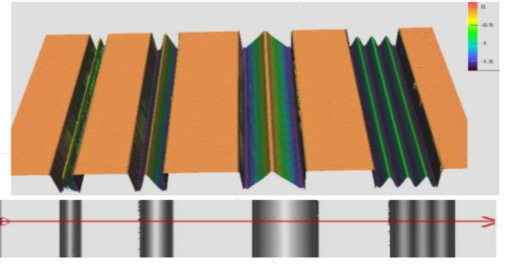
Heidelberg, GERMANY, October 21, 2014 – *Heidelberg Instruments,* a leading supplier of equipment and process solutions for laser lithography related markets and GenISys GmbH, a provider of high-performance software solutions for nanoscale fabrication, today announced a cooperation agreement to combine the Heidelberg Instruments laser lithography tools with the GenISys data-preparation, simulation and process correction software packages of BEAMER™ and LAB™.

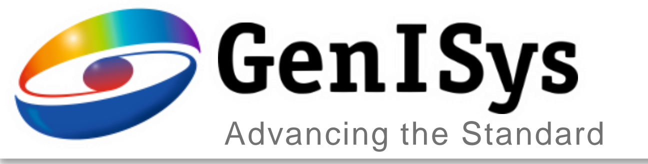
Within the cooperation GenISys BEAMER™ has been adapted to support Heidelberg Instruments laser exposure systems with advanced layout data preparation. The 3D simulation software LAB™ has been extended to model the exposure of HIMT laser systems in 3D, enabling a subsequent simulation of the resist process. Both parties have joined forces to market the Heidelberg systems with the GenISys lithography software packages. The combination of advanced lithography equipment and powerful data preparation, simulation and process correction software is a key success factor for cost effective process and device development for the end user.

……









AIST TIA Central Office

TIA推進センター

TIA Central Office

GenISys offers software solutions for optimization of micro and nano fabrication processes

Company:

- Founded in 2005
- Headquartered in Munich, Germany
  - Expert team for lithography software development
- Subsidiaries in USA-California, **Japan-Yokohama**
- Global Technical Support
- Fast, Flexible, Responsive

Foto Sterflinger

Products

Electron and Laser Beam Direct Write Software

- Market leader for Gaussian beam direct write systems
- Installed at most major nano-fabrication centers worldwide
- Has become a MUST for advanced e-beam lithography

BEAMER

Monte Carlo simulation software

- MC- Simulation of electron distribution for e-beam lithography modeling and correction
- Process Calibration, PSF visualization, extraction and management

TRACER

3D lithography simulation & OPC software

- Proximity Lithography (mask aligner) & Projection Lithography (stepper / scanner)
- Electron Beam Lithography
- Laser Beam Lithography (Heidelberg Instruments laser systems)

SEM Image Analysis & Metrology

- Metrology software for SEM

Our customers

> 500 commercial licenses in World Wide

- > 230 BEAMER (83 EU, 80 APAC, 70 US/CA)
- 140 TRACER
- 65 LAB
- 30 ProSEM

Europe & Middle East

Asia-Pacific & Japan

United States & Canada

De facto standard EBL software for Gaussian tools

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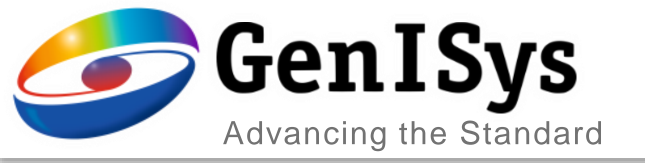
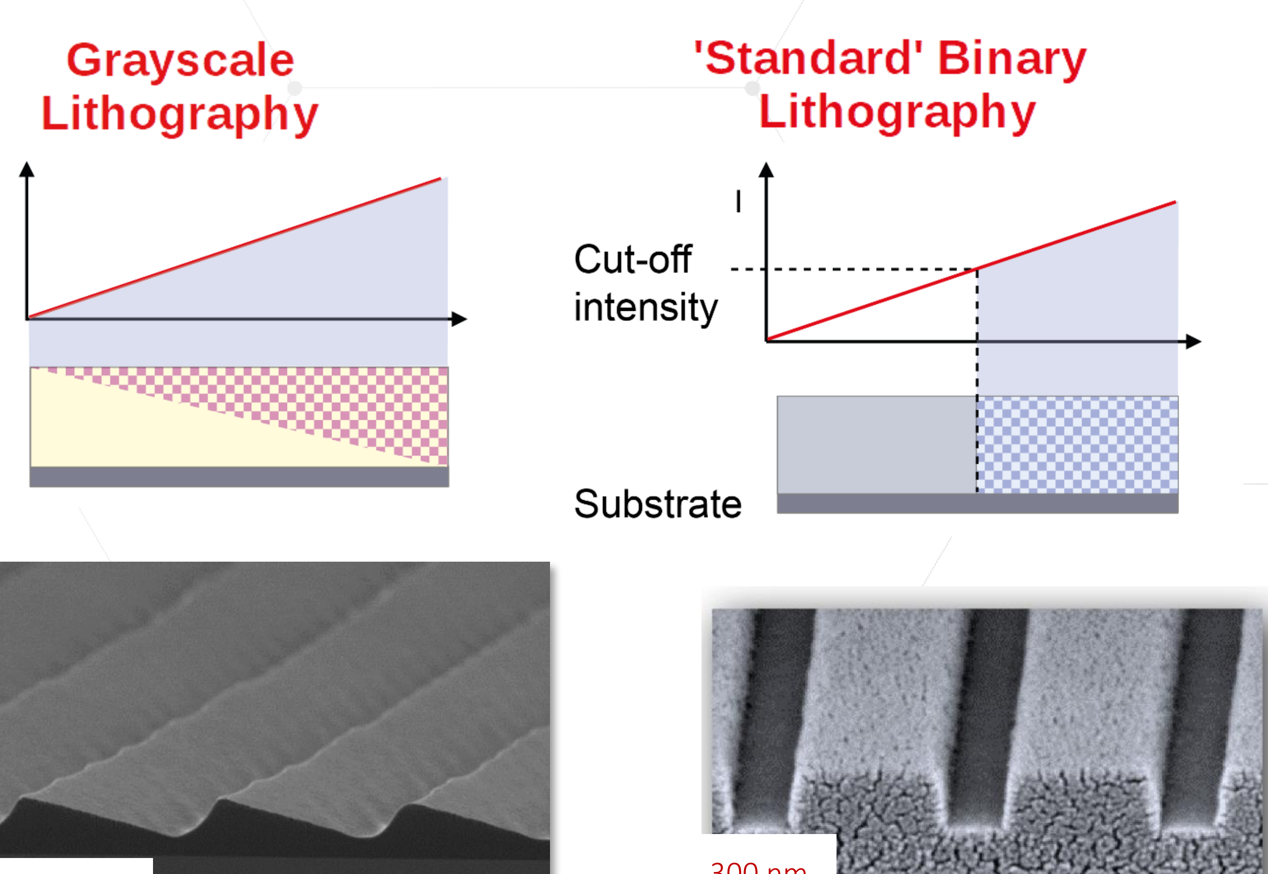
- レーザー描画概要
- バイナリ露光の為の「Model-OPC」及び「Rule-OPC」補正
- グレイスケール露光の為のドーズ量最適化補正
- まとめ



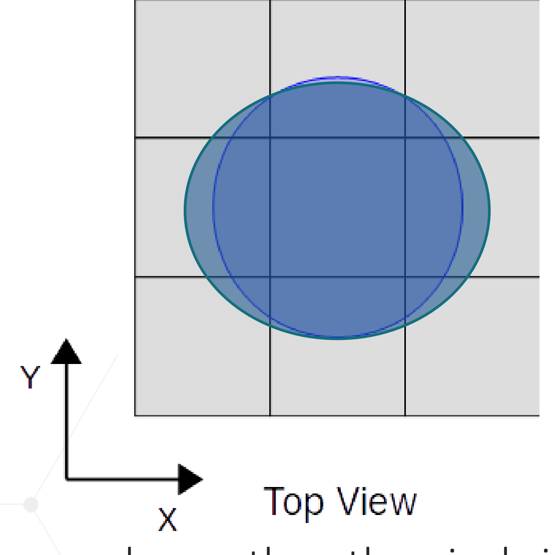
Greyscale vs. Binary

- Standard binary laser lithography sounds rather „simple“ (compared to greyscale)
  - Increase the intensity above dose to clear of the resist
  - Resist will be cleared in exposed area, remain on unexposed area (for positive resist)

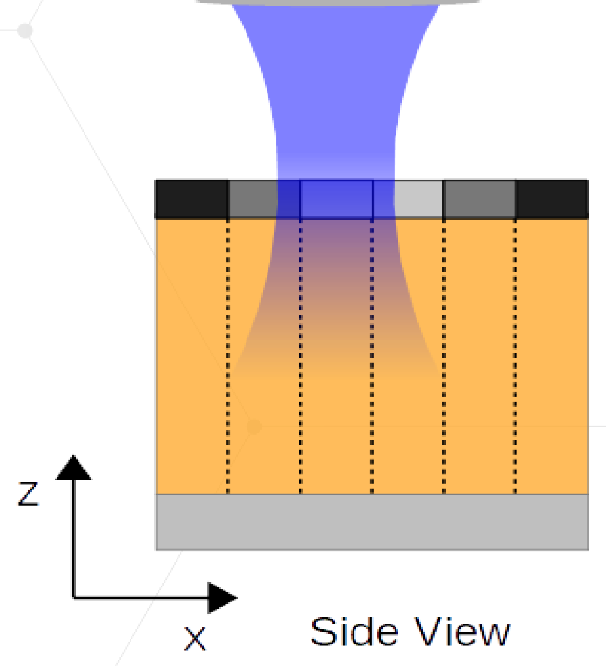


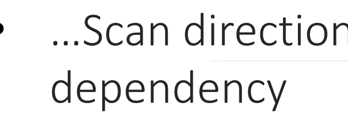
Proximity & Process Effects

- Unfortunately nothing is binary in lithography
  - Beam has a „blur“ (shape) which spreads the intensity radially, not necessaraly radial-symetric
  - Exposure is on a pixel grid, typicall much smaller than the beam
  - x/y dependency by scan / step
  - Beam is focused to one plane, depth of focus is NA dependent (write head)
  - Resist is not fully transparent, mostly bleaching, leading to depth dependent intensity



- ...larger than the pixel size
  x-y may be different
  (not to scale!)





- ...Scan direction dependency

Analysis using 3D Laser Simulation

Layout

Laser Beam Lithography
Source
Modulator
Deflector
Lens
SiO2
Substrate

Laser Exposure

3D Bulk Intensity

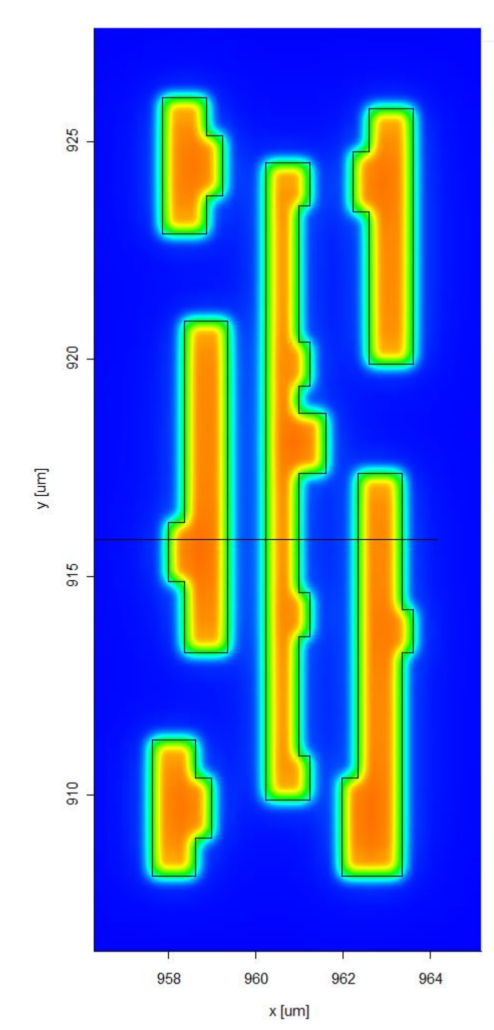
3D Concentration

3D Resist

LAB

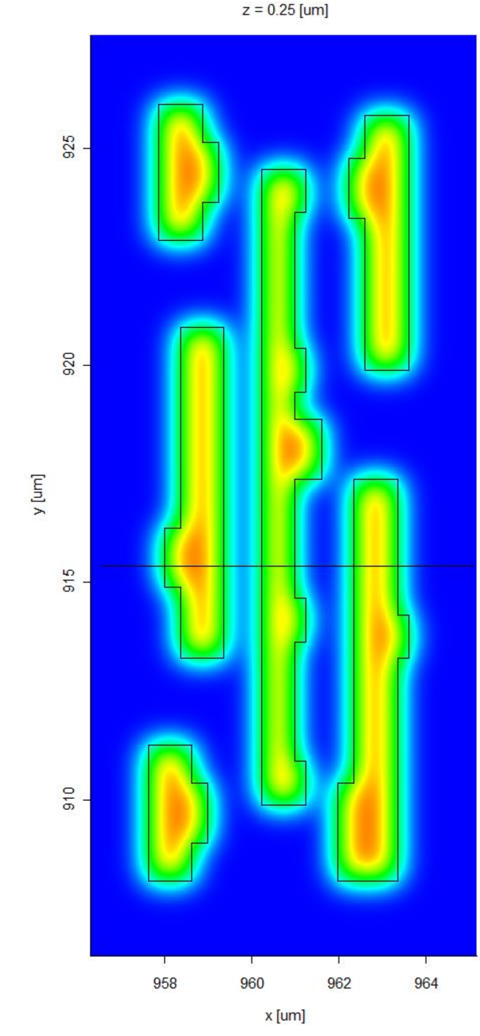
Optical Proximity Effects

- Small Beam Size (0.4 µm)



Optical Proximity Effects

- Midium Beam Size (0.8 µm)



Optical Proximity Effects

- Large Beam Size (1.2 µm)

GenISys
Advancing the Standard

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  - Model OPC : 露光物理モデルによる全体形状補正
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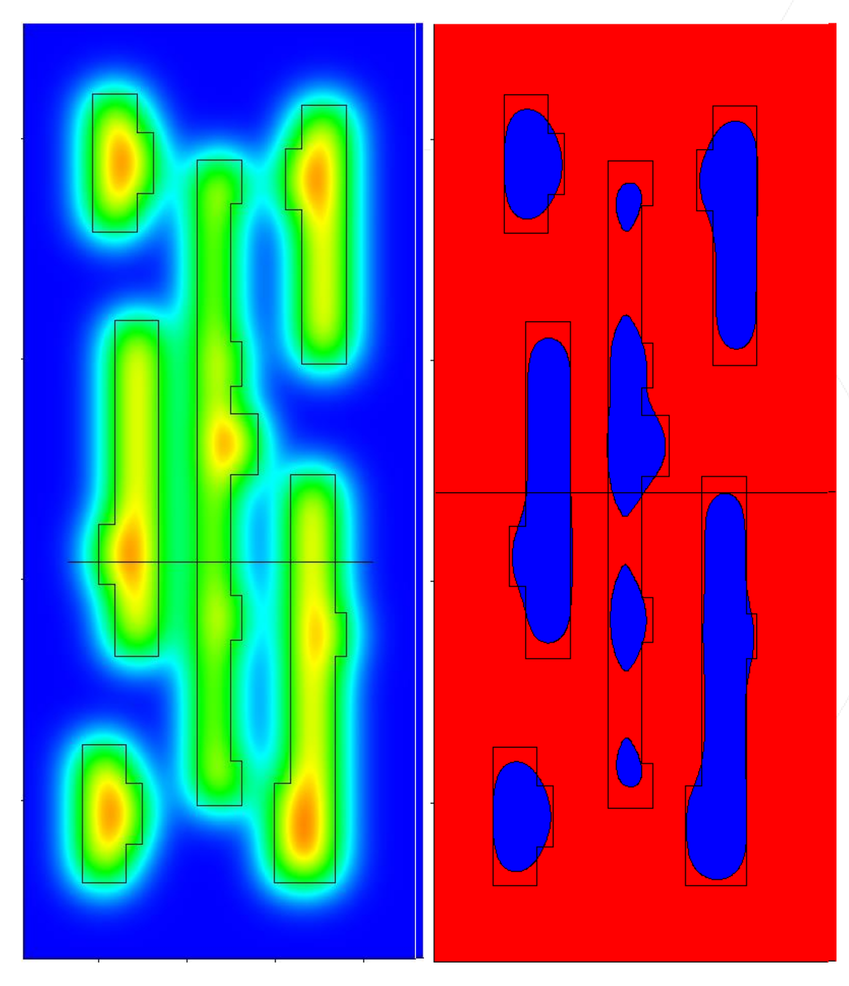
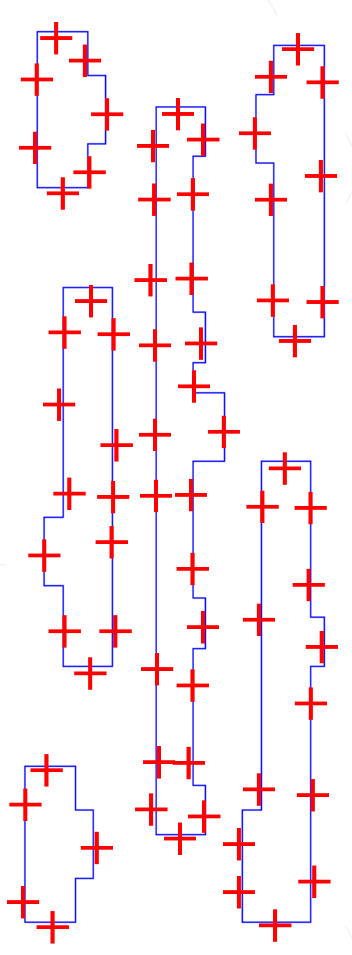
Self consistent edge equalization method

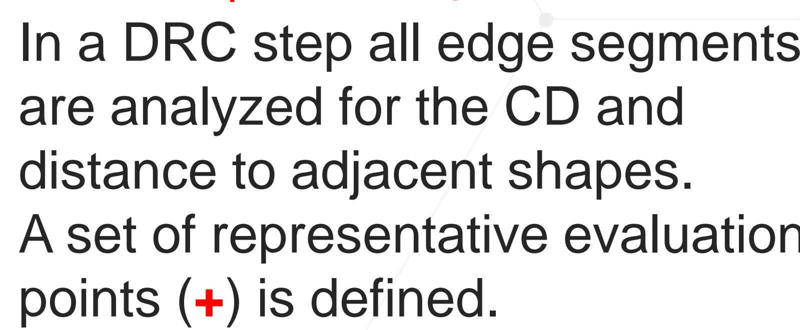
Each bias adds or subtracts exposed area : energy at the evaluation point is changed until a self consistent solution has been found.

Shape PEC / Model OPC principle

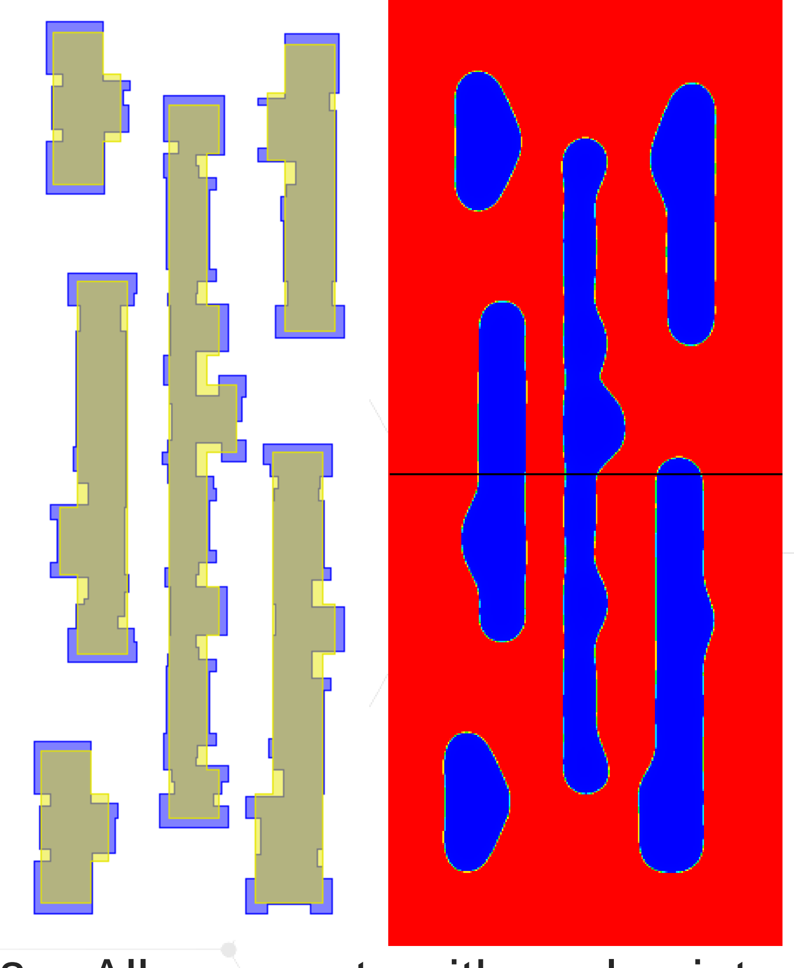


To solve:
Intensity at layout edges are not equal
- ➢ resist edge does not match layout edge
- ➢ Move edges locally to get equal intensity





In a DRC step all edge segments are analyzed for the CD and distance to adjacent shapes.
A set of representative evaluation points (+) is defined.



