adolphe merkle institute
excellence in pure and applied nanoscience
UNIVERSITY OF FRIBOURG SWITZERLAND

Focused ion beam

Nanobuilder – Advanced settings

Version 1 – September 2024

Universal rules

Rule 1: don't touch a control if you are not sure of the outcome of that action

Rule 2: never, ever force anything beyond finger strength

Rule 3: wear gloves when touching anything that goes into the chamber

Rule 4: if in doubt, ask for help

Demonstration: Line scan alignment

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

Nanobuilder provides two types of alignments: Line Scan Alignment & Correlation Alignment

The line scan alignment works by scanning several line segments with the beam and measuring the detector signal along each line. Assuming the lines intersect with known features on the sample, transitions (jumps in the signal) will occur at these intersections. By comparing the actual transition locations with the expected locations, or the measured line profile with a reference profile, you can find the shift for each line. A fit to all the lines gives the shift, rotation, scale, and shear parameters that best match the measured shifts.

- Creating a Line Scan Alignment

1. Create a GDSII file with shapes on the Line Scan Alignment Layer that indicate where the lines are to be scanned and shapes on any other layer that indicate the features that the lines will scan over (the fiducial marks).

Make sure that LineScanAlignmentLayer is set to 61 in the Preferences dialog box.

2. Load this file into NanoBuilder.
3. Use Insert > Alignment > Line Scan Alignment (or right-click on Alignments in the Overview tree) to create a new line scan alignment.
4. The new alignment will automatically import the shapes on the Line Scan Alignment Layer as the lines to scan, checking for intersections with shapes on other layers.
5. Optionally, train the alignment if you need best layer-to-layer accuracy (at the cost of absolute accuracy to the fiducial marks).

- Line scan alignment properties

The following table provides detailed information on each of the properties of a line scan alignment.

Alignment	
DwellTime	1 µs
Elasticity	4 %
EqualizeDose	True
HorizontalFieldWidth	**300 µm**
IntegrationWidth	8
MinScore	0.5
Name	**Line scan alignment 1**
Optimization	BestRobustness
SearchWindow	80 %
Sensitivity	3
SmoothSigma	5
UseAutoGainOffset	True

Property	**Description**
DwellTime	This is the pixel dwell time for scanning the lines. A larger value will give better signal to noise, but also cause more damage per scan. It will also increase the total time to scan the alignment lines, but this is generally not a limiting factor.
Elasticity	If a line has more than a single transition, the real spacing between the transitions might be different from the expected spacing, causing the match to fail. This number influences how much the actual spacing may differ from the expected spacing by broadening each transition with a Gaussian. For example, for a line segment of 5 µm length, a value of 1% of the Gaussian has a sigma of 0.05 µm, meaning that each edge can be off by that amount relative to the other edges.
EqualizeDose	Keeps the dose constant at varying beam currents.
HorizontalFieldWidth	This is the horizontal field width (HFW ~ 1/magnification) at which to scan the lines. Use the same HFW in the alignment and in the layers that use the alignment to avoid small errors that might be caused by changing the HFW. This value must at least be so large that an image acquired at this HFW will contain all the lines that are to be scanned.

IntegrationWidth	By setting a number larger than 1, you can automatically scan multiple parallel lines. This will increase accuracy and reliability.
MinScore	Each line scan line receives a score from 0 to 1 indicating the confidence in the correctness of the measurement. The alignment accepts only lines with a score greater or equal to the value specified by the MinScore parameter. Use the MinScore parameter to control the probability of a false measurement.
Name	The name of the particular line scan alignment.
Optimization	Determines the impact of redundant scan lines with a failed measurement on the alignment. There are two selections: • HighestAccuracy requires that all scan lines successfully measure the location of the underlying fiducials. Use this setting when the patterning process demands consistent alignment with the highest achievable accuracy. • BestRobustness tolerates measurement failures of redundant scan lines. The number of redundant scan lines is the total number of lines minus the number of parameters calculated by the alignment, which depends on the AlignmentStrategy field for the layer. The AlignmentStrategy field for the layer has two selections: — CorrectShiftWithMicroscope calculates two scalar parameters, namely shift in X and Y, — CorrectWithShapes computes scale in X, scale in Y, shear and rotation, in addition to shift in X and Y, resulting in a total of six scalar parameters. For example, a job uses the line scan alignment module located in the documentation folder to define an alignment. The alignment module defines four pairs, with each pair consisting of one horizontal and one vertical line. When using CorrectShiftWithMicroscope, the line scan alignment will tolerate the measurement failure of up to three horizontal and three vertical lines. On the other hand, the CorrectWithShapes selection will only tolerate the failure of

	one horizontal and one vertical line because of the higher number of alignment parameters calculated in this case.
SearchWindow	Reduces the search range to a fraction of the profile data acquired over the entire scan line. The search range is centered to form equal margins from either end of the scan line. Decrease this parameter to suppress the detection of scan artifact peaks near the extremes of the scan line.
Sensitivity	The Transition method matches inflection points in the scan profile to line transitions. The Sensitivity parameter filters the inflection points according to the strength of the slope at which they occur. A small value will suppress inflection points with soft slopes and, consequently, will lead to fewer detected inflection points to be matched to transitions.
SmoothSigma	Sets the width of the Gaussian used to smooth the detector signal. It is in units of points on the line that was scanned (similar to pixels).
UseAutoGainOffset	When set to True, the detector contrast and brightness will automatically be adjusted if the signal is too dark or bright. When set to False, you must manually adjust the detector signal while patterning with the real time monitor enabled.

