Applications of computer programming in image acquisition, structural analysis, and machine vision

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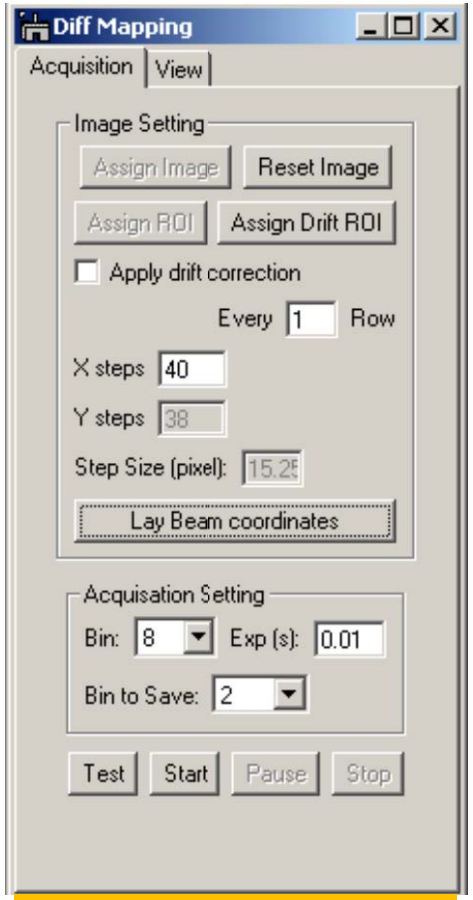
1. Diffraction mapping and crystal grain maps

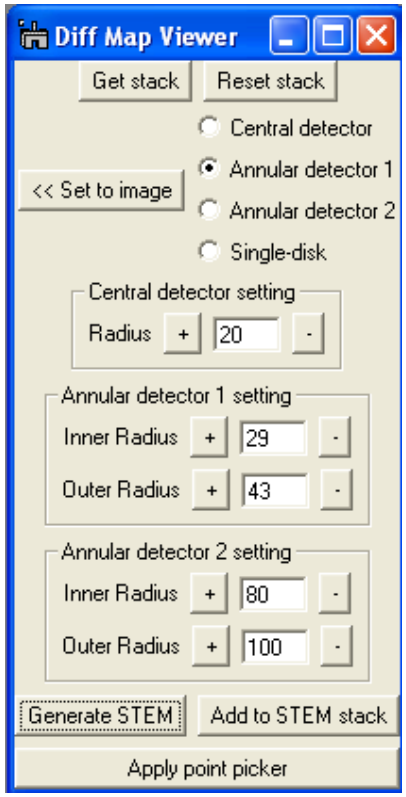
The control and analyzing programs

- A suite of programs written with Gatan DigitalMicrograph© scripting language.
- Data collection performed in DigitalMicrograph with DigiScan package.

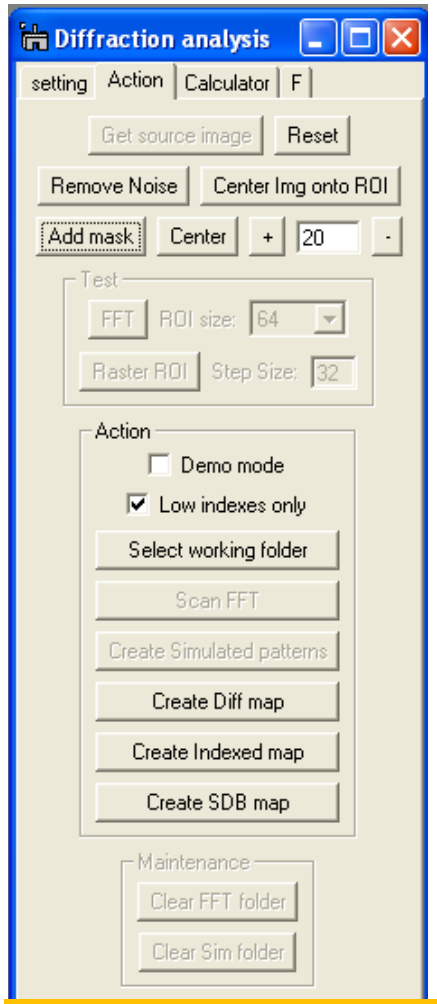
Reference STEM image



Acquisition program

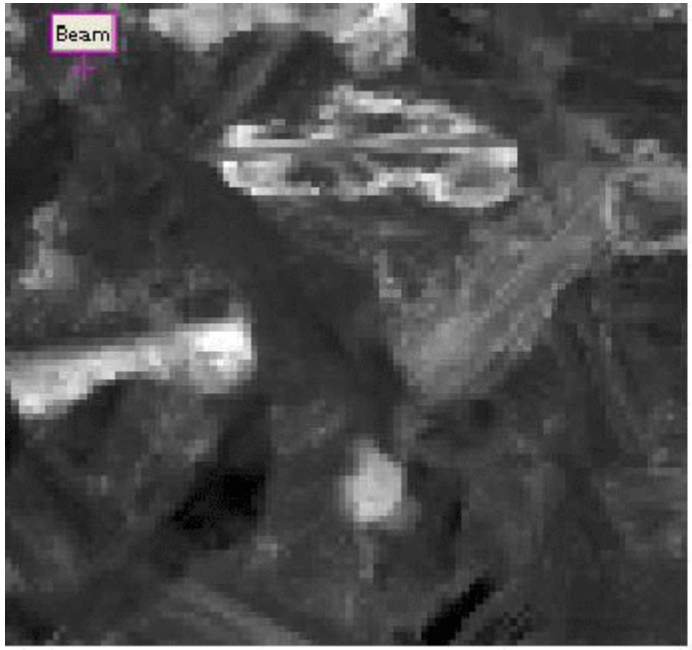


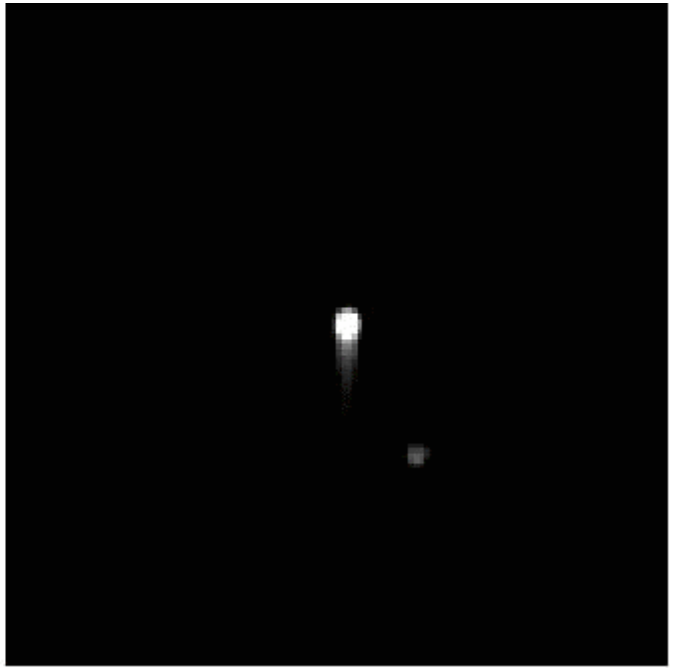
Viewer – direct method to generate diffraction contrast maps



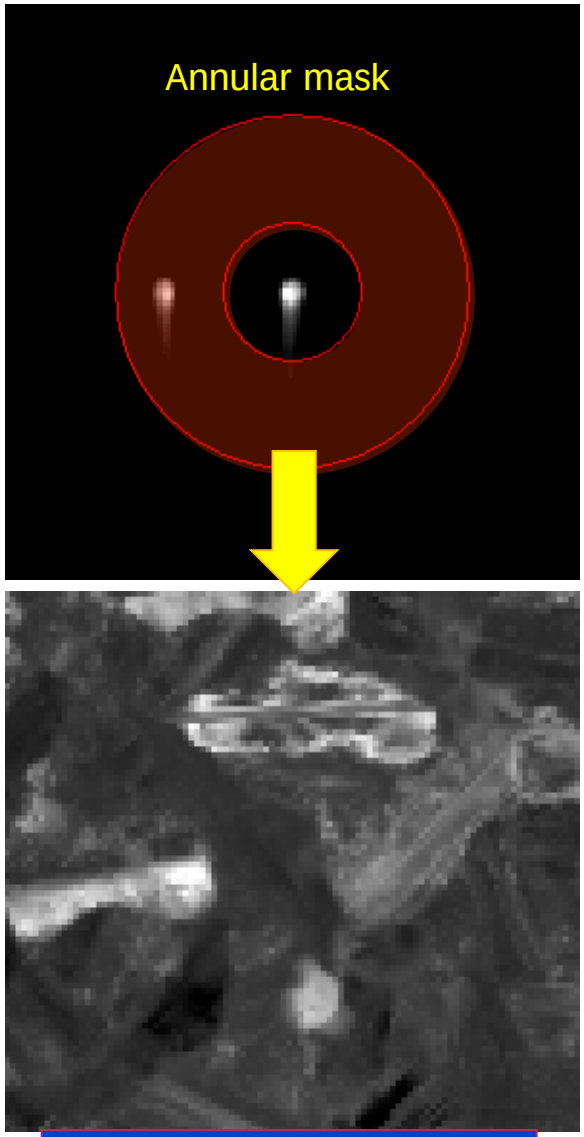
Analyzer – indirect methods to generate diffraction contrast maps

Diffraction mapping data collection

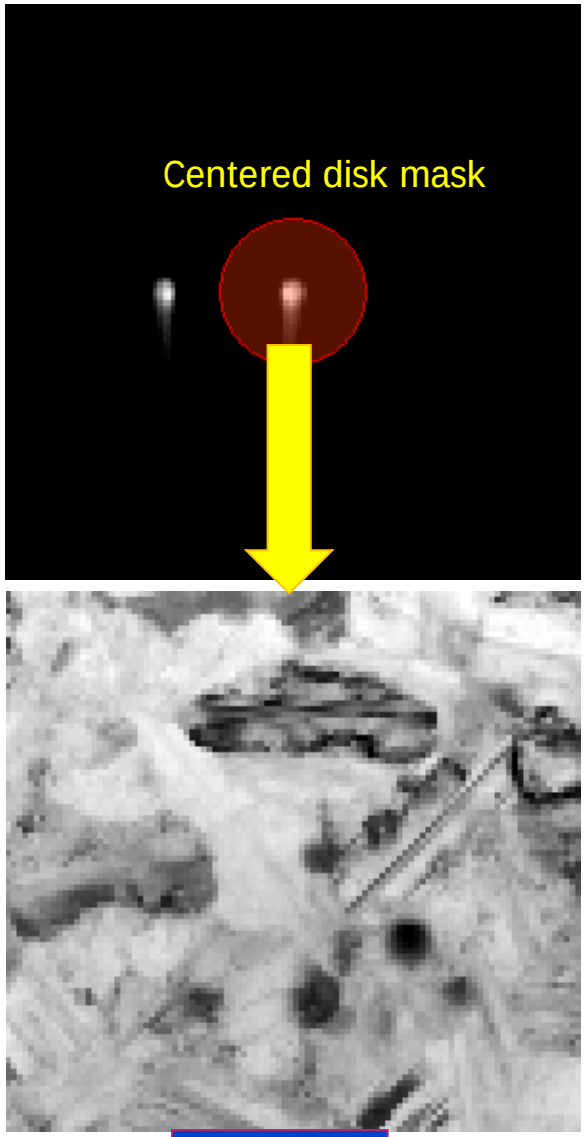




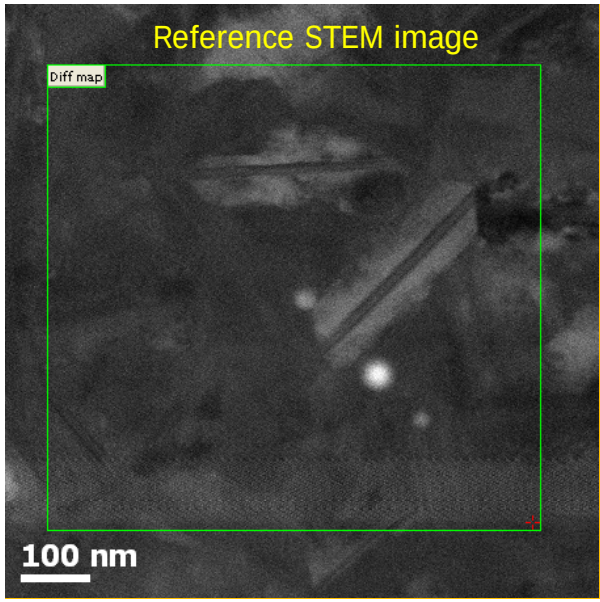
Direct method to extract maps: “Annular DF STEM” and “BF STEM” (polycrystalline Si)

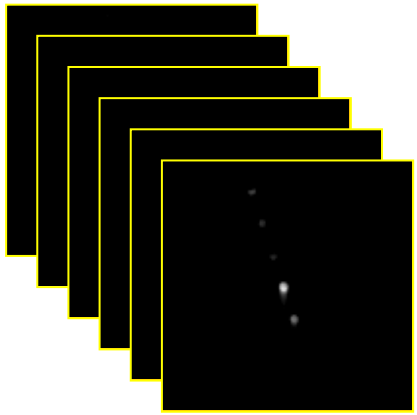


“Annular dark field STEM”

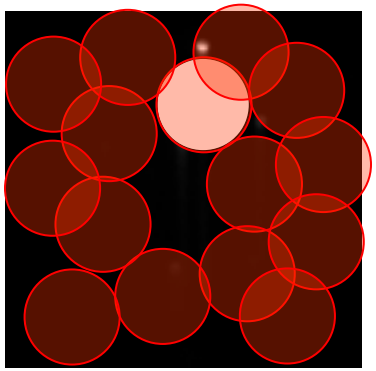


“BF STEM”

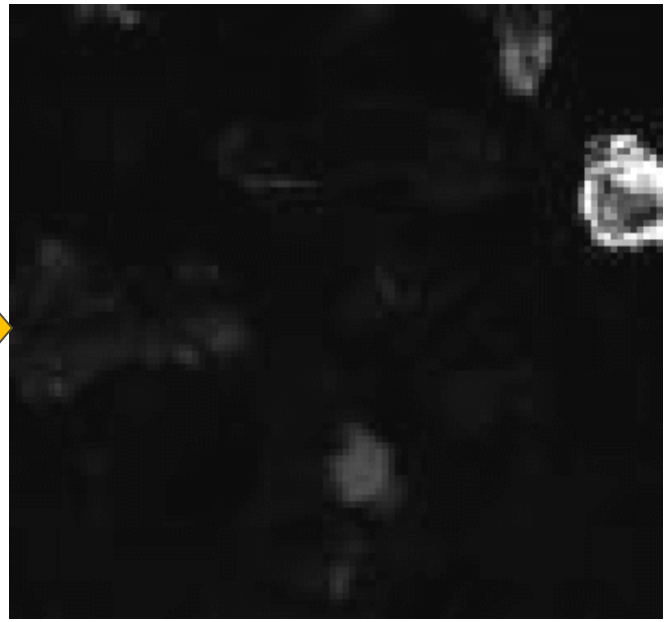




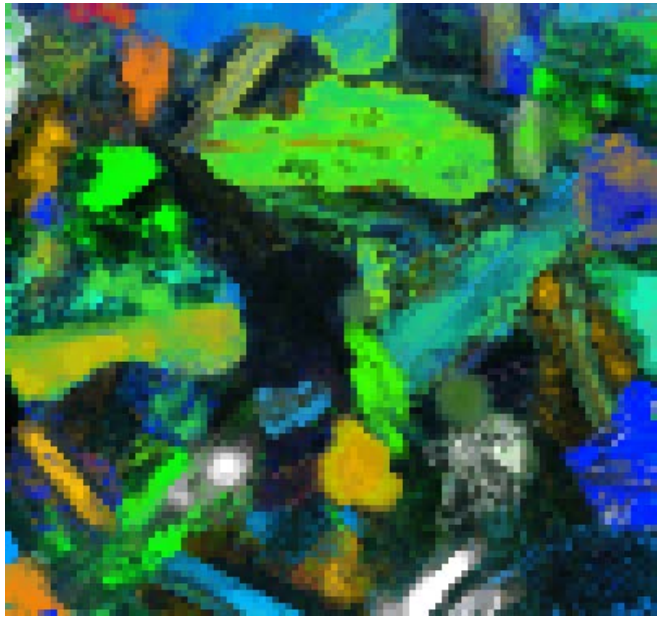
Direct method to extract maps : Dynamic orientation map and a color-coded orientation map (polycrystalline Si)



Applying multiple off-centered detectors



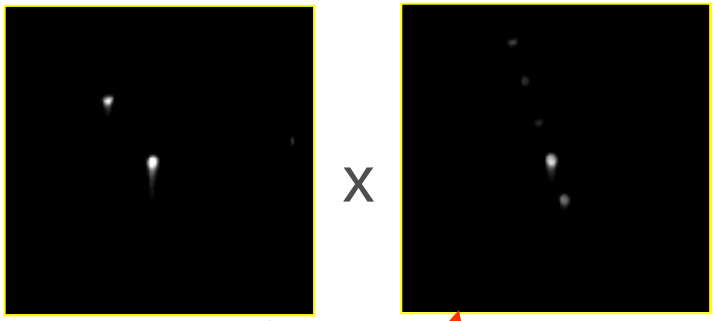
Dynamic orientation map:
An animation of sequence of DF STEM generated by varying the single disk detector position.



Color-coded orientation map:
The color coded sum of the DF STEM stack.