All segments with eval points are moved iteratively to adjust intensity at target layout edge to get equal

Model Based Correction for L&S

In GDSII

Shape-PEC

Out GDSII

10um

5um

3um

2um

1um

iso gap

1:1

1:3

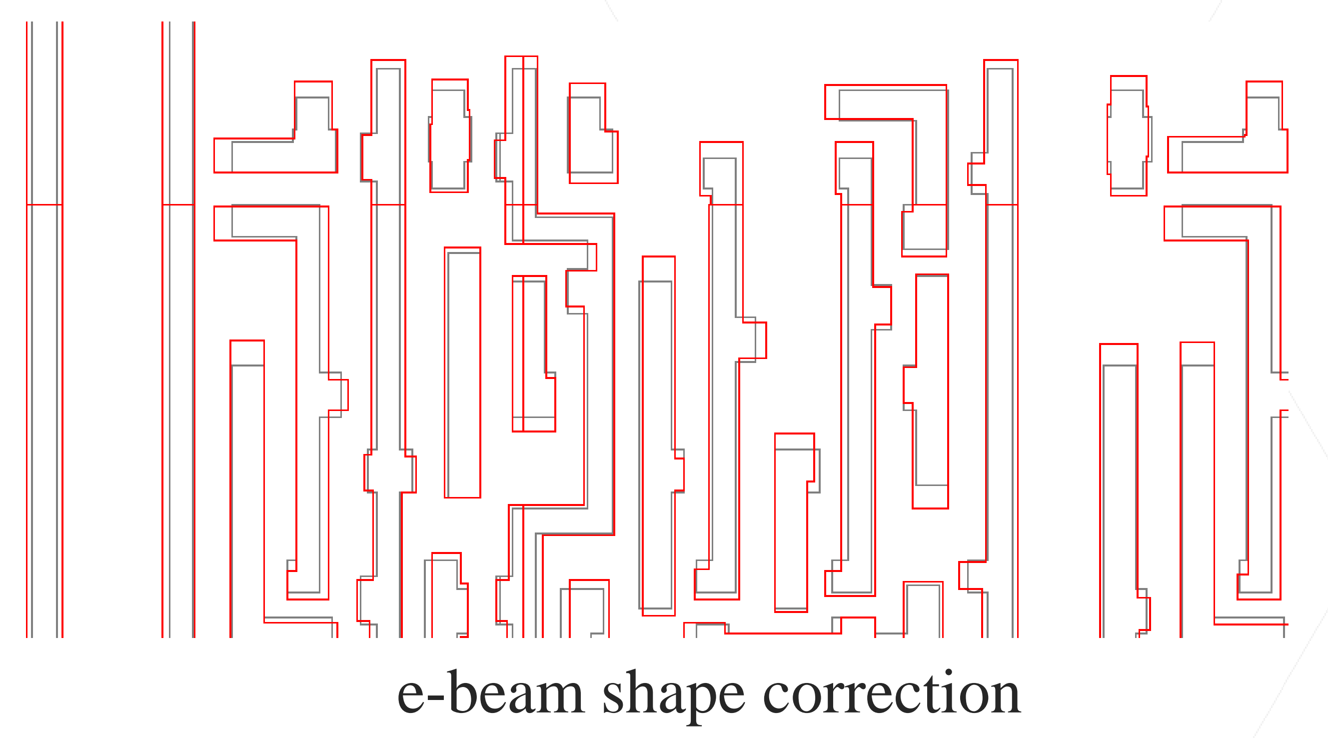
1:5

1:10

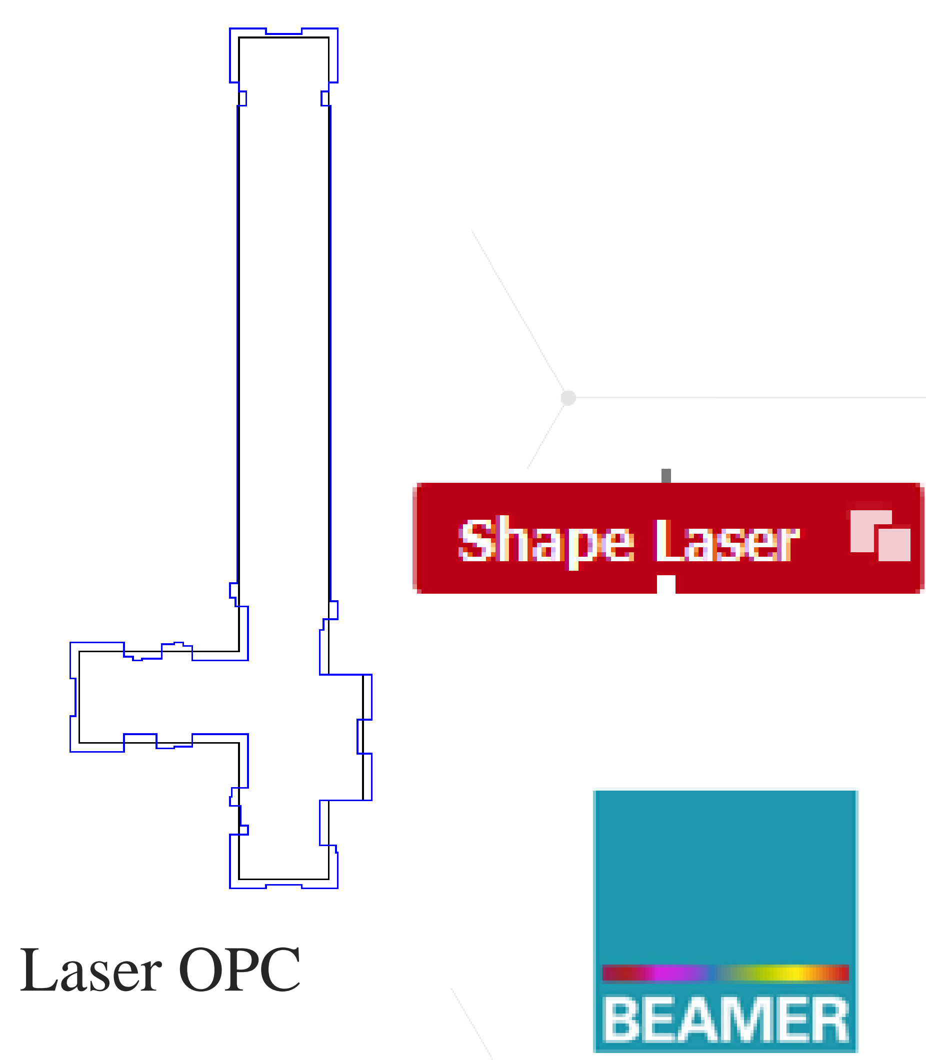
iso line

Model Based Correction for L&S

- Short and Mid-range effects are corrected by modifying the layout (instead dose modulation)
- Same supports OPC for laser writing



e-beam shape correction



Laser OPC

Model Based Correction for L&S

In GDSII

Shape-PEC

Out GDSII

2.0um

Shape Proximity Effect Correction

General | Accuracy | Advanced | Label/Comme...

Correction Layer Selection

Layer(s): *

Tool

- E-Beam
- (●) Laser

Laser Beam Size FWHM [um]: 0.6

Dose Factor: 1.5

Shape Proximity Effect Correction

General | Accuracy | Advanced | Label/Comment | Quick Access

Options

- (●) Overdose/Undersize
- Shape

- [ ] Process Loading Effects — Loading Settings...
- [ ] Etch Bias Open Area inside — Etch Settings Inside...
- [ ] Etch Bias Open Area outside — Etch Settings Outside...
- [ ] Etch Bias Contrast — Etch Settings 2...
- [ ] Etch Bias Curvature — Etch Settings 3...
- [ ] Etch Bias Density — Etch Settings Density...
- [ ] Write Convergency Information in additional Layer
- [ ] Blur Dependency of Shape — Blur Variability...

Model Based Correction for L&S

In GDSII
Shape-PEC
Out GDSII

2.0um

Shape-PEC

1.89um

Shape Proximity Effect Correction

General | Accuracy | Advanced | Label/Comme...

Correction Layer Selection

Layer(s) *

Tool

E-Beam ◉ Laser

Laser Beam Size FWHM [um] 0.6

Dose Factor 1.5

Shape Proximity Effect Correction

General | Accuracy | Advanced | Label/Comment | Quick Access

Options

◉ Overdose/Undersize ○ Shape

- ☐ Process Loading Effects — Loading Settings...
- ☐ Etch Bias Open Area inside — Etch Settings Inside...
- ☐ Etch Bias Open Area outside — Etch Settings Outside...
- ☐ Etch Bias Contrast — Etch Settings 2...
- ☐ Etch Bias Curvature — Etch Settings 3...
- ☐ Etch Bias Density — Etch Settings Density...
- ☐ Write Convergency Information in additional Layer
- ☐ Blur Dependency of Shape — Blur Variability...

ProSEM - Batch Mode Measurement

SEM Image | Lines & Spaces Table

Image	Group ID	Measurement ID	Validation	CD Mean[um]	CD StdDev[um]	CD Min[um]	CD Max[um]	Quality	E0 Fit Error Mean[um]	E0 Fit Error StdDev[um]	E0 LER 3-Sigma[um]
Dose_080	Lines & Spaces	M_1	Success	0.2082	0.0007	0.2064	0.2101	0.9953	0.0006	0.0004	N.A.
Dose_100	Lines & Spaces	M_1	Success	0.2243	0.0008	0.2215	0.2265	0.9950	0.0006	0.0005	N.A.
Dose_120	Lines & Spaces	M_1	Success	0.2373	0.0006	0.2353	0.2391	0.9964	0.0005	0.0004	N.A.
Dose_140	Lines & Spaces	M_1	Success	0.2402	0.0008	0.2381	0.2423	0.9957	0.0005	0.0004	N.A.
Dose_160	Lines & Spaces	M_1	Success	0.2443	0.0007	0.2423	0.2461	0.9961	0.0005	0.0004	N.A.

Results

1um Model
2um Model
10um Model
1um no Correction
2um no Correction
10um no Correction

Difference (um)

0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15

Target CD

iso-line
1:10
1:5
1:3
1:1
Pad

Exposure : MLA 150
write head = 4mm,
80mJ/cm^2

Resist : AZ1500 positive,
500 nm thickness.
on Cr/SiO2 substrate

Development : AZ 400K
(1:4 dilution) for 1 min.

Results

Line width:
1, 2 and 10um

Model correction results in improved CD linearity in the various CD and pattern density range.

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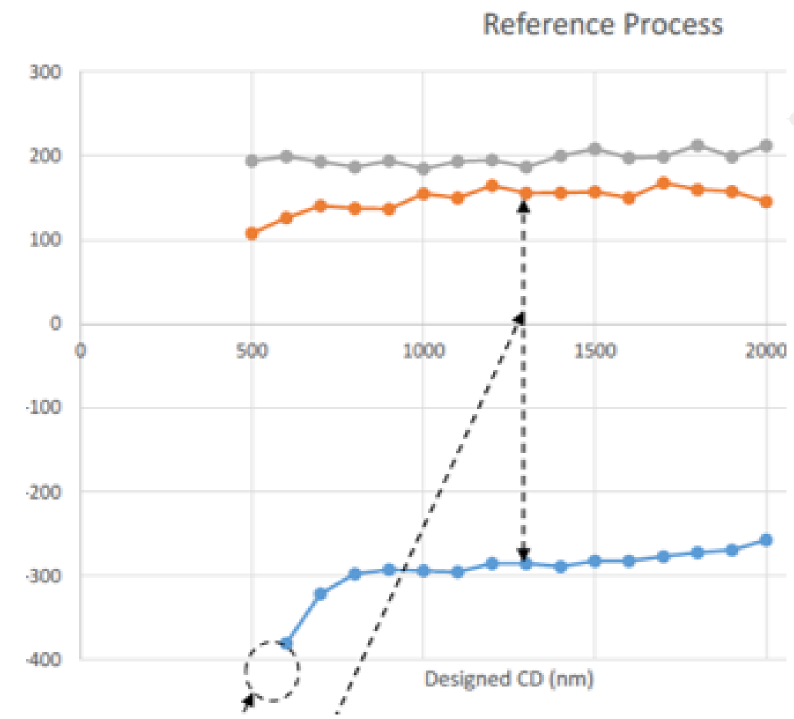
Laser Binary Exposure & Process Distorsion

CD variation

- Size → CD linearity
- Density → Iso-dense bias
- X-, Y- direction
- Angle dependent

Source:
IMS Chips Stuttgart

Rule Based OPC



Action

- Bias
- Serif
- Hammerhead
- Bar

Rule based Process Correction

General | Signal Definitions | Label/Comment

Hierarchical P

Edge Size [um] 0.050000 Min Segment Size [um] 0.1000

er Size [um] 0.150000

Dependence Param	Scenario	
CD	AnySegment	true

Dependence Param options: CD, Density, Space, Angle

LineEnd	true
AnySegment	true
Corner	true
AnySegment	true

Scenario options: LongSegment, Corner, Line/Space End, SmallFigure, InnerCorner, OuterCorner, LineEnd, SpaceEnd, SmallHole, SmallDot, AnySegment

Edit...

true

CD [um]	Bias [um]
2	0.000000
1	0.05
0.5	0.1
0.1	0.15

Bias

OK Cancel Help

Application of Shape - OPC

Experimental CD linearity after pattern correction (step size: 10nm)

Reference Process

horizontal iso-line
horizontal iso-space
horizontal line/space

Axis Title

Designed CD (nm)

After correction

- CD linearity is improved, esspecially for iso
- Iso-dense bias is largely corrected
- Resolution limit is improved to print 500nm

Source:
IMS Chips Stuttgart

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Corner Corrections

Corners are rounded
One common solution is to add Serifs at each corner

CAD

Modified Design

Corner Corrections

Rule-OPC

Rule based Process Correction

General | Advanced | Signal Definitions | Label/Comment | Quick Access

Layer(s): *

Min Free Edge Size [um]: 0.050000
Min Segment Size [um]: 0.100000
Min Corner Size [um]: 0.150000
Max Segment Size [um]: 1000000.000000
Bias Limit [um]: 0.000000

Action	Dependence Param	Scenario	Condition
Serif	-	Corner	true

Type of Serif	Manhattan
Min Edge Length [um]	0.010000
Min Distance [um]	0.055000
Size [um]	0.050000
Overlap [um]	0.010000
Condition	true

overlap
size
size
overlap

Design

Exposed structure

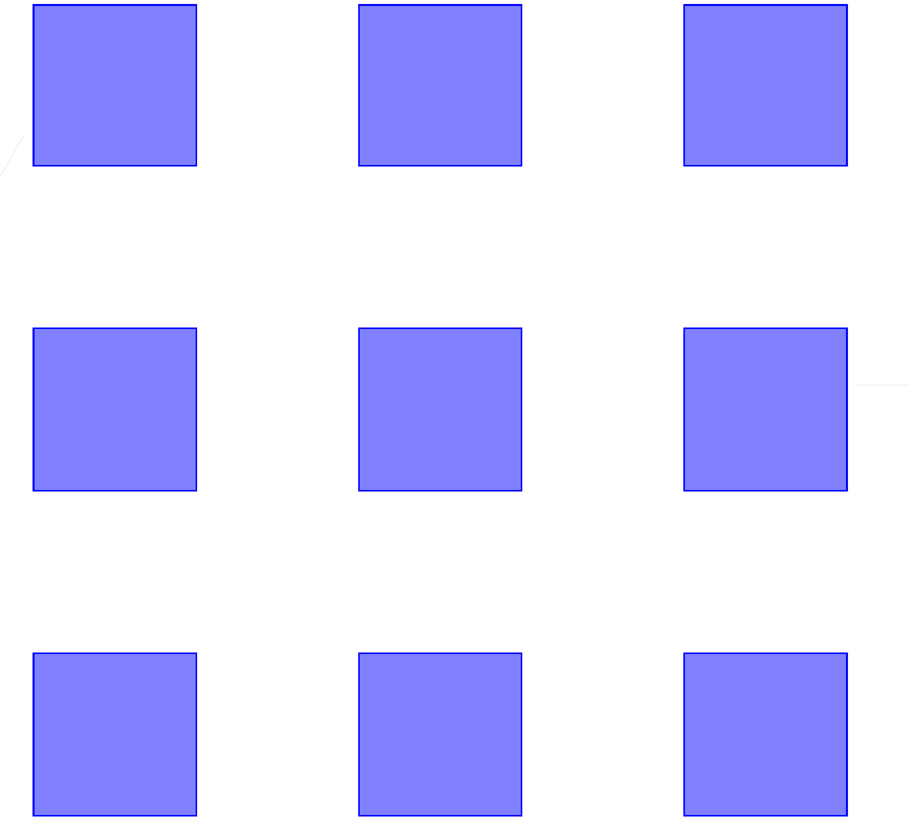
Without OPC

With OPC

Serifs

2um Square Dots

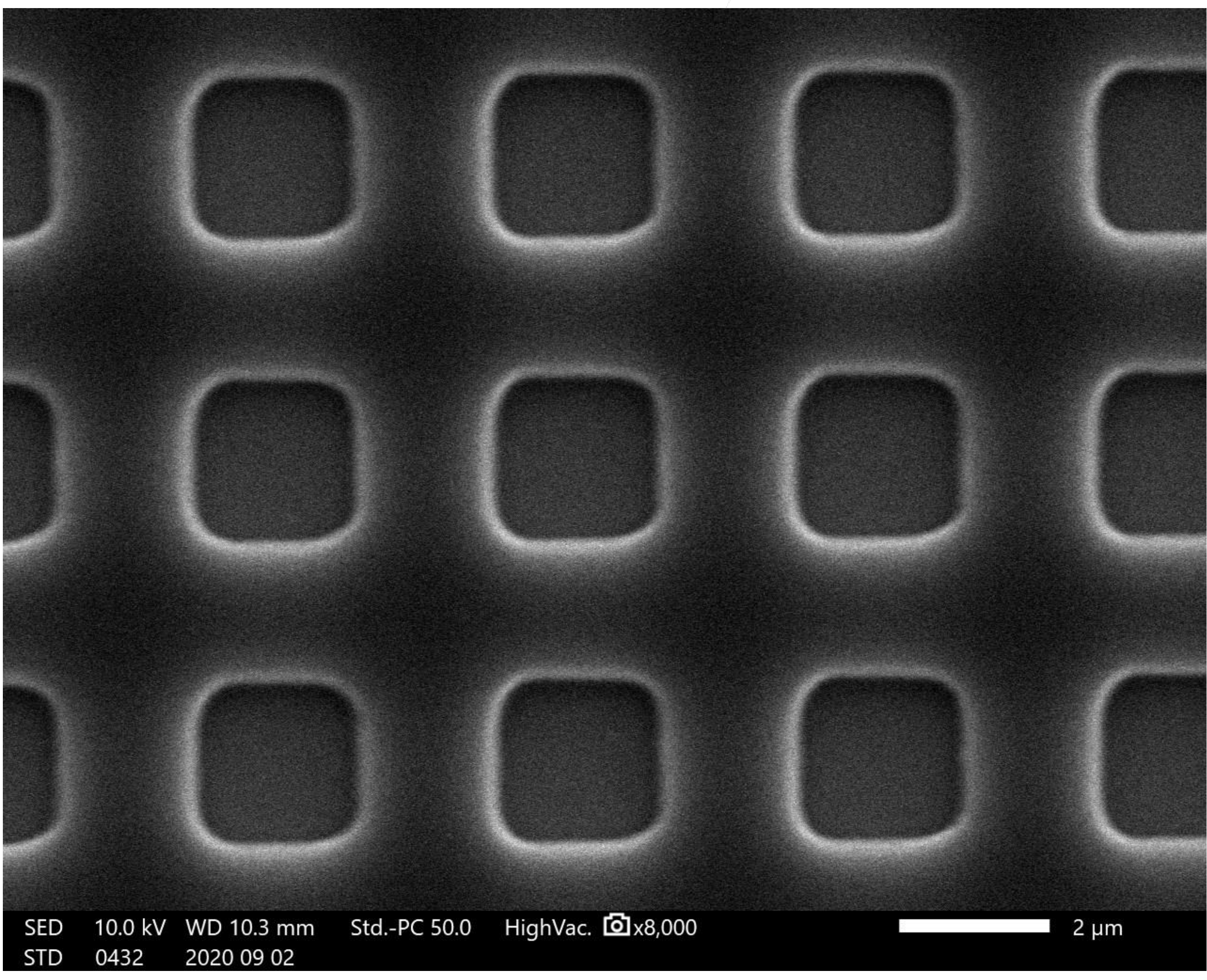
without correction



2um Squares

2um Square Dots

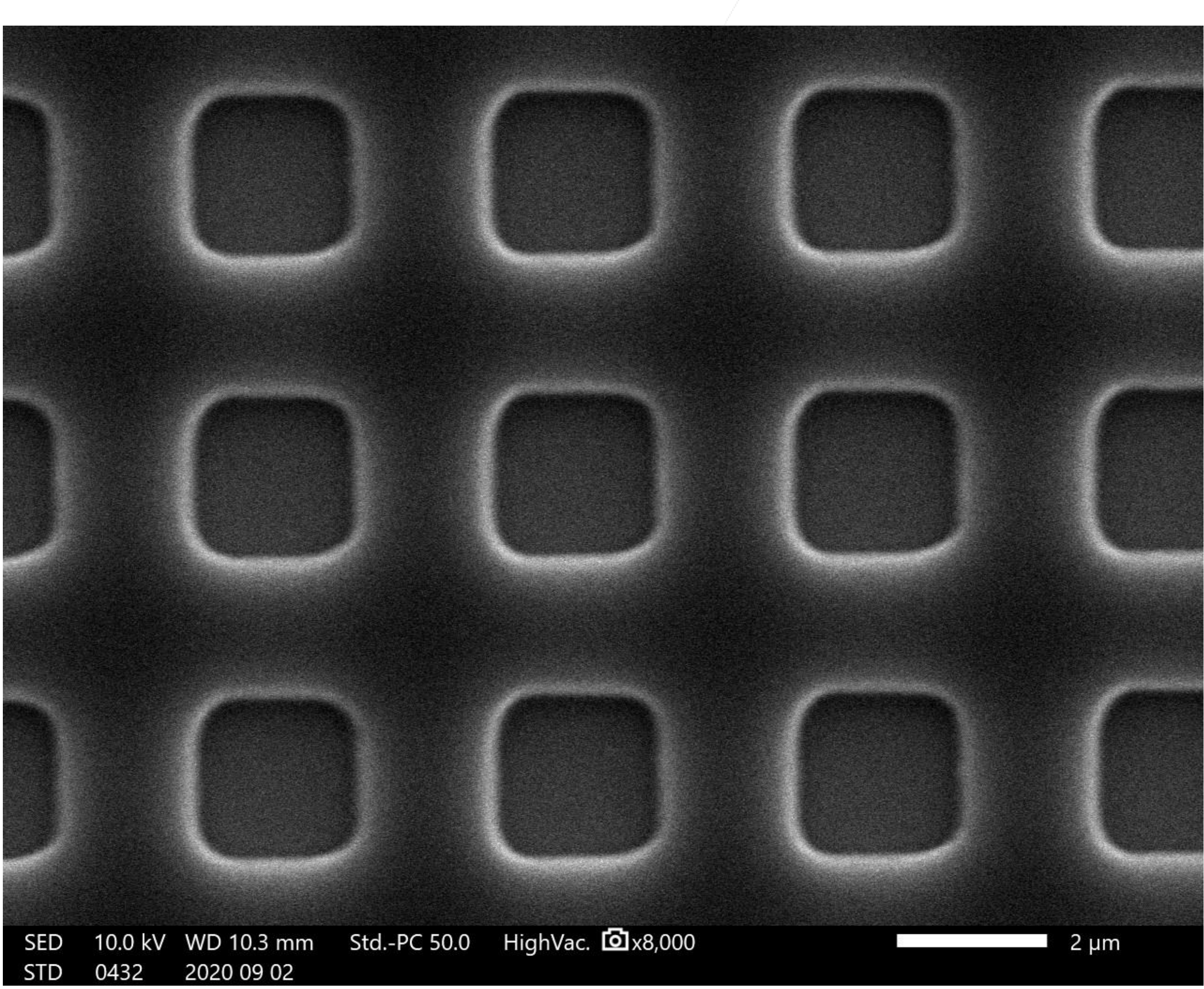
without correction



Corner Rounding = **0.65 um** (av.)