- Line properties

The line scan alignment has a list of lines that are to be scanned when the layer is executed. At least two lines (nonparallel, ideally perpendicular) are required for measuring and performing a translation (shift) in X and Y. At least six lines (not all parallel) are needed to measure translation, rotation, scaling and shear.

Property	**Description**
StartPoint	The starting point of the line. Expand to edit the x- and y value.
EndPoint	The end point of the line.
Length	Read only, the distance between the start and end points.
SearchMethod	• Transition: This method searches for inflection points in the profile and matches them to the line transitions. This is

	typically used when the intersection information comes from a GDSII CAD file and no knowledge is available on the actual detector signal profile. This works best if there are multiple transitions; the algorithm can then search for a sequence of jumps at the correct intervals. The more transitions, the less likely other features (like a piece of dirt) will match, decreasing the chance of a false match. • ScanProfile: Compare trained line profiles with the measured line profiles. This defines the scan field location where the training was done as the 'perfect' location, which the alignment will try to reproduce. If you want to position patterns with absolute accuracy relative toexisting features, use Transition. For the best layer-to-layer alignment, use ScanProfile.
TrainedBeam	The beam that was used for training.
TrainedDetector	The detector that was used for training.
TrainedHFW	The horizontal field width at which training was done.

- Use Single Lines with IntegrationWidth Parameter

Line scan lines can be widened to a larger scan area by using the IntegrationWidth parameter. All pixels perpendicular to the line direction are averaged to reduce noise and lessen the impact of fiducial line roughness. Values of 4–8 typically achieve good results for beam currents ranging from 50 pA–1 nA. In general, use larger values for smaller beam current.

- Choose Search Method for Line Scan Alignment

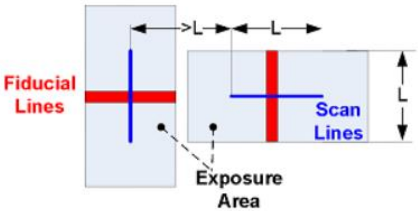
The line scan alignment can search for the fiducial location in two different ways:
- *The Transitions method* matches inflection points in the line profile with material or topography transitions described by the fiducial layer in the GDSII file. Depending on the nature of the fiducial and the particular imaging conditions, the location of the detected inflection points may differ slightly from their respective calculated transitions. The Transitions method calculates the total shift from the average of the transition deviations to achieve "center

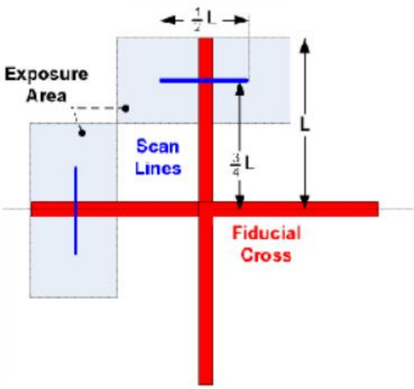
of mass” alignment.
- *The ScanProfile method*, on the other hand, uses a sample scan profile recorded during the training step of the line scan alignment to find the fiducial.

Use the Transitions method when absolute pattern placement is critical and the edges of the fiducial display as bright narrow lines in the image. Typically, this is the case for features produced by a lithography process applied to a silicon substrate. The ScanProfile method is recommended when robust and precise alignment of the layers to each other is more important than absolute placement of the entire structure.

- Line Scan Alignment Capture Range and Line Placement

The capture range of the line scan alignment is determined by the length of the fiducial line. Individual fiducial lines milled by NanoBuilder should be spaced from each other by at least their length to avoid the sample-staining or mill artifact of one scan line to alter the acquired profile of a neighboring scan line. For fiducial crosses, place the scan line 3/4 from the center and set its length to 1/2 of the length of the cross arm. This will ensure a maximum capture range without scan line interference.





Tutorial: Correlation alignment

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

Nanobuilder provides two types of alignments: Line Scan Alignment & Correlation Alignment

The correlation alignment is based on cross correlation techniques, using a predefined template image that is searched in an image that is acquired on the microscope during the alignment task. Correlation alignment is most useful when:
- Aligning to sites with prefabricated alignment fiducials. The following tutorial demonstrates how multiple crosses on the mapping wafer test substrate can be modified consistently with one NanoBuilder job.
- You expect a relatively large shift. The line scan alignment typically has limited range, while the correlation alignment can handle much larger shifts.
- When the amount of noise in the acquired line scans is too significant for a stable line scan alignment. Cross correlation is generally less sensitive to noise.

Before beginning, prepare the microscope for patterning. Drive to a location on the mapping wafer sample, bring it to eucentric height, optimize the SEM and FIB images, and then align the ion beam with the E-beam using beam shift.