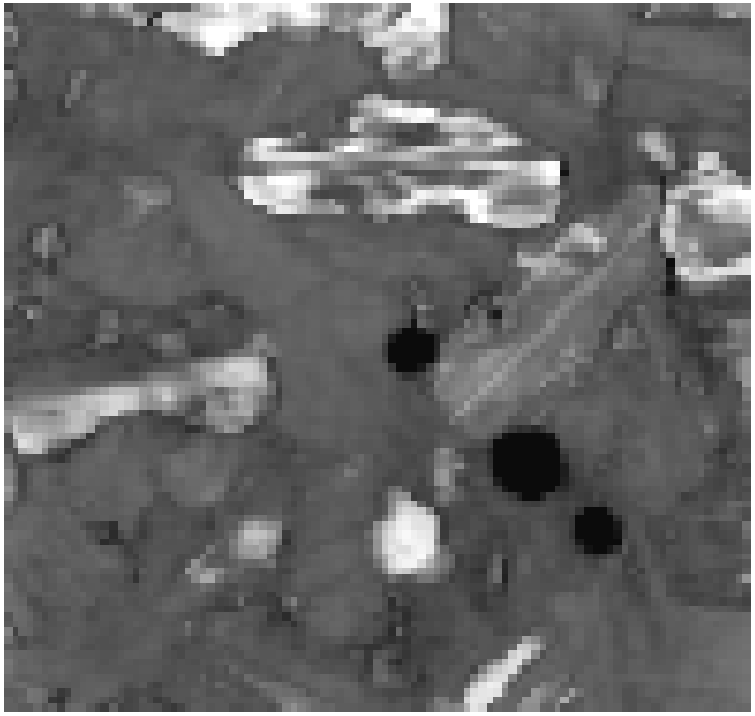
Indirect method #1, similarity map (polycrystalline Si)

$$Map(x,y) = \sum_i \sum_j (DF_{(x,y)}(i,j) \cdot DF_{(x+1,y)}(i,j))$$



X

DF(x,y) *DF(x+1,y)*



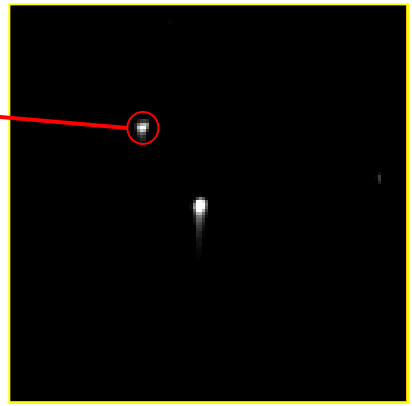
similarity map

Reference STEM image

Note: The transmitted beam spot is generally omitted to emphasize the DP differences.

Indirect method #2: SDB-q map (polycrystalline Si)

Map (x,y) = max[DP(x,y)]



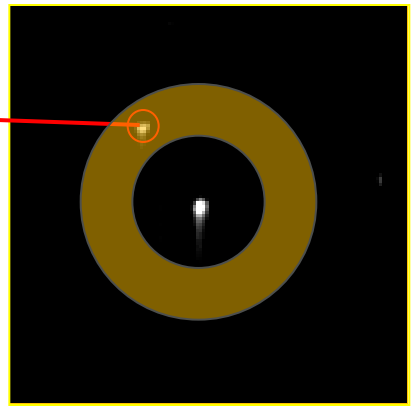
SDB-q map

Reference STEM image

Note: The transmitted beam spot is excluded for this process.

Indirect method #3: SDB-q ratio map (polycrystalline Si)

Map(x,y) = max(DP(x,y))/(annular average)



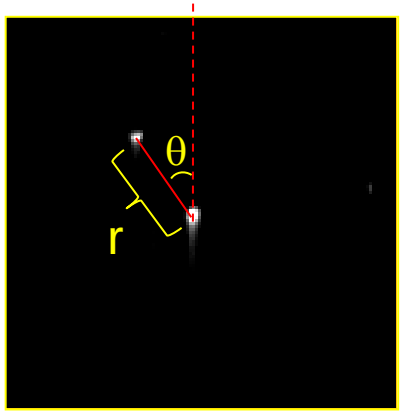
SDB-q ratio map

Reference STEM image

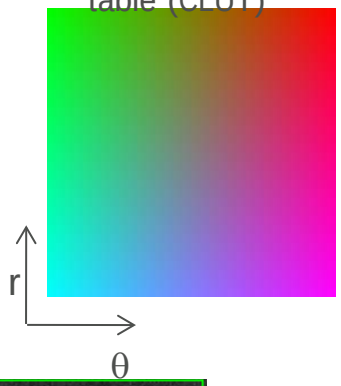
Note: The transmitted beam spot is excluded for this process.

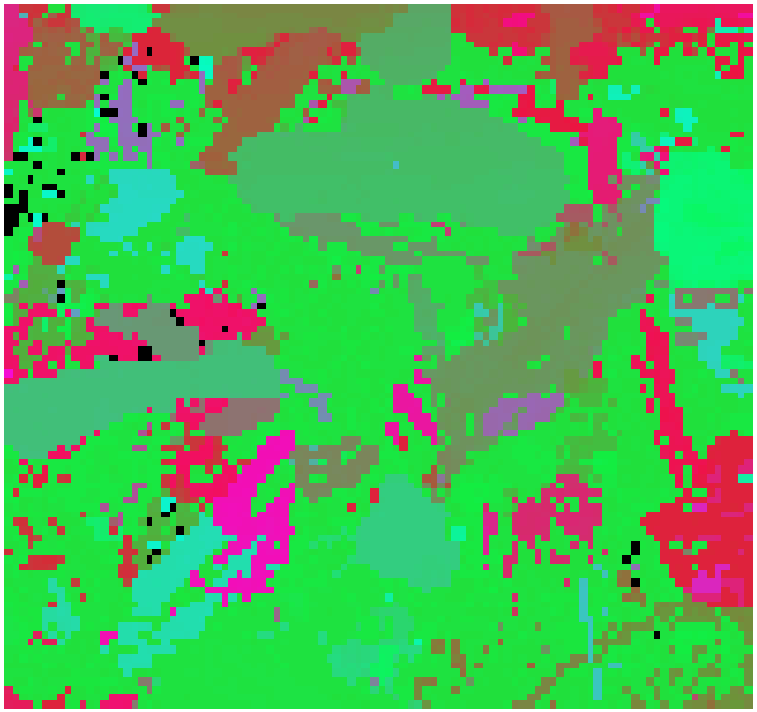
Indirect method #4: SDB orientation map (polycrystalline Si)

map(x,y) = CLUT(r, θ),
where (r, θ) is from SDB location.



Color lookup table (CLUT)





SDB orientation map

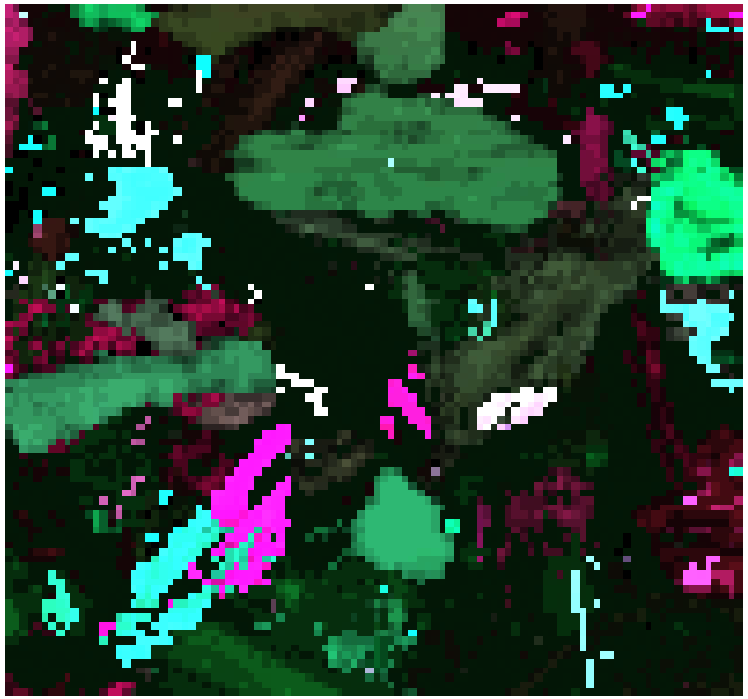
Reference STEM image

Note: The transmitted beam spot is excluded for this process.

Indirect method #5: Weighted SDB orientation map (polycrystalline Si)

A combination of SDB-q ratio and color-coded SDB angular coordinate maps.

$$map(x,y) = CLUT(r, \theta) \cdot (\text{SDB-q ratio map})$$

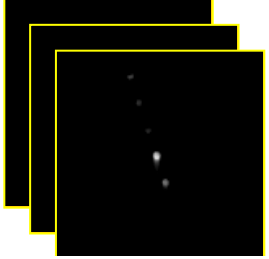


Weighted SDB orientation map

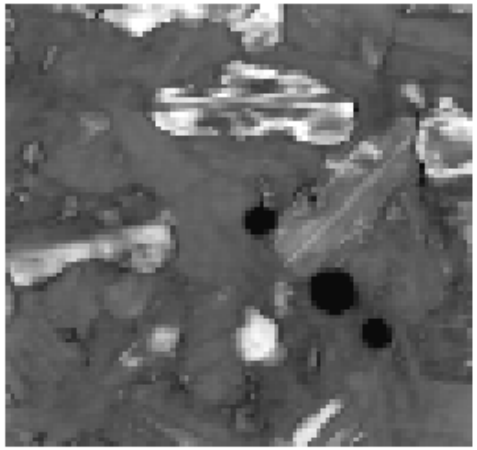
Reference STEM image

Note: The transmitted beam spot is excluded for this process.

Putting them together for comparison (polycrystalline Si, pseudo-parallel beam)



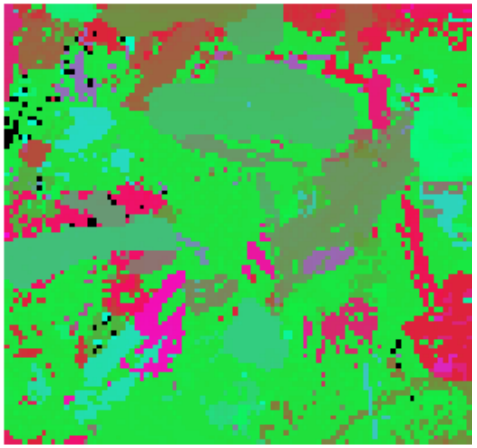
Reference STEM



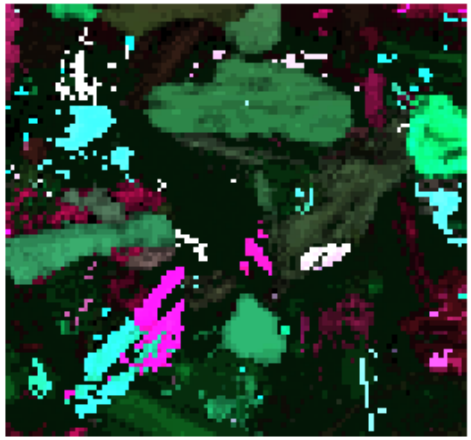
Similarity map

SDB-q map

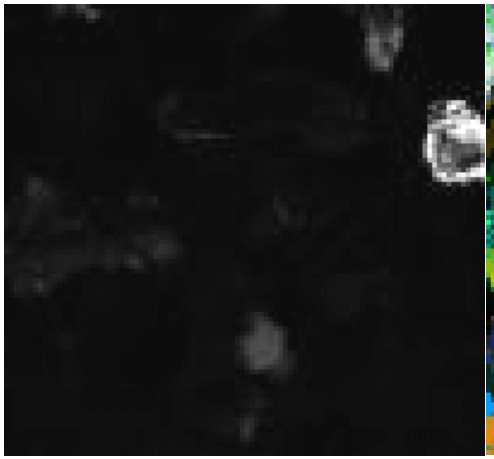
SDB-q ratio map



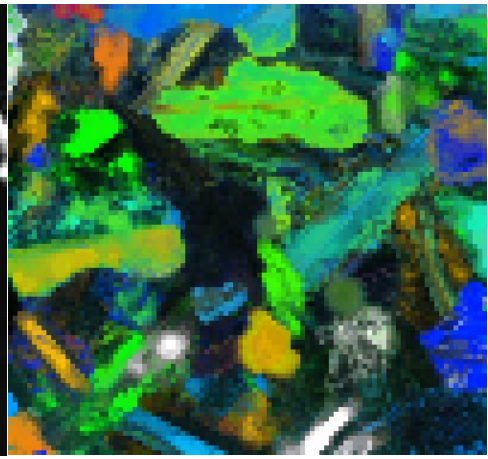
SDB orientation map



Weighted SDB orientation map

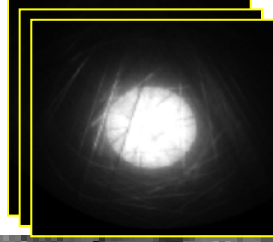


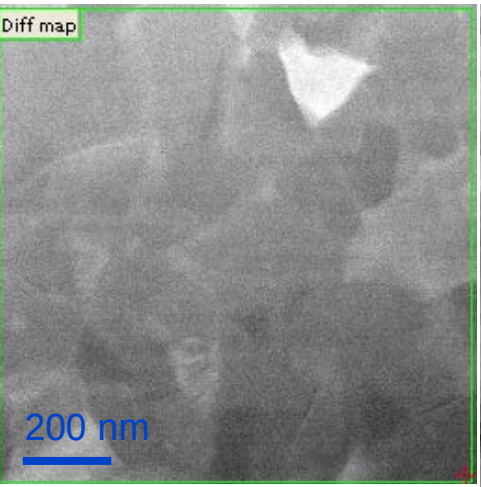
Dynamic grain map.



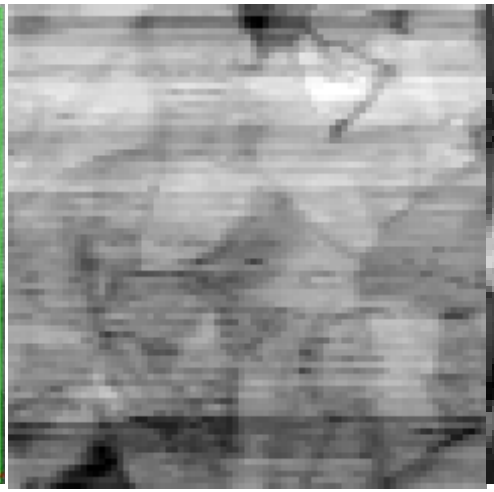
Color-coded grain map

Application with convergent beam (polycrystalline Si)

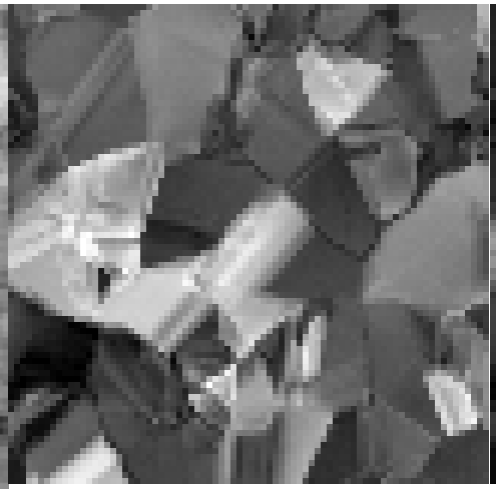




Reference STEM



Similarity map

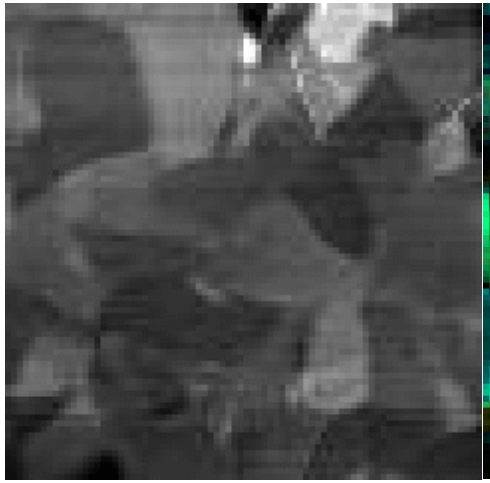


SDB-q map

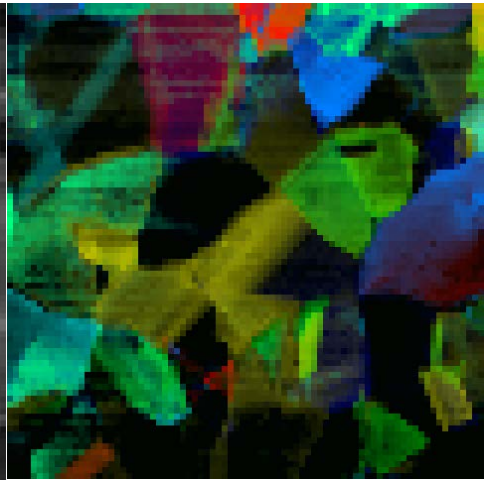
SDB-q ratio map

SDB orientation map

Weighted SDB orientation map



Dynamic orientation map.