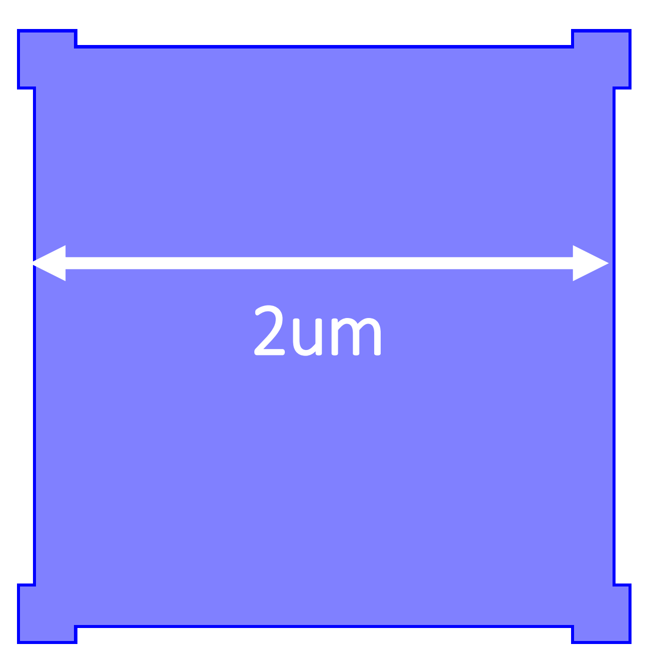
2um Square Dots

without correction



Corner Rounding = **0.65 um** (av.)

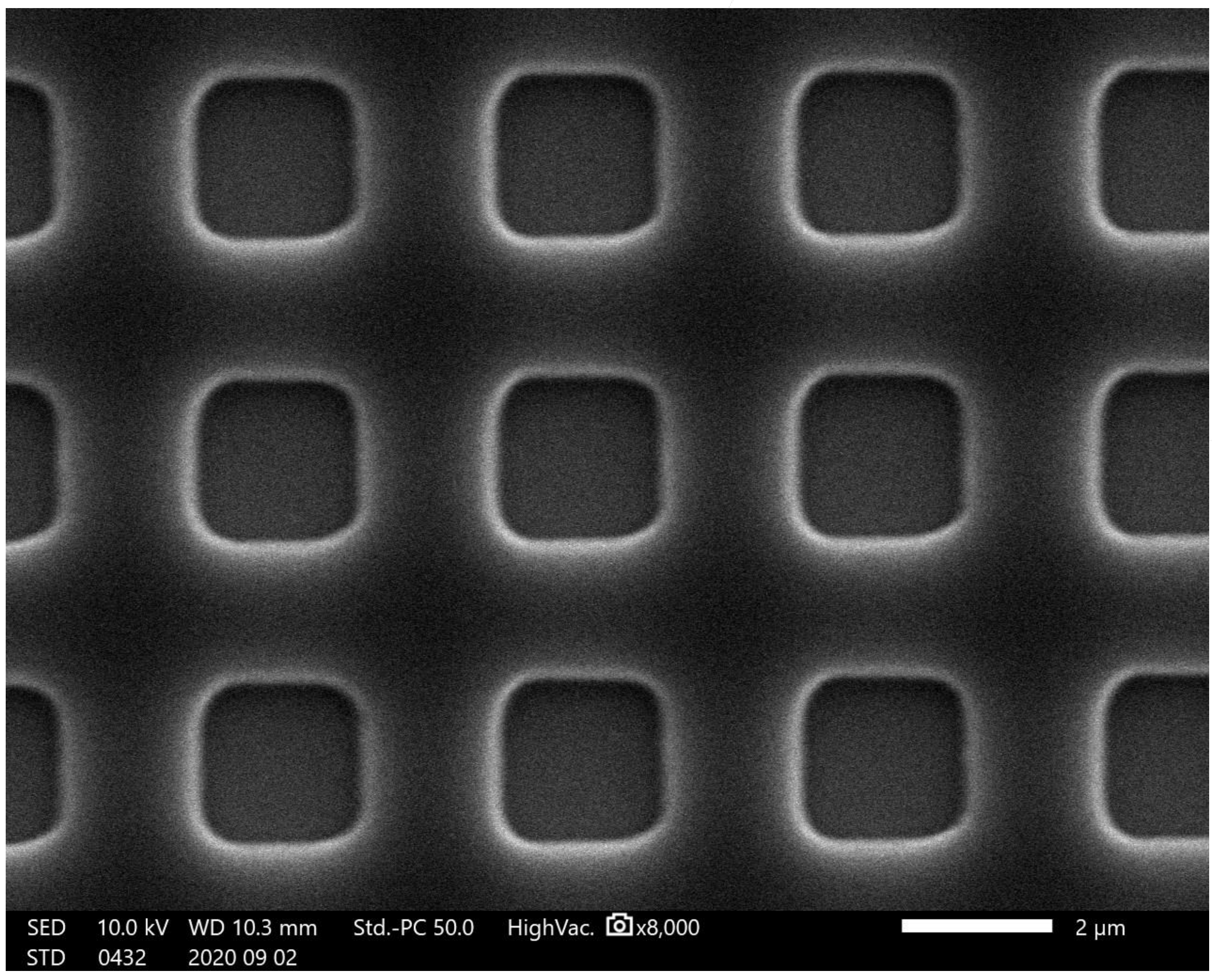
200nm Serif with 70% overlap



Rule-OPC

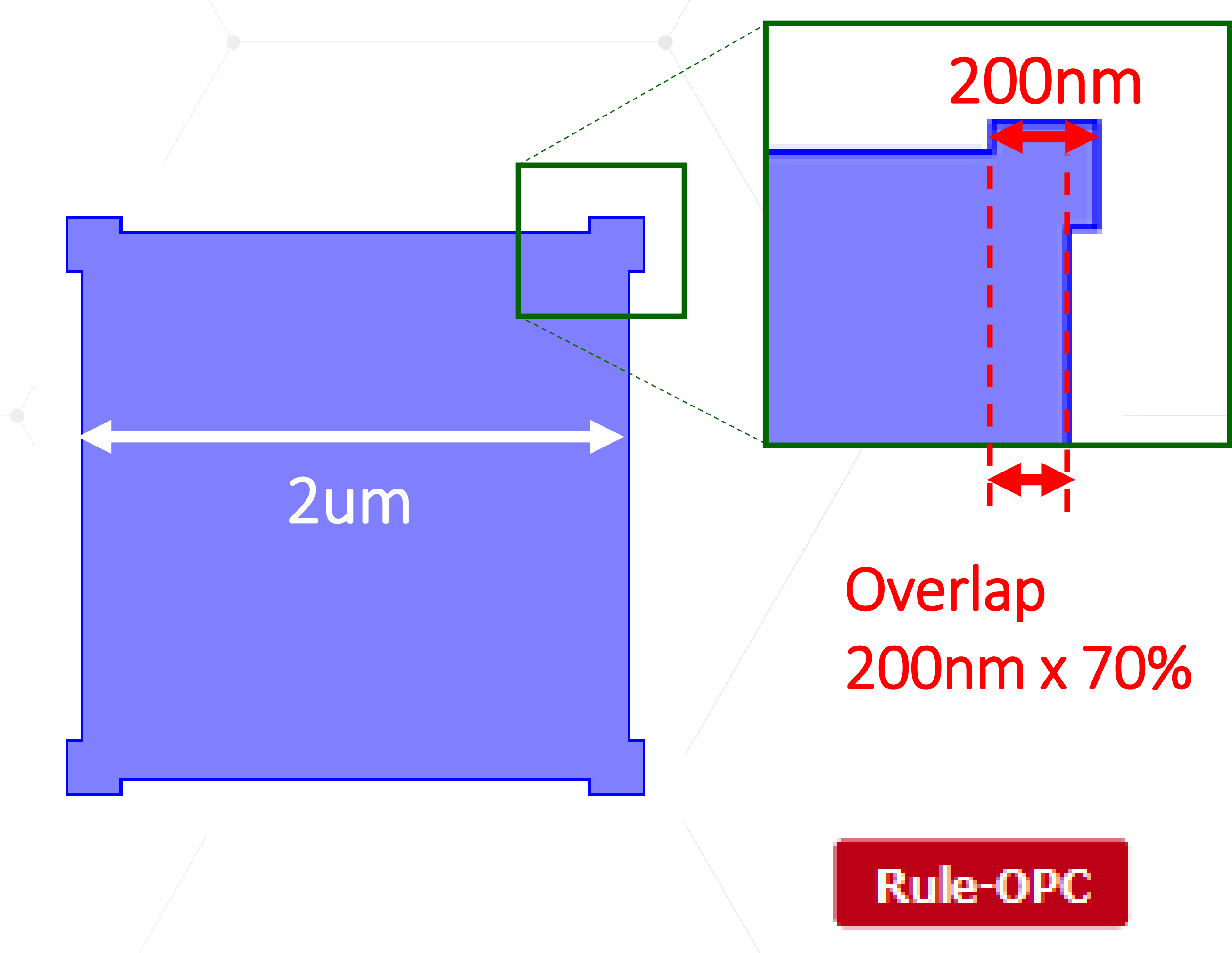
2um Square Dots

without correction



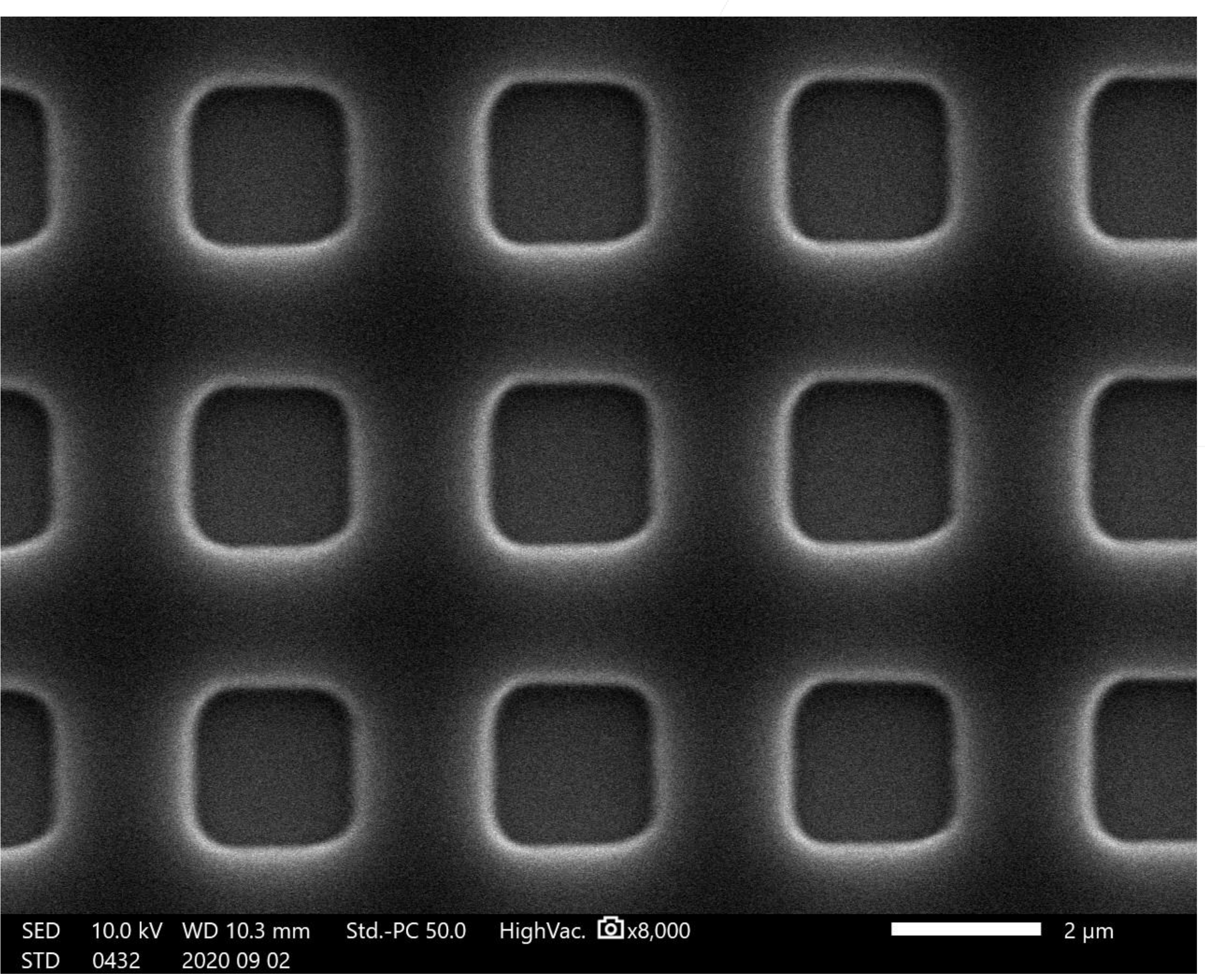
Corner Rounding = **0.65 um** (av.)

200nm Serif with 70% overlap

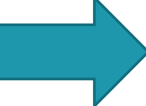


2um Square Dots

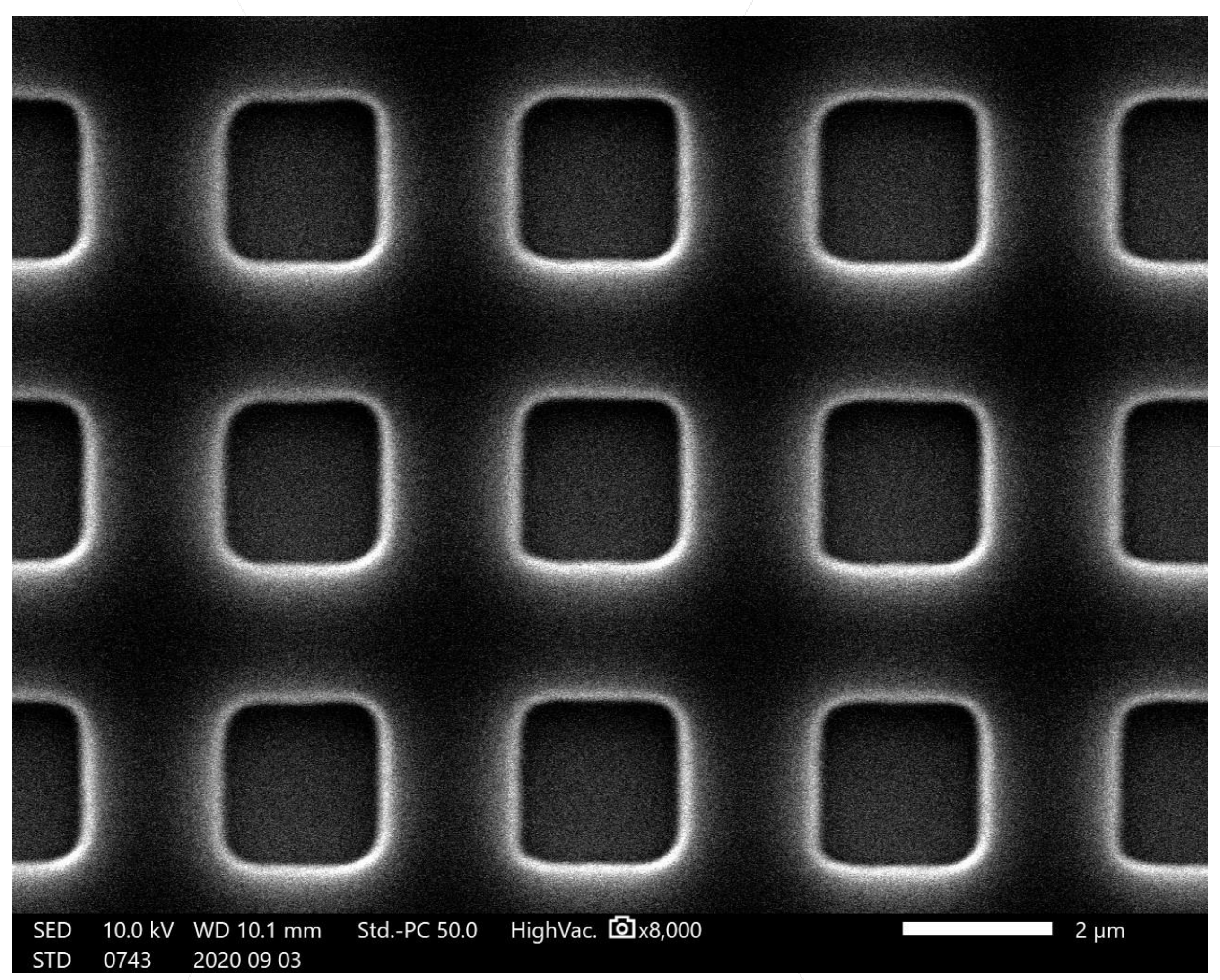
without correction



Corner Rounding = **0.65 um** (av.)



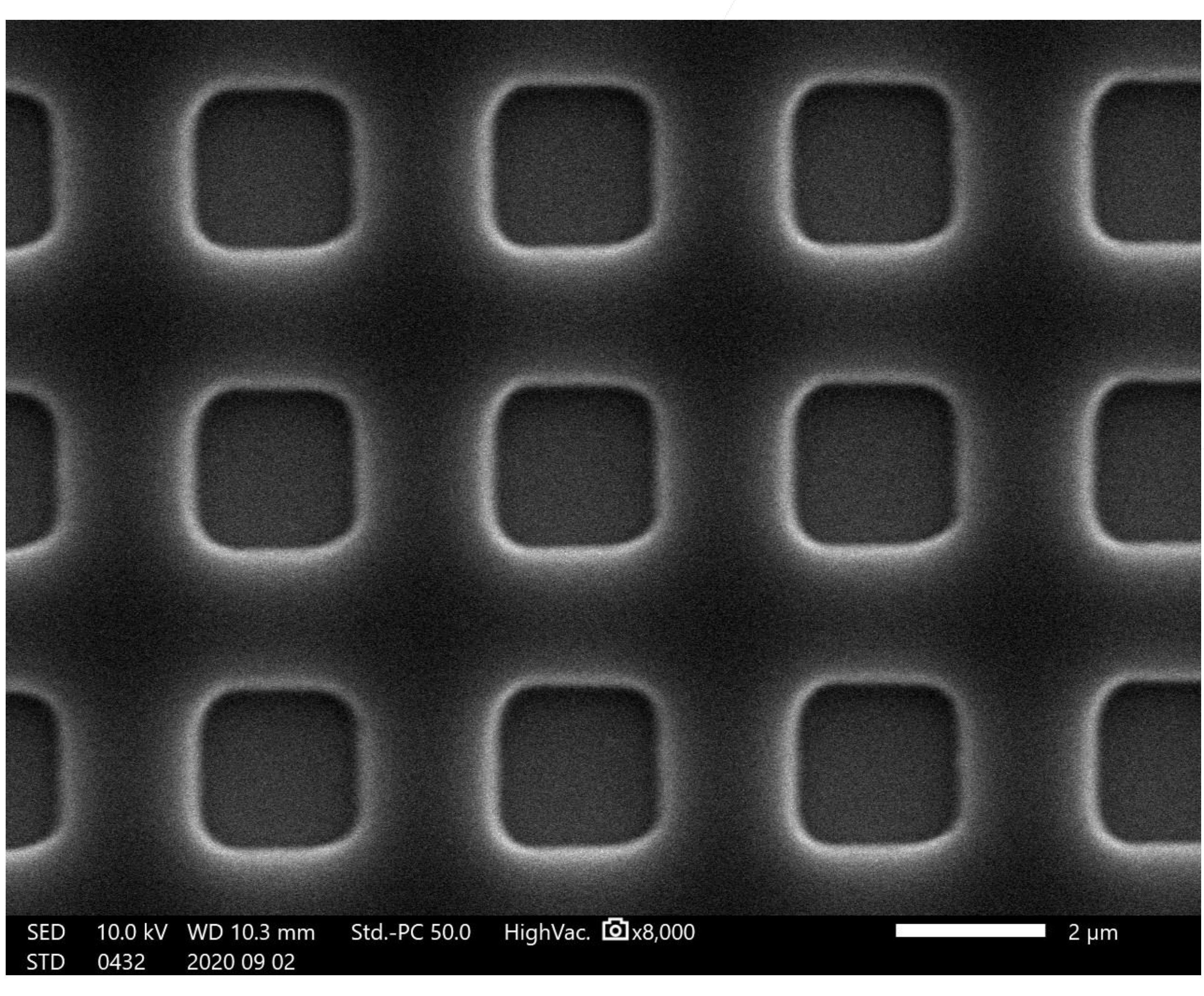
200nm Serif with 70% overlap

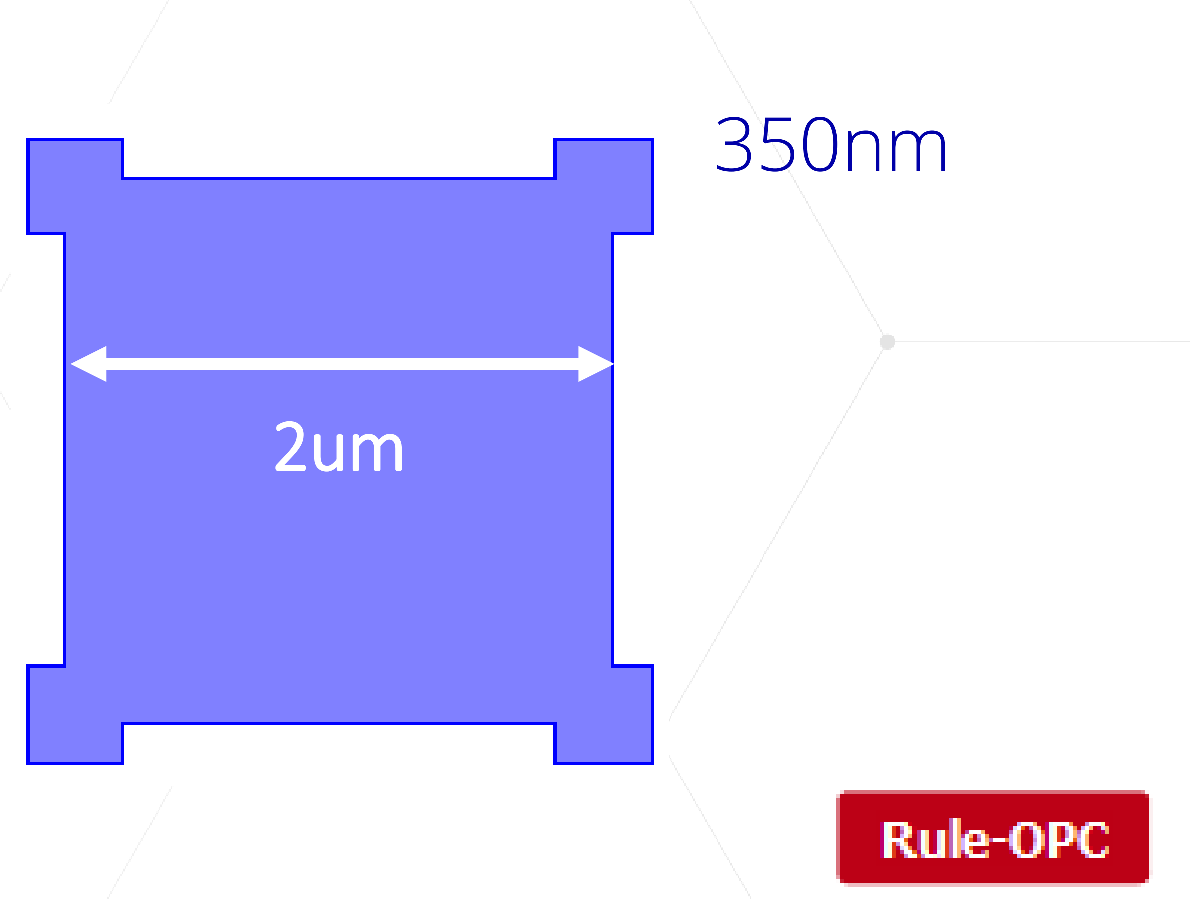


Corner Rounding = **0.56 um** (av.)

