Electron beam lithography for ultra-low-loss photonic devices and systems

SNSF Fellowship Final Report

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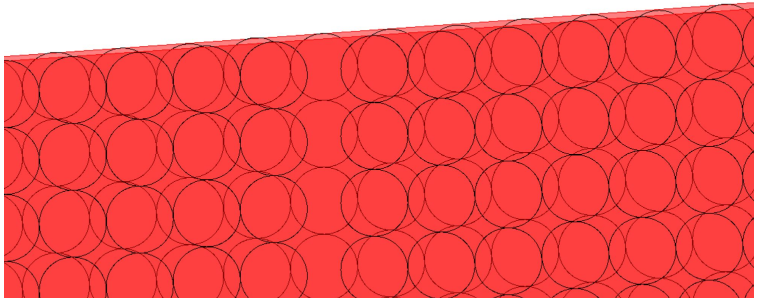
Contents

General principles

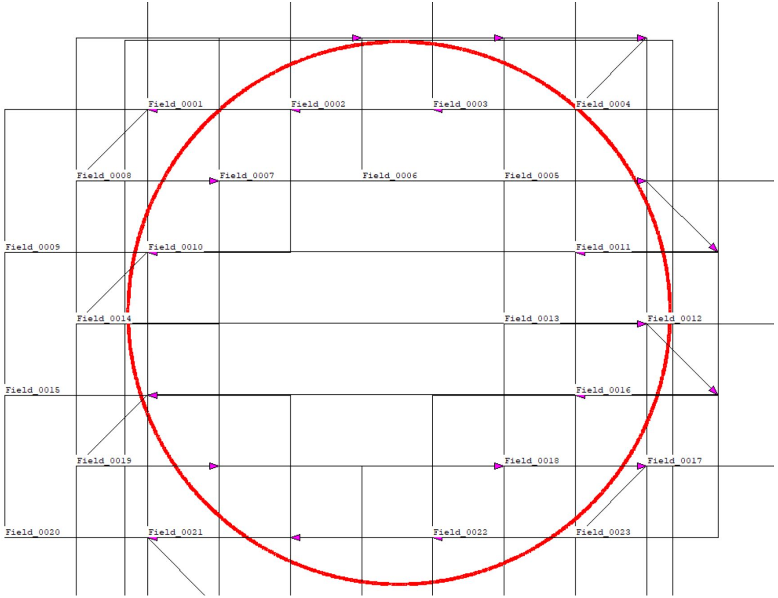
- Make sure you have the proper dose. Perform a dose sweep if you have questions. Underdosing can especially cause rough shape edges.
- Minimize stage movement to reduce write field boundary errors
  - The goal is to have adjacent fields written sequentially. This is not always possible. Fracturing your pattern into multiple .v30 files can give finer stage movement control at the cost complexity.
- Minimize beam deflector movement
  - The goal is to have adjacent shapes within a write field written sequentially
- Multipass gives an averaging effect which can minimize write errors
- Trade-off between minimum dose and shot size can occur when using multipass.
  - Min. area dose = (beam current)/(DAC rate * shot size)
    - DAC rate is 25 MHz
- Consider stage movement/boundaries when you are making your CAD files!

Multipass exposure

- Exposes the pattern multiple times with a 50% stage movement offset.
- For example, 2x multipass exposed every area twice, so the dose needs to be lowered in the JDF file.
- It reduces random statistical errors of the shot placement due to noise in the beam deflector system
- It reduces writing errors at the write field boundaries due to stage movement errors



Overlapped shot placement. Multiple shots dose a given location.



50% write field offsets

Why not multipass?

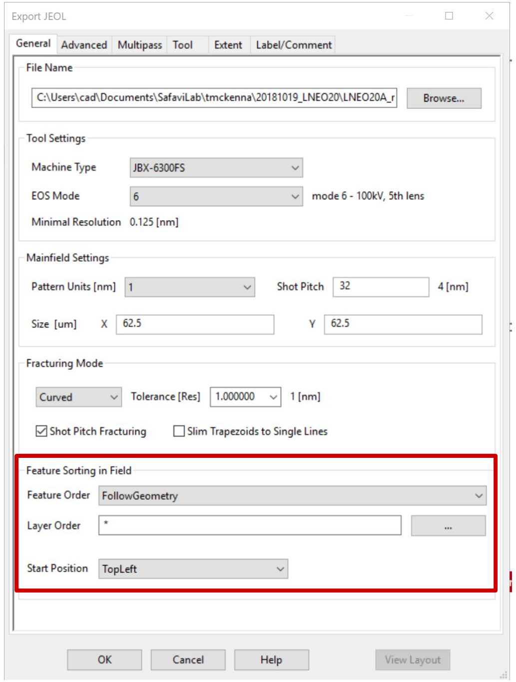
1. The critical features of your pattern only occupy a single write field
2. You don't want to spend extra write time with additional stage movement.
3. The trade-off between minimum dose and shot size could force you to use very low current, which increases your write time.