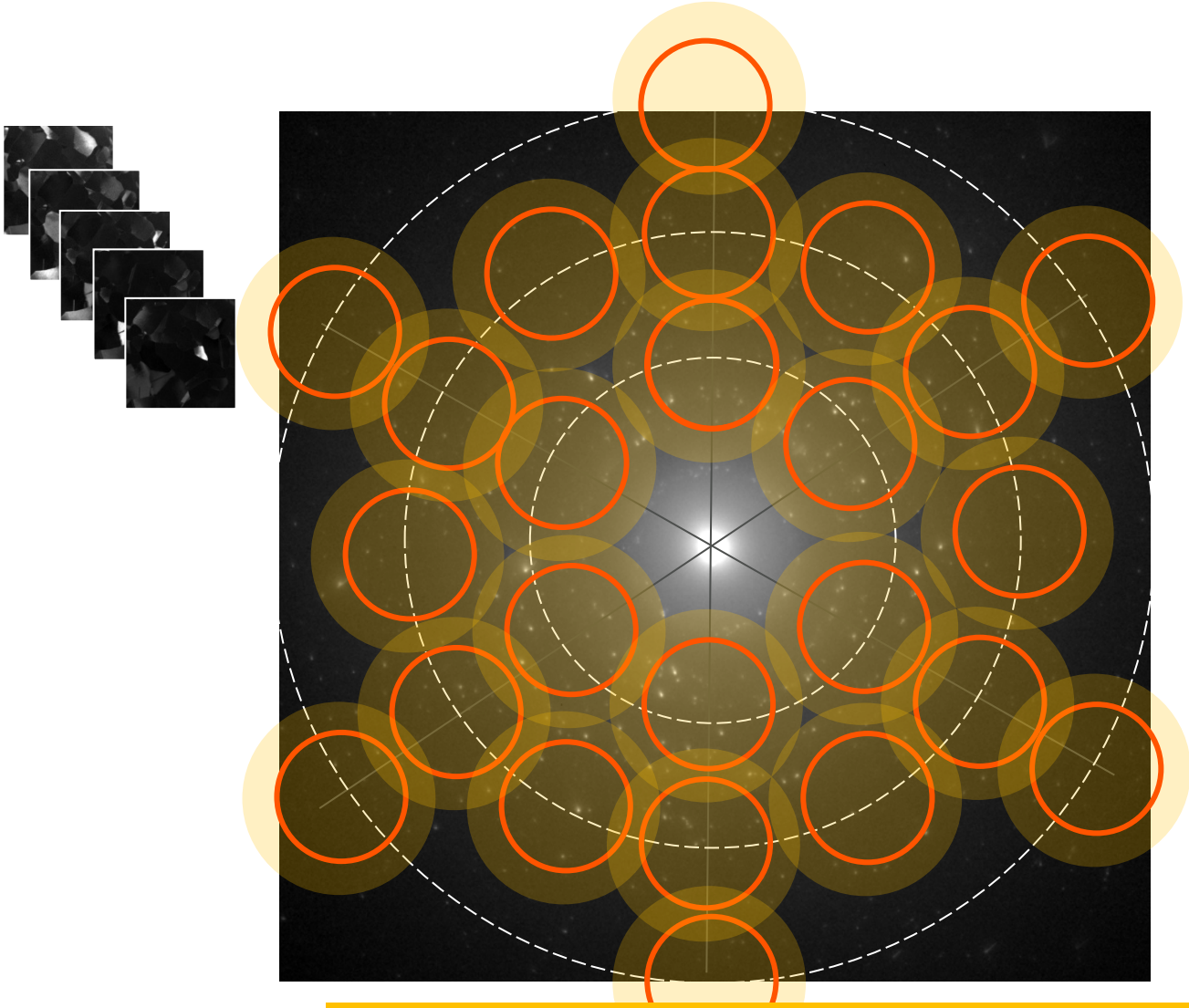


Color-coded orientation map

2. Rocking beam Tableau DF imaging

Schematics of Tableau DF imaging

Through positioning the objective aperture according to a pre-defined pattern, a sequence of DF TEM is formed.

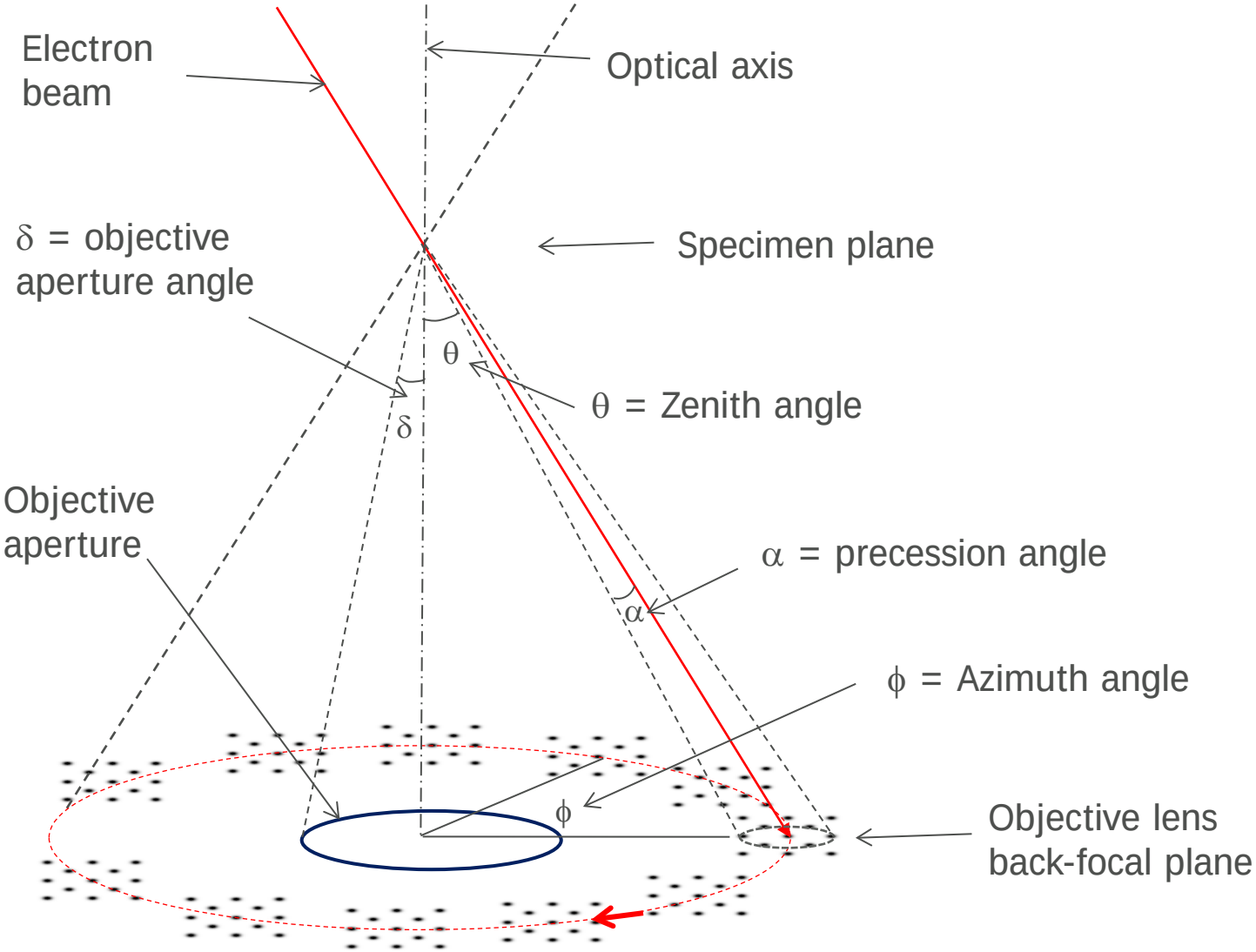


Obj. Aperture

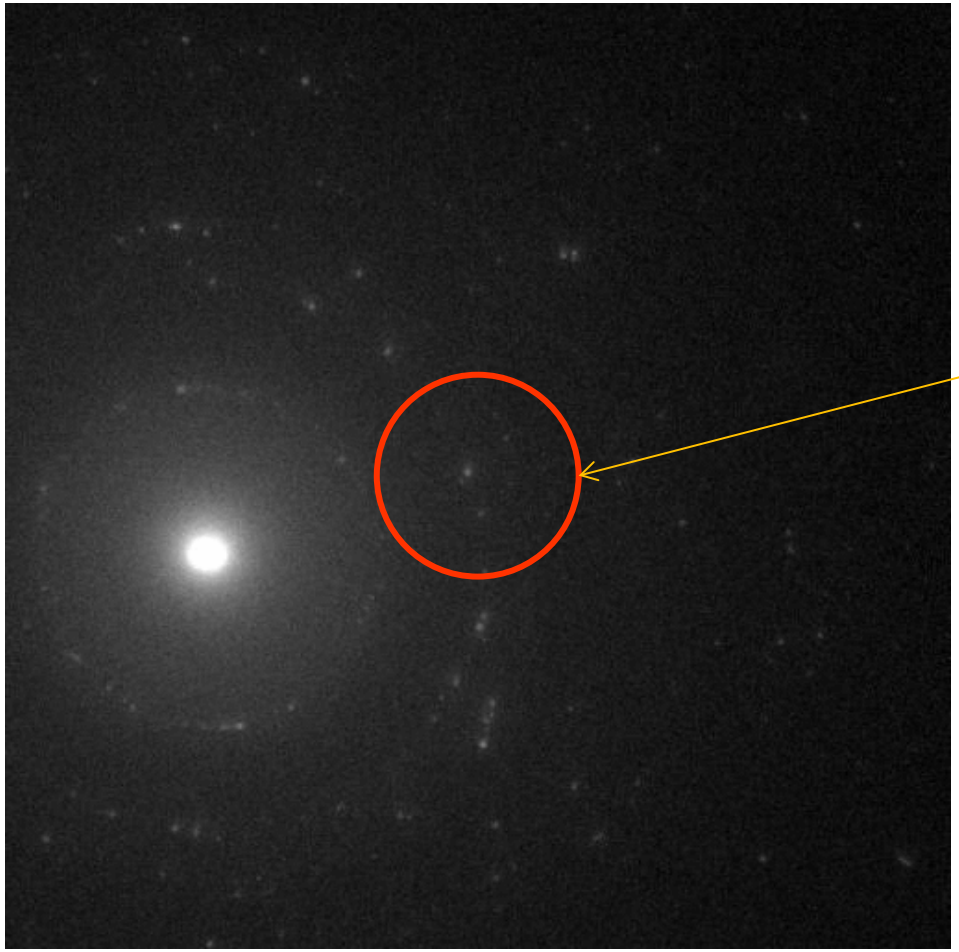
Effective Obj. Aperture due to beam precession

In practice, aperture is fixed and beam is tilted.

Ray-diagram of tableau imaging

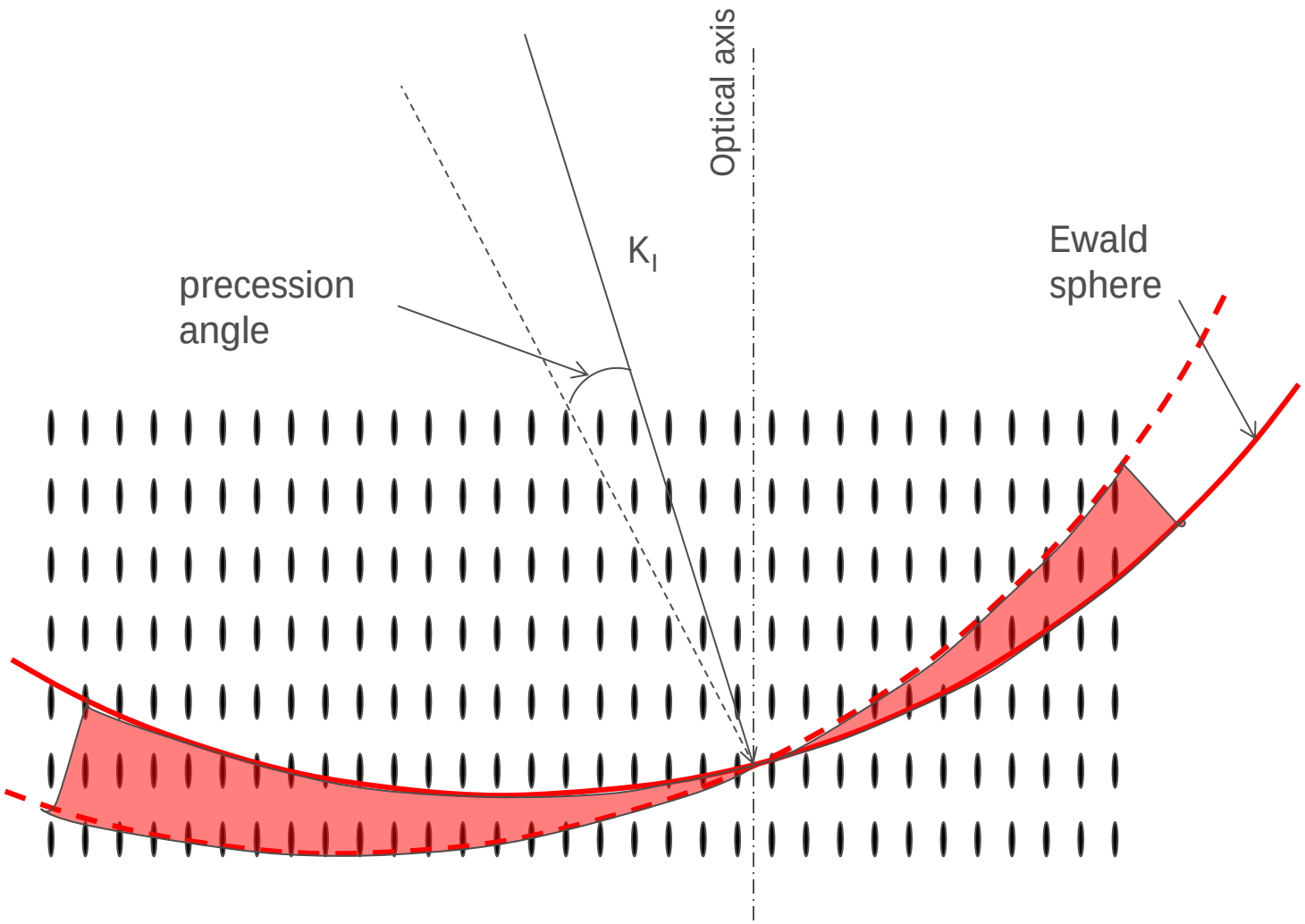


The beam actions viewed at back-focal plane during Tableau DF imaging



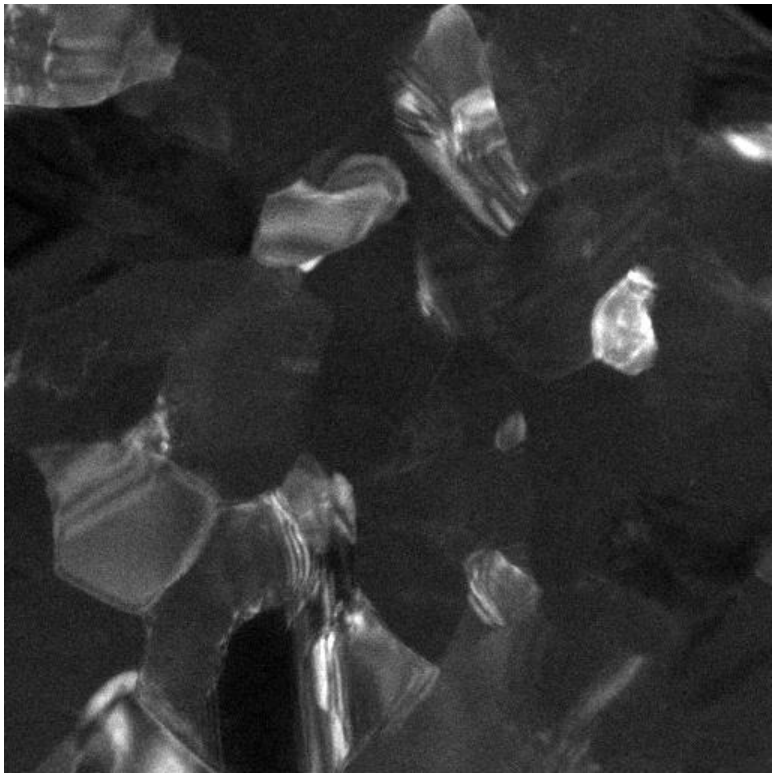
Fixed obj. aperture centered on optical axis

The effect of rocking beam

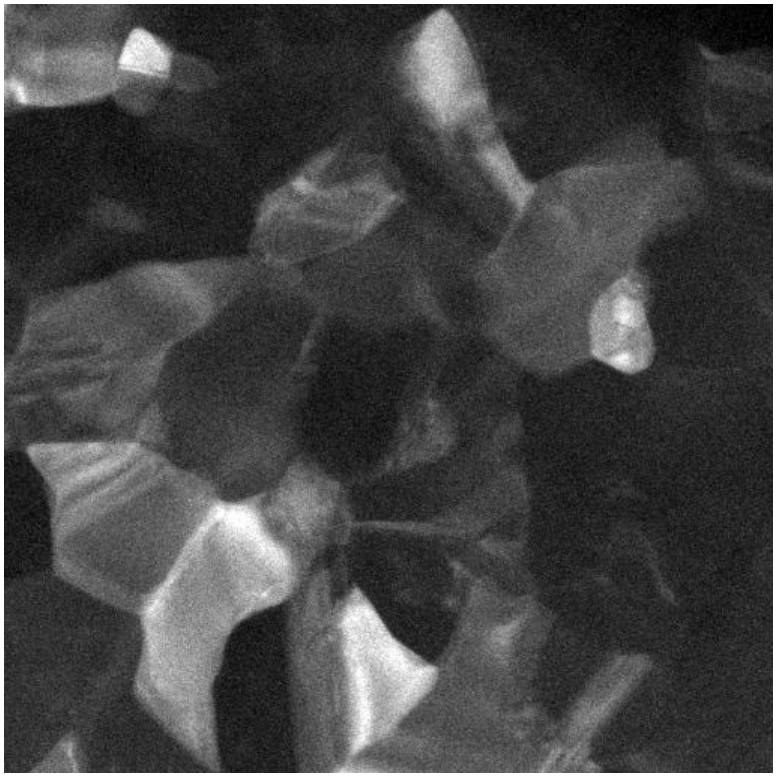


Minor lattice variation is blurred,
Dynamic effect is reduced.