2um Square Dots

without correction

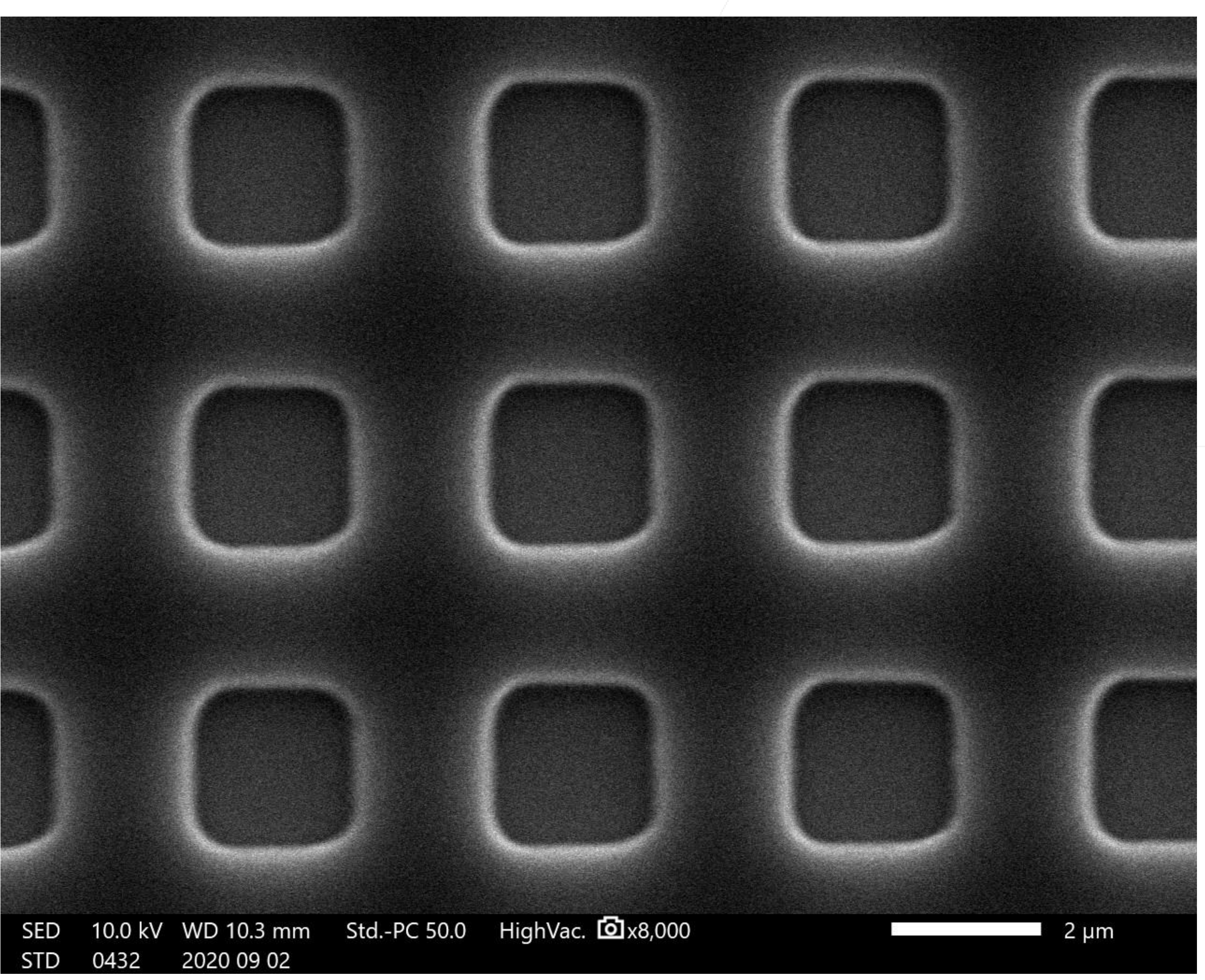




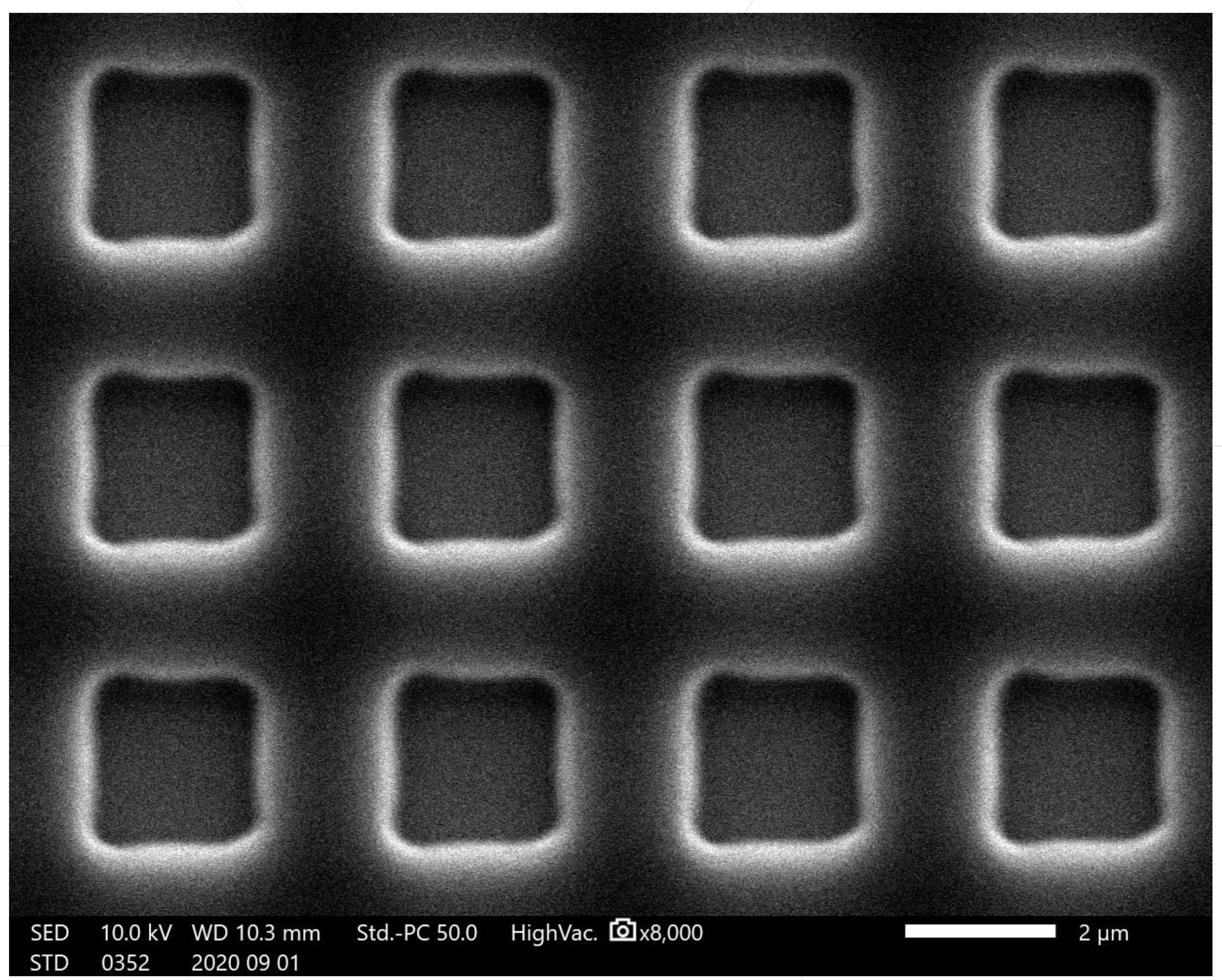
Rule-OPC

2um Square Dots

without correction



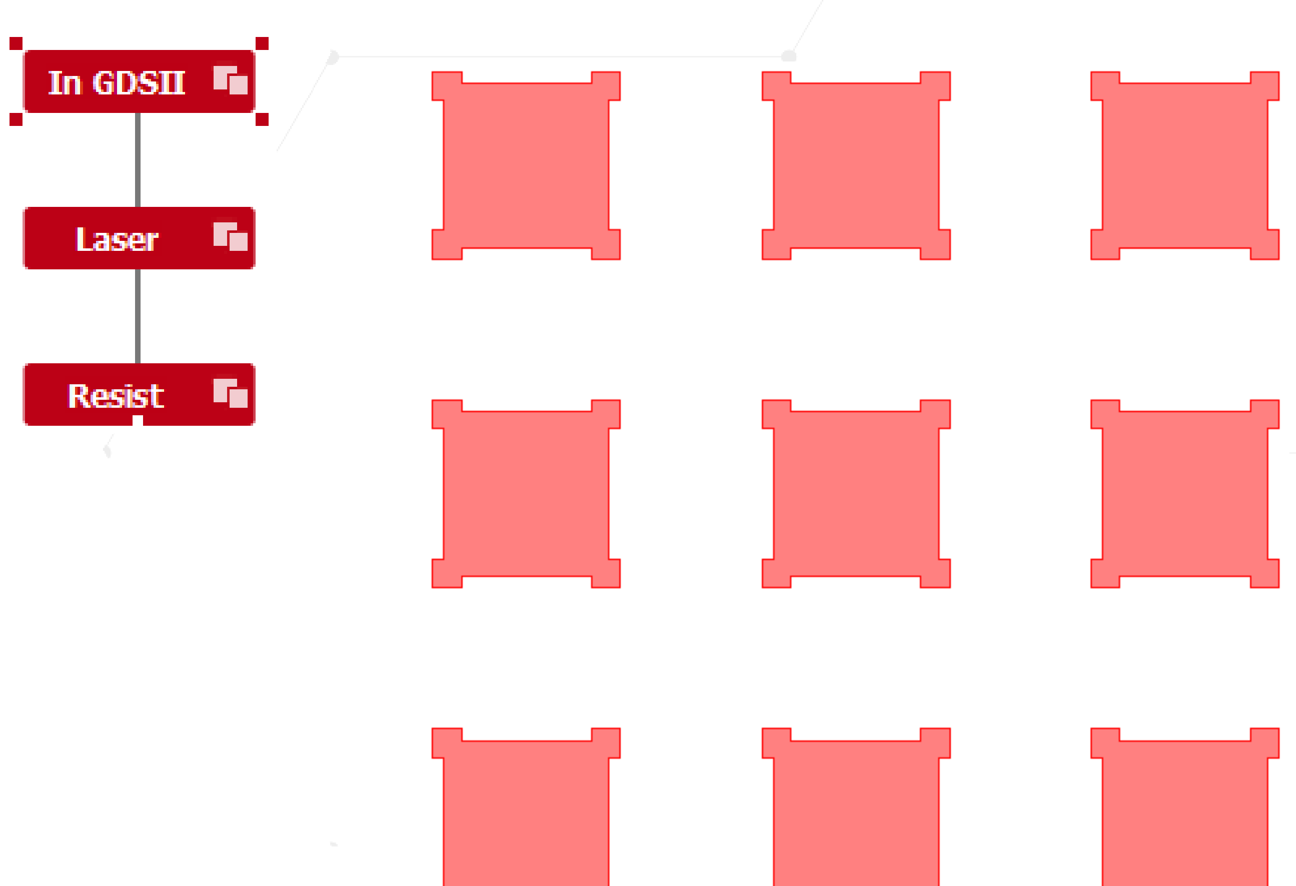
350nm Serif with 60% overlap

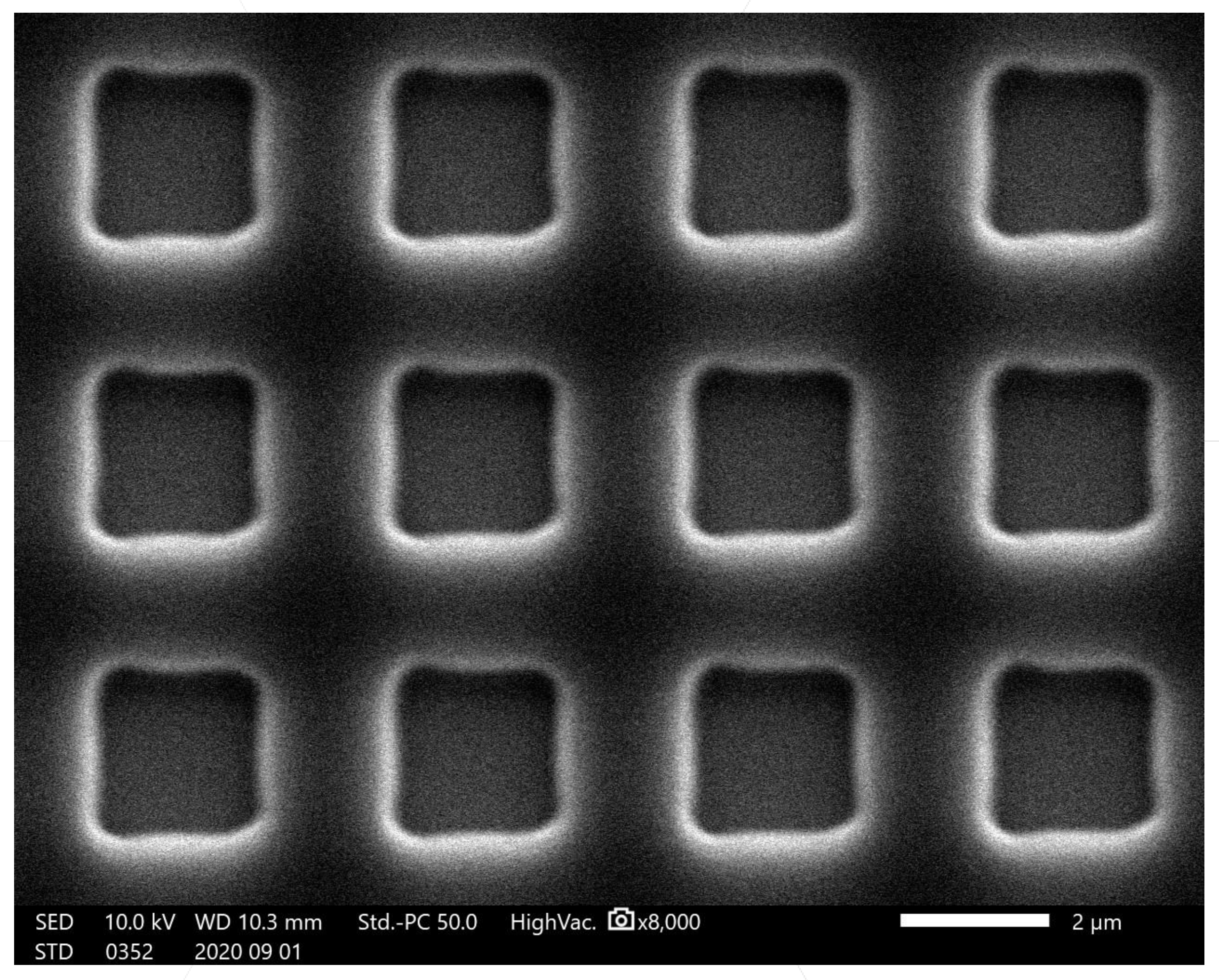


Overshooting correction

LAB Simulation : 2um Square Dots

Pattern with Corner Serifs





Overshooting correction

LAB Simulation : 2um Square Dots

Absorbed Energy (405nm)