Feature Sorting Order

- Determines the write order of features within a single write field.
- Must add “SRTPRM 0” to your JDF for the JEOL to follow the Featuring Order defined in the .v30
- If “SRTPRM 0” is omitted, the JEOL uses its default featuring ordering, which is in general a safe option.
- Choosing the wrong Feature Order can result in worse performance than the JEOL default.

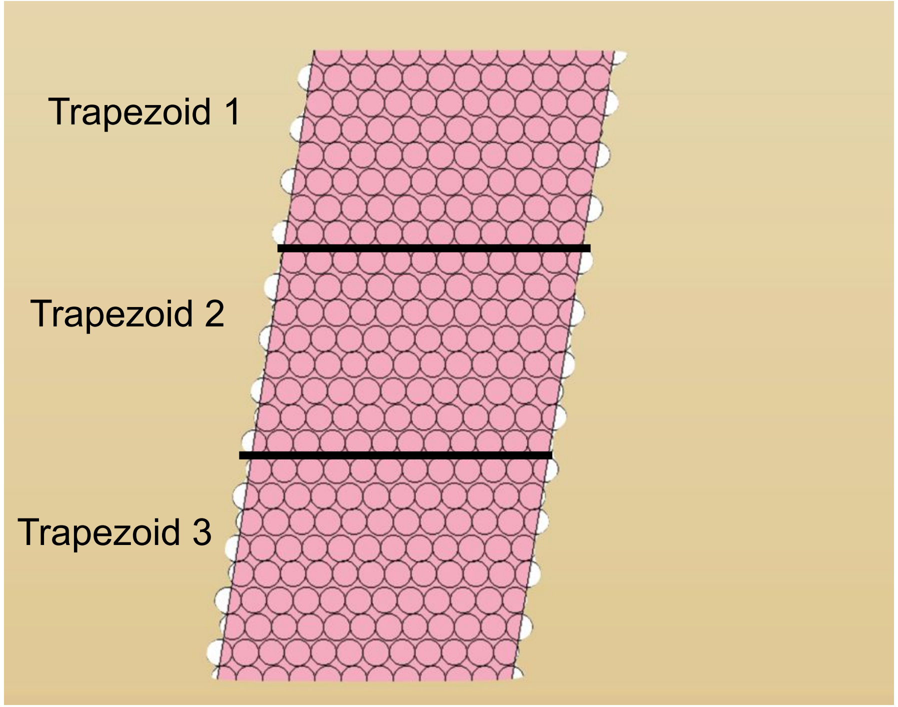
```
;---------------------------------------
LAYER    1
    P(1) 'waveguides.v30' (0,0)
    P(2) 'ring.v30' (0,0)
    SRTPRM 0
    P(3) 'marks.v30' (0,0)
```

Example .JDF snippet has P(2) use the Feature Order defined in .v30. P(1) and P(3) use the JEOL default feature order.

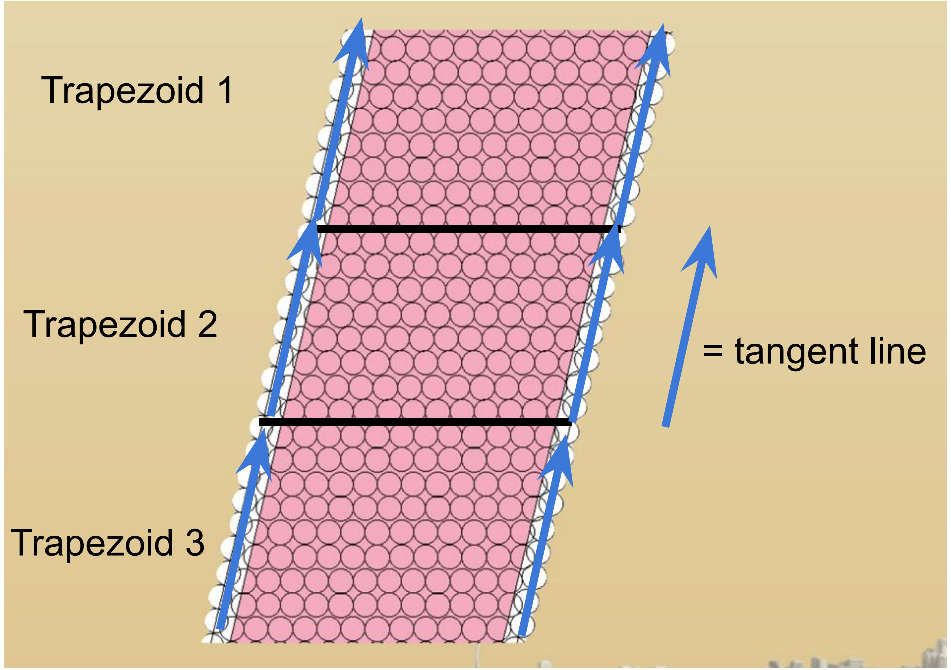


Single Line Smoothing

- Outlines the shape with a line dose for uniform shot placement at the edge
- Writes a single vector tangent to the curve