Experiment

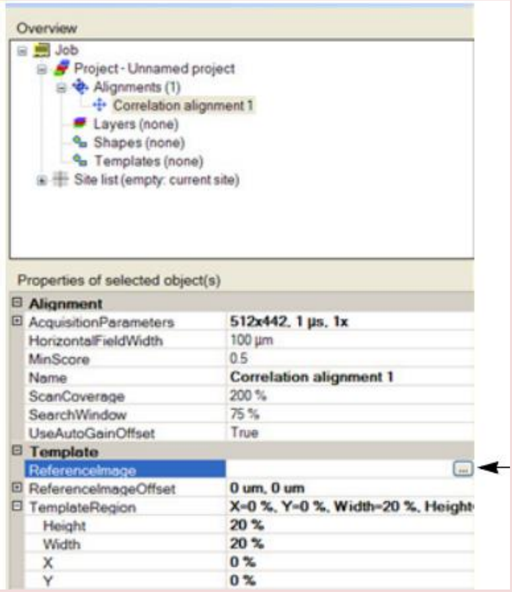
1. Start NanoBuilder and go to File > Import GDSII... > C:\Program Files (x86)\FEI\NanoBuilder\Documentation\Tutorials\Tutorial03 and select the file Tutorial03.gds

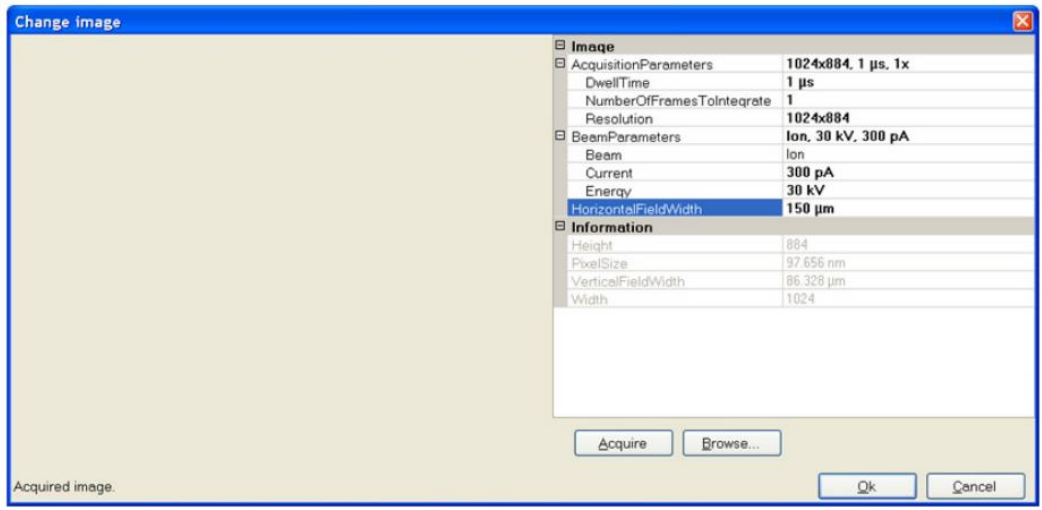
2. Right-click on Alignments in the Overview window and select Correlation alignment from Add alignment.

3. In the Properties window, set HFW to 150 µm.

4. In the Template pane, click Reference Image to enable a Browse button at the right of that property.

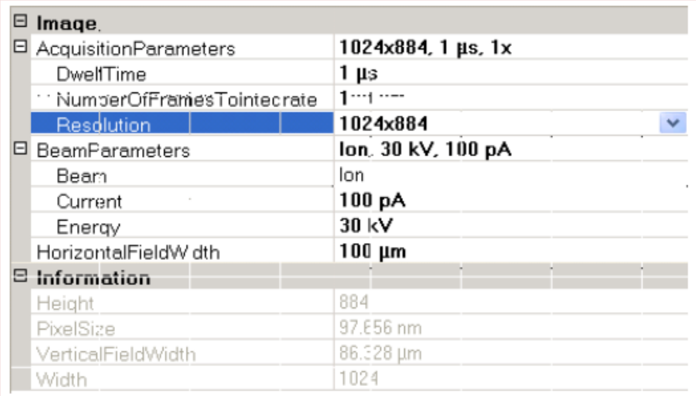
5. Click the Browse button to display the Change Image dialog box.





6. Expand the Acquisition Parameters and Beam Parameters properties and set:

- Resolution: 1024x884
- Current: 100 pA
- HFW: 150 µm



<u>If the correlation alignment is not good, increase the dwell time for better signal-to-noise.</u>

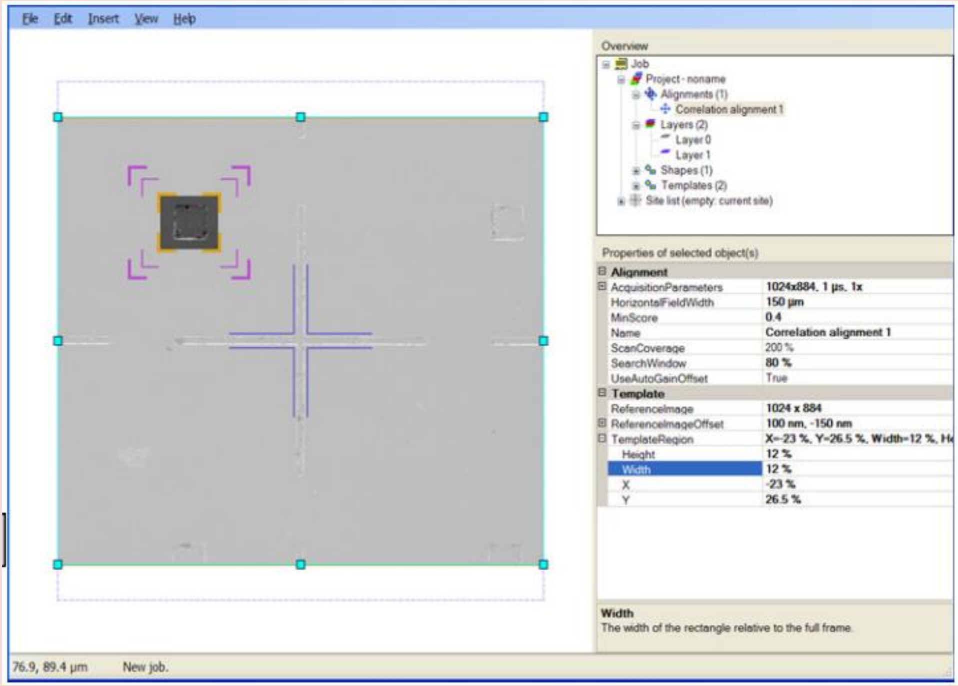
7. Click Acquire.