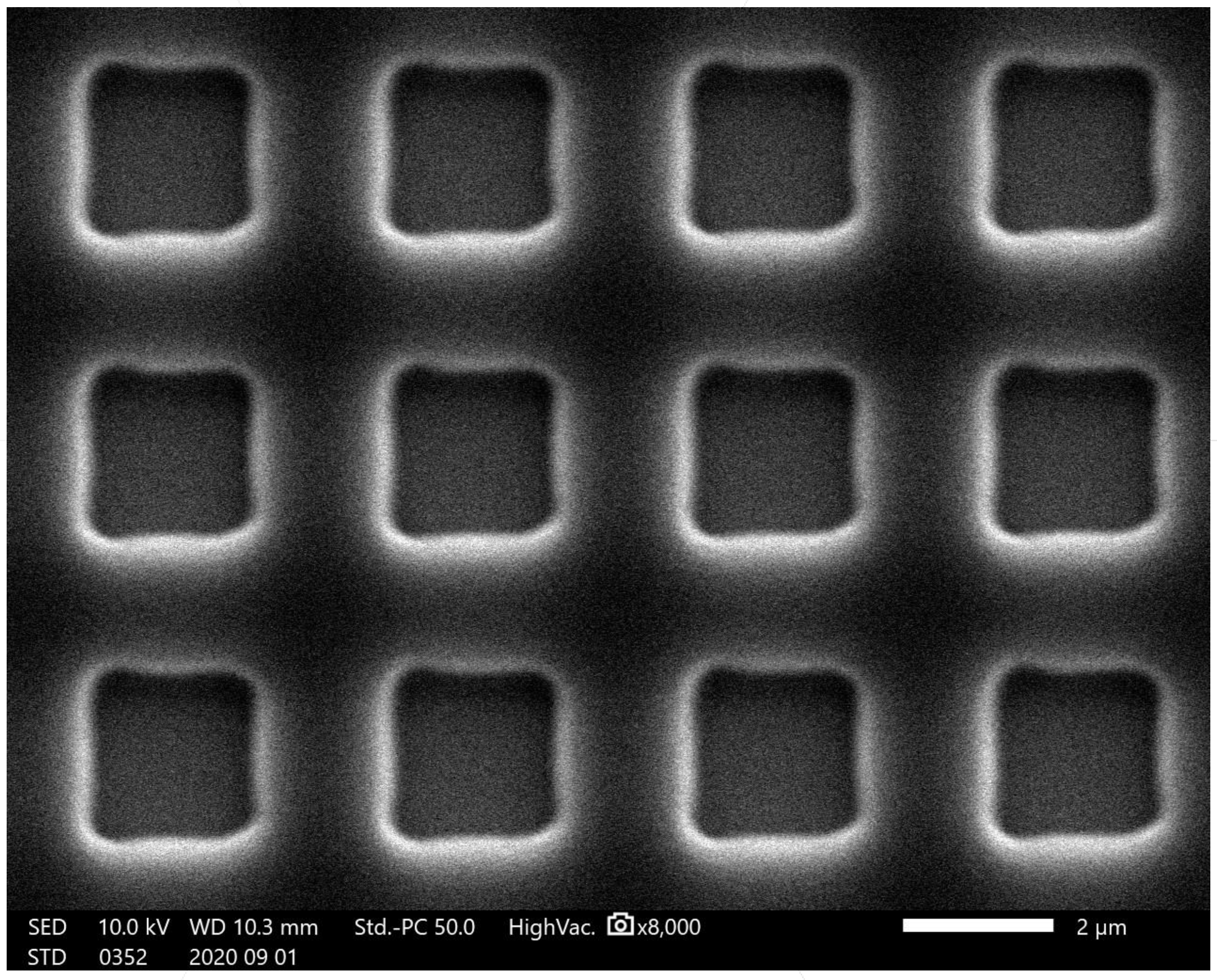
In GDSII
Laser
Resist

y [um]: -3398, -3400, -3402, -3404, -3406, -3408

x [um]: 10098, 10100, 10102, 10104, 10106, 10108, 10110

LAB

350nm Serif with 60% overlap



Overshooting correction

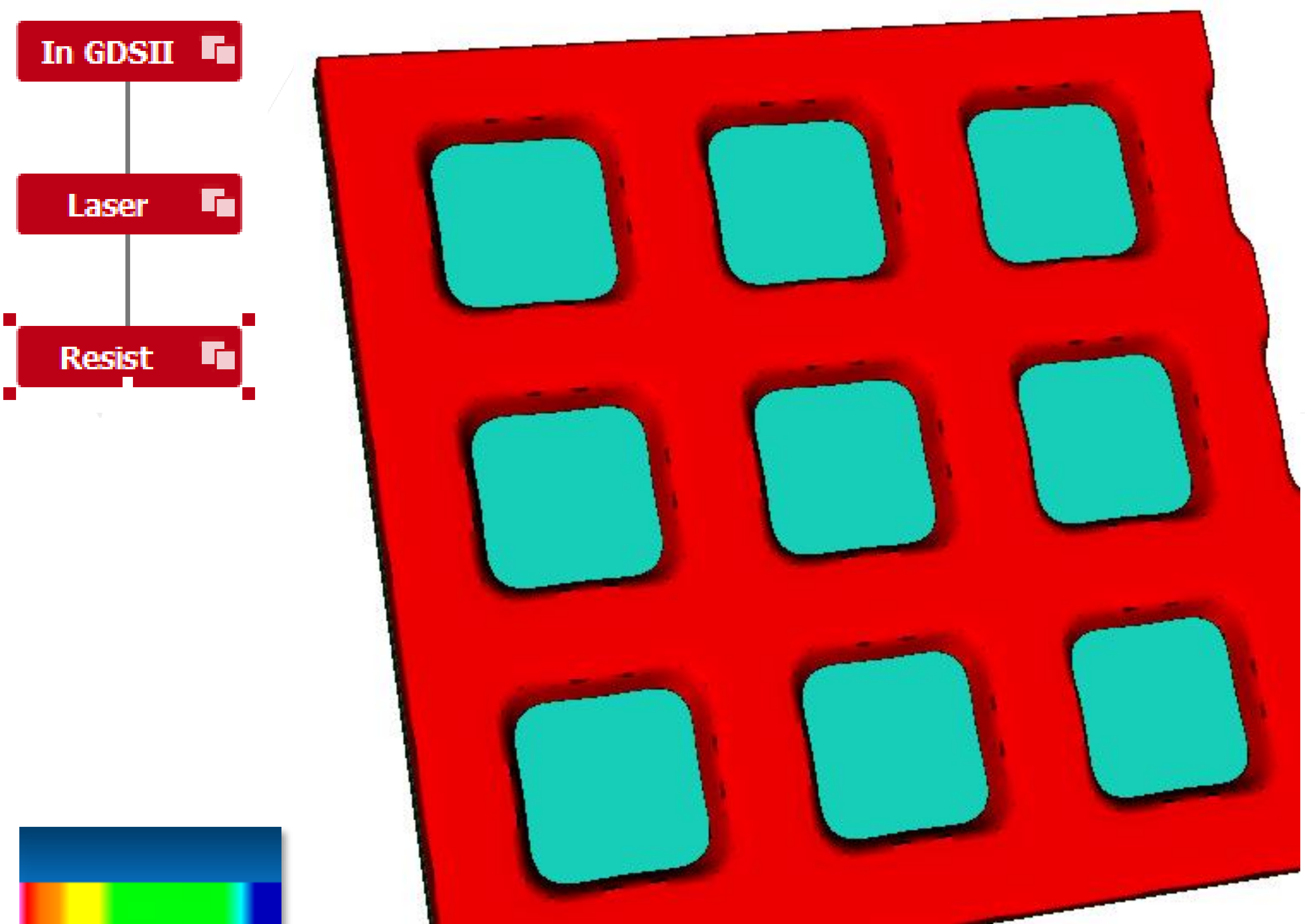
LAB Simulation : 2um Square Dots

3D Resist View

In GDSII

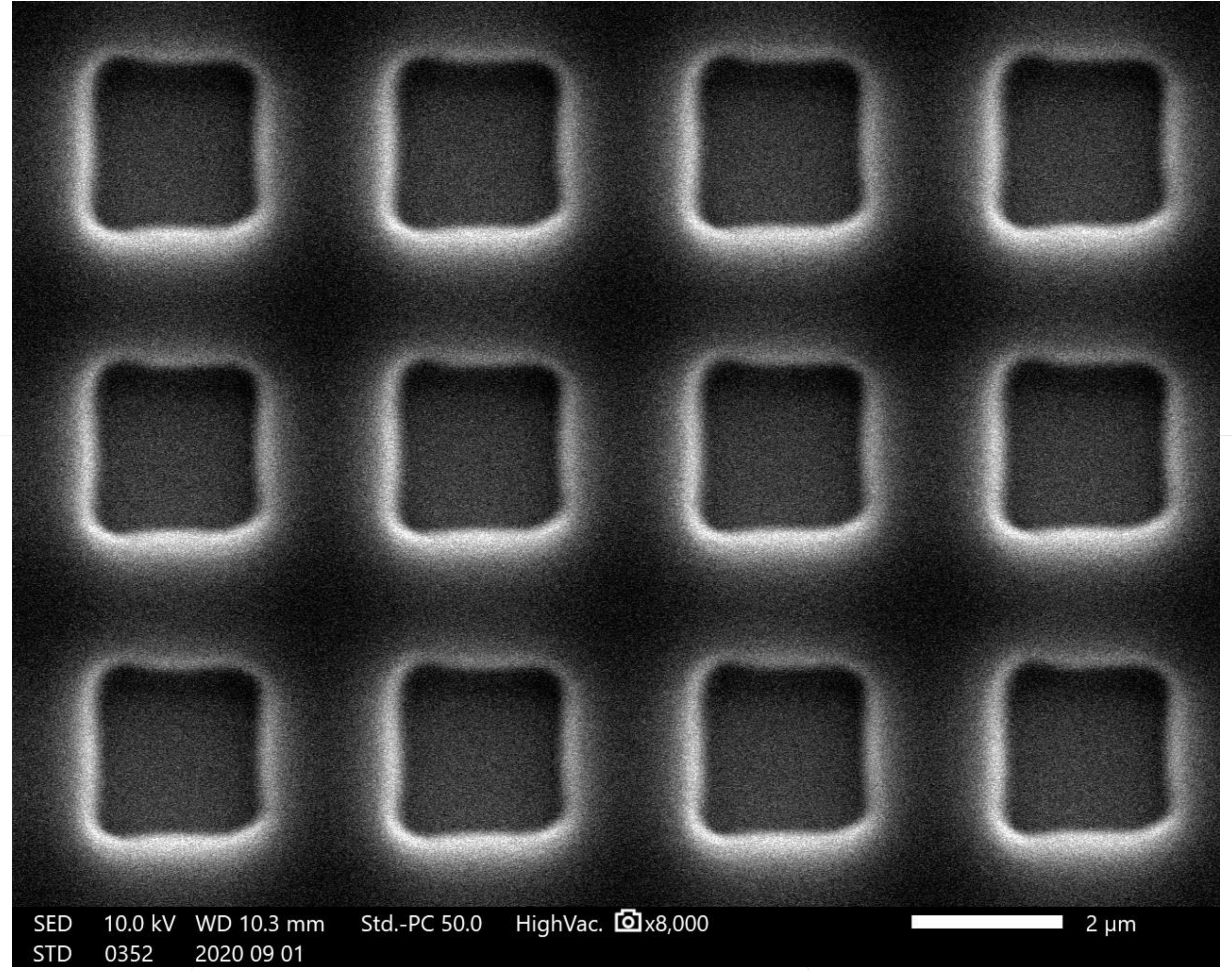
Laser

Resist



LAB

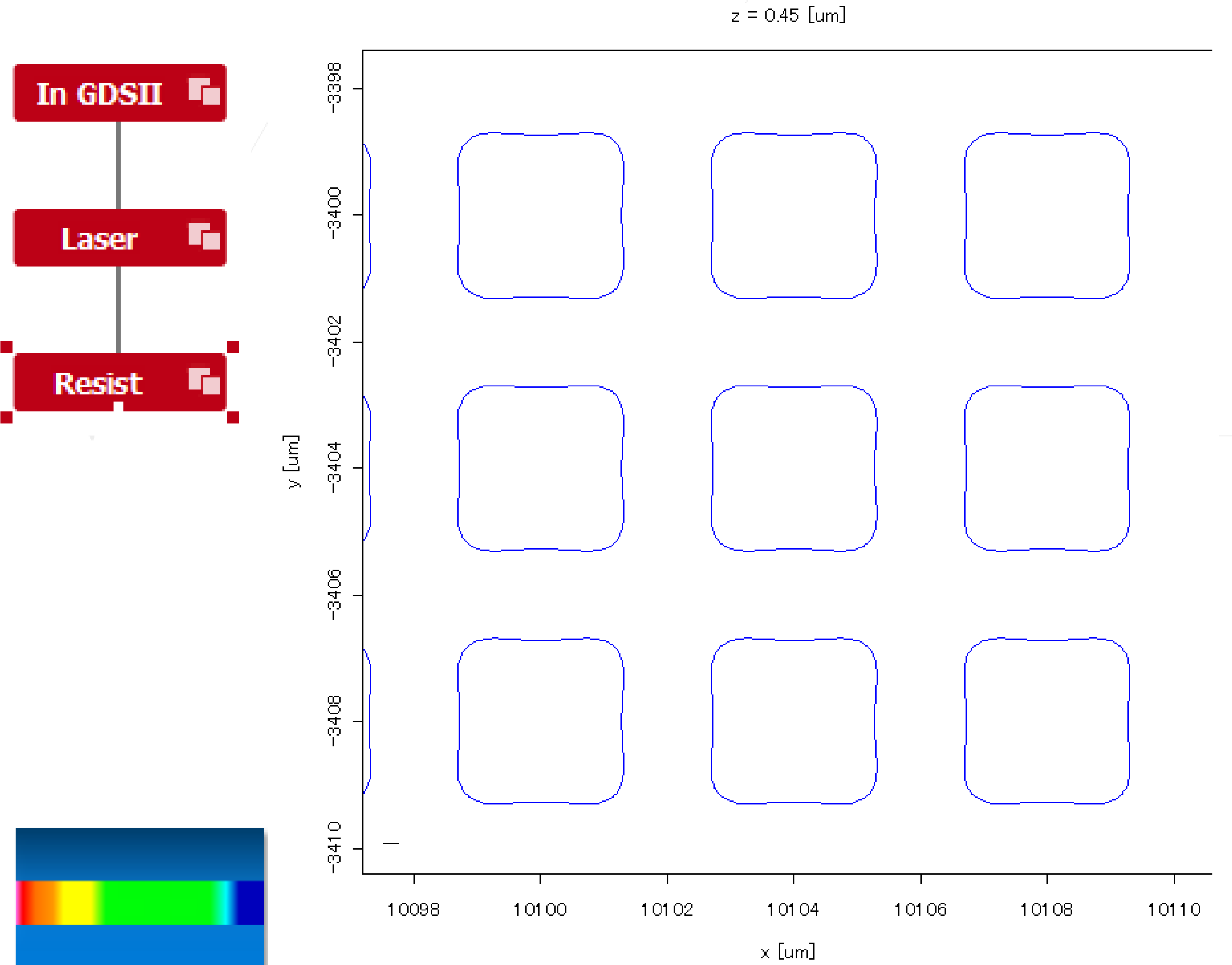
350nm Serif with 60% overlap



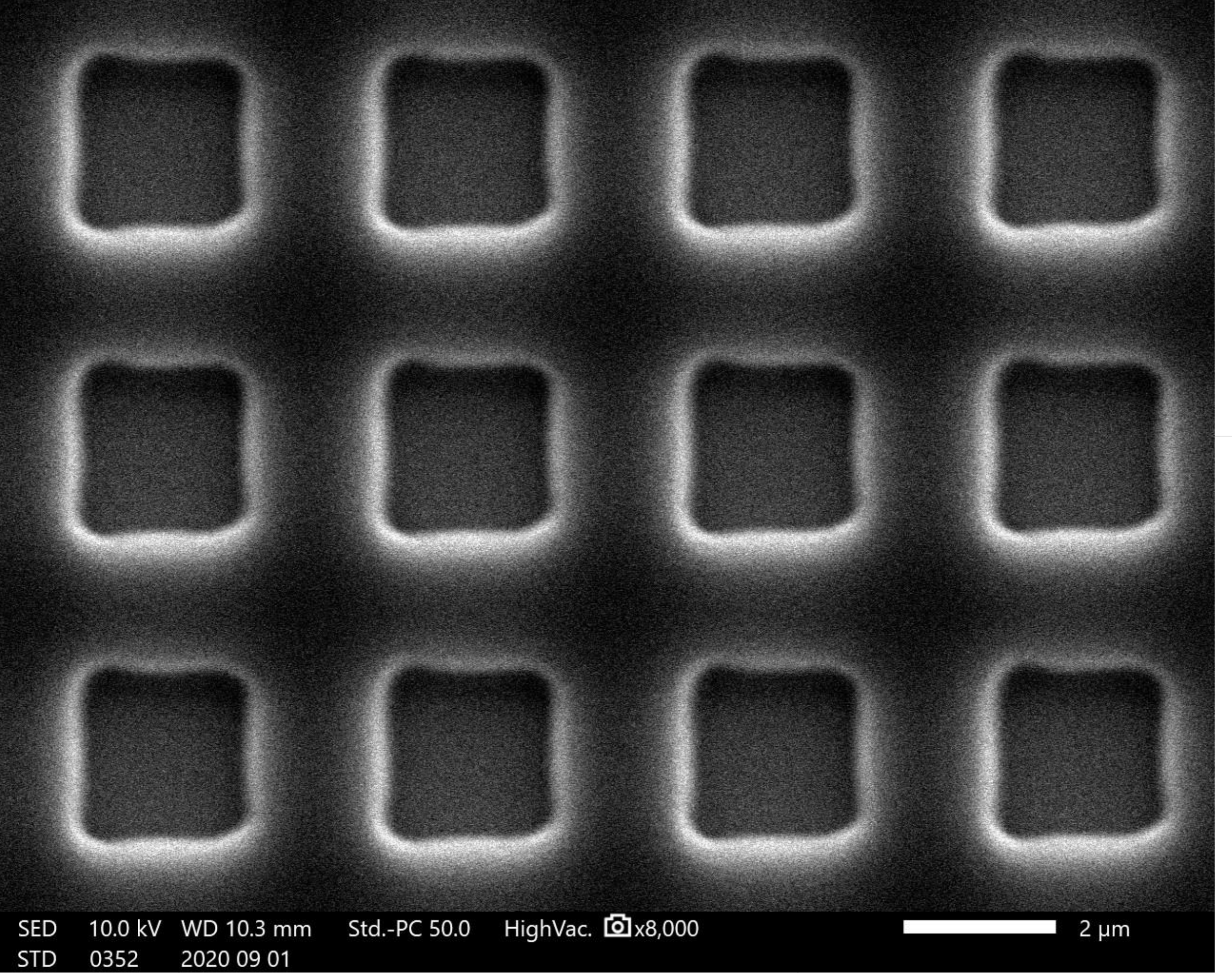
Overshooting correction

LAB Simulation : 2um Square Dots

Resist Contour



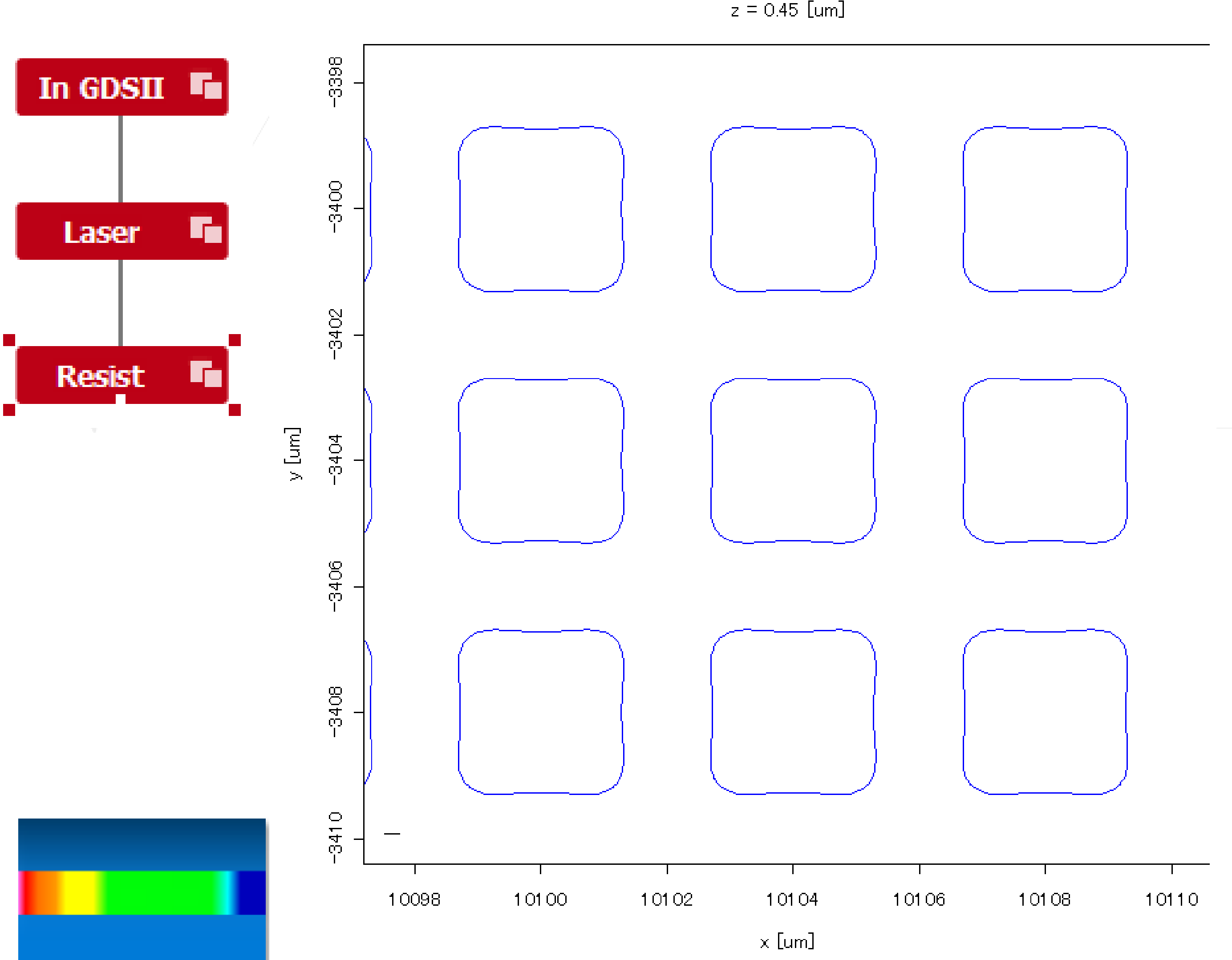
350nm Serif with 60% overlap



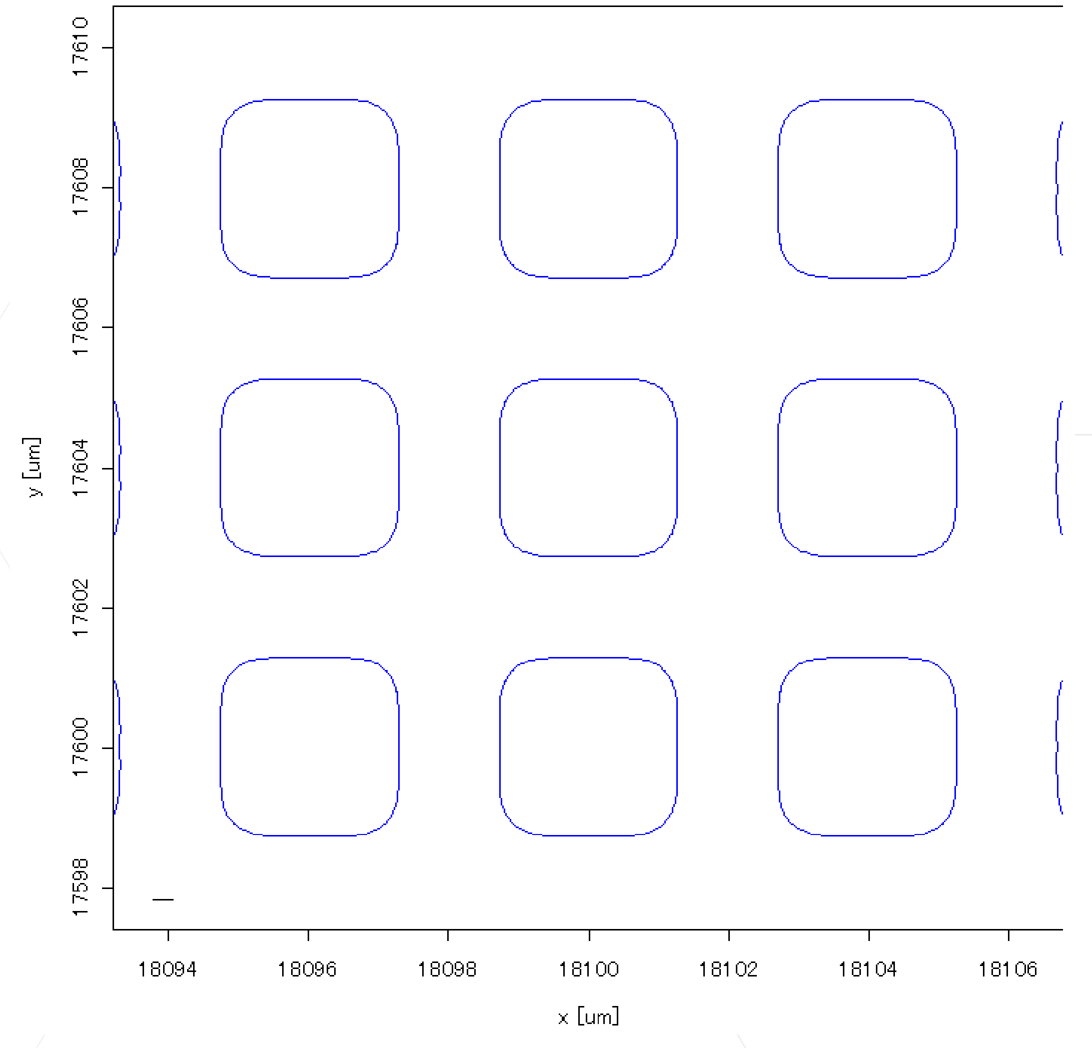
Overshooting correction

LAB Simulation : 2um Square Dots

350nm Serif with 60% overlap



200nm Serif with 70% overlap



LAB

LAB Simulation : 2um Square Dots

In GDSII
Laser
Resist

350nm Serif with 60% overlap

z = 0.45 [um]

y [um]: -3398, -3400, -3402, -3404, -3406, -3408, -3410
x [um]: 10098, 10100, 10102, 10104, 10106, 10108, 10110

200nm Serif with 70% overlap

z = 0.45 [um]

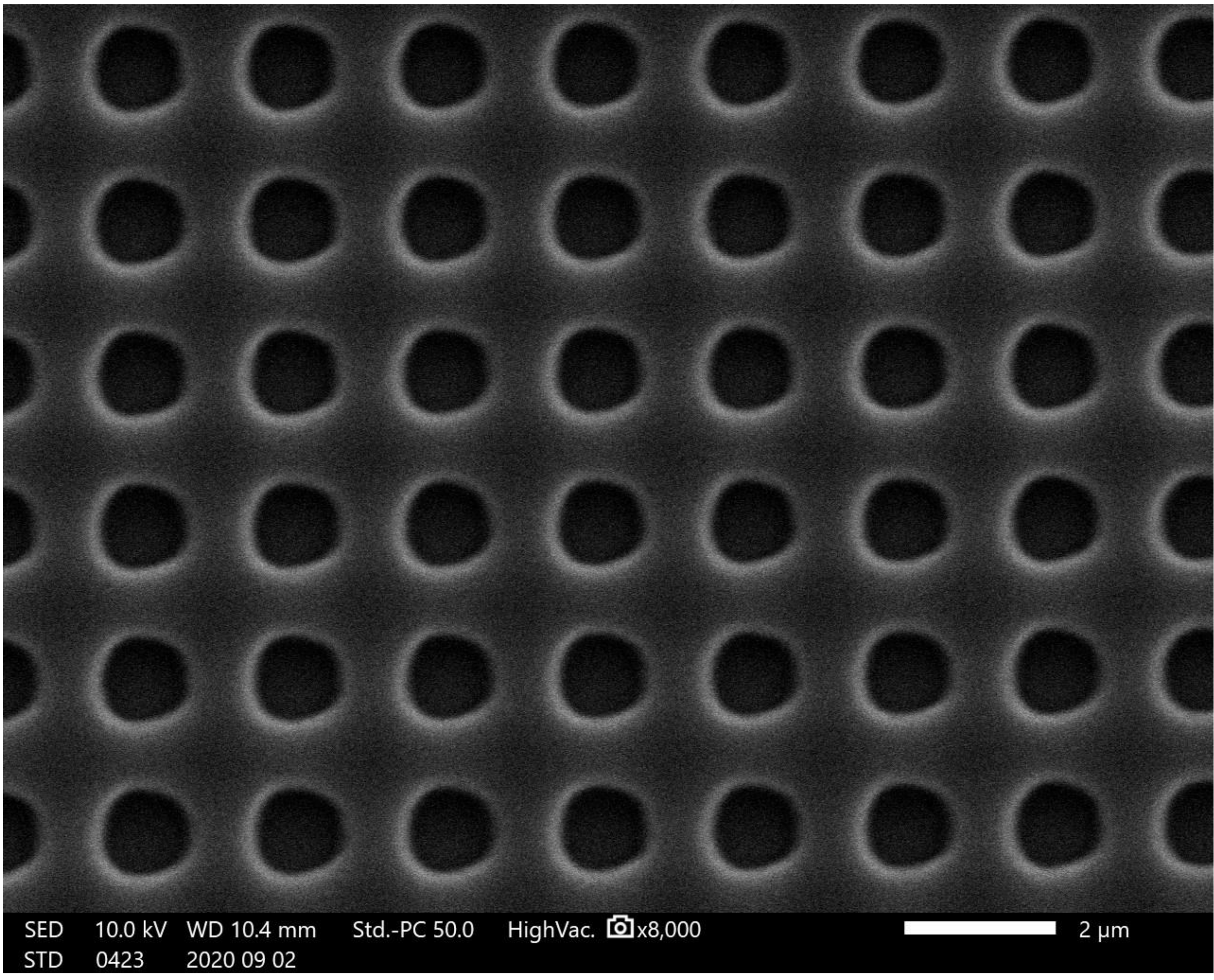
y [um]: 17610, 17608, 17606, 17604, 17602, 17600, 17598
x [um]: 18094, 18096, 18098, 18100, 18102, 18104, 18106