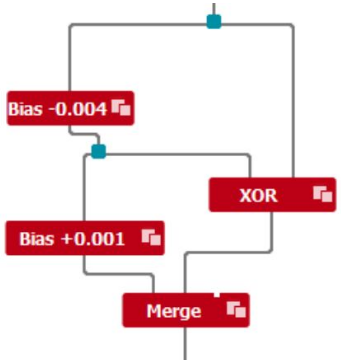
Without single line smoothing

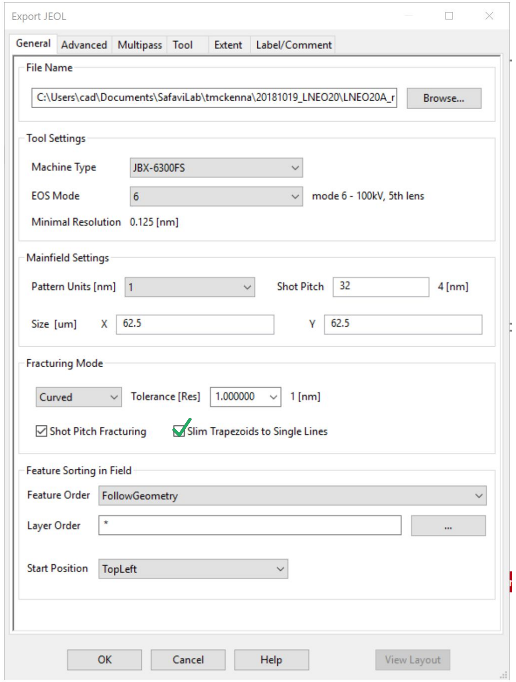


With single line smoothing

Single Line Smoothing

1. Bias the shape smaller by 4 nm
2. XOR the the biased shape from the original shape to form slim trapezoids
3. Bias the shape 1 nm to overlap with slim trapezoids and merge
4. Check the “Slim Trapezoids to Single Lines” option in the Export block to convert the slim shapes to line objects
5. Don’t forget to set the line dose in the .JDF file