The effect of rocking beam - examples



No precession

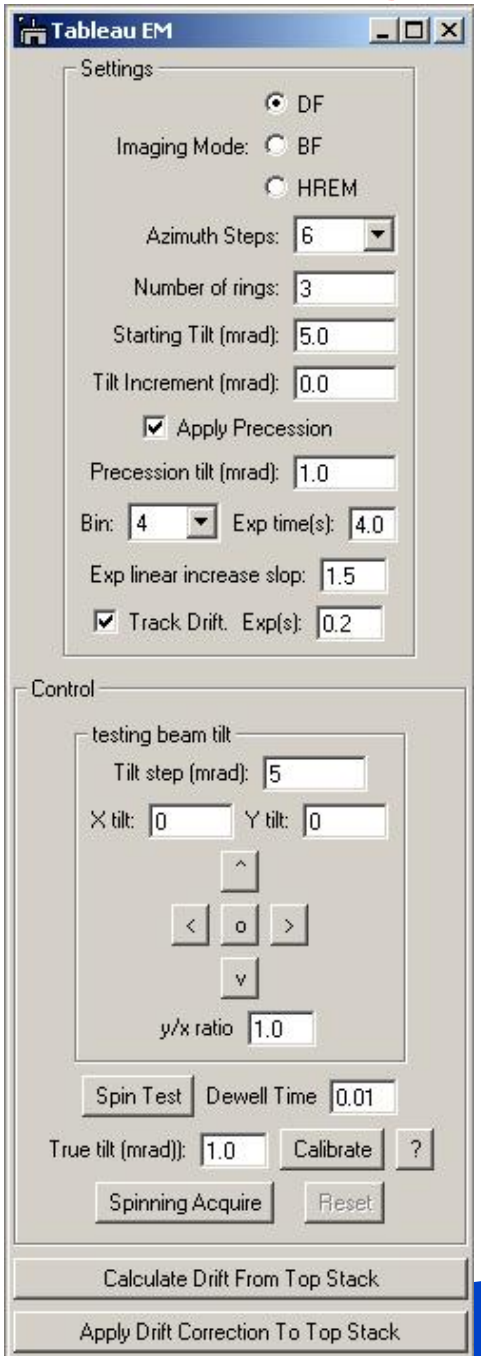


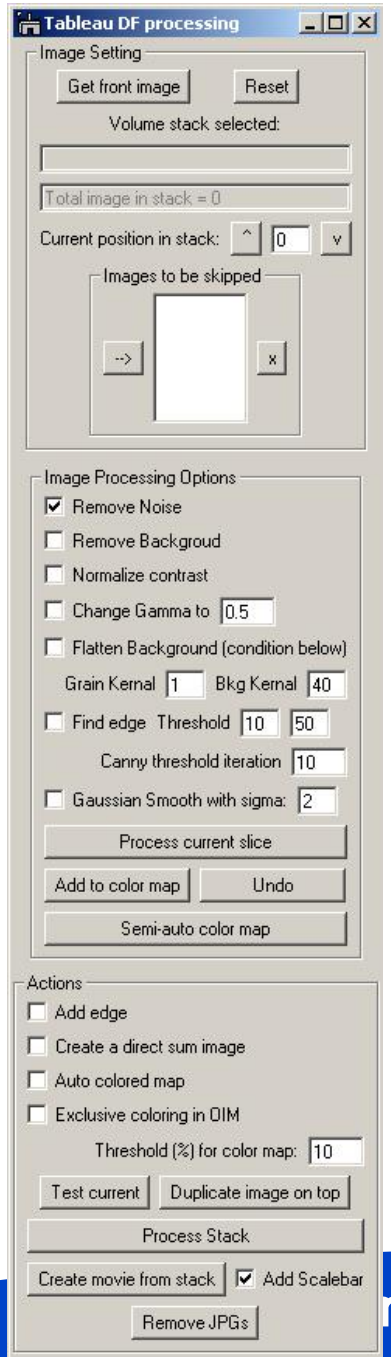
With precession

Due to the rocking beam, the minor variation in reciprocal lattice is blurred, while the main orientation character is preserved.

Tableau EM control and processing software

- Software package written with Gatan DigitalMicrography scripting language.
- Control program to be run in DigitalMicrography interfaced with a conventional TEM.





A dynamic grain orientation map: Tableau DF animation.

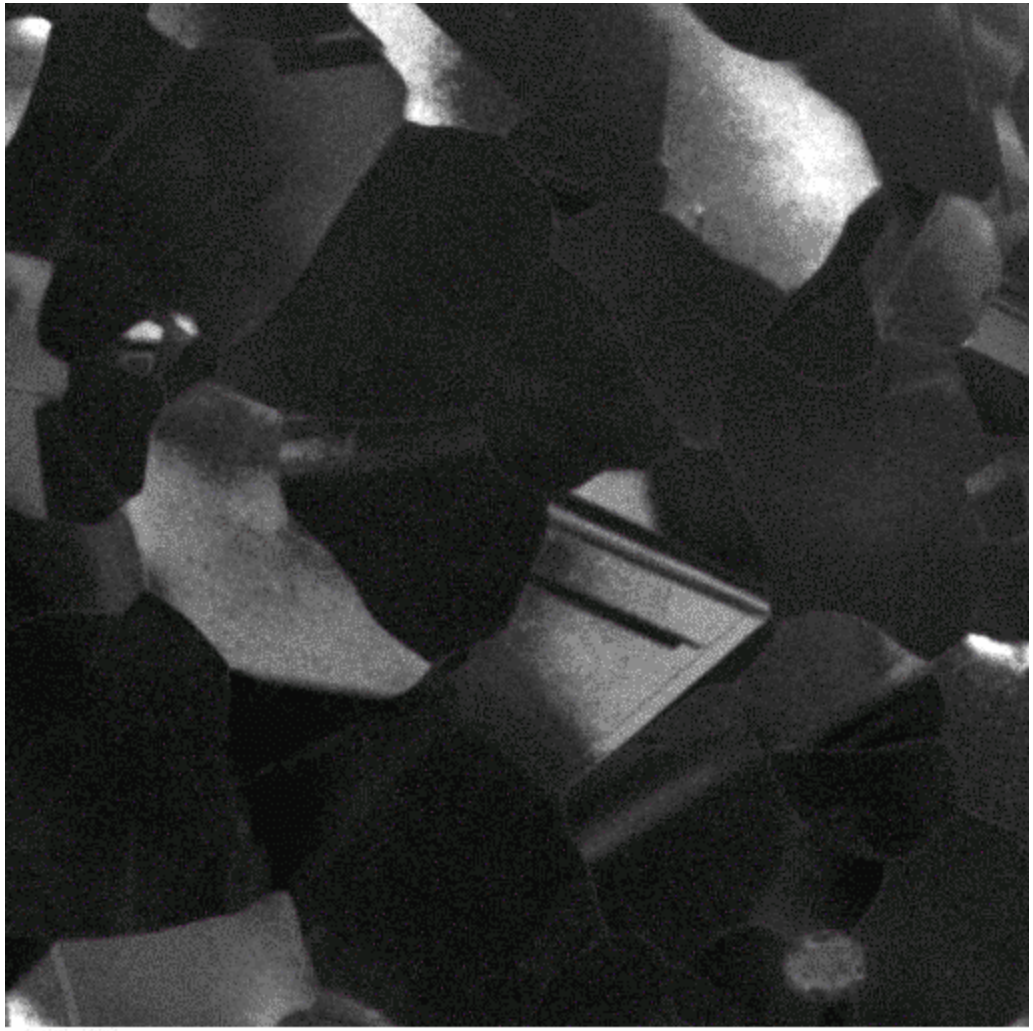
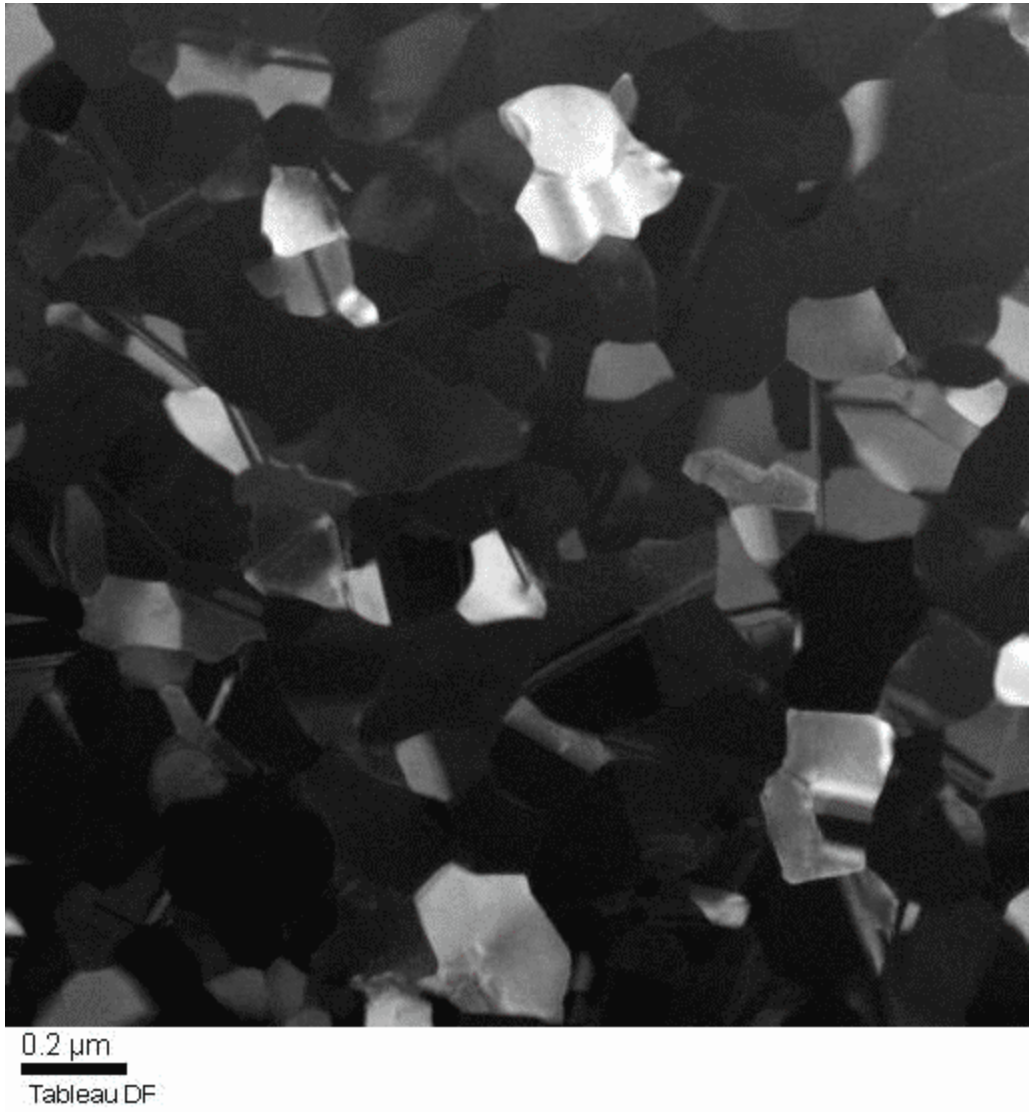


Tableau DF_2

Grain orientation map based on a tableau dark field image stack.

Another example with larger field of view



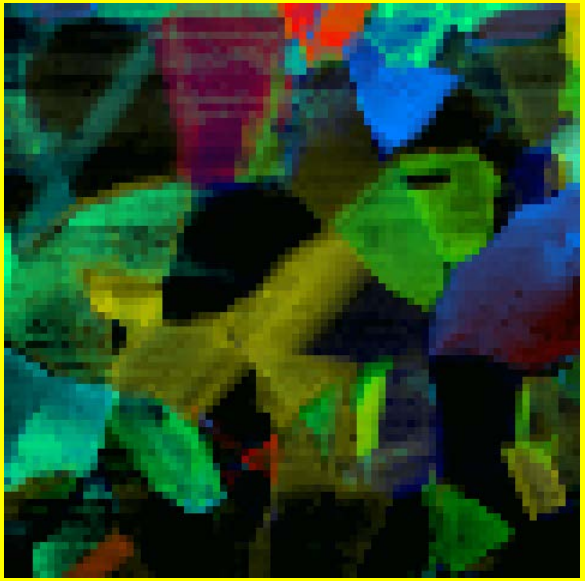
Comparison

From STEM diffraction mapping

SDB-q map

SDB-q ratio map

Dynamic orientation map.