LAB

Simulation is able to predict proper serif size in advance

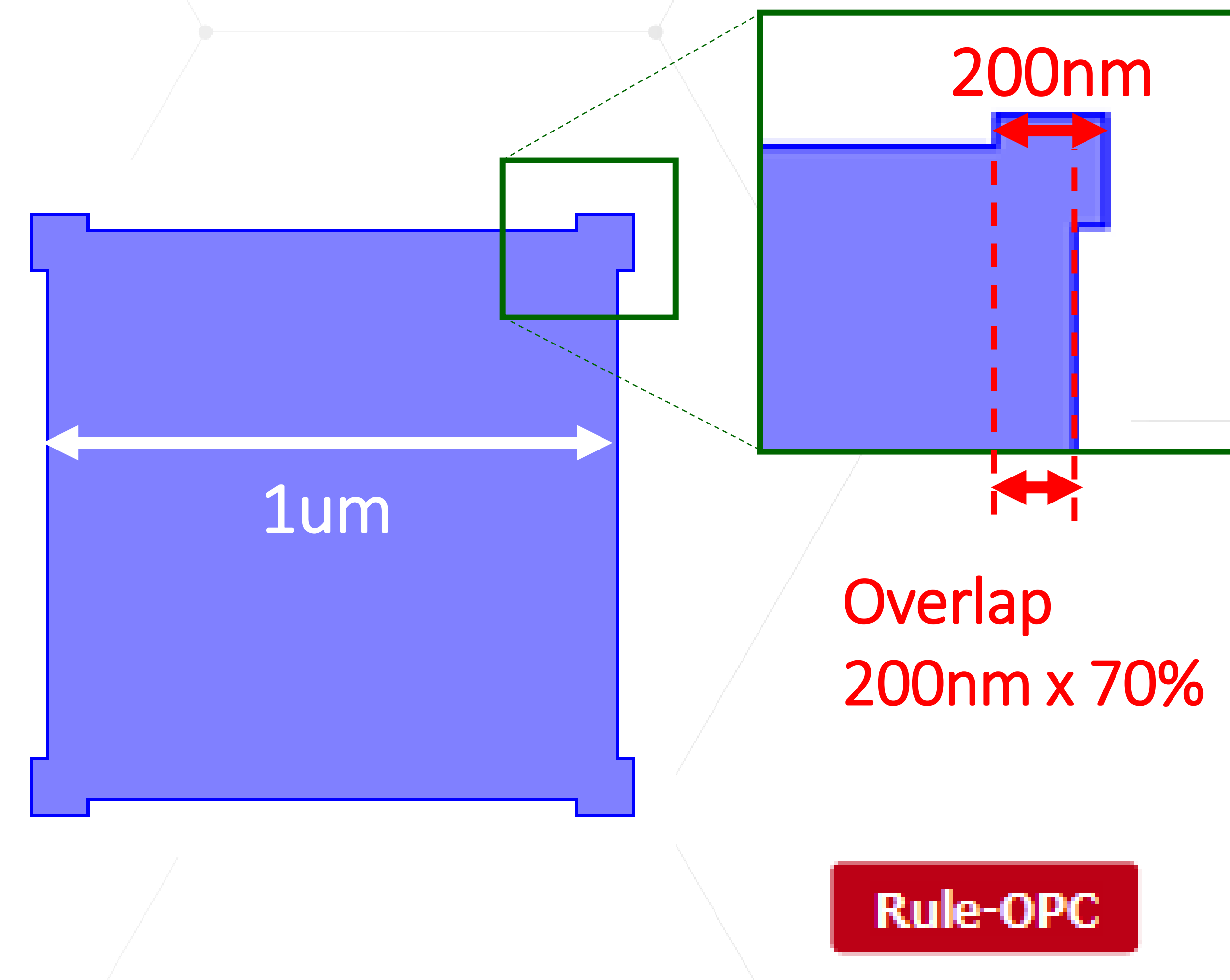
1um Square Dots

without correction Resist = 500nm



Corner Rounding = **0.55 um**

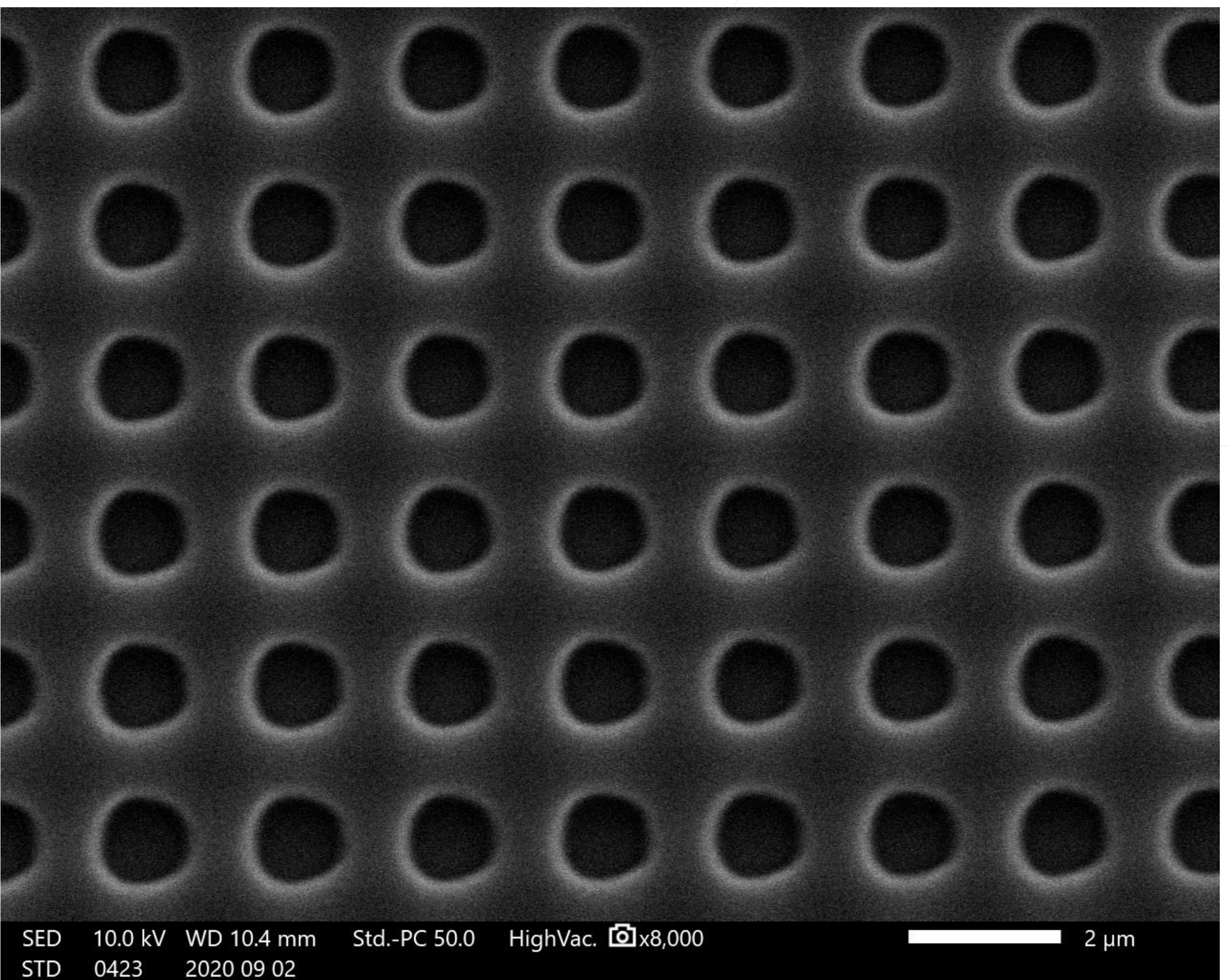
200nm Serif with 70% overlap

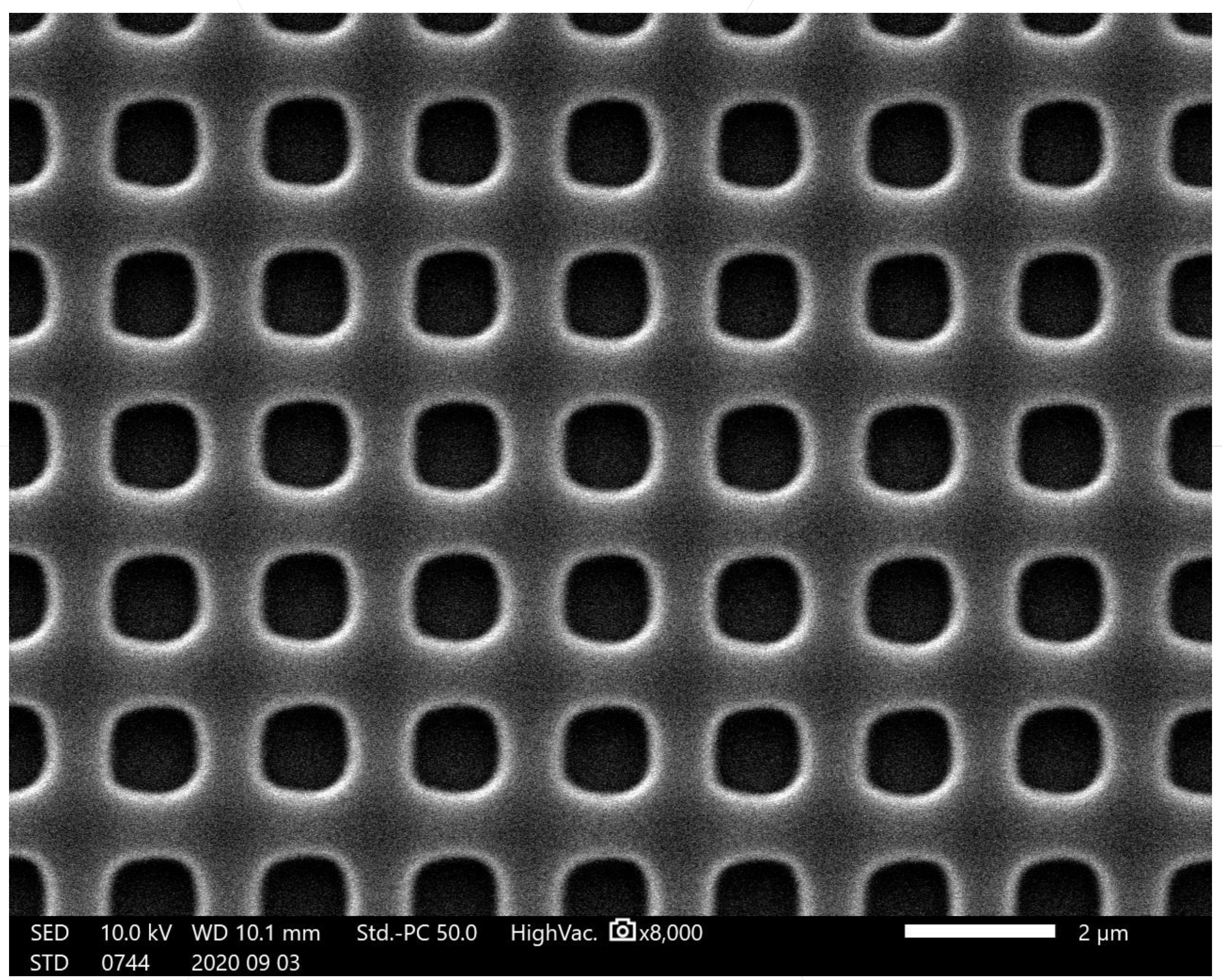


1um Square Dots

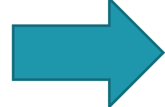
without correction Resist = 500nm

200nm Serif with 70% overlap





Corner Rounding = **0.55 um**



Corner Rounding = **0.44 um**

Corner Rounding

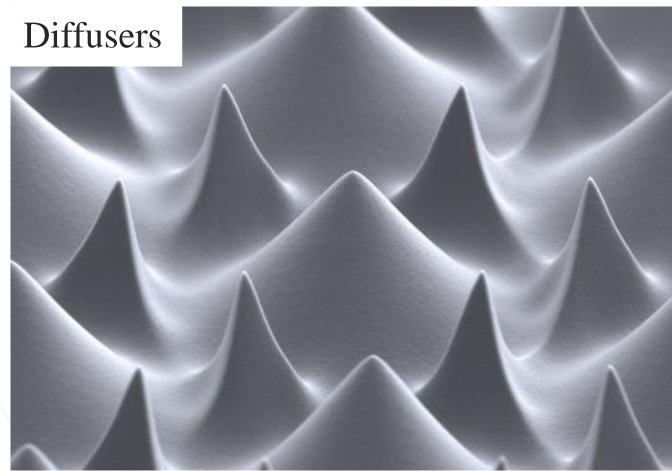
Overall 100nm improvement oveserved especially at small corner size range

Agenda

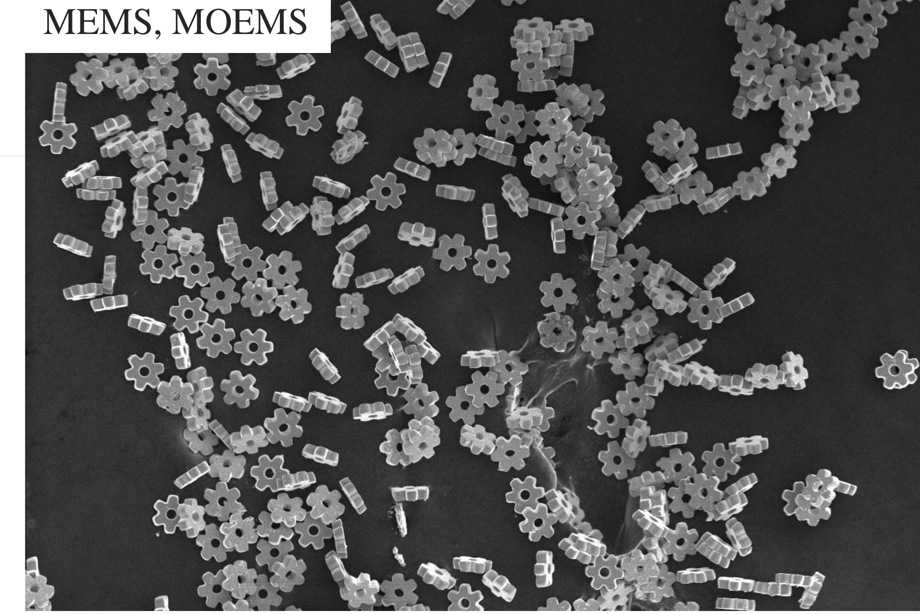
- レーザー描画概要
- バイナリ露光の為の「Model-OPC」及び「Rule-OPC」補正
- グレイスケール露光の為のドーズ量最適化補正
  - 概要
  - 入力ファイル準備と3Dドーズ量補正の実行
- まとめ