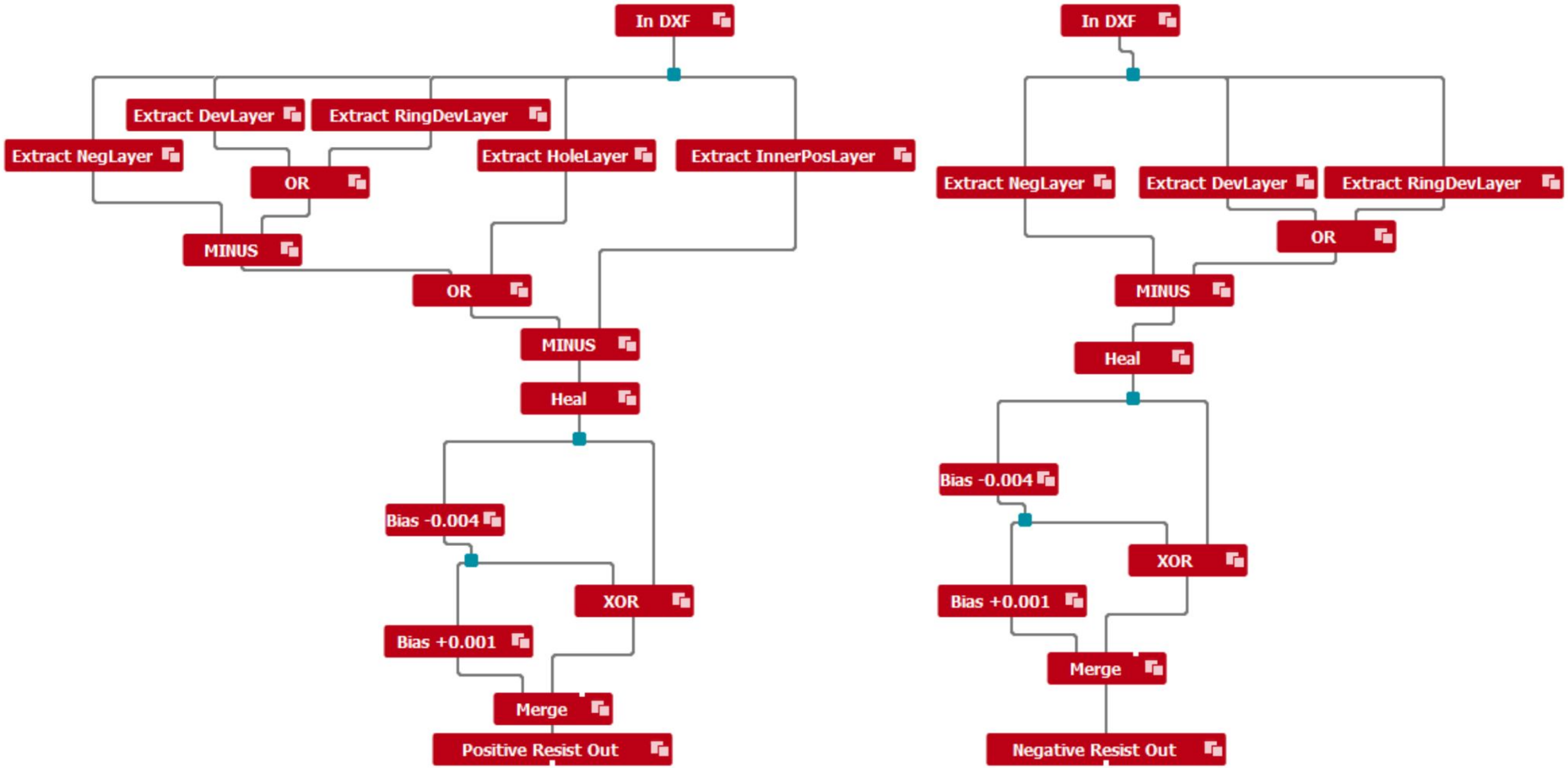




Tip: The line dose can be different than the area dose. Choosing a larger line dose can smooth the edges of shapes due to the proximity effect, while still keeping reasonable shape fidelity since the majority of the shape is at the proper base dose.

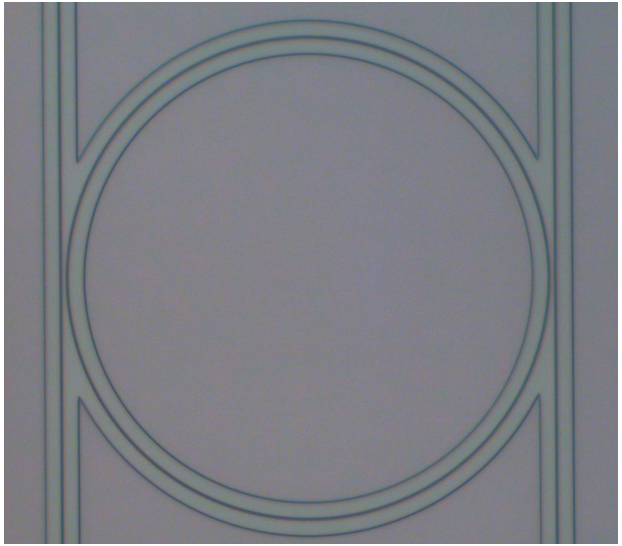
Single Line Smoothing Flow example

This example outputs for both positive and negative resist, just for comparison.



Silicon Photonics Ring Resonators

- The quality factor of a silicon ring resonator is very sensitive to edge roughness due to writing errors
- Silicon-on-insulator process, 220 nm silicon layer, 3 um silicon dioxide, silicon handle.
- Overview of ring resonators: https://doi.org/10.1002/lpor.201100017



Ring after development of CSAR resist

SOI process documentation

Main steps:

1. Sample preparation
2. Electron beam lithography
3. Development
4. Etch
5. Clean

SOI Process documentation

- Runsheet for a proven silicon photonics process

Authors:	Tim McKenna and the lab of Prof. Amir Safavi-Naeini			
	Process Runsheet	**Silicon Photonics Process Parameters**		
	Material	**220 nm SOI, 3 um BOX, 5 by 10 mm chip**		
Process	**Step**	**Parameters**	**Tool**	**Location**
Spin and Bake	Chip Clean	Acetone soak for ~ 20 min, IPA rinse, N2 blowdry	solvent wb	**SNC (Spilker)**
	Dehyrdration Bake	3 min dehydration bake @ 180 C OR 5 min at 150 C if only one hotplate available	hotplate	
	CSAR Spin	**CSAR 62.09,** 60s @ 6000 rpm, 2000 rpm/s ramp	SNC spinner	
	Bake CSAR	1 min bake @ 150 C	hotplate	
	Check Resist	Filmetrics Characterization, (~175 nm thickness)	filmetrics	
JEOL Lithography	ebeam write	4 nm shot size. 320 uC dose	JEOL	**SNC (Spilker)**
	Develop	40s Xylenes, 10s IPA, gentle N2 blow dry	solvent wetbench	
	Pattern check	Inspect and take pics	microscope	
Lampoly Plasma Etch (Cl2 HBr)	Mount on Carrier Wafer	5% PMMA for chip adhesion to wafer, bake 2 min 80 C or 90 C	solvent wb	**SNF (Allen)**
	Clean	Standard Chamber Clean on Lampoly (5 min)	lampoly	
	Condition	Condition (5 min)	lampoly	
	Etch	[see params in lampoly spreadsheet tab]	lampoly	
	NMP Clean	> 1hr at 80 C. Rinse with acetone and IPA after, then N2 blowdry	solvent bench/hotplate	**SNC (Spilker)**
SNF Piranha Clean	Piranha	9:1 sulfuric acid:hydrogen peroxide, ~120 C, 15 min, dump rinse after	wbflexcorr	**SNF (Allen)**
	HF Dip	50:1 HF dip, 30 s, gentle swirling, six rinse cycles	wbflexcorr	
		Do this 2x, recharge with peroxide between. Finish with gentle N2 blowdry	wbflexcorr	