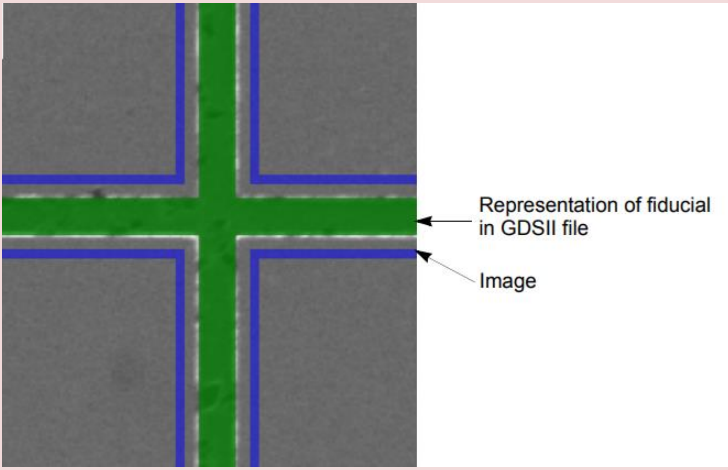
8. Click OK to close the dialog box.

9. In the Template pane, set the following parameters:
   - X: –13%
   - Y: 26%
   - Width: 12%
   - Height: 12%

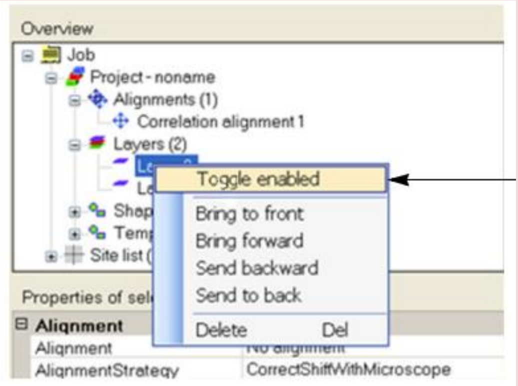
10. Set the ReferenceImageOffset to precisely align the template to the fiducial displayed in Layer 0. The display of the fiducial pattern in Layer 0 helps align the image template, as shown in below.

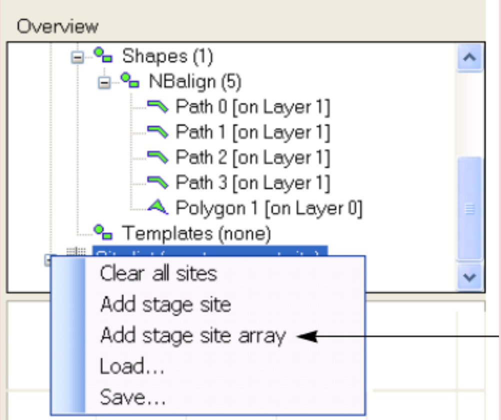
Once you have developed a robust alignment job, you can reuse it: save the alignment job. When needed, use the Merge Job selection on the File menu. After you have merged the alignment job, move the fiducial layer and the burn-in layer, if present, to the start of the patterning list.





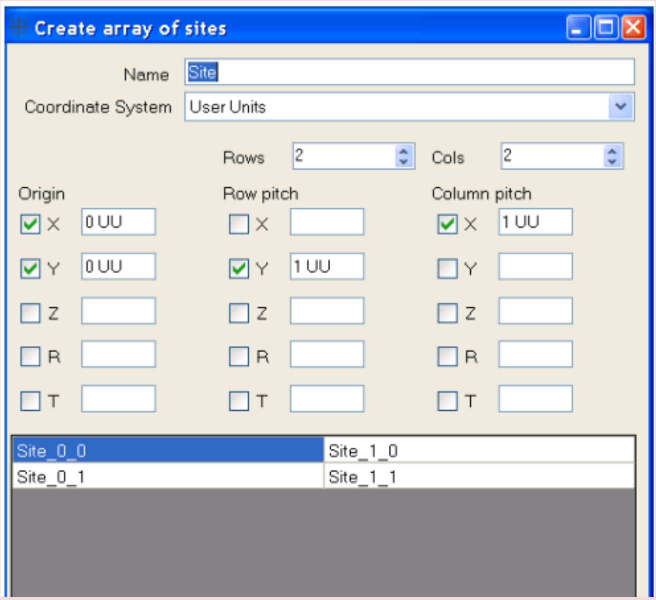
11. Right-click on Layer 0 to disable it so that the fiducial will not be patterned.





12. Right-click on the Site List and select Add stage site array.

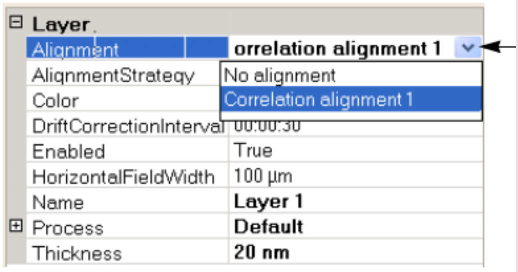
13. Click OK on the Create array of sites dialog box that displays.



14. Select Layer 1 in the Overview window and make the following property changes:

- HFW: 100 µm (to pattern with the same HFW that is used for the alignment)

- Thickness: 20 nm (to shorten patterning time)
- Alignment: Correlation alignment 1



15. Save the job (Go to File > Save)

16. Execute the NanoBuilder job to modify the fiducials at four sites

Demonstration: Patterning with a certain dose

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

Patterning with a certain dose is useful when exposing a resist layer.

- Dose and Fluence

Fluence: the number of particles per area, expressed in C/m² (typically in nC/µm² or pC/µm²)

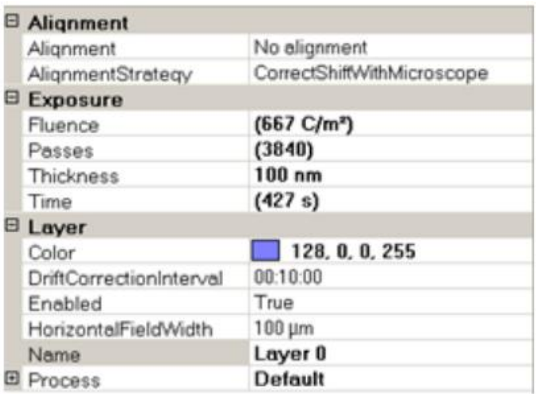
Dose: the total number of particles that hit the sample, expressed in Coulomb (typically in the pC or nC range).

(The term dose is often loosely used, sometimes even in the meaning of fluence)

The relation between dose and fluence is that the dose is the fluence times the exposed surface area. For a specific layer in NanoBuilder, the dose is its fluence multiplied by the combined surface area from all the patterns on that layer.

- Set Thickness, Fluence, Passes, and Time

Specify the exposure for a layer by setting either Thickness, Fluence, Passes, or Time in the Layer Properties section. NanoBuilder will automatically calculate the other quantities and display their values in parentheses to indicate that they were calculated rather than specified.



The following formulas are used:

$$Fluence = \frac{Thickness}{VolumePerDose}$$

$$FluencePerPass = Current \cdot Pitch^2 \cdot DwellTime$$

$$Passes = INT\left[\frac{Fluence}{FluencePerPass}\right]$$

$$Time = Passes \cdot TimePerPass$$

Calculated exposure values may be inaccurate as a consequence of the rounding to an integer in the calculation for the Passes property. Moreover, the Passes property cannot be smaller than 1. To reduce the dose with a Passes value of 1, you can select a smaller beam current or dwell time.

- Selecting Apertures

When a current is selected that is available by more than one aperture, the one closest to the lowest index (lowest beam current) is used.

Demonstration: Parallel and sequential patterning

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

The concept of Parallel and Sequential patterning in NanoBuilder

There are some subtle differences between Parallel and Sequential patterning in NanoBuilder and xT. Conceptually the meaning is as follows:
- **Parallel**: All shapes in a layer receive a single pass of the beam, then they all receive the next pass, etc., until the required number of passes has been reached.
- **Sequential**: The first shape receives the number of passes specified for its layer, then the next shape, etc., until all shapes on the layer have been patterned.

- Sequential Patterning Displays as Parallel in the xT UI

Even if you set a NanoBuilder Layer to pattern Sequentially, the Patterning page in the xT UI will still show Parallel. The reason is that NanoBuilder patterns the shapes one by one, starting/stopping patterning for each shape. This allows it to use the maximum number of points (currently 8 million) per shape, rather than all shapes having to fit in this limitation together.

- Always Pattern Parallel

Arrays

By default the individual elements of an Array will be patterned one-by-one in Sequential mode. However, this can result in a very high number of start/stop patterning cycles, which is slower due to the cumulative overhead (especially for nested structures like Arrays of Arrays).

If the total number of points for the Array is less than the maximum number of points it is more efficient to select the Always Pattern Parallel option of the array. This will pattern all the points for the array in one go, treating it as a monolithic shape.

Structures
Structure = a collection of shapes (which can even be on different layers).

When a layer is executed in Sequential mode, all the shapes in the structure that are on the executing layer will be patterned one by one. As with the Arrays, the overhead of start/stopping patterning can be reduced by selecting the Always Pattern Parallel option for the Structure, in which case all the shapes in the structure which are on the executing Layer will be patterned in one go, treating the structure as a single shape.

Demonstration: Creating stream files

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

GDStoDB installed

Create stream files with GDStoDB and import them into NanoBuilder.