Laser Gray Scale Application

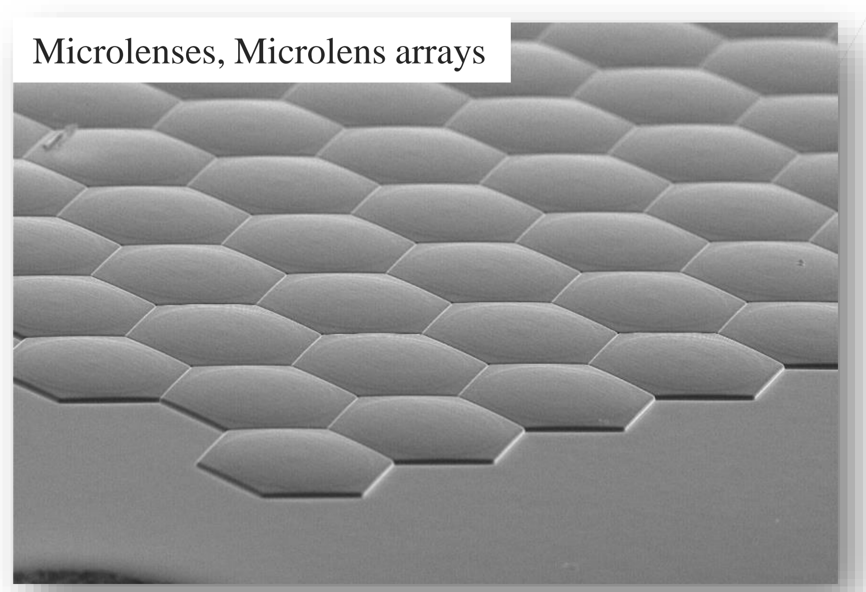
- Large variaty of application need 3D

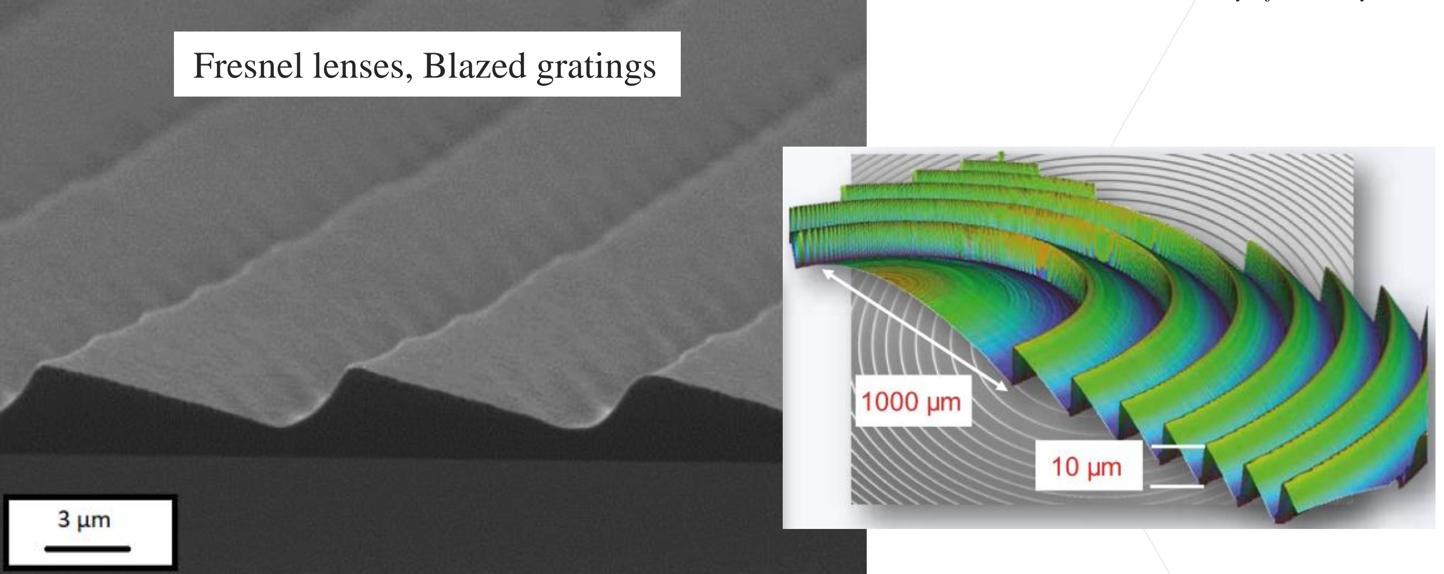


Courtesy of IGI



Courtesy of Kuraray

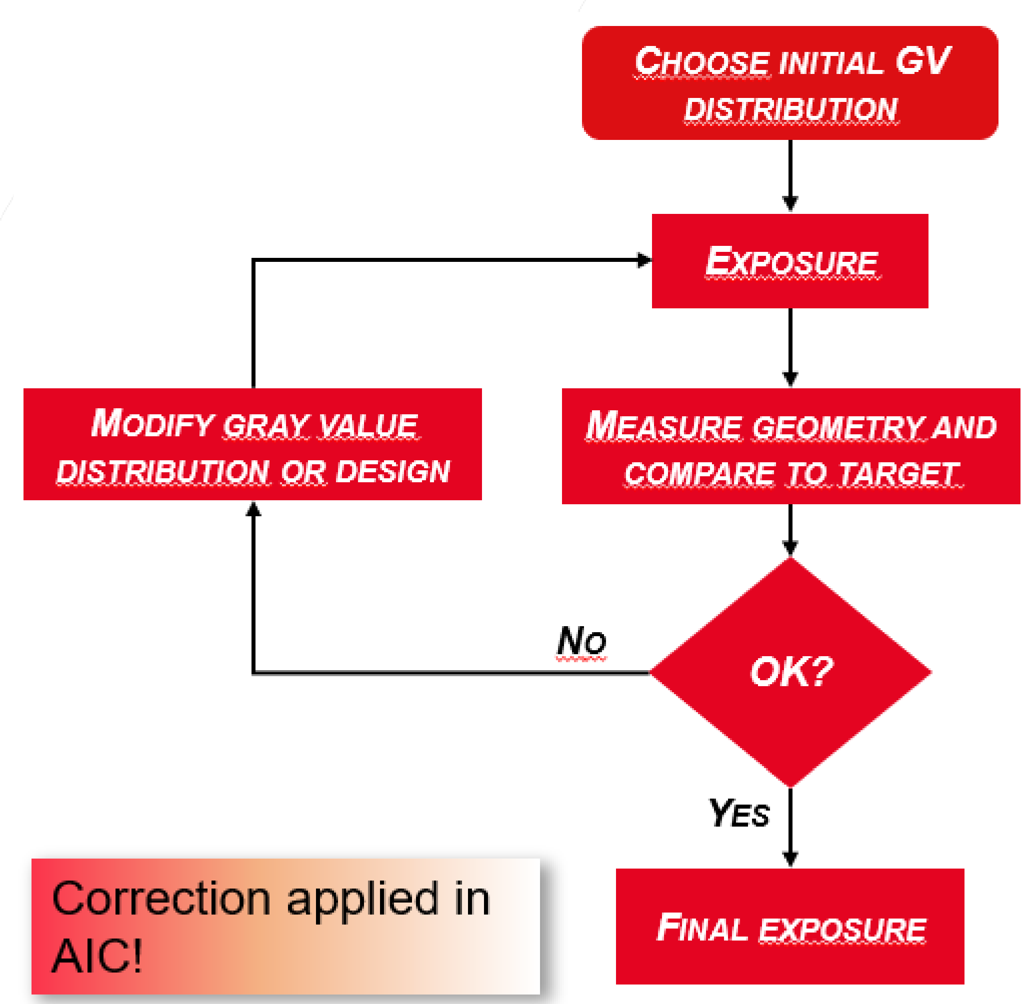




Gray Scale Exposure

Laser Grey-Tone Correction

Experimental / iterative approach



WORKS QUITE WELL, BUT…

- … can be very time consuming

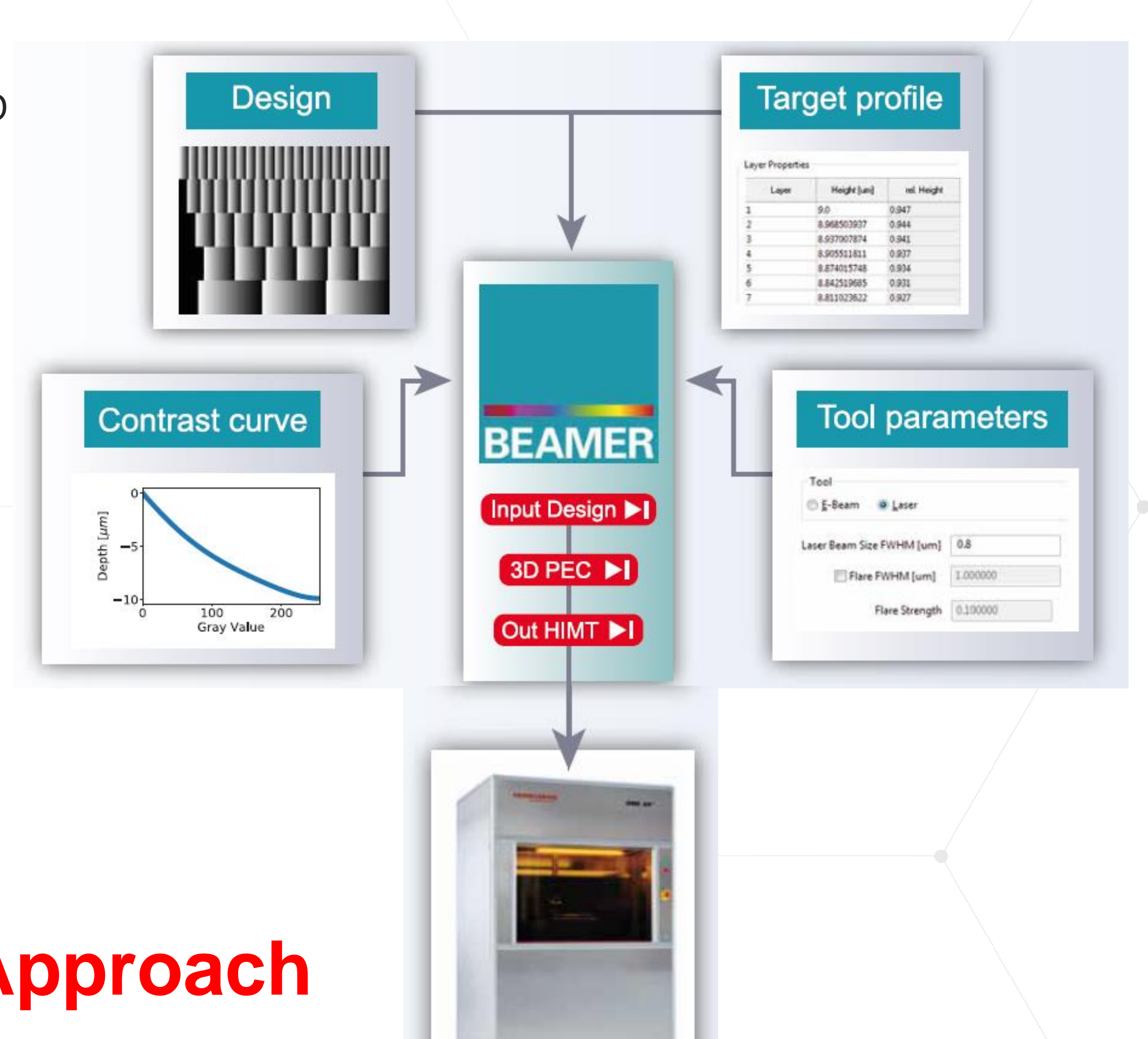
Laser Grey-Tone Correction

BEAMER offers a streamlined workflow to prepare exposure data for generating 3D resist profiles:

-Import PNG or GDS with target resist heights

-Import resist contrast curve

-Output: Corrected data in native Heidelberg Instruments machine-readable format. No further data preparation required for exposure



Model Based Approach

Laser Example Process

- Wafer stack
  - Substrate: 4" glass plate (soda lime)
  - Resist: 2.2µm of AZ1512HS
- Exposure
  - DWL66+ Write Mode II and optical autofocus.
  - 1% (filter) of 230mW (405nm diode laser)
- Development
  - Developed with AZ726MIF 3min. @21°C
- Measurement
  - confocal microscope (Nanofocus)

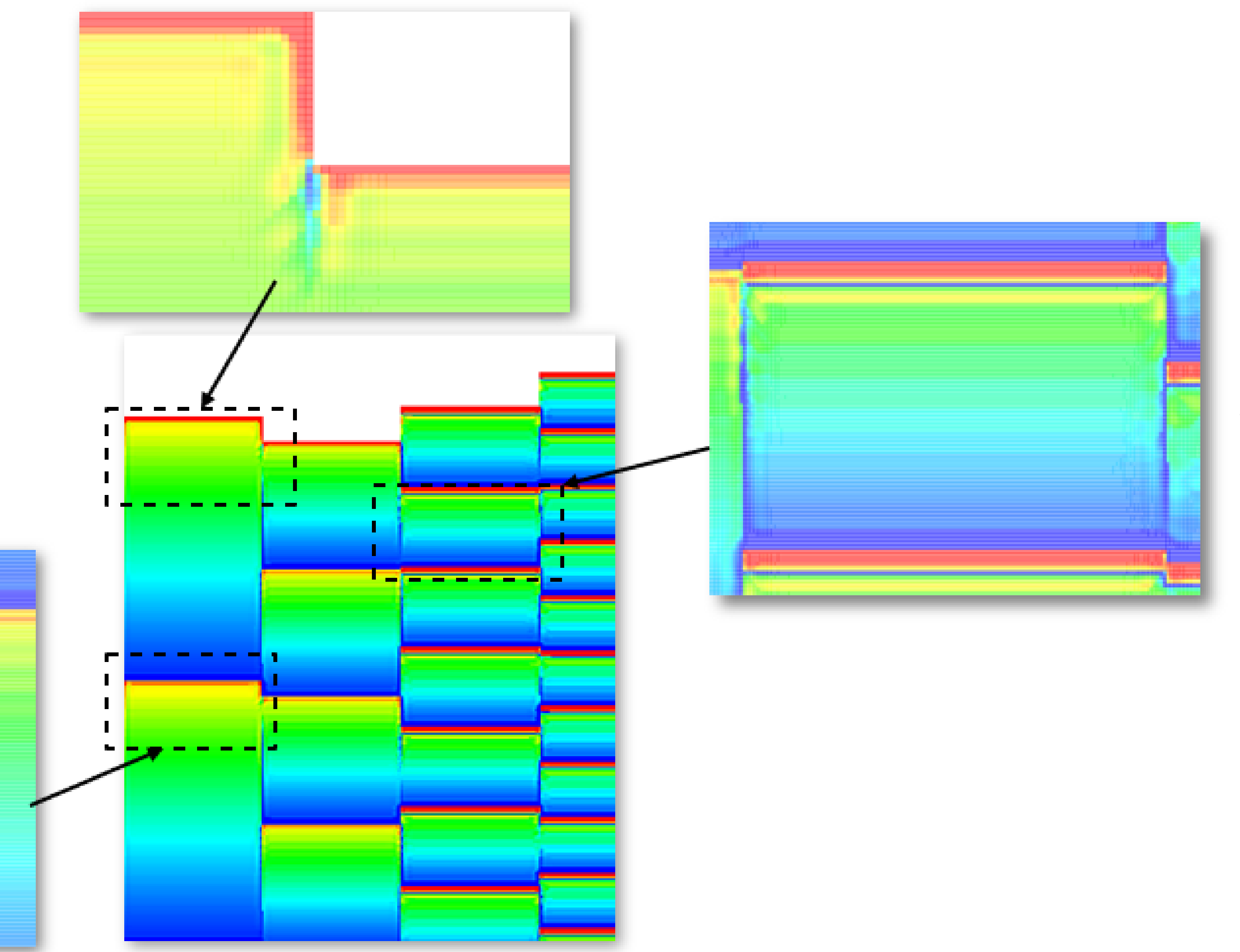
Contrast Curve

# Dose	# Remaining resist [um]
0.000000000	1.977904402
0.039215686	1.972304427
0.078431373	1.929308975
0.117647059	1.855677802
0.156862745	1.7581985
0.196078431	1.64344109
0.235294118	1.517549345
0.274509804	1.38606885
0.305882353	1.280121692
0.352941176	1.124758517
0.392156863	1.001995736
0.431372549	0.887691585
0.470588235	0.783107333
0.509803922	0.688645854
0.549019608	0.603936834
0.588235294	0.527958712
0.62745098	0.459197359
0.666666667	0.395841481
0.705882353	0.336014773
0.745098039	0.278044797
0.784313725	0.220768597
0.823529412	0.163875053
0.862745098	0.108283967
0.901960784	0.056561883
0.941176471	0.013374647
0.952941176	0.003090683
0.960000000	0.001
1.000000000	0.0

Remaining Resist [µm]
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1
Relative Dose

Exposure Data after Correction

Correction is including the proximity area



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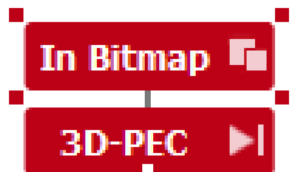
  - 入力ファイル準備と3Dドーズ量補正の実行
- まとめ

Bitmap File Import



☑ Gray Values to Layer

Gray Value	Bundle Ratio
1	2

90 or 45 degree

Layer Tree Dose

In B...
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37

STL File Import

STLファイルの入力

BEAMERでは、STLファイルの高さに応じてLayer分けを行い、2次元平面図として読み込みます。

設計値の最大高さ

設計値の最低高さ

Layers

☑ Create Layers Corresponding to Slices along the Z-Axis

Number of Z-Layers:	256
Lower Bound of Z-Coordinates [um]:	0
Upper Bound of Z-Coordinates [um]:	20
Spatial Arrangement of Layers:	Linear

Layer 1
Layer 2
Layer 3
Layer 4
Layer 5

レンズの例

3D-PEC : Design Example

In GDSII

3D PEC

layer 1 2 3 4 5 1 2 ...

各高さに相当する部分をそれぞれのレイヤーとして設計します。

BEAMER - 3D-PEC

BEAMER

File Edit View Help

Cut | Copy | Paste | Up | Save | Variables | Run | Run To | Cancel | Pause | Resume | Reset | Viewer | Detach | visual-Job

Modules | Flow Libraries | Examples

Layout Operation

Import | Export | Edit
Heal | Transform | Bias
AND | OR | MINUS
XOR | P-XOR | NOT
Extract | Replace | Merge
Grid | Mapping | Filter
Fracture | ChipPlace | visual-Job

Process Correction

PEC | Shape-PEC | 3D-PEC
Corner-PEC | FDA | Rule-OPC

Verification

Simulation | Metrology

Control

Split | Exit | Loop

new flow

In GDSII

3D PEC

Module Info | Log Info | Error/Warnings

Single Path Import OFF
Boxes Import ON
Keep Element Order OFF
Flatten Layout: false
Curve detection OFF
Zero Path Width: 0.000000

90 or 45 degree

Layer | Tree | Doses

In GDSII
1(0)
2(0)
3(0)
4(0)
5(0)

All | Hide | Show

Cell Information

File Name: LE_Base_[
Layout Bbox[um]
Database Units [

Mouse position (Layout Origin) [um]: 1.0643,-12.4327

View Area [um]: -6.926, -15.096; 35.688, 41.101

3D-PEC : Height Setting

In GDSII

3D-PEC

3D Proximity Effect Correction

General | 3D-PEC | Accuracy | Advanced | Label/Comment | Quick Access

Mode: 3D-Surface

Surface Definition Type: AbsoluteThickness

Resist Contrast Parameter

Base Dose [mJ/cm^2]: 128 — Laser Contrast Curve...

Work Range Min - Max [-]: 0.000000 — 1.000000

Pixel Size [um]: 0.200000

Optical Parameters

Absorption unbleached [1/um]	Absorption bleached [1/um]	Refractive Index
0.000000	0.000000	1.000000

Layer Properties

Layer	Height [um]	rel. Height	rel. Dose	Dose [mJ/cm^2]
1(0)	1.8	0.900	0.576056	73.7352
2(0)	1.6	0.800	0.744256	95.2648
3(0)	1.4	0.700	0.844743	108.127
4(0)	1.2	0.600	0.9375	120
5(0)	1.0	0.500	1.02385	131.05

Layer Properties

Layer	Height [um]	rel. Height	rel. Dose	Dose [uC/cm^2]
1(0)	1.8	0.900	0.368676	73.7352
2(0)	1.6	0.800	0.476324	95.2648
3(0)	1.4	0.700	0.540636	108.127
4(0)	1.2	0.600	0.6	120
5(0)	1.0	0.500	0.655249	131.05

Export... | Insert Row | Delete Row

Layer: 1(0), 2(0), 3(0), 4(0), 5(0)

Drop-down list: 5(0), 4(0), 3(0), 2(0), 1(0)

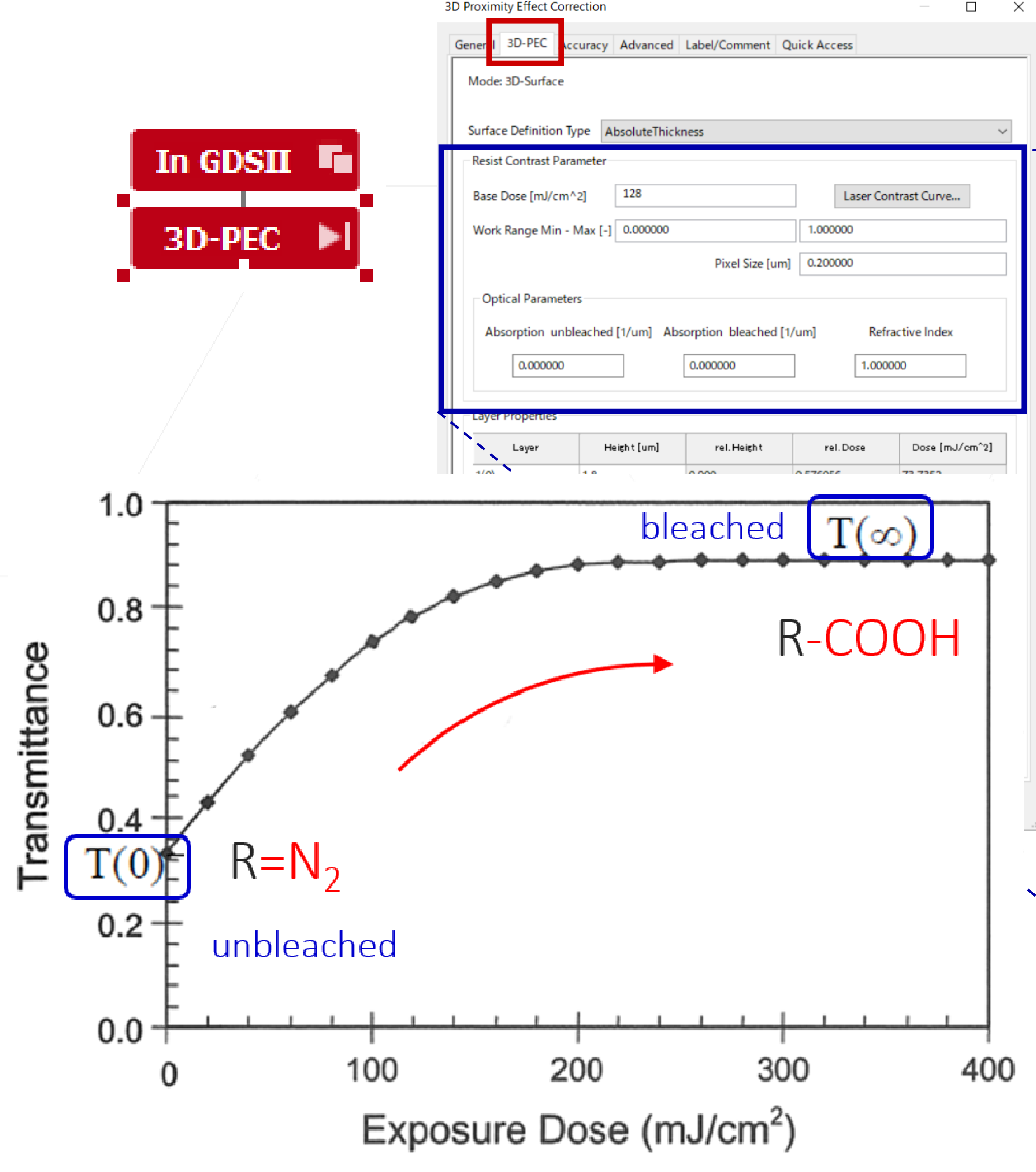
Layer | Tree | D

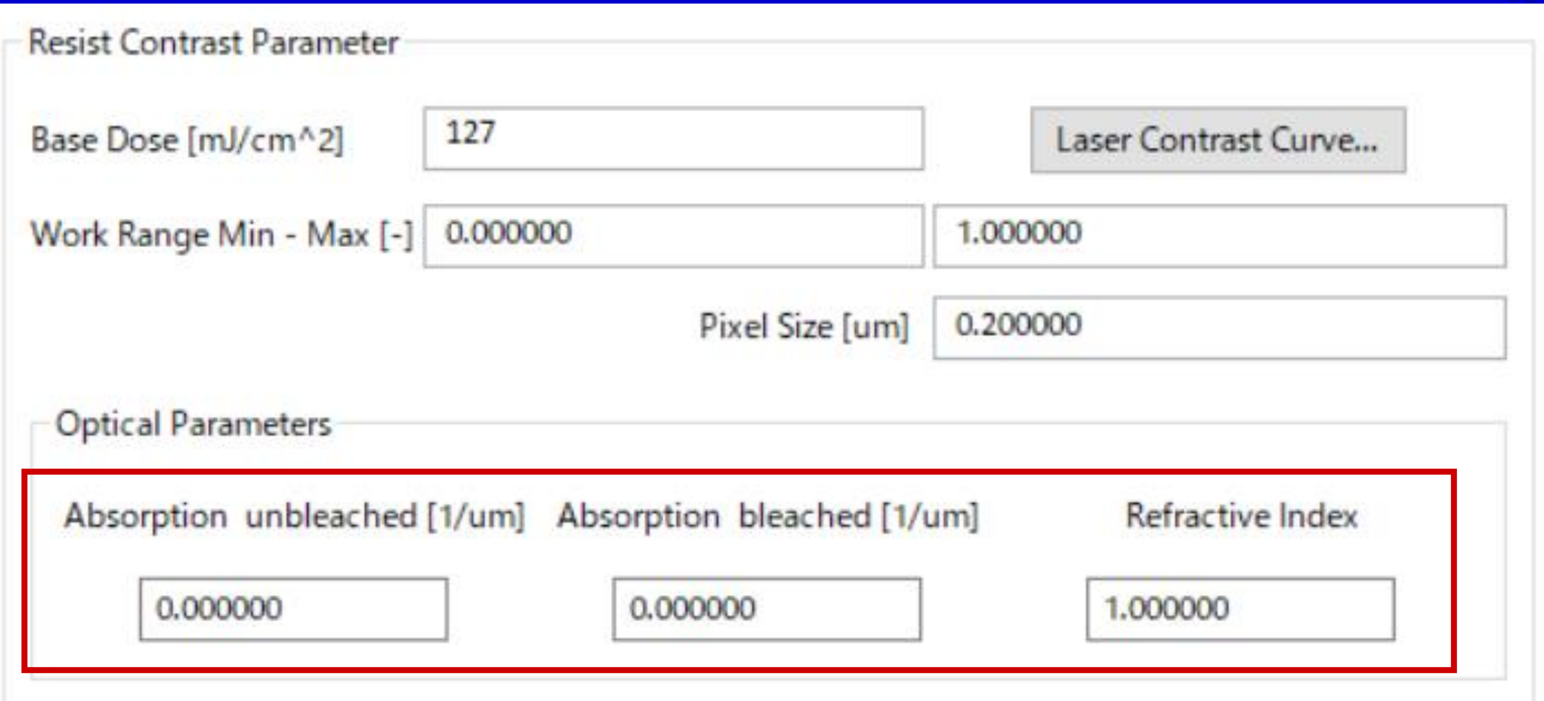
In G...

1(0), 2(0), 3(0), 4(0), 5(0)

レイヤー番号はプルダウンから選択できます。

3D-PEC : Resist Optical Parameters





3D-PEC : Contrast Curve

実際に使う現像条件で取得した感度曲線を入力します（Dose vs. 残膜厚）

3D Proximity Effect Correction

General | 3D-PEC | Accuracy | Advanced | Label/Comment | Quick Access

Mode: 3D-Surface

Surface Definition Type: AbsoluteThickness

Resist Contrast Parameter

Base Dose [mJ/cm^2]: 128 | Laser Contrast Curve...