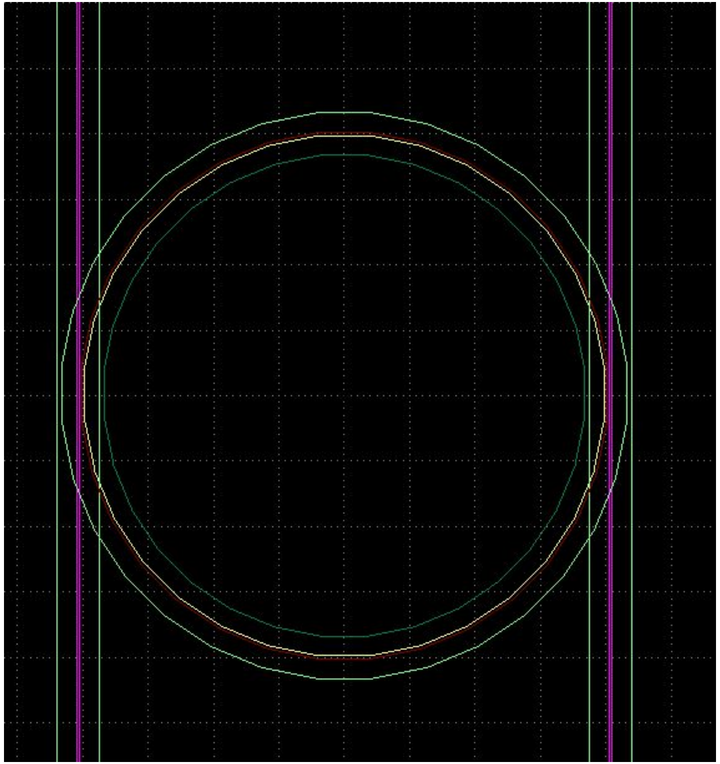
SOI Process documentation

- Lampoly Cl2/HBr etch parameters

Lampoly Parameter	Breakthrough	Main Etch	Overetch
chamber pressure (mtorr)	13	10	15
TCP RF Forward (W)	250	250	250
Bias RF Forward (W)	45	60	65
Gap (cm)	5.9	5.9	5.9
Cl2 (sccm)	0	40	0
HBr	0	100	50
O2/He	0	5	5
SF6	0	0	0
He	0	0	0
C2F6	100	0	0
O2/He	0	5	0
N2	0	0	0
Clamp Pressure	6	6	6
Time (s)	10	30	40

Example CAD files

- DXF file format, in this example
- Large ring resonator that consume multiple right fields
  - Avoids waveguide bending loss
  - Sensitive to write field boundaries
- Separate ring and feed waveguide layers
  - Allows BEAMER algorithm for “Follow Geometry” feature write order to function better.
- Boolean operations of the layers required in Beamer
- More information about ring resonators: https://doi.org/10.1002/lpor.201100017



BEAMER Flow example

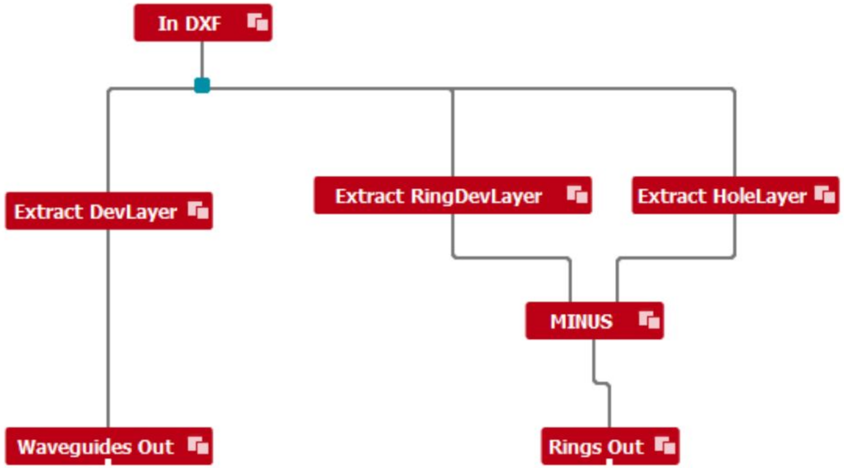
Steps:

1. Separate the ring layer from the feed waveguide layer using Boolean operations
2. Export the feed waveguide layer to a single .v30 file. We don't need to apply the advanced Export features to the feed waveguides. We only need a simple fracture.
3. Export the ring layer to another .v30 that uses the multipass settings of the Export block.
4. Organize the .v30 files in a JDF and SDF

Note: Single line smoothing can also be added to the pattern by incorporating the single line smoothing flow example into the overall flow

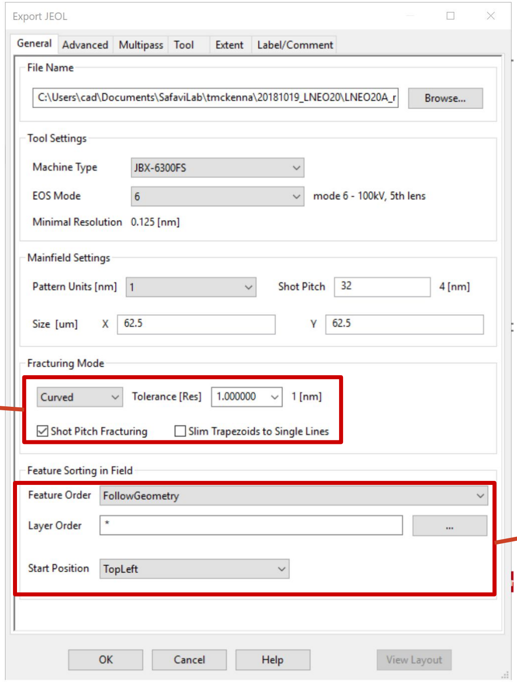
BEAMER Multipass Flow example

- This flow is suitable for negative resist.
- Rings and waveguides get exported separately to avoid unnecessary stage movement when writing the rings. It also provides better feature write order within a single write field.
- The disadvantage is that the gap between the ring and waveguides won't be as accurate.