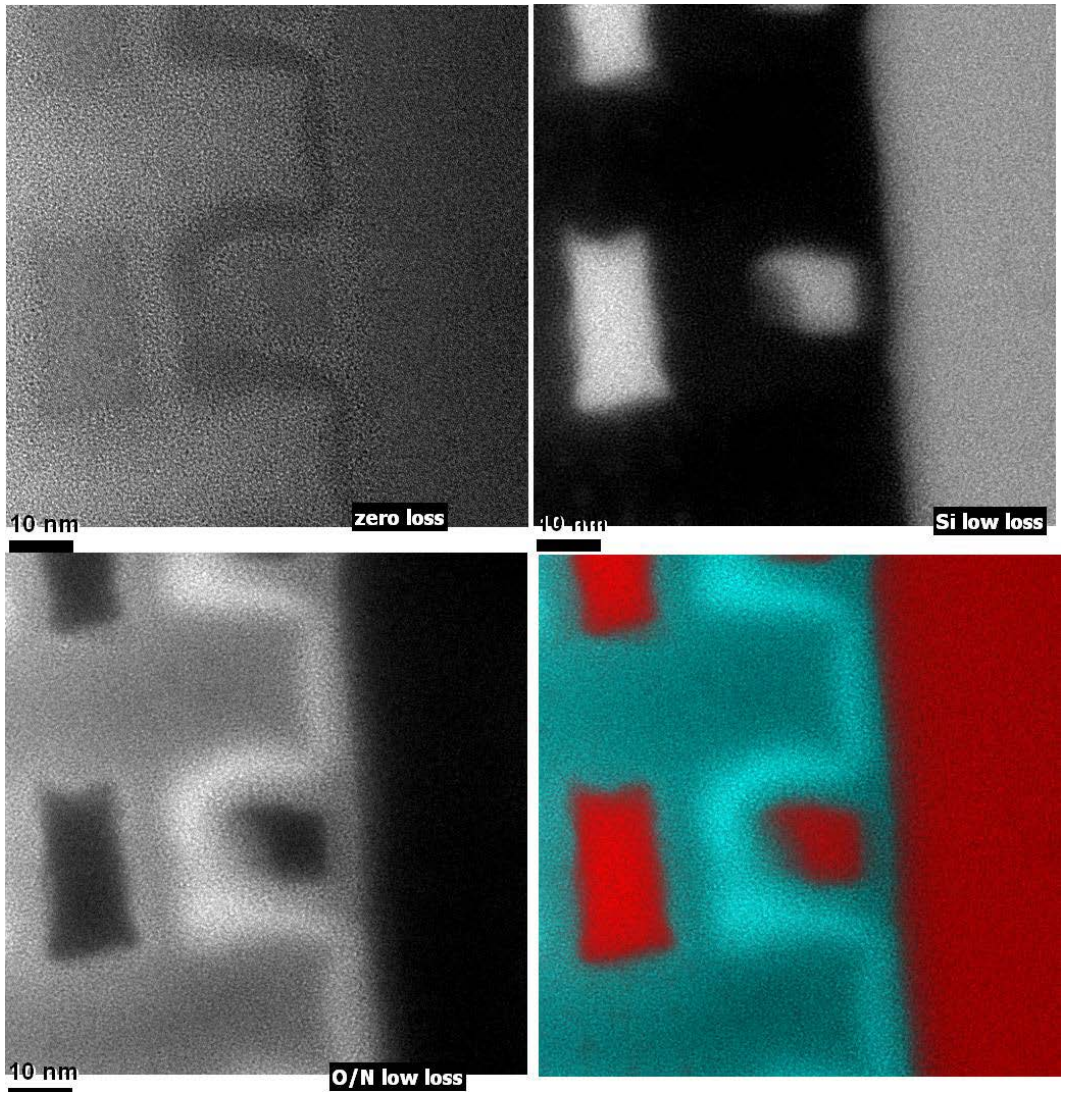
Color-coded orientation map

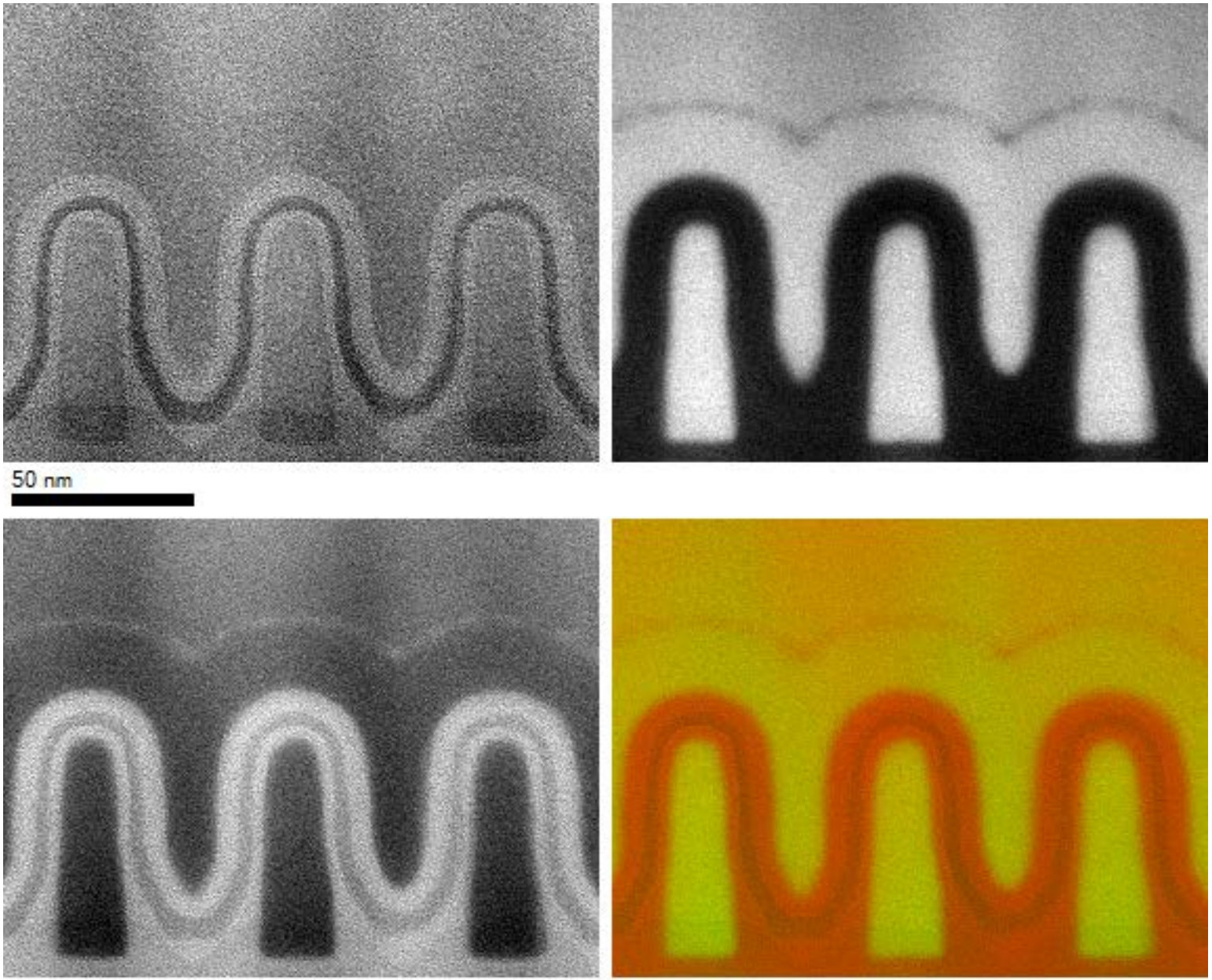
From Tableau DF Imaging

3. Hybrid Image

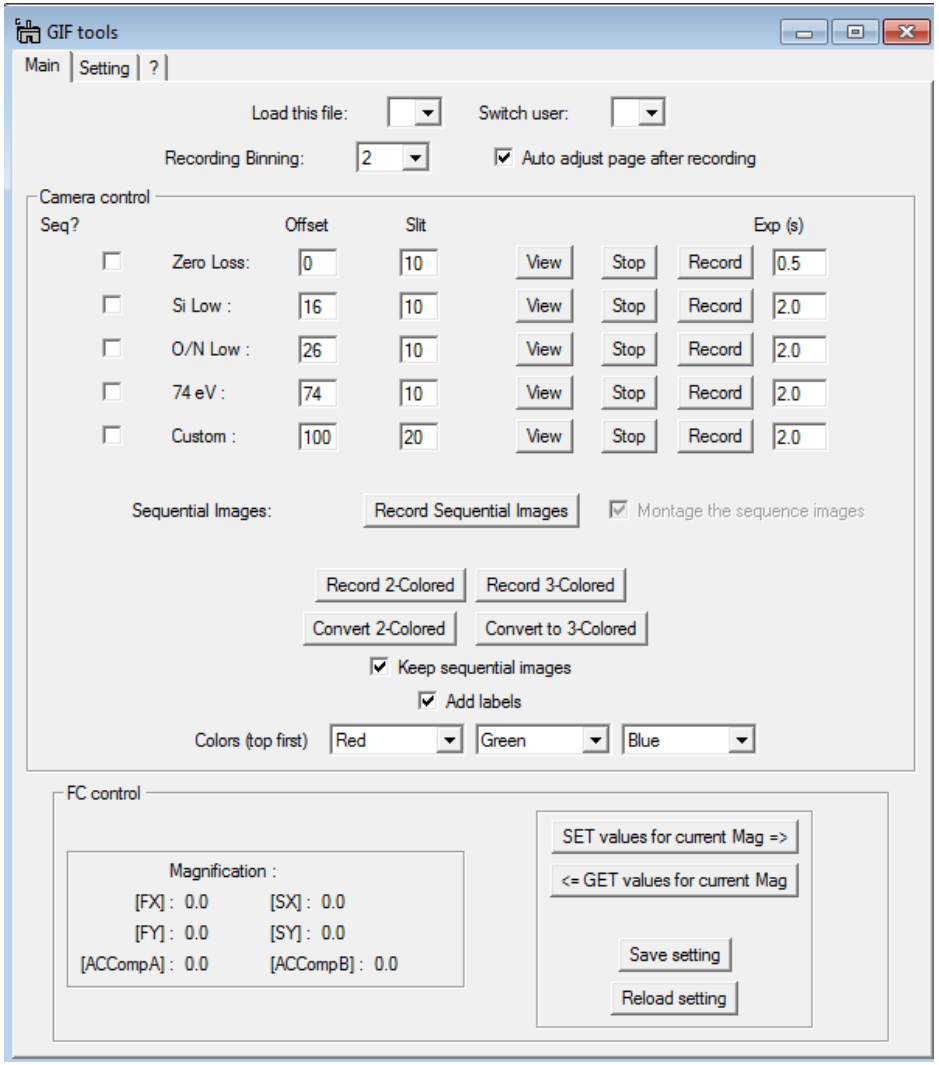
The difficulties seeing the 3D NAND structures

Purpose: To see low contrast features and to enable multi-channel imaging




50 nm

Hybrid image



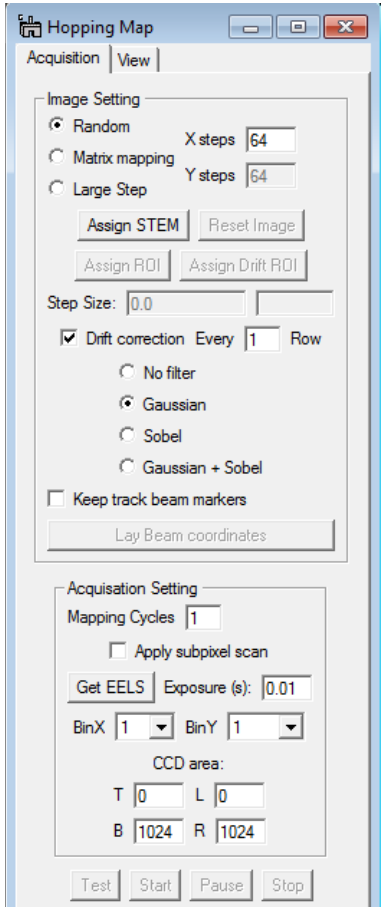
This is a program interfaced with TEM in EFTEM mode.

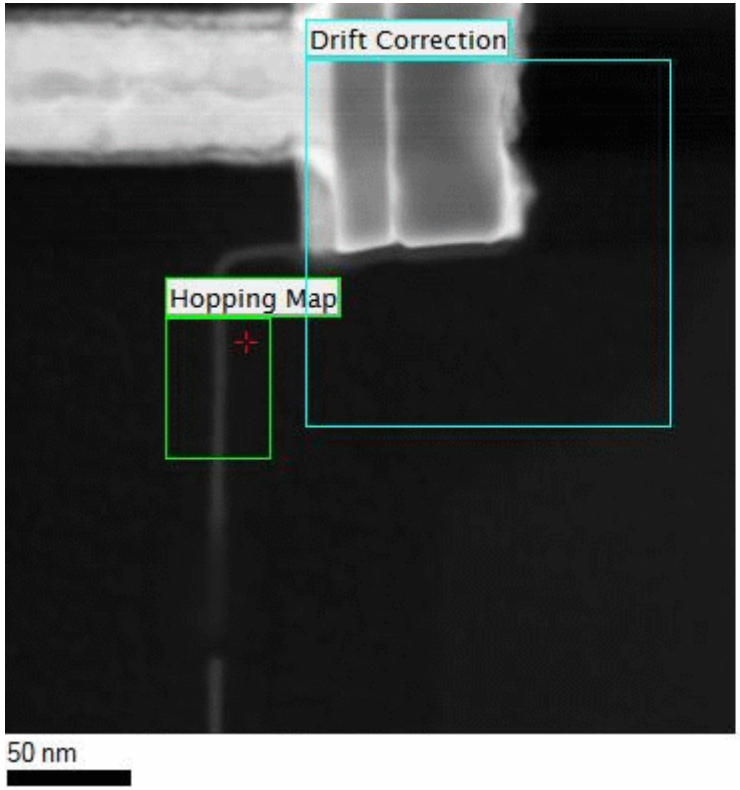
The program features

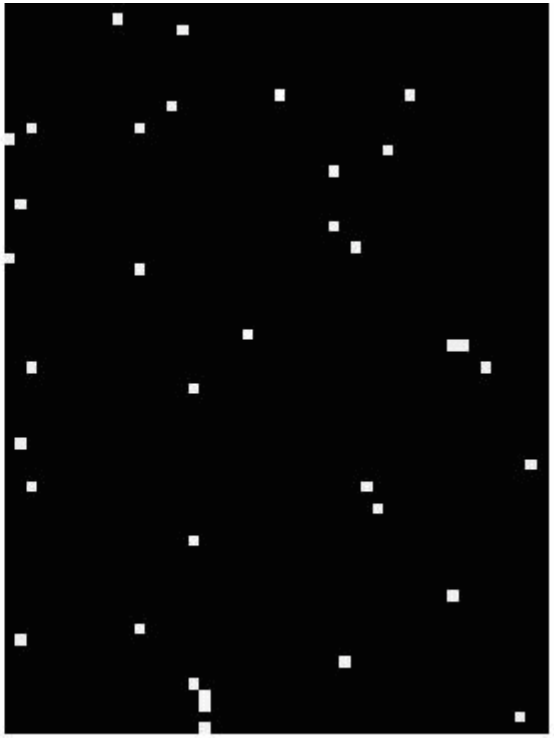
- Saving and loading Gatan GIF control
- Viewing and recording mode
- Virtual multi-channel camera