Work Range Min - Max [-]: 0.000000 | 1.000000

Pixel Size [um]: 0.200000

Optical Parameters

Refractive Index: 1.000000

In GDSII

3D-PEC

Contrast Curve

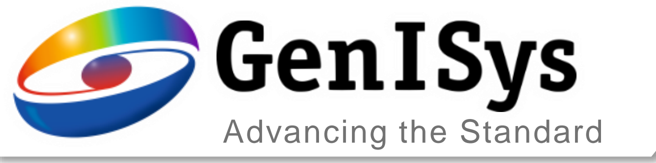
Original Thickness [um]: 2

Dose [uC/cm^2]	Remaining Resist [um]
0	2
40	1.95
80	1.78
100	1.55
120	1.2
140	0.85
160	0.45
180	0.18
200	0.07
220	0.02
240	0

Import... | Export... | Insert Row | Delete Row

OK | Cancel | Help

Contrast Curve (chart): Remaining Resist [µm] (0–2) vs. Relative Dose (0–1)



3D-PEC : Result

Dose Table

In GDSII

3D-PEC

VIEWER - 3D-PEC

File View E-Beam Properties Help

90 or 45 degree

Drawing Speed:

Layer Tree Doses Cell Selection

3D-PEC
0.2798 (0)
0.2826 (1)
0.2854 (2)
0.2883 (3)
0.2912 (4)
0.2941 (5)
0.2970 (6)
0.3000 (7)
0.3030 (8)
0.3060 (9)
0.3091 (10)
0.3122 (11)
0.3153 (12)
0.3185 (13)
0.3216 (14)
0.3249 (15)
0.3281 (16)

Above Upper Limit Color:

Upper Limit: 0.9327

Lower Limit: 0.2798

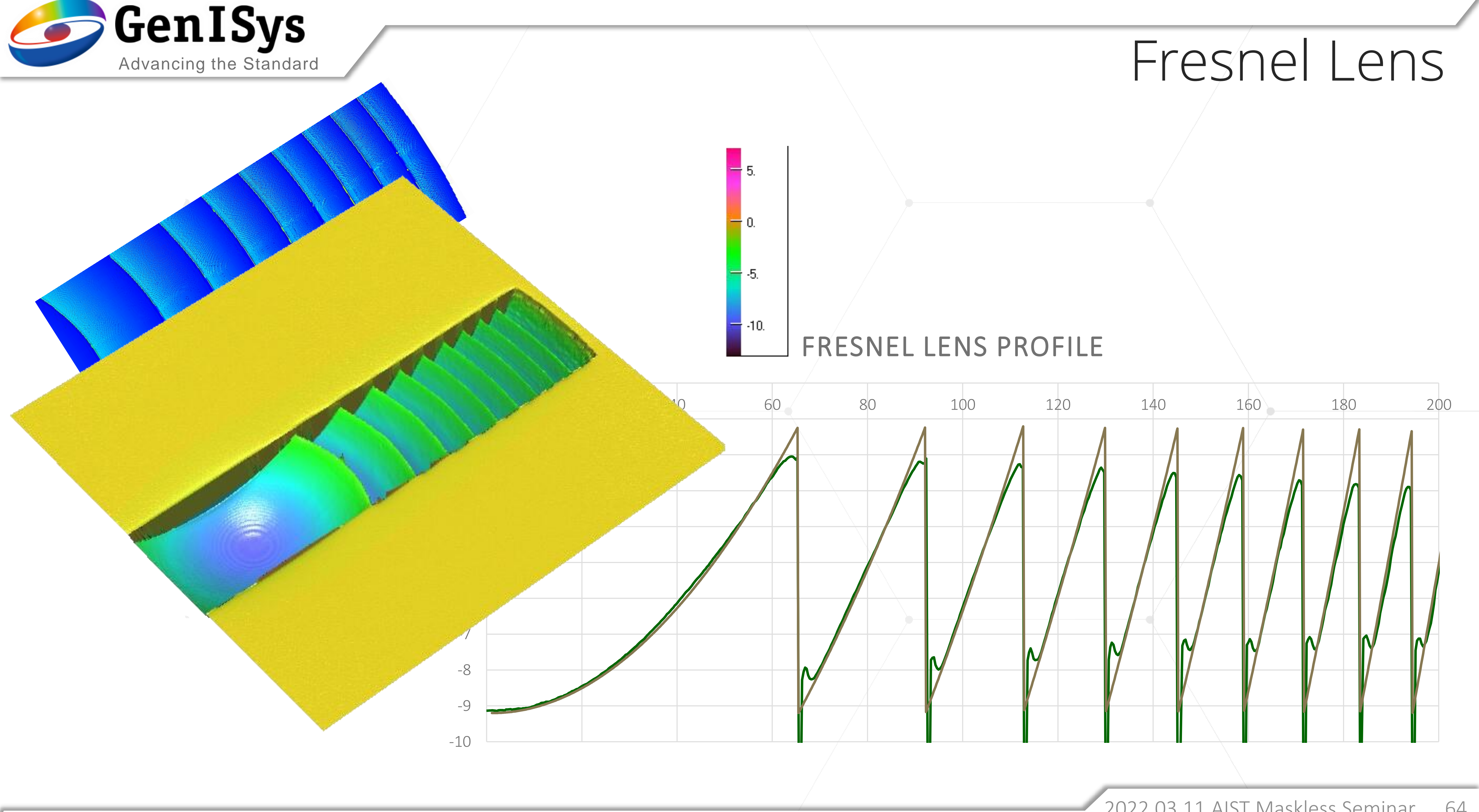
Below Lower Limit Color:

Get Limits Automatically

Cell Information Measurement Information

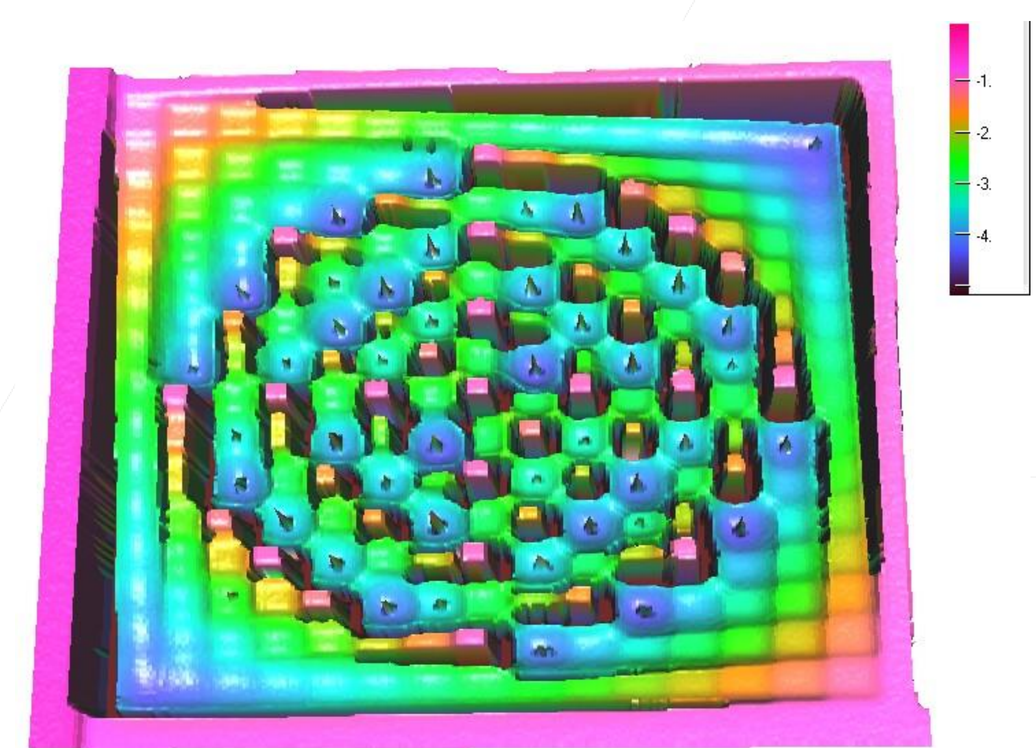
```
File Name:
  Layout Bbox[um]        : (0.000000, 0.000000), (25.000
  Database Units [um]    : 0.001000
```

処理結果：
近接効果を含めたドーズ量補正が行われます。


GenISys
Advancing the Standard
Fresnel Lens
5.
0.
-5.
-10.
FRESNEL LENS PROFILE
60
80
100
120
140
160
180
200
-8
-9
-10
2022.03.11 AIST Maskless Seminar
64

Convex Lens

DOE – 3.2 µm Squares/Pixels



HIMT conventional

with BEAMER

BEAMER is significantly better for the DOE.

Measurement Feedback

3D Proximity Effect Correction - 3D Laser Surface

General | 3D-PEC | Accuracy | Advanced | Label/Comment | Quick Access

Layers considered with fixed dose

Beam Divergence

Wavelength [um] 0.405000

Focus Offset [um]

☑ 3D Measurement Feedback [Topography Data...]

Variables | Run | Run

In GDSII → 3D PEC

Measurement Import Dialog

X Start [um] 0.000000 | Y Start [um] 0.000000 | Import...

X Grid [um] 0.000000 | Y Grid [um] 0.000000 | Z Offset [um] 0.000000

Measured Resist Height [um] (after exposure with corrected pattern)

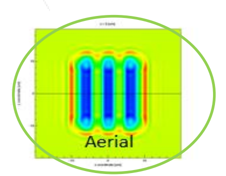
	A	B	C	D	E	F
1						
2						
3						
4						

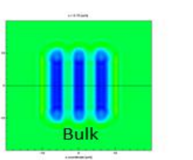
☑ 3D Measurement Feedback [Topography Data...]

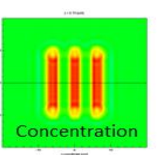
Laser Image Formation

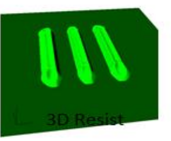
3D imaging kernels calculate the aerial image

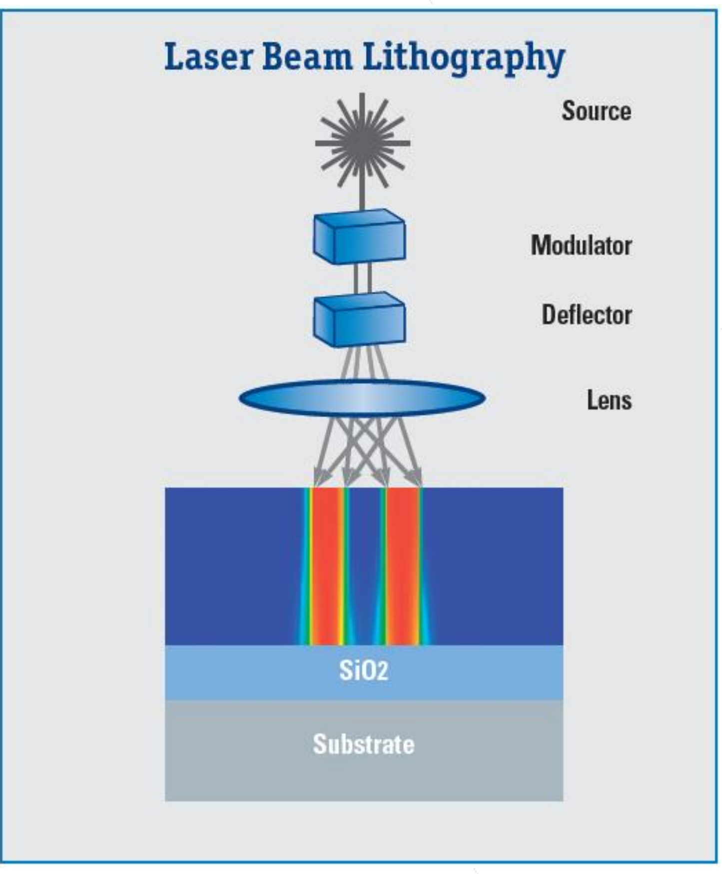
- Source Modelling
  - Any laser source, h-line, i-line, DUV
  - Arbitrary machine
    - Exposure strategy
      - beam step size (pixel)
      - machine specific (e.g. VPG, DMD)
    - Optics
      - NA
      - Defocus
      - Flare
- Fast and accurate calculation of aerial image





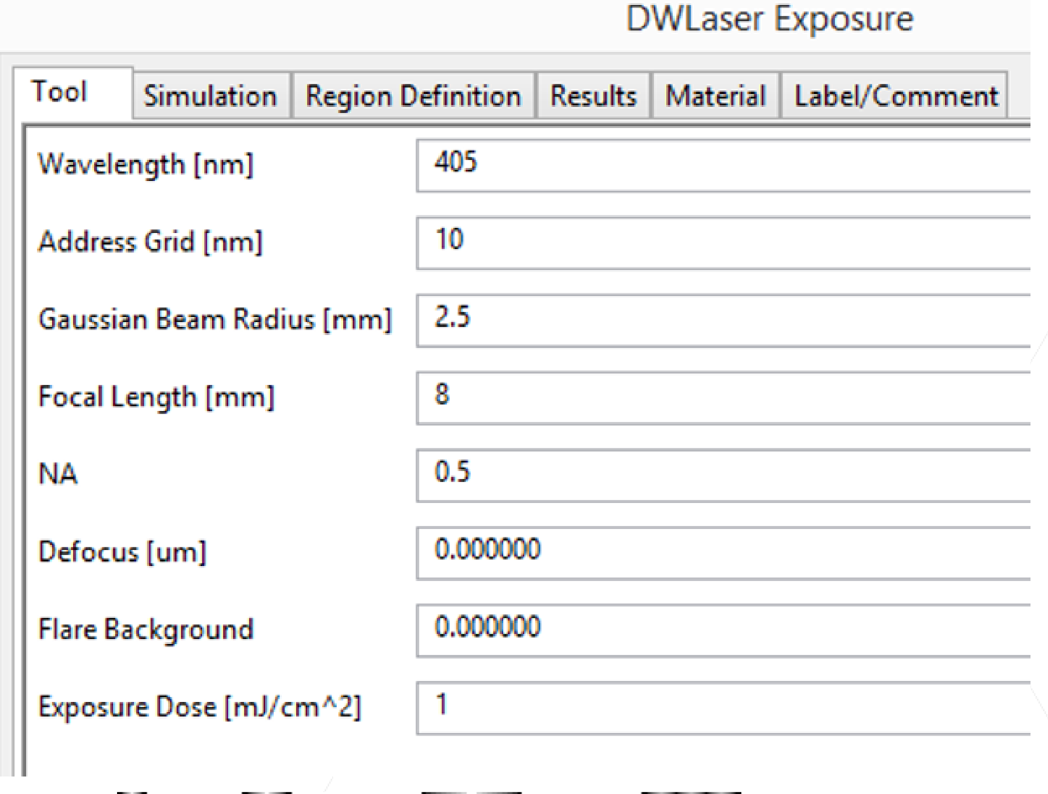


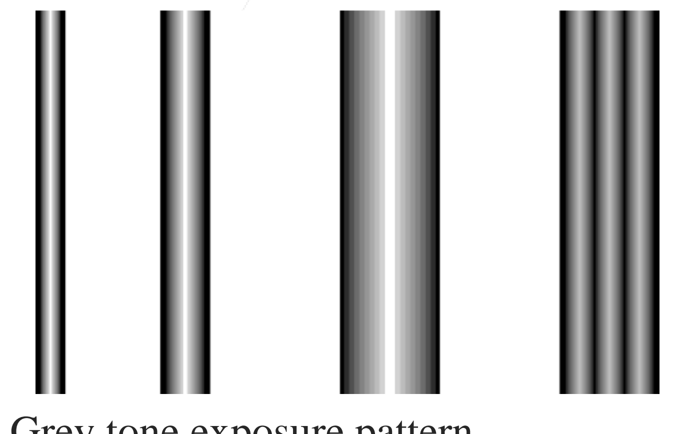




Simulation of Laser Exposure Process

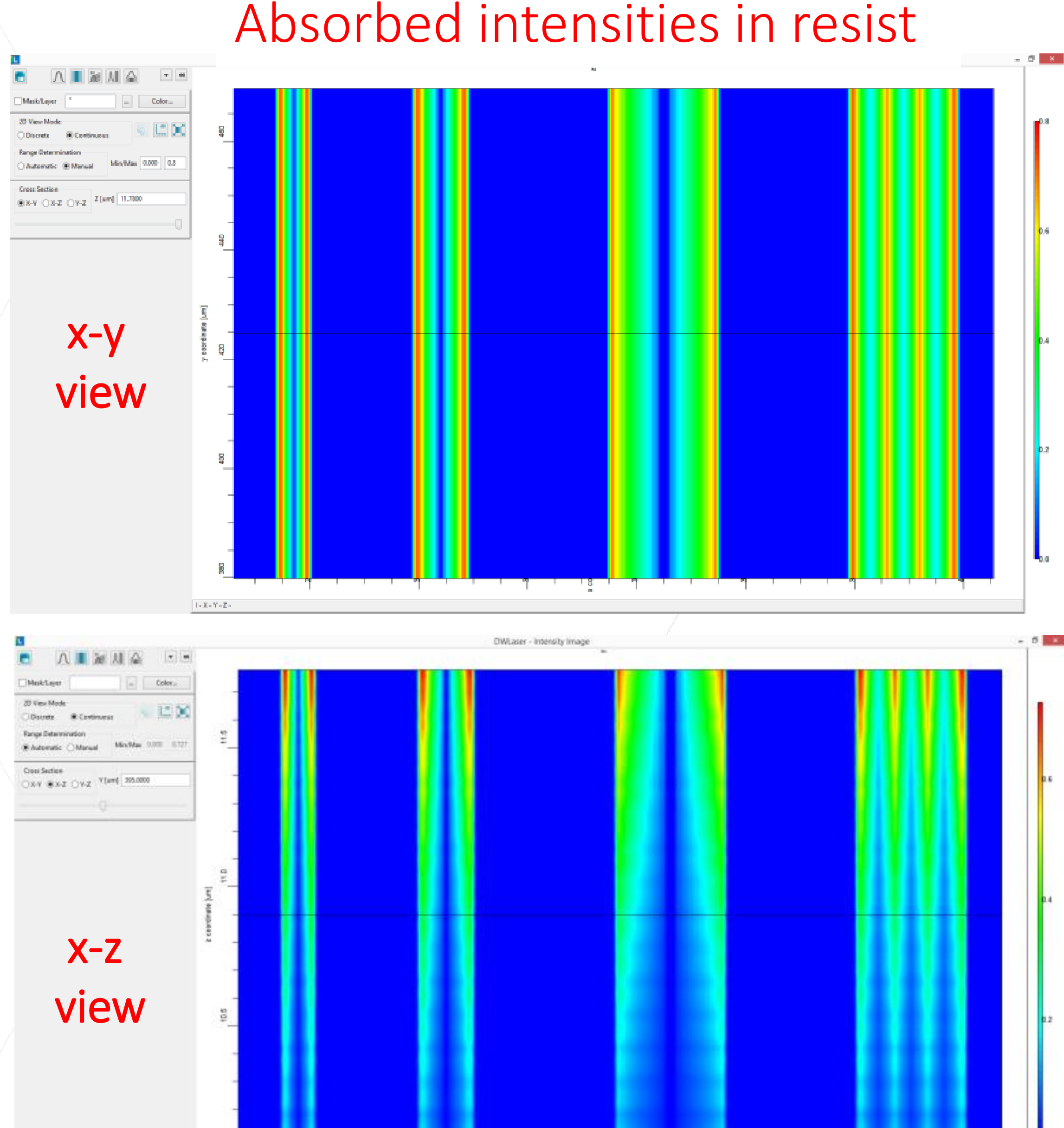
Exposure parameters

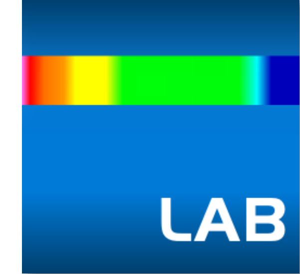




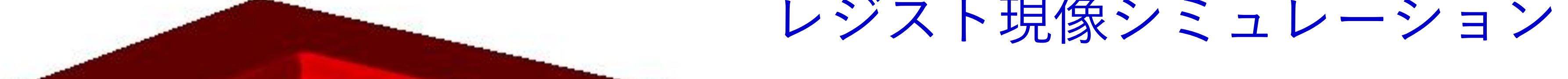
Grey tone exposure pattern

Absorbed intensities in resist



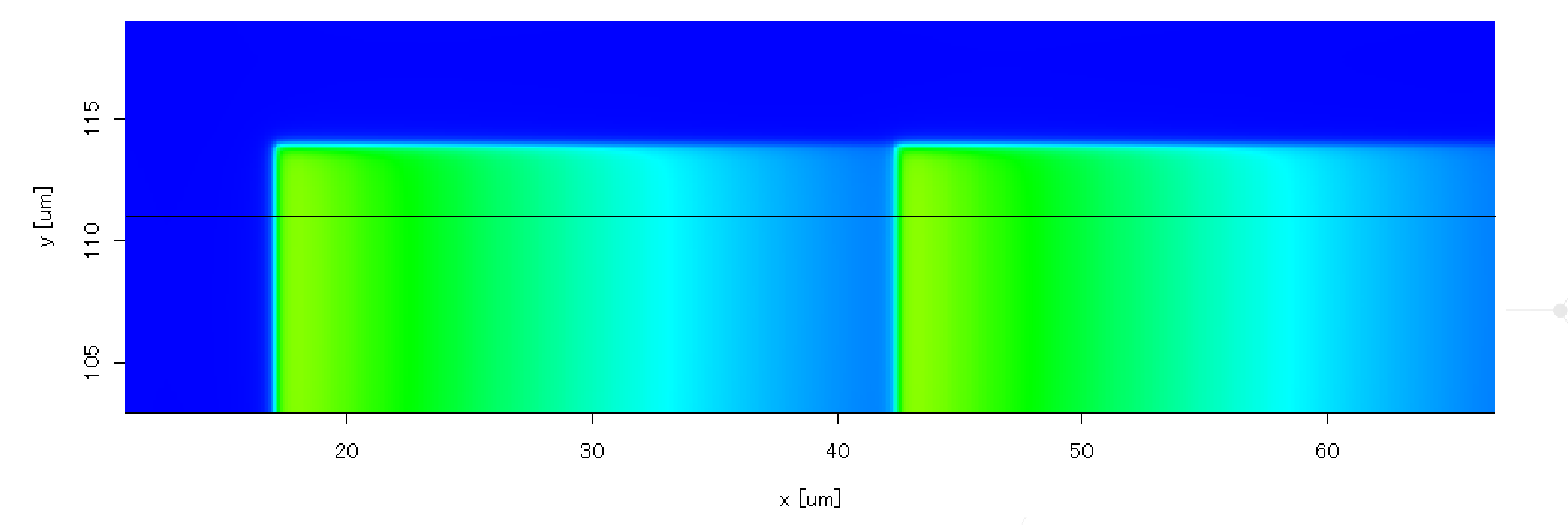


LAB Simulation



レジスト現像シミュレーション

レーザー露光シミュレーション



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- まとめ

Summary

- レーザー描画において、レーザー光による近接効果や現像の影響で（横方向現像等）仕上がり形状が影響を受ける。そのため感度曲線からの「ドーズ vs. 高さ」の１:１補正では、期待した補正結果とならないことが多い。
- 物理露光モデルをベースとしたModel-OPCでは、ガウス分布のレーザー光の重なりを考慮して線幅や形状の自動補正を行う。また「設計線幅 vs. 現像後仕上がりサイズサイズ」の検量線があれば、Rule-OPCツールを用いて線形なフィードバックを掛けられる。このRule-OPCではコーナー形状補正も可能。
- グレイスケール露光では、レジスト光学パラメータやガウス分布を含む露光条件、及び感度曲線情報から、BEAMERの自動計算により設計値に対する適切な露光量を求めることが出来る。応用例：マイクロレンズ、フレネルレンズ、DOEなど。

GenISys

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