BEAMER settings, General tab

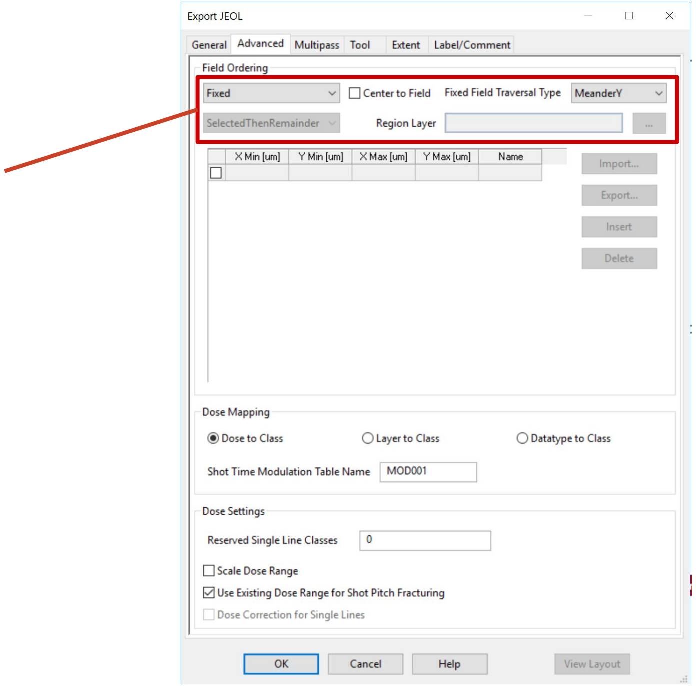
- “Curved” allows BEAMER to optimize fracturing for rings and circles
- Shot pitch fracturing allows for shot overlap to better fill shapes of arbitrary size



- “FollowGeometry” tells the JEOL to write the fractured shapes in an order that follows the waveguide
- Avoids excessive beam deflection movement

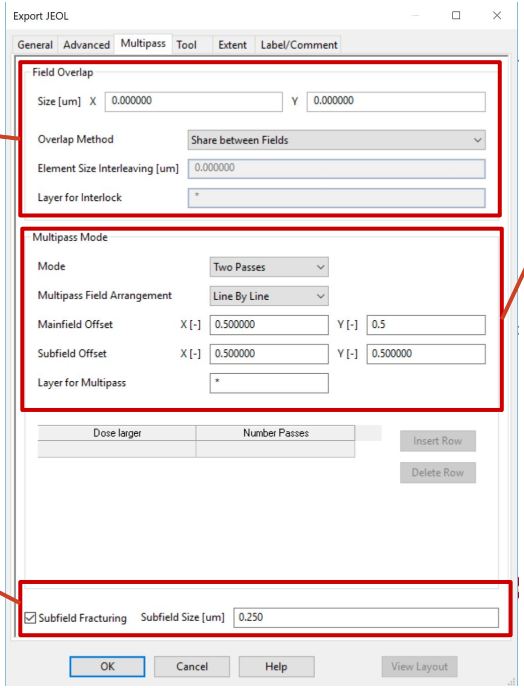
BEAMER settings, Advanced tab

- Multipass is only compatible with “Fixed” field ordering
- The best “Fixed Field Traversal Type” depends on the specific pattern
  - The goal is to minimize stage movement near critical areas of the pattern



BEAMER settings, Multipass tab

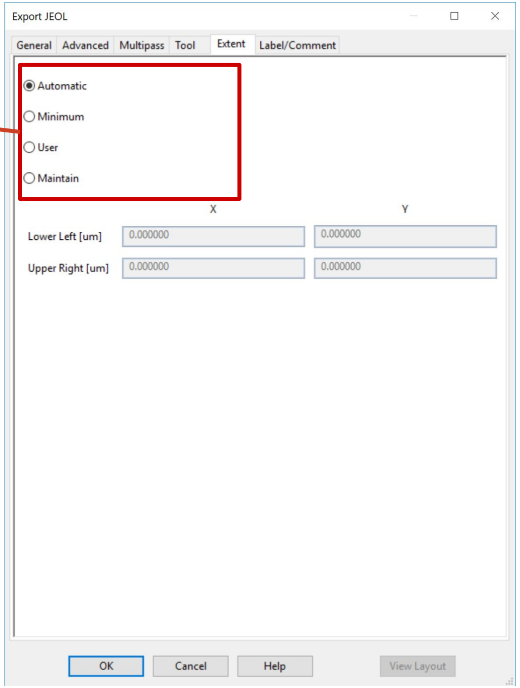
- These settings are misleading and are not used for multipass
- Offsets the subfields to prevent subfield boundaries
- EOS6 subfield size is 0.250 um