4. Random mapping

Random mapping: Data collection

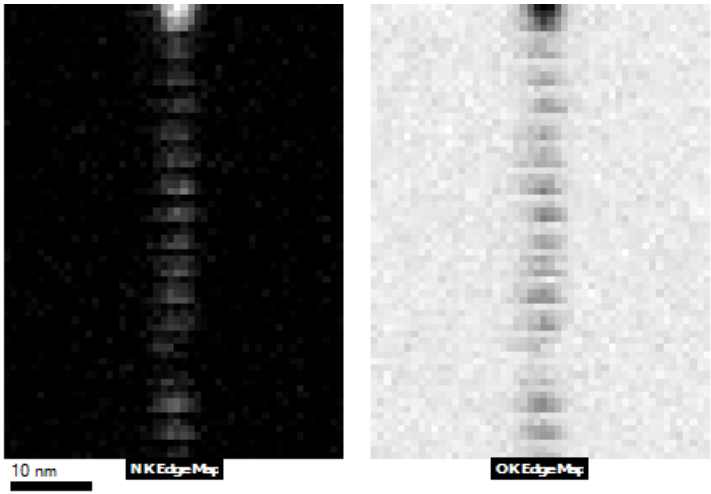




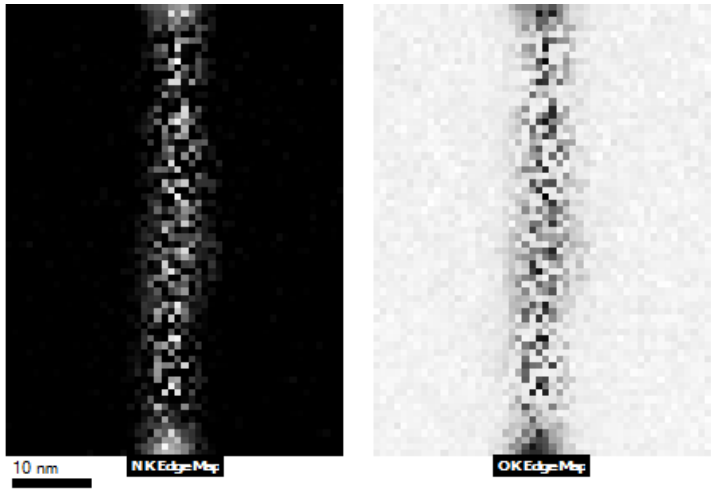


Comparison between sequential and random mappings

Sequential Mapping

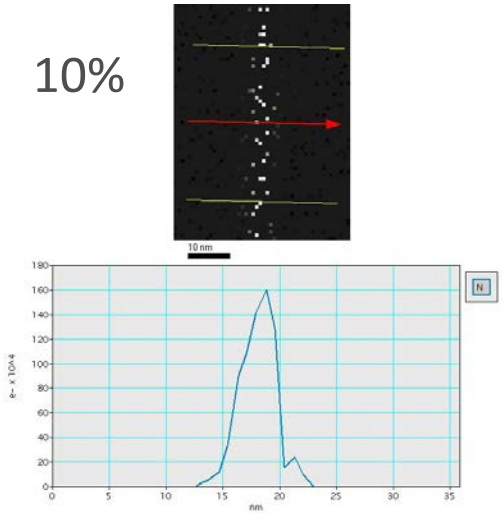


Random Mapping

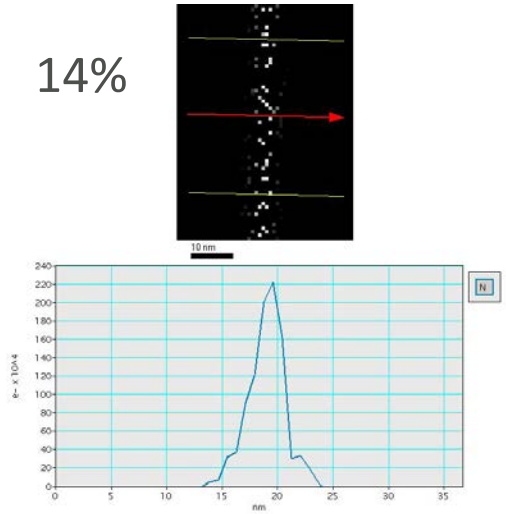


Sparse sampling from random mapping data

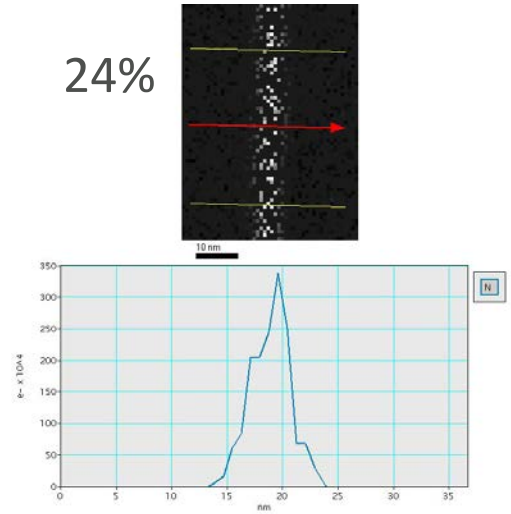
10%



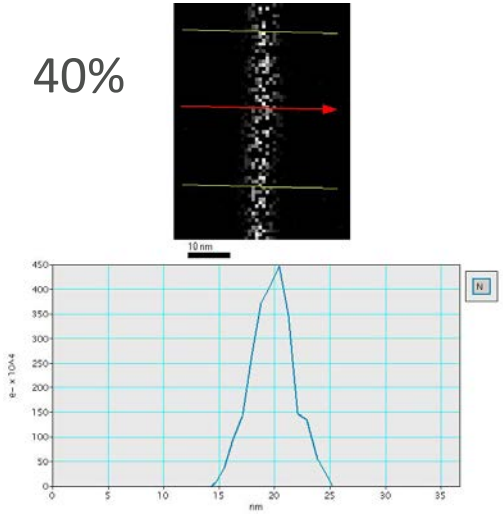
14%



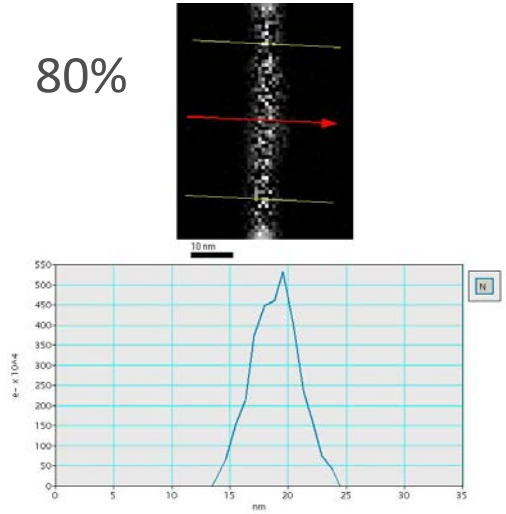
24%



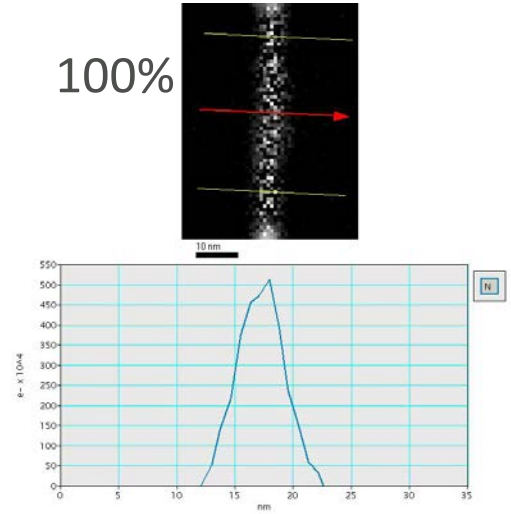
40%



80%

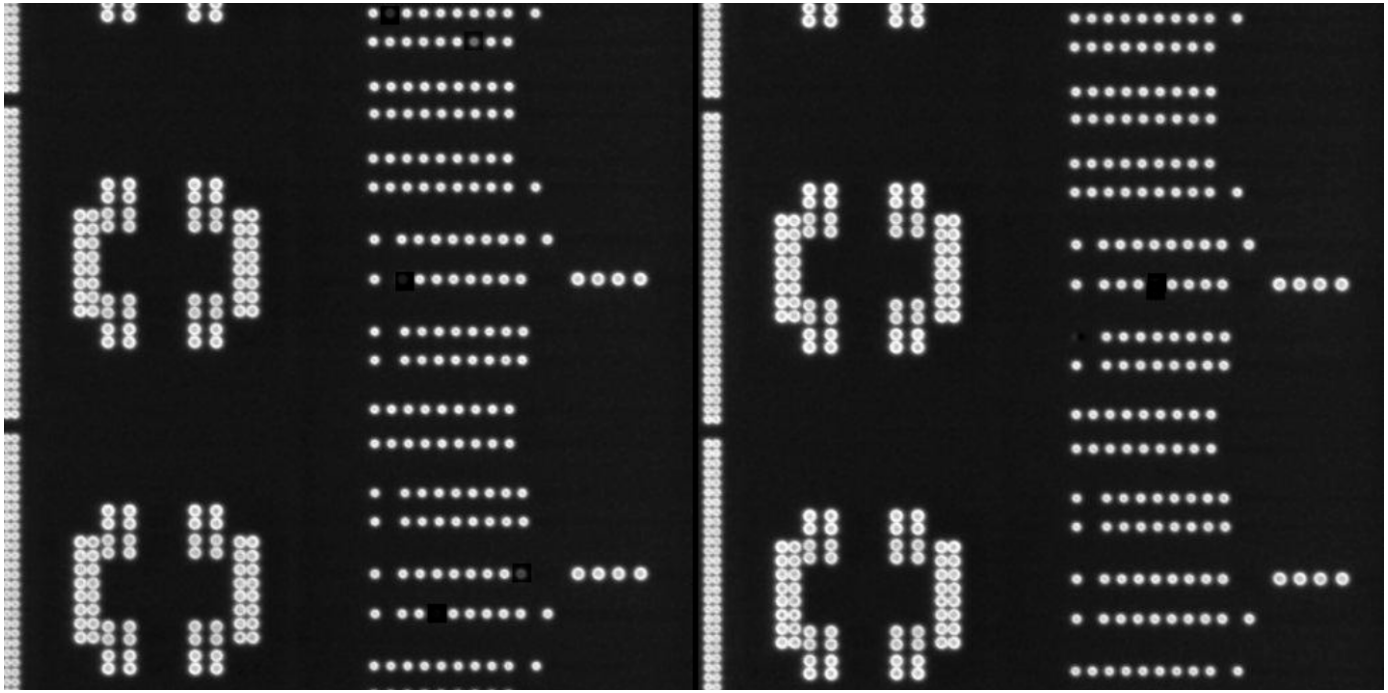


100%

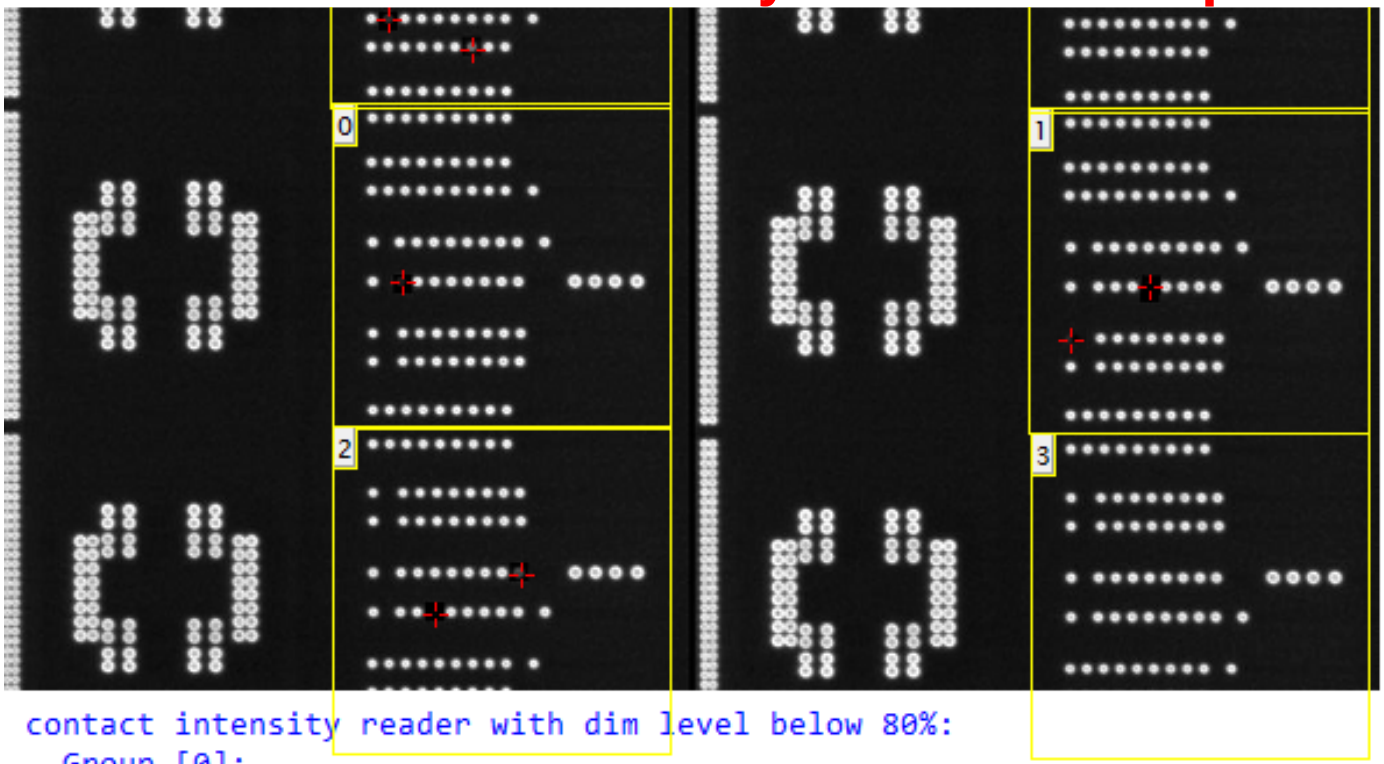


5. Pattern recognition and structural analysis

Task: locate and identify the darkened spots



Task: locate and identify the darkened spots

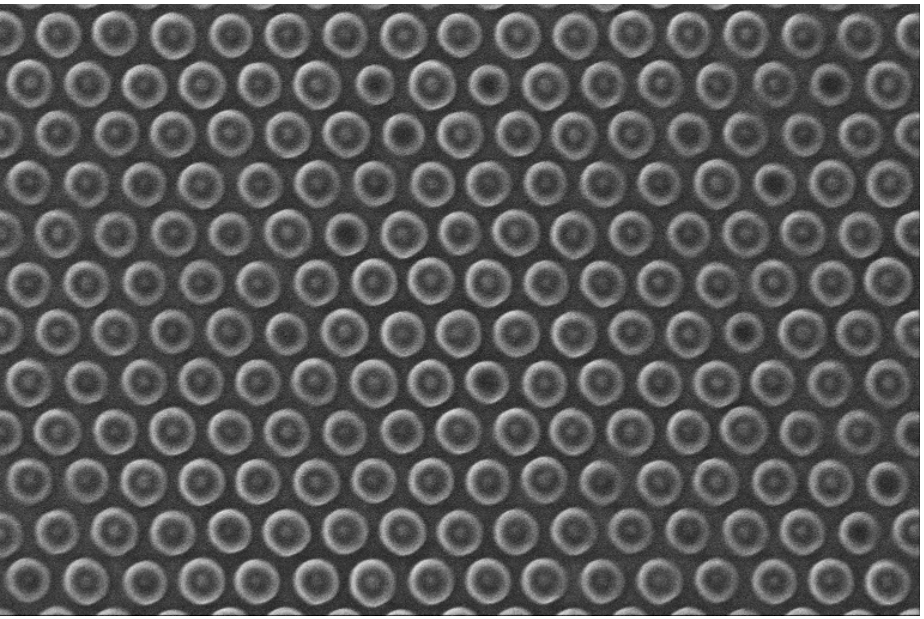



```
contact intensity reader with dim level below 80%:
- Group [0]:
15, 16%
- Group [1]:
9,  10%
35, 21%
- Group [2]:
12, 8%
1,  34%
- Group [3]:
(None)
- Group [4]:
(None)
- Group [5]:
42, 49%
53, 24%
```

This is done with pattern recognition and image registration.

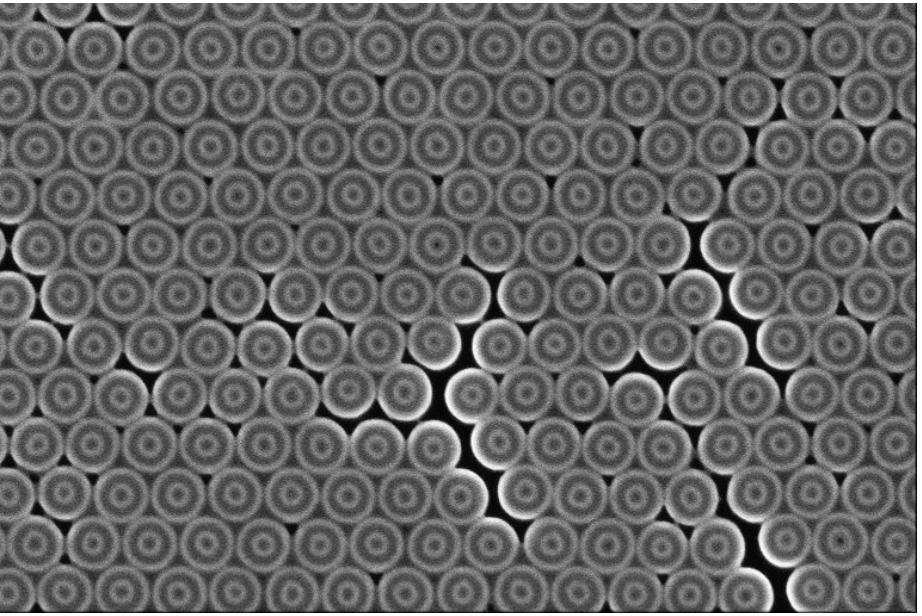
The program is built into a robotic crawler going through designated folders to find the data and generate reports.

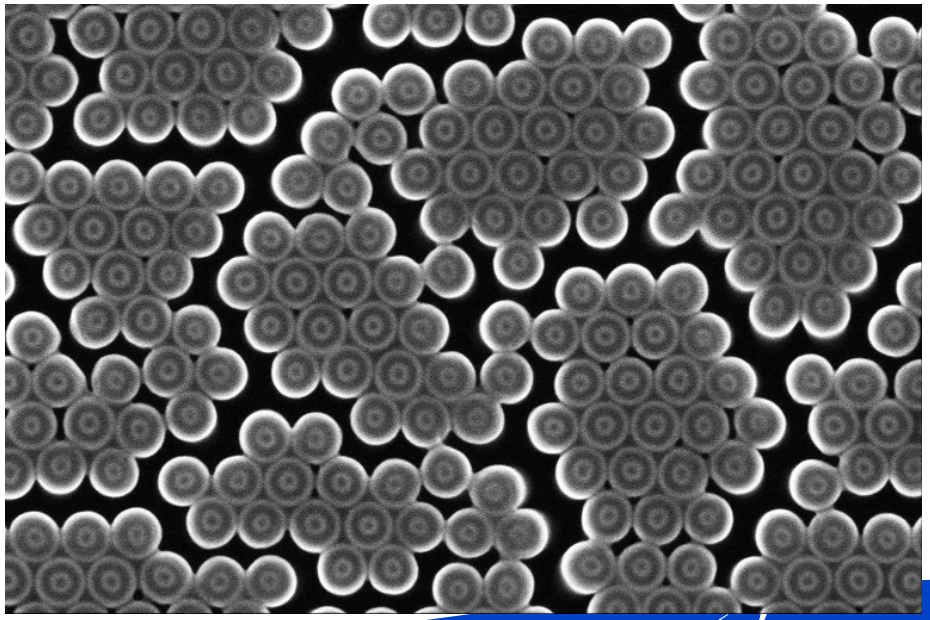
Task: Characterizing cell buckling



Q: How do we characterize the position shifting of cells?

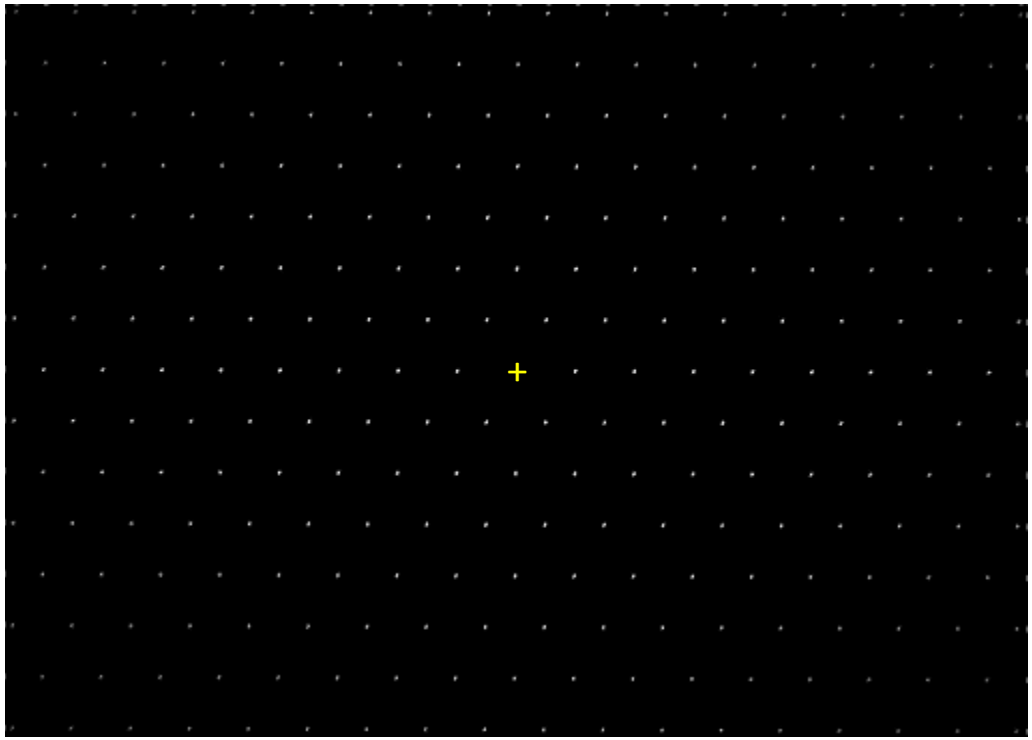
Can we find a single quantity to monitor this variation?



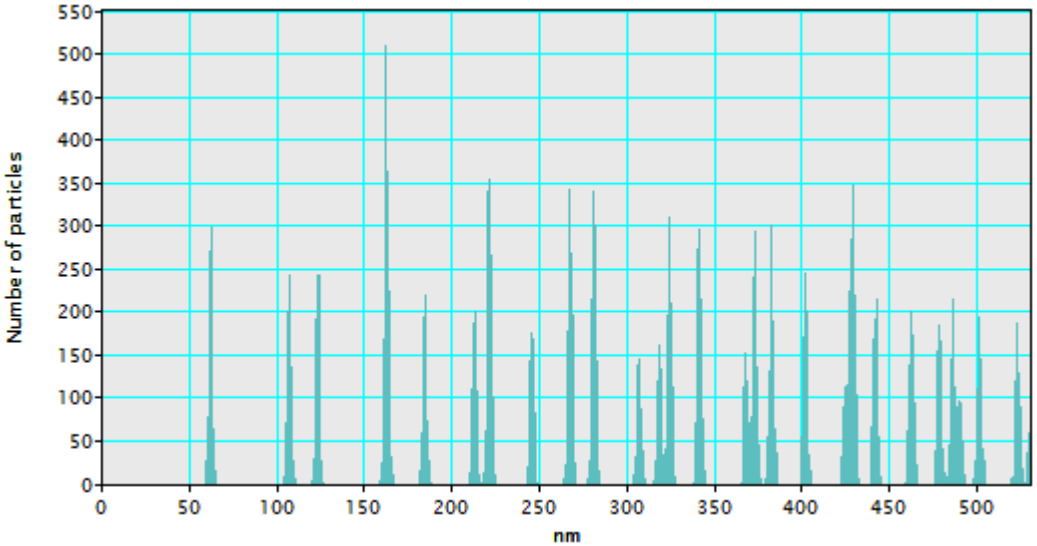


Visualizing the distance distribution

A neighbor distribution map (PDF – pair distribution function)



A Radial distribution plot (RDF – radial distribution function)



Fast algorithms calculating RDF and PDF

$$ptyMatrix = ptY \times ones = \begin{bmatrix} y1 \\ y2 \\ \vdots \\ yn \end{bmatrix} [1 \quad 1 \quad \dots \quad 1] = \begin{bmatrix} y1 & y1 \dots & y1 \\ y2 & y2 \cdots & y2 \\ \vdots & \vdots \ \dots & \vdots \\ yn & yn \cdots & yn \end{bmatrix}$$

$$ptyMatrix = ptY \times ones = \begin{bmatrix} y1 \\ y2 \\ \vdots \\ yn \end{bmatrix} [1 \quad 1 \quad \dots \quad 1] = \begin{bmatrix} y1 & y1 \dots & y1 \\ y2 & y2 \cdots & y2 \\ \vdots & \vdots \ \dots & \vdots \\ yn & yn \cdots & yn \end{bmatrix}$$

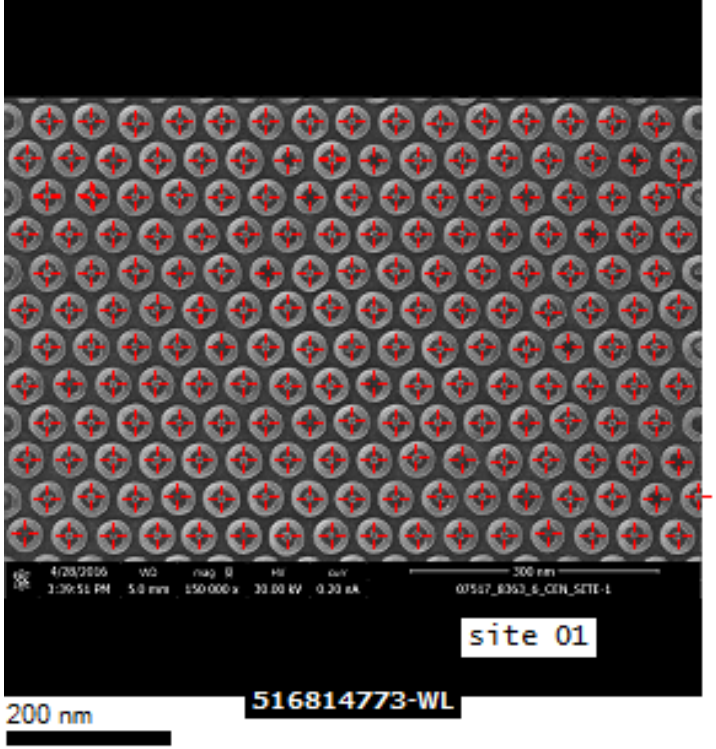
$$ptXMatrixShifted = ptXMatrix - ptXMatrix^T = \begin{bmatrix} 0 & x1 - x2 \dots & x1 - xn \\ x2 - x1 & 0 \quad \cdots & x2 - xn \\ \vdots & \vdots \quad \dots & \vdots \\ xn - x1 & xn - x2 \cdots & 0 \end{bmatrix};$$