- Create a stream file set

Experiment

1. Start GDStoDB.

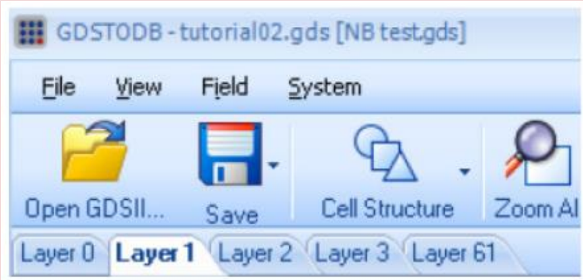
2. In the System menu, select the tool type you will use (e.g., Helios NanoLab™).

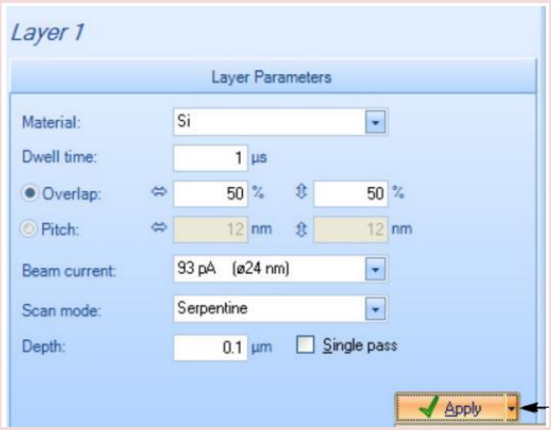
3. Go to File > Open GDSII and navigate to tutorial02.gds and click Open.

4. Select Layer 1 by clicking on the corresponding tab.

5. In the Layers Parameters dialog box that displays, make the following selections:

- Material: Si
- Dwell time: 1 µs
- Overlap: 50%
- Beam current: 93 pA





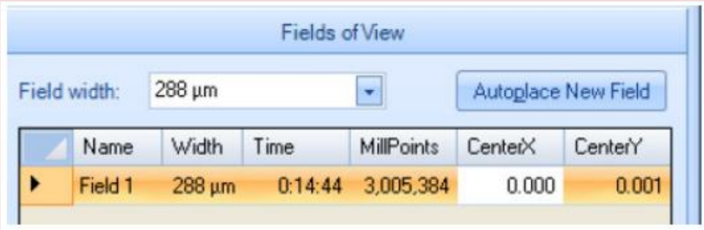
- Scan mode: Serpentine
- Depth: 0.1 µm

6. Click the down arrow next to the Apply button to display the Apply To All Layers button and click the button.

7. Select Layer 2 and change the beam current to 920 pA (for this layer only).

8. Select Layer 3 and change the beam current to 2.8 nA (for this layer only).

9. In the Fields of View dialog box, select 288 µm for Field width



10. Go to Add field and click in the center of the structure to create a field.

11. Select the CenterX box in the Field 1 row that was just added to the Fields of View box and change the value to 0. Do the same for CenterY.

12. Repeat Steps 11 and 12 for Layers 1 and 2.

13. Navigate to File > Save > ASCII Stream File and open the Browse for Folder dialog box.

14. Select the folder that contains the tutorial02.gds file (or create a new folder) and click OK. This will create two files in the selected folder.

15. Select Layer 2 and repeat the above step, using the same folder.

16. Repeat for Layer 3.

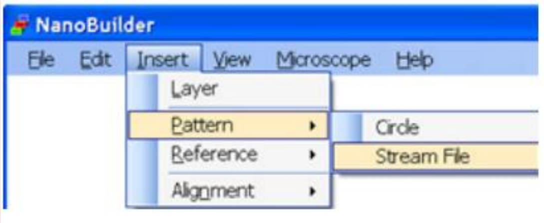
The folder should now contain 6 files:
- Layer 1 - Field 1 [288µm 93pA].str
- Layer 1 - Field 1 [288µm 93pA].txt
- Layer 2 - Field 1 [288µm 920pA].str
- Layer 2 - Field 1 [288µm 920pA].txt
- Layer 3 - Field 1 [288µm 2.8nA].str
- Layer 3 - Field 1 [288µm 2.8nA].txt

- Load GDStoDB Output into NanoBuilder

To add a stream file to a job, you must first have a layer to which to add it.

- If you load a GdsToDb.txt output file, NanoBuilder will create a layer based on the settings in the file and will load the stream file into that layer.
- If you load the .str file, it will end up in the active layer. You will need to set the layer parameters manually.