- "Two passes" means the pattern is exposed twice
- "Line by Line" option limits stage movement from field to field
- "Mainfield Offset" defines how the fields overlap
- "Subfield Offset" defines how the subfields overlap

BEAMER settings, Extent tab

- Multipass only compatible with "Automatic" extent



.SDF file example

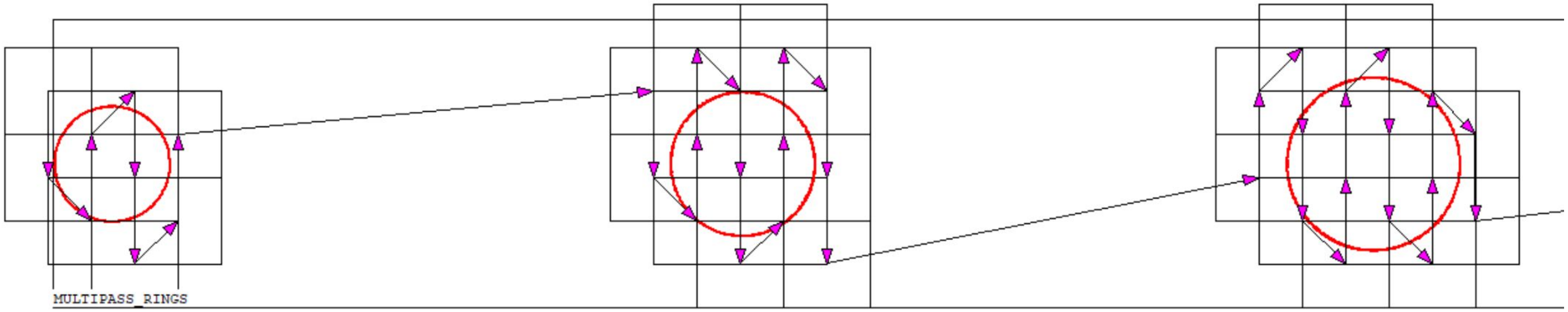
```
MAGAZIN 'ring_ex'

#1
%2F
JDF 'ring_ex',1

GLMDET   C    ;Global alignment ( C is for None)
HSWITCH  OFF,ON     Chip Height Correction Only
CHIPAL   V1   ;Chip alignment ( V1 is for height
measurement at M1)

OFFSET (0, 0)
END
```

.JDF file example

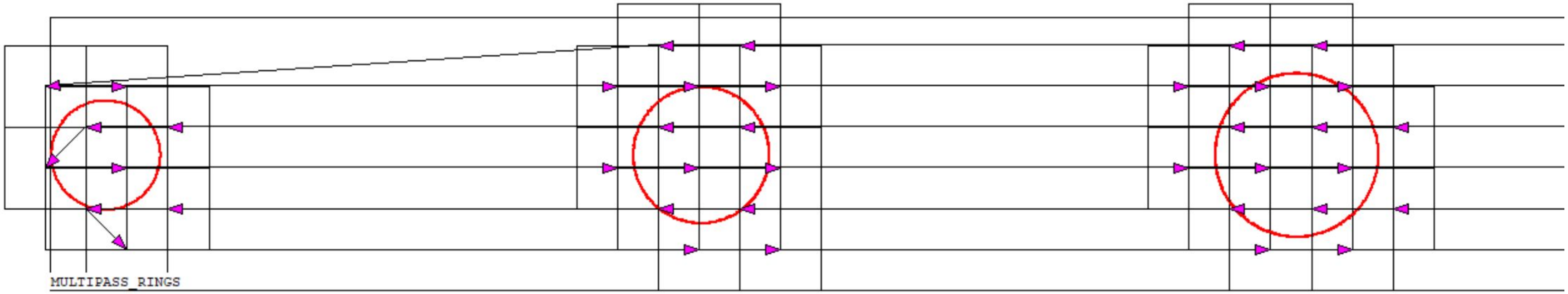
```
JOB/W  'ring_ex',2,0

; ======== PQRS  GLOBAL MARK POSITION OPTIONS ============
 GLMPOS     P=(-5000,0),Q=(5000,0),R=(0,2300),S=(0,-2300)  ; 4 inch Wafer with
3um Mark
 GLMP 3.0,300.0,0,0 ; P Mark width = 3um, Length = 3000um
 GLMQRS 3.0,300.0,0,0 ; QRS Mark width = 3um, Length = 3000um
; ----------------------------------------
PATH;

;waveguides
1:  ARRAY (0,1,0)/(0,1,0)
        CHMPOS M1=(0,0)
        CHMARK 3.0,20.0,0,0
        ASSIGN P(1) -> ((*,*),DOS1)
    AEND

;ring
2:  ARRAY (0,1,0)/(0,1,0)
        CHMPOS M1=(0,0)
        CHMARK 3.0,20.0,0,0
        ASSIGN P(2) -> ((*,*),DOS2)
    AEND

;alignment marks
3:  ARRAY (0,1,0)/(0,1,0)
        CHMPOS M1=(0,0)
        CHMARK 3.0,20.0,0,0
        ASSIGN P(3) -> ((*,*),DOS3)
    AEND
PEND
```

```
;----------------------------------------
LAYER    1
    P(1) 'waveguides.v30' (0,0)
    P(2) 'ring.v30' (0,0)
    SRTPRM 0
    P(3) 'marks.v30' (0,0)

    SHOT A, 32
    RESIST 320,320,A
    EOS 6, 'EOS6_1000pA_025u'
    STDCUR 1.0
    OBJAPT 3

DOS1: MODULAT((0, 0))
DOS2: MODULAT((0, -50.0)) ;reduce dose for 2x multipass
DOS3: MODULAT((0, 0))

END
```