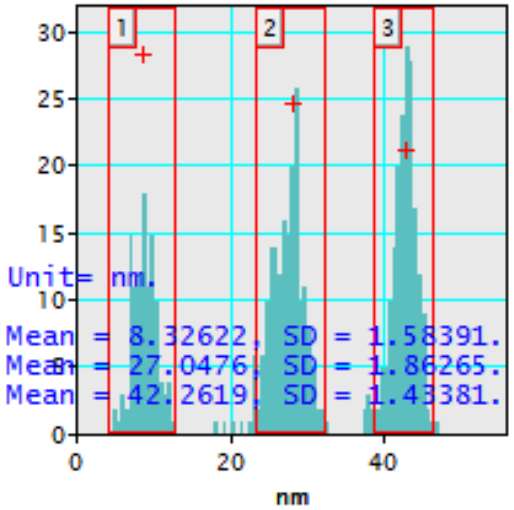
$$ptYMatrixShifted = ptYMatrix - ptYMatrix^T = \begin{bmatrix} 0 & y1 - y2 \dots & y1 - yn \\ y2 - y1 & 0 \quad \cdots & y2 - yn \\ \vdots & \vdots \quad \dots & \vdots \\ yn - y1 & yn - y2 \cdots & 0 \end{bmatrix};$$

$$distMatrix = \sqrt{ptXMatrix^2 + ptYMatrix^2} =$$

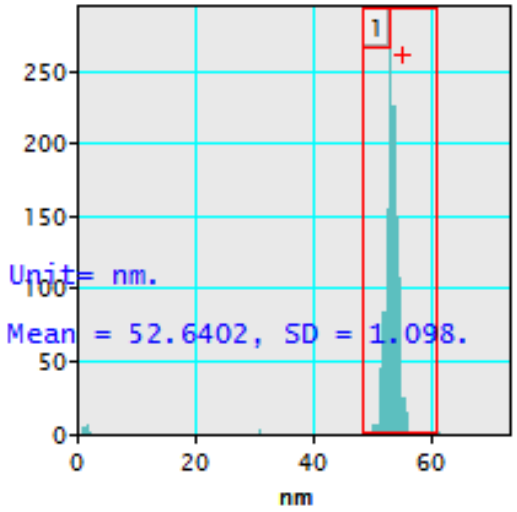
$$\begin{bmatrix} 0 & \sqrt{(x1 - x2)^2 + (y1 - y2)^2} \dots & \sqrt{(x1 - xn)^2 + (y1 - yn)^2} \\ \sqrt{(x2 - x1)^2 + (y2 - y1)^2} & 0 \quad \cdots & \sqrt{(x2 - xn)^2 + (y2 - yn)^2} \\ \vdots & \vdots \quad \dots & \vdots \\ \sqrt{(xn - x1)^2 + (yn - y1)^2} & \sqrt{(xn - x2)^2 + (yn - y2)^2} \cdots & 0 \end{bmatrix}$$

$$RDF = RDF[distMatrix, 0] + 1$$

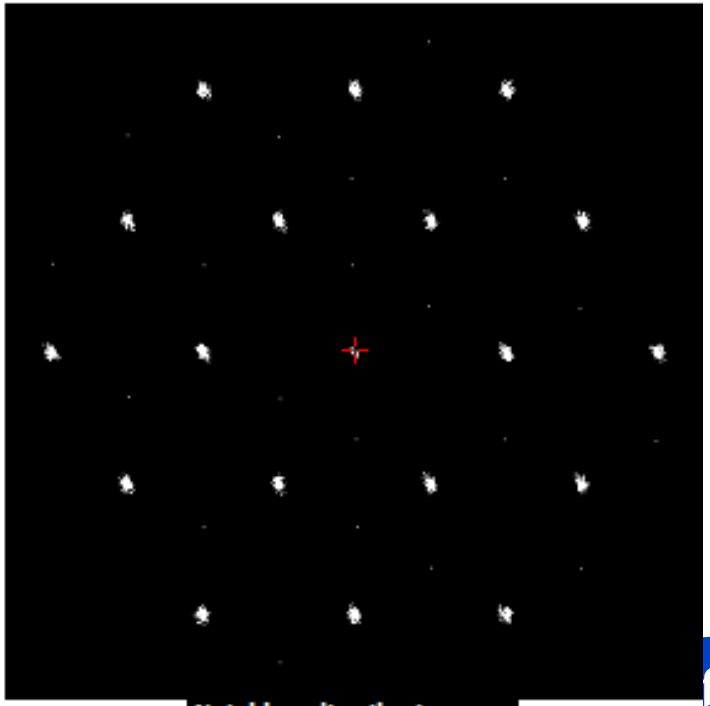




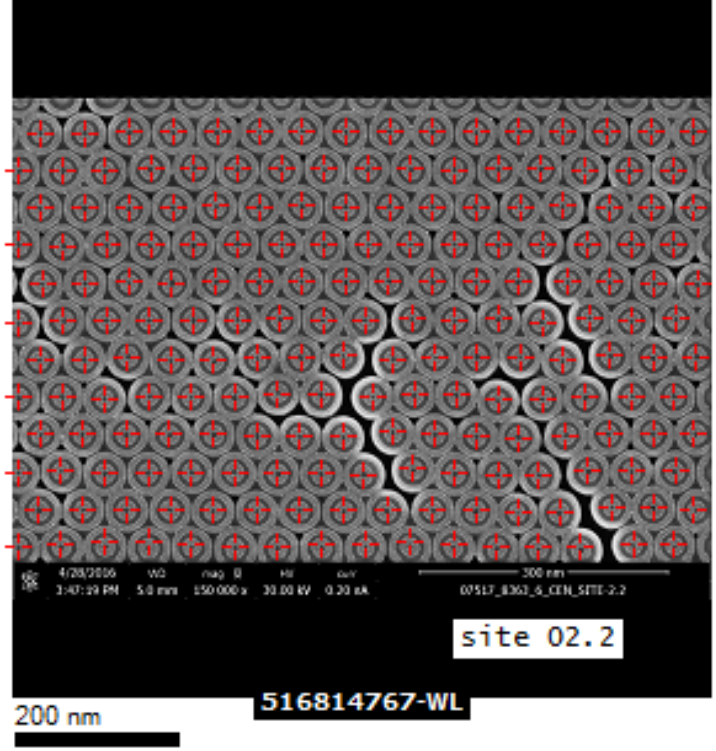
Diameter distribution

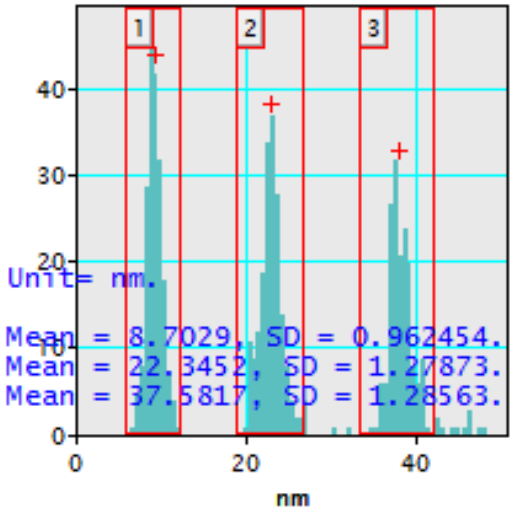


RDF

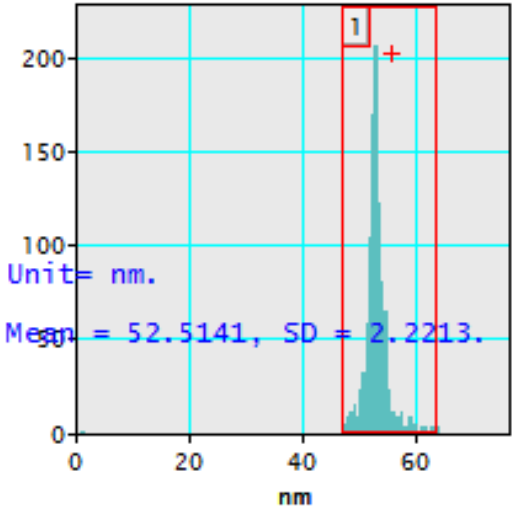


Neighbor distribution map

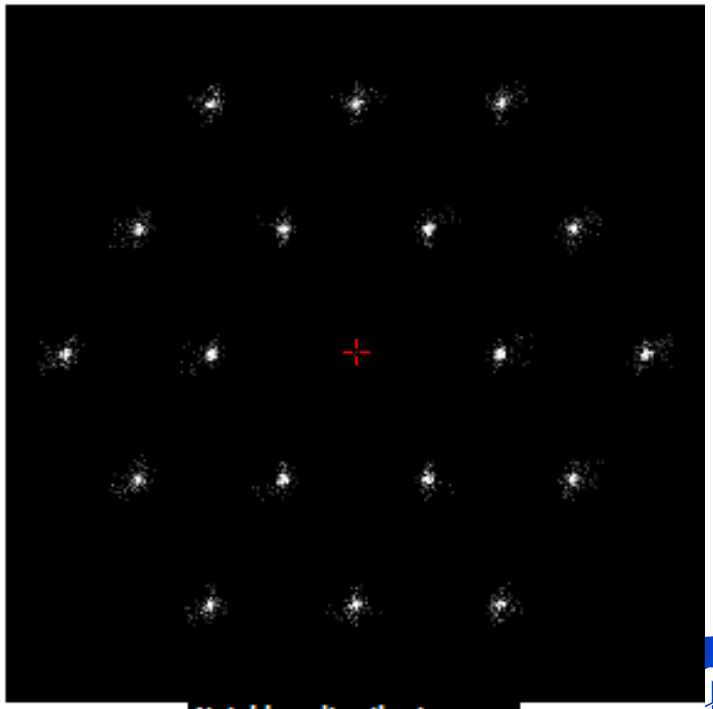




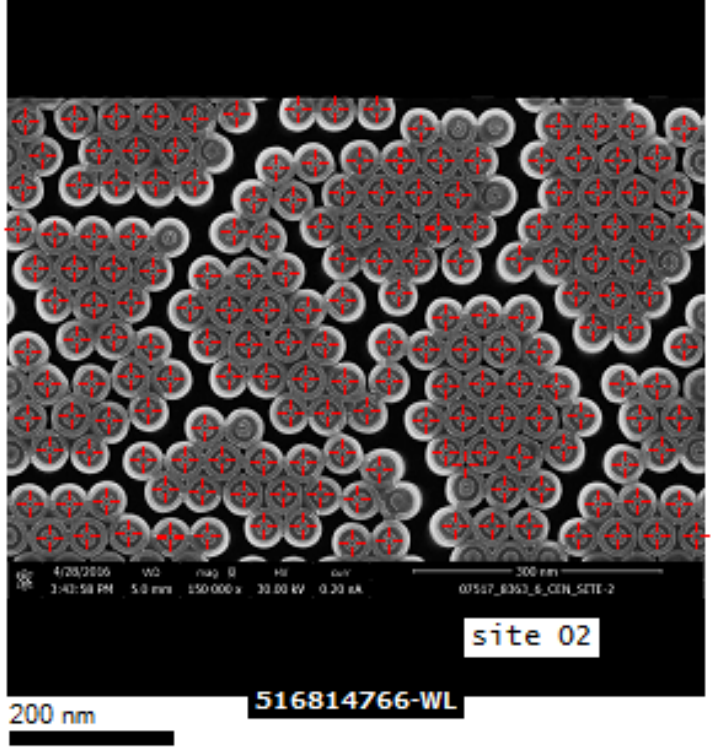
Diameter distribution

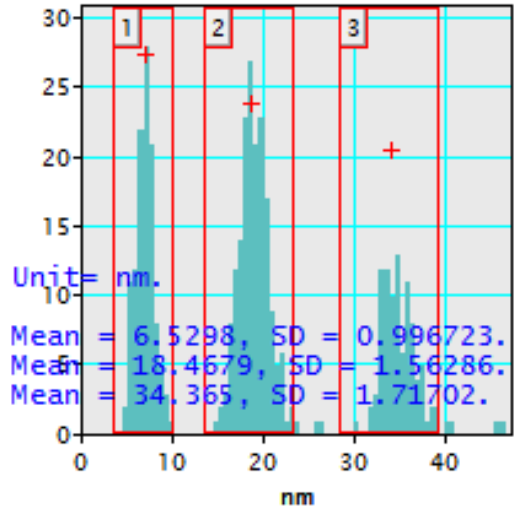


RDF

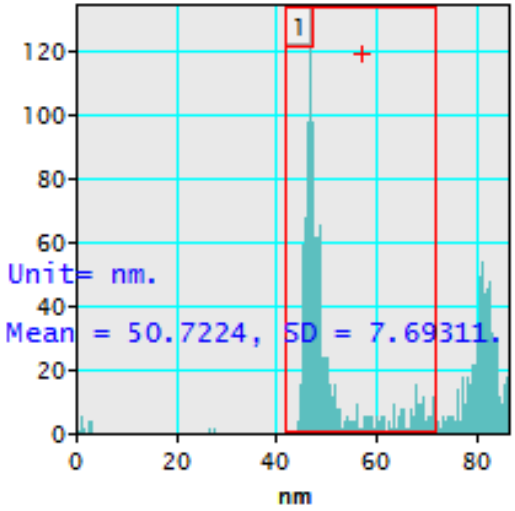


Neighbor distribution map

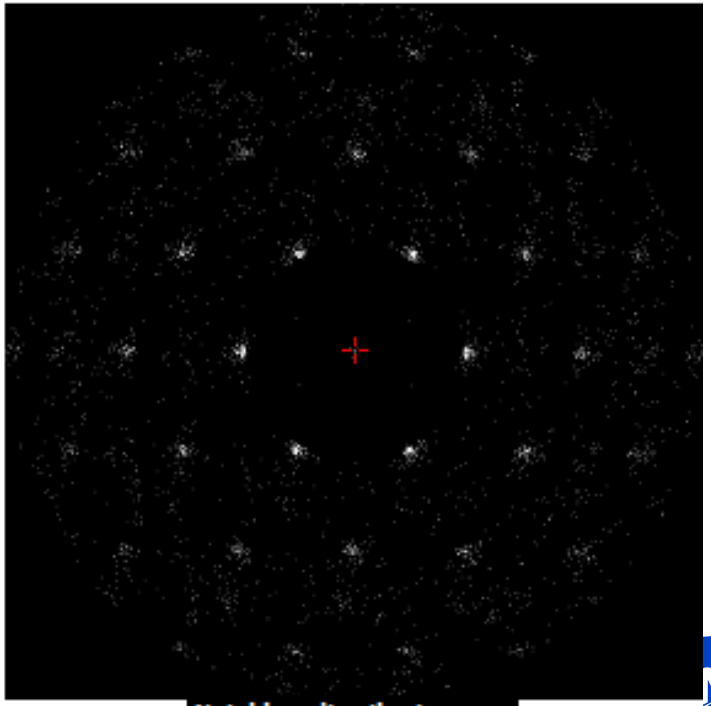




Diameter distribution



RDF



Neighbor distribution map

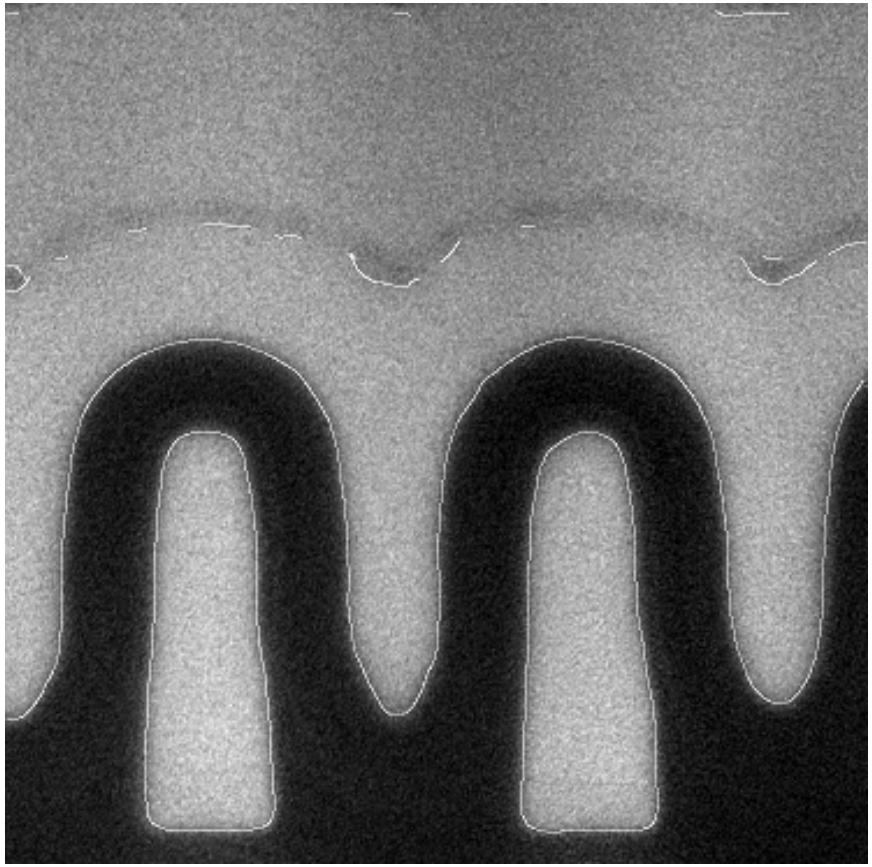
6. Computer vision used onto TEM – TEM metrology

Theoretical foundations

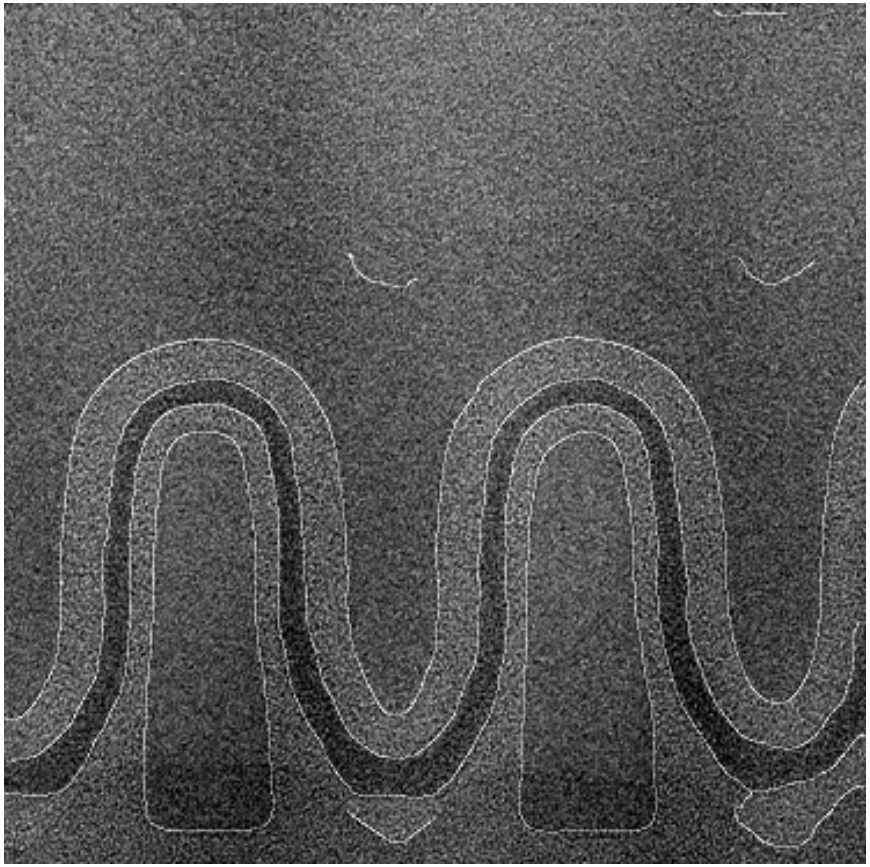
Three theoretical “principles” governing this metrology method:

1. Symmetrical or non-symmetrical smoothing does not change edge position when edge finding is based on first derivative and when there is no neighboring edge. (from Fourier analysis)
2. Neighboring edges start to interfere edge position when Gaussian smooth sigma > distance/π. (from Fourier analysis).
3. Sample thickness and centering invariance. (Developed in this project).

Edge finding

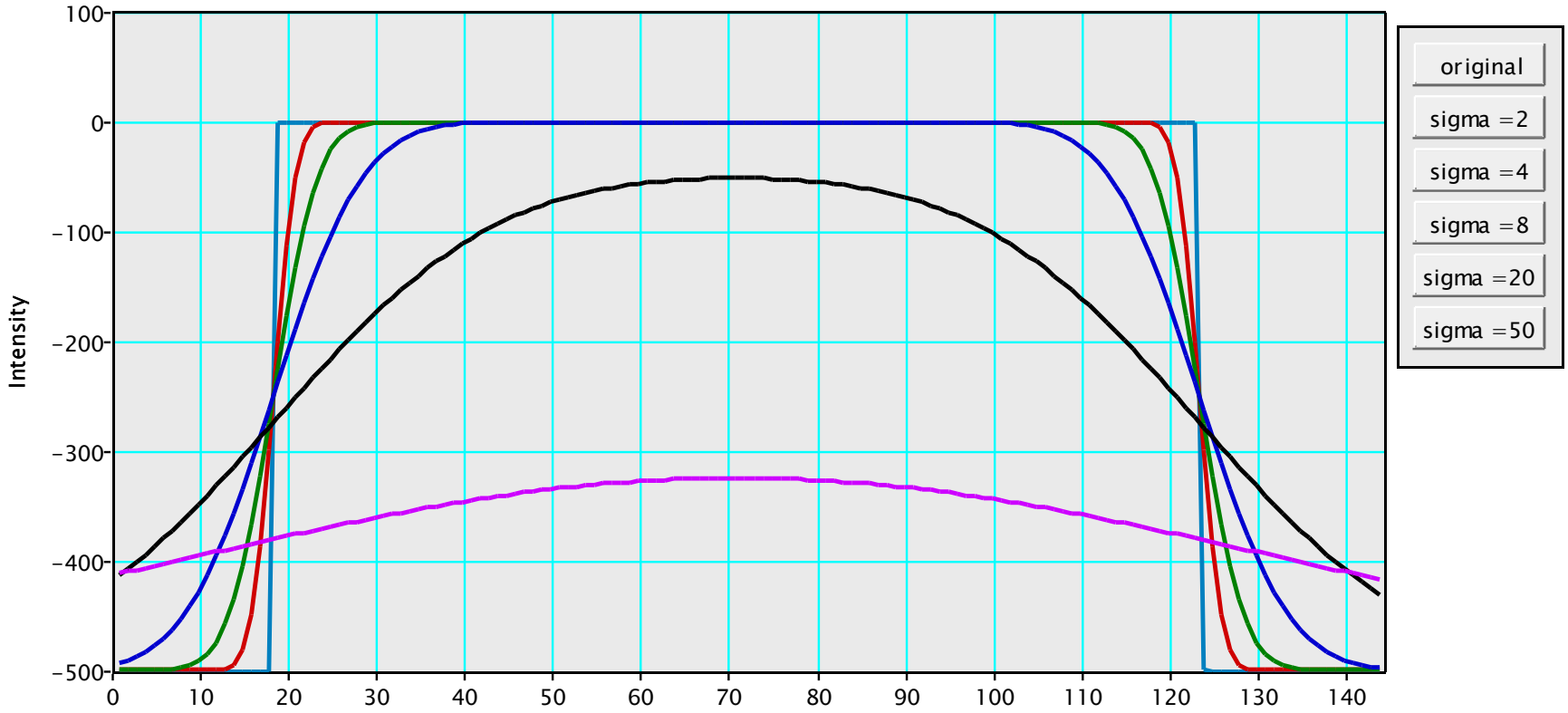


Straight edge-finding.



Intelligent hybrid edge finding

Mathematical basis for using reflection point as edge location



A certain degree of smoothing is needed in order to pick out main feature, and eliminating the complication due to fine features.

If we do not smooth the feature too much (relative to feature size), the refection point is always a faithful indication of object edge.

The limit of smoothing

$\sigma_{criticfal}=L/\pi$,
where L is feature length, $\sigma_{criticfal}$ is the Gaussian sigma beyond which the edge position is changed.

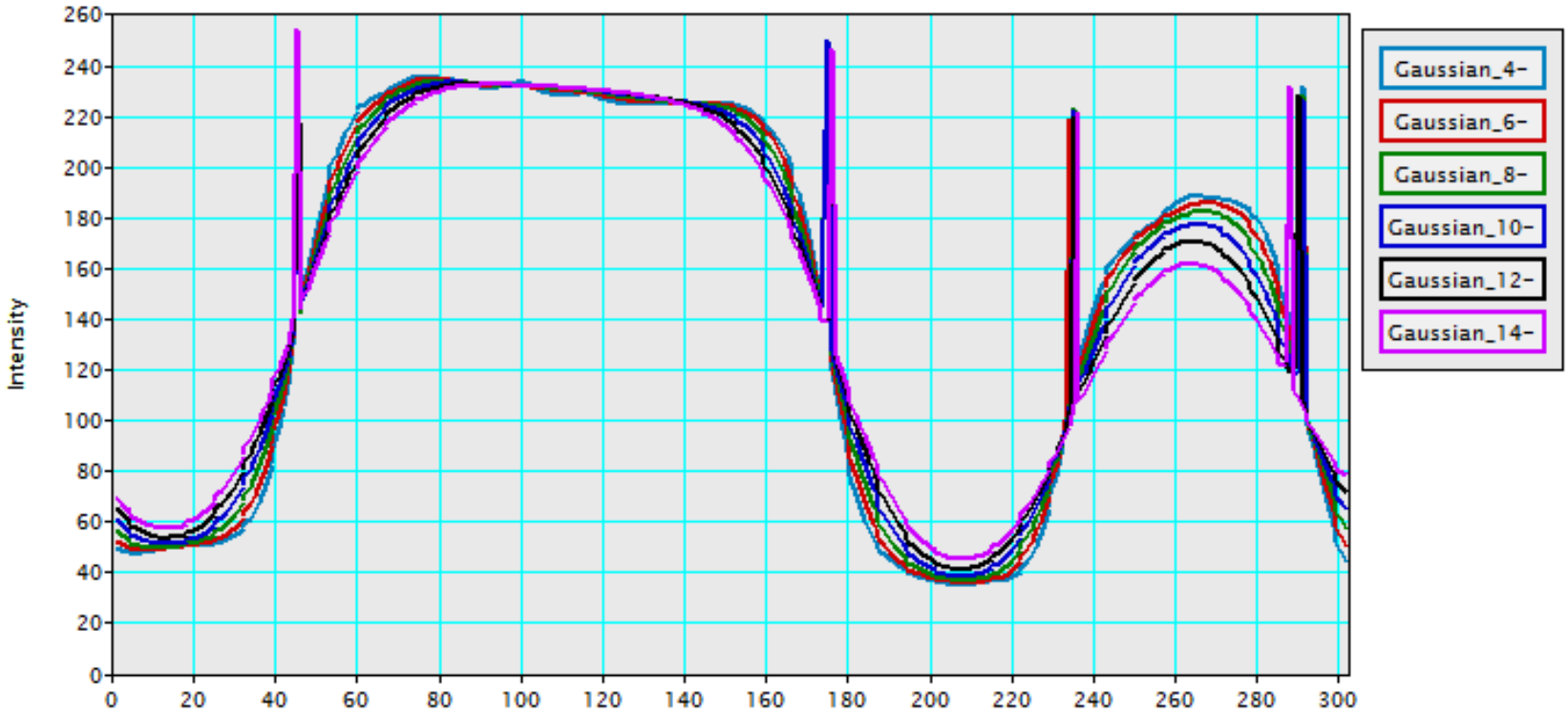
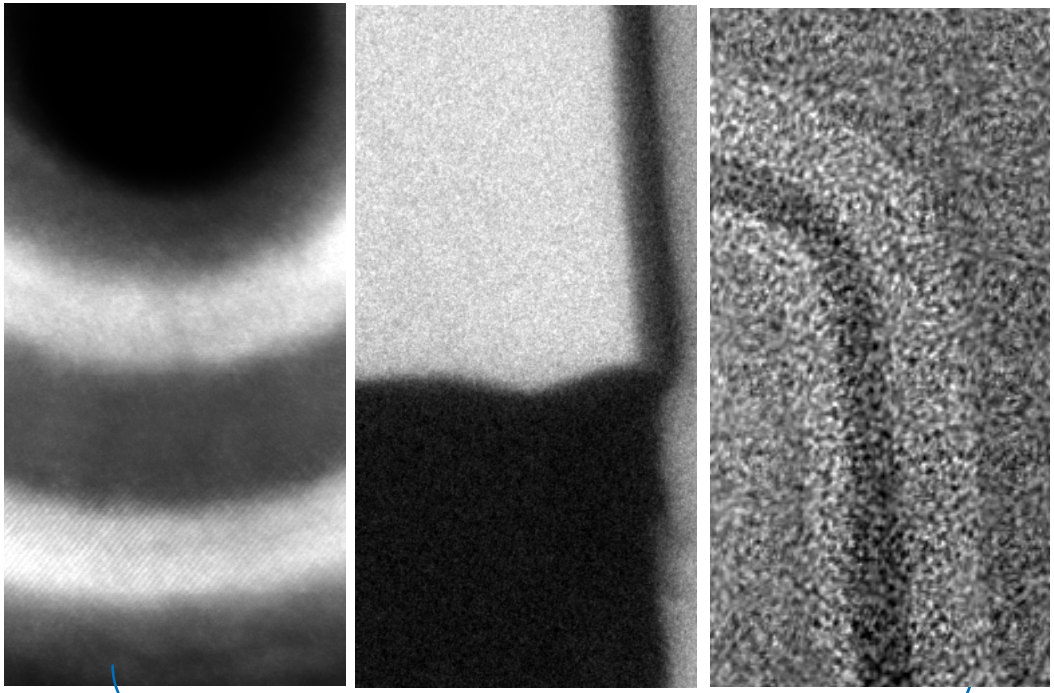
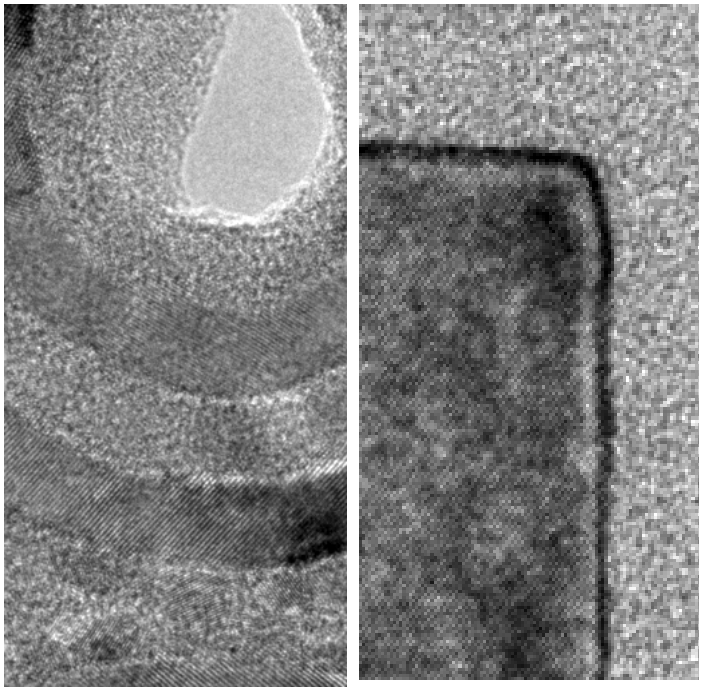


Image contrast requirement





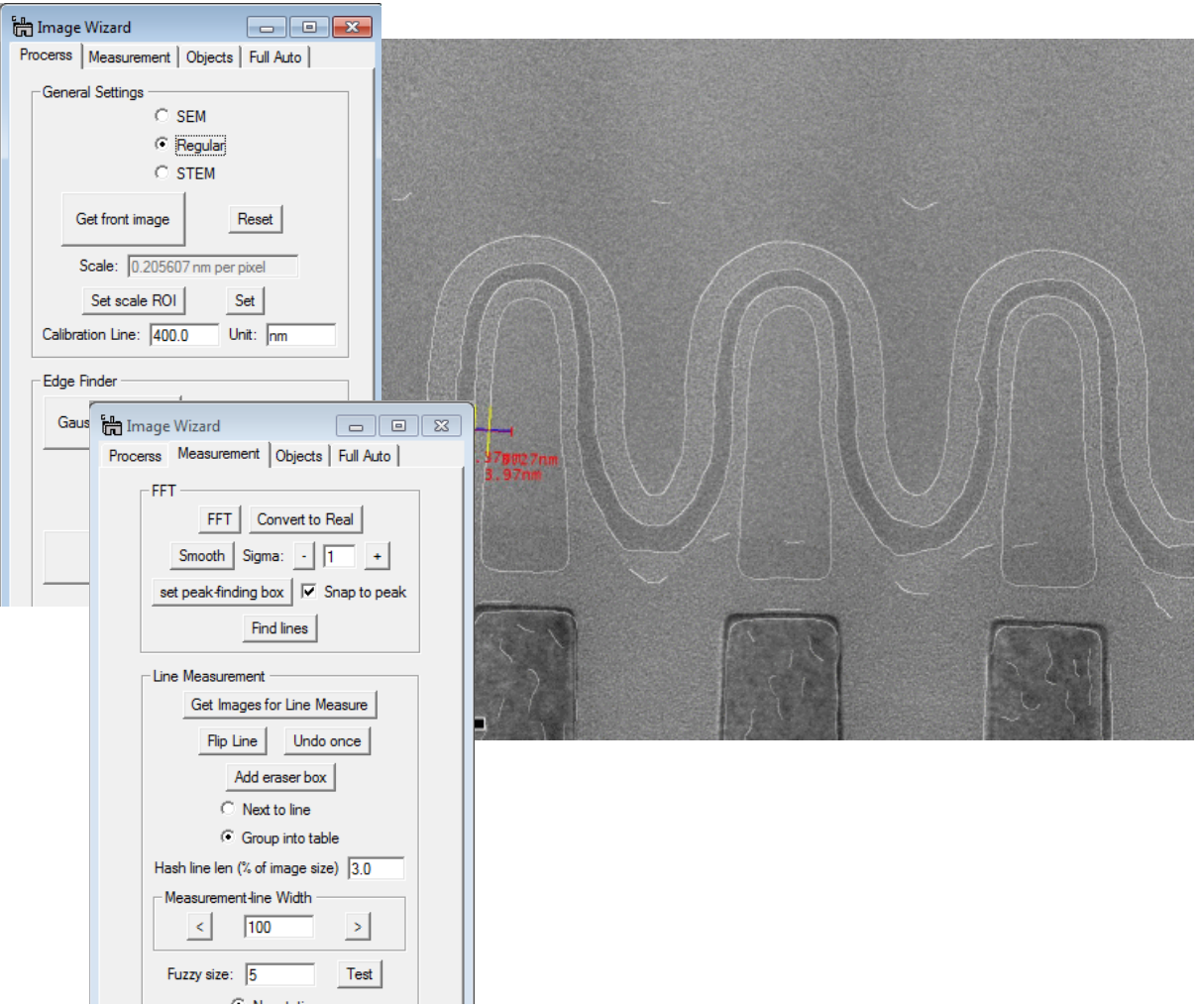
Mass-thickness contrast is suitable for metrology