Experiment



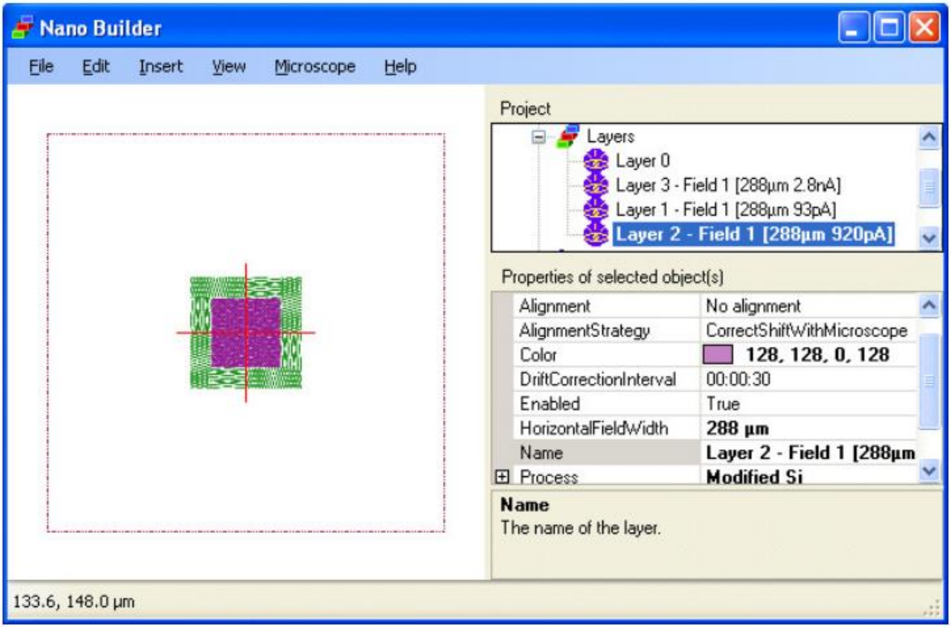
1. Start NanoBuilder.

2. Select Layer to create a new layer.

3. Select Insert > Special Shapes > Stream File.

4. In the Open dialog that appears, navigate to the folder that contains the result of Step 16, above. Select the three .txt files and click Open.

5. After loading the stream files, you should see three new layers.



- Executing the Job

Experiment

Select Microscope > Execute and begin patterning.

The job will now be executed. The status bar at the bottom of NanoBuilder displays the overall progress (0…100%), as well as a progress bar for the current activity.

Demonstration: Setting default processes

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

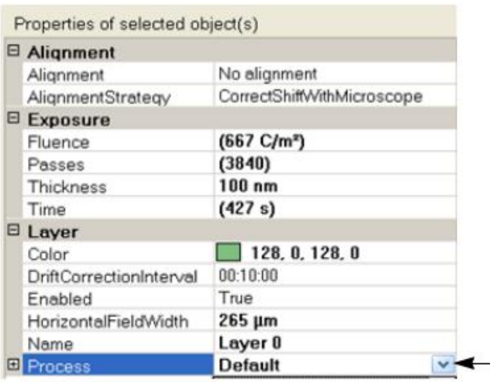
A process in NanoBuilder contains all the settings to pattern a layer

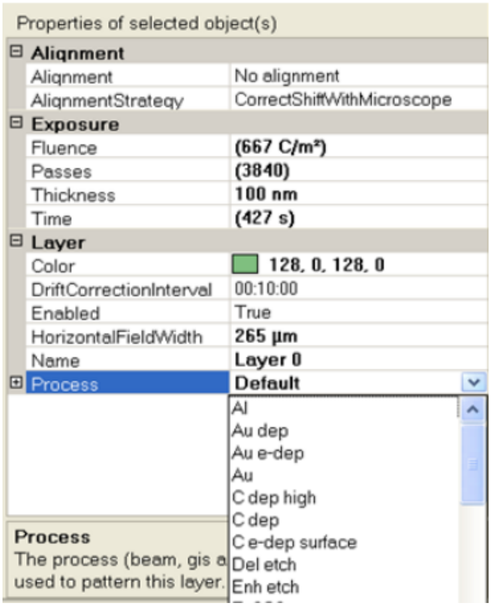
A process contains:

- the beam settings
- the patterning parameters
- the GIS parameters.

Aim:

- Set all the parameters at once, without having to know any of the details, by selecting a predefined process from a list.
- Easily fine-tune any of the parameters by expanding the Process.



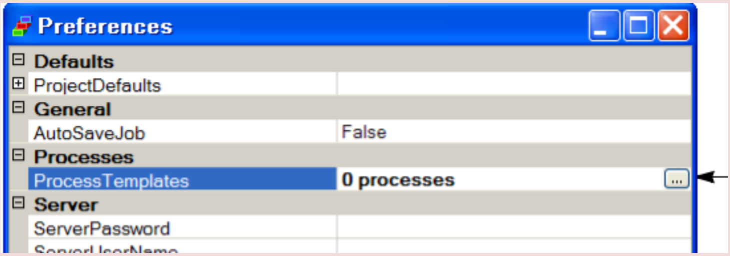


- Changing Available Processes

Experiment

1. Open the Preferences dialog box by selecting File > Preferences.

2. Select the field to the right of ProcessTemplates (see “0 processes”, ->) to display the Browse button



3. Click the Browse button (…)to display the Available Processes dialog box.

The Available processes are shown on the left.

- Import from Server: This link is enabled if NanoBuilder is connected to a microscope. Selecting it will import all the patterning applications from xT to equivalent processes (as far as possible, as the applications do not specify a beam or its settings).

- Import from Current Project: This link will import the processes from the layers in the currently open project in NanoBuilder (also see Editing a process below).

- Remove Selection from List: This link will remove the items you have selected in the list. This is useful when importing more items than you need;

4. Click OK to store the new list, which you can use in any project.

- Editing a Process

Modifying a layer's process influence only that specific layer. To make changes available to other layers, change the name of the process (give it a unique name), then select the Import from Current Project as described above.

f you change a process called "ABC", its name will change to "Modified ABC" to indicate it no longer corresponds to the original ABC. By typing in a new name, the "Modified" is removed, as it is now a different process.

Demonstration: Troubleshooting

Prerequisites:

Sample loaded, stage pumped

E-beam and ion beam active

Known bugs or peculiar behavior and how to rectify it

- General xT issues

Issue	Workaround
Actual milled thickness does not match the specified value in NanoBuilder	There are two main causes for this variation: • NanoBuilder does not read the actual current before calculating patterning times. Thus, if the aperture is delivering more current than its nominal value, the current applied to the sample will be off by a factor. Apertures allow more current through as they age (wear out), and this will lead to deeper mills or thicker than expected depositions. • Beam chemistry depends on the precursor flux. If the needle alignment is off, or if the precursor has aged, the actual process speed will differ from the expected value. Perform a test exposure of critical layers, and if the actual mill depth or deposition height is different from what is expected, adjust the layer's thickness correspondingly. For example, if the requested thickness is 1 µm but the actual depth is 1.2 µm, change the layer thickness to 1/1.2 = 0.833 µm.
NanoBuilder does not support the xT wide screen display.	NanoBuilder sets the display area automatically to fit with the server XT display screen ratio. For example: when setting HFW in NanoBuilder to 150 µm, the height is automatically set to 100 µm for the patterning area

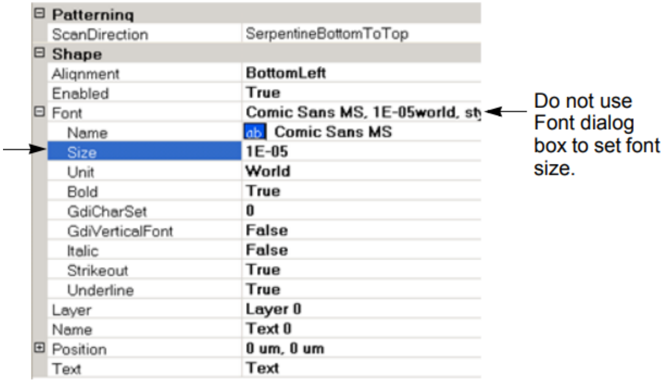
Restarting the xT server while NanoBuilder runs, will cause a crash (selecting the Microscope menu).	Shut down NanoBuilder before you start xT.
The graphical display updates slowly when a job containing many shapes is loaded.	Reduce the number of shapes in the design to only those that need to be patterned with NanoBuilder.
Using dwell times shorter than 25 ns will fail with a general error message	Use larger dwell times
E-Beam patterning fails with the message: “Cannot set the target value of ElectronBeamSourceTilt...”	First, inform the instrument admin At the start of job execution NanoBuilder prepares Quad 3 for patterning and Quad 4 for alignments. As part of this preparation, NanoBuilder grabs an image frame with the beam blanked so that sensitive areas on the sample are not unintentionally exposed to the E-Beam. The workaround for this issue is to turn off blanking and consequently expose the entire write field to the E-Beam for a short period. Instructions: 1. Start Windows Explorer and set the folder path to *C:\Program Files\FEI\NanoBuilder*. 2. Create a backup copy of *NanoBuilder.exe.config*. 3. Open *NanoBuilder.exe.config* in Notepad. 4. Find line: `<add key="UseSourceTiltForBlankingEBeam" value="true"/>`. 5. Set the value property to “false”: `<add key="UseSourceTiltForBlankingEBeam" value="false"/>`. 6. Save the file. 7. If NanoBuilder does not start up after the modification to *NanoBuilder.exe.config* file, restore the original file and start over.

- Line scan alignments

Issue	Workaround
Linescan alignment for layer fails with the error message: "Cannot access data pipeline for RTM."	Save your NanoBuilder job and close the application. Restart the xT UI and the xT server, then start the NanoBuilder application again and load the job to continue.
Line scan alignment limitation	A standard detector mode must be used during line scan alignment.
Alignment fails because the real-time monitor cannot be accessed.	Restart the xT server
Line scan alignment fails with insufficient signal error	Use the build-in diagnostics of the line scan alignment (see "Line Scan Alignment"), try to identify the root cause of the failure. - If the transitions are not visible at all in the scan profiles, the scan field may be outside of the alignment's capture range. Either increase the length of the scan lines to increase the capture range, or realign the beam apertures. - If the scan profiles contain noise that obscures the transitions, increase the dwell time and the IntegrationWidth parameter. - If the transitions are too broad, calibrate focus and stigmation for the beam aperture that is being used.

- Text issues

Issue	Workaround
Text shapes do not display after creation.	Change the zoom level of the shape display to force the newly created Text shape to be drawn.
Text position does not refresh after changing coordinates.	Zoom in/out to refresh the changes

The font size of a Text pattern cannot be set from the Font dialog.	Expand the Font property and set the size of the font directly.
Text size does not change when using Insert Pattern > Text > Change Font/Size.	
The Strikeout and Underline properties in the Text Font dialog do not work.	Do not use.

- SEM and scanning issues

Issue	Workaround
Mode II Snapshot causes job to fail	Do not perform this action.
SEM blur does not work. If you specify a value for the blur and the SEM as the beam, the blur (defocus) is not applied during patterning.	None. This does not work
The immersion lens is not available after closing NanoBuilder.	Closing the NanoBuilder application may switch off the UHR lens. When this happens, restart xT to reactivate the UHR lens and make sure to leave the password field empty in the *Preferences* dialog.