Good vs. Bad Stage Movement

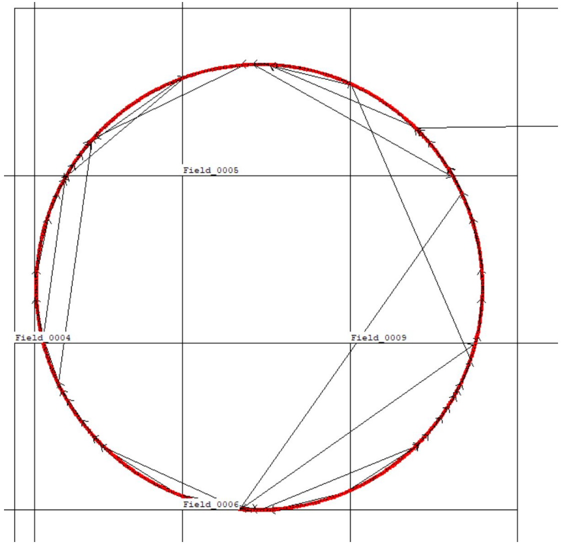


Good: write one ring before starting the next. Minimum stage movement.

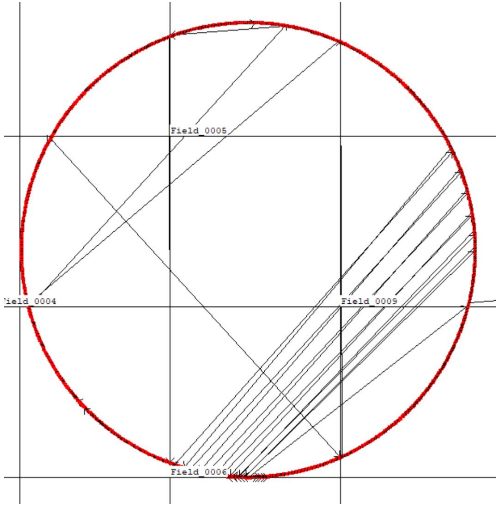


Bad: move to write the next ring before finishing the first. Excessive stage movement.

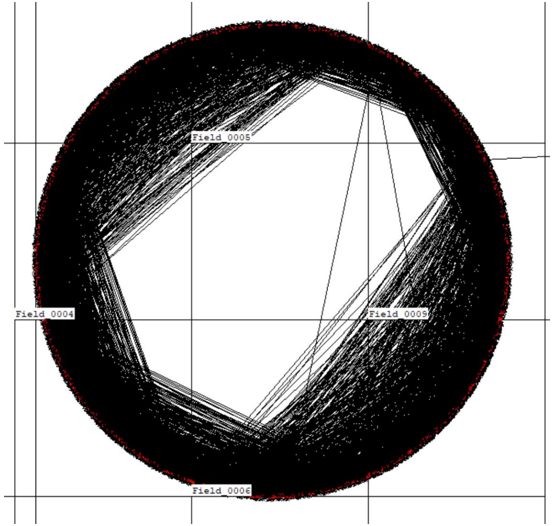
Good vs. Bad Feature Sorting



Good: FollowGeometry



Okay: NoCompaction



Terrible: Random

Note: Some discontinuities in stage movement are inevitable because the pattern occupies multiple write fields
Note: JEOL only takes these settings into account if “SRTPRM 0” is included in the JDF file

Files

Multipass Beamer flow example

Single line smoothing Beamer flow example

Ring DXF file

JDF file

SDF file

SOI Runsheet

Note: SDF and JDF files are for example only. Please don't rely on them blindly.

References

S. Patrick, et al, “Improvement of silicon waveguide transmission by advanced e-beam lithography data fracturing strategies”, Journal of Vacuum Science & Technology B 35, 06G504 (2017); https://doi.org/10.1116/1.4991900

R. Bojko, et al, “Electron beam lithography writing strategies for low loss, high confinement silicon optical waveguides”, Journal of Vacuum Science & Technology B 29, 06F309 (2011); https://doi.org/10.1116/1.3653266

W. Bogaerts, et al, “Silicon microring resonators”, Laser & Photonics Review, Vol 6., No. 1, https://doi.org/10.1002/lpor.201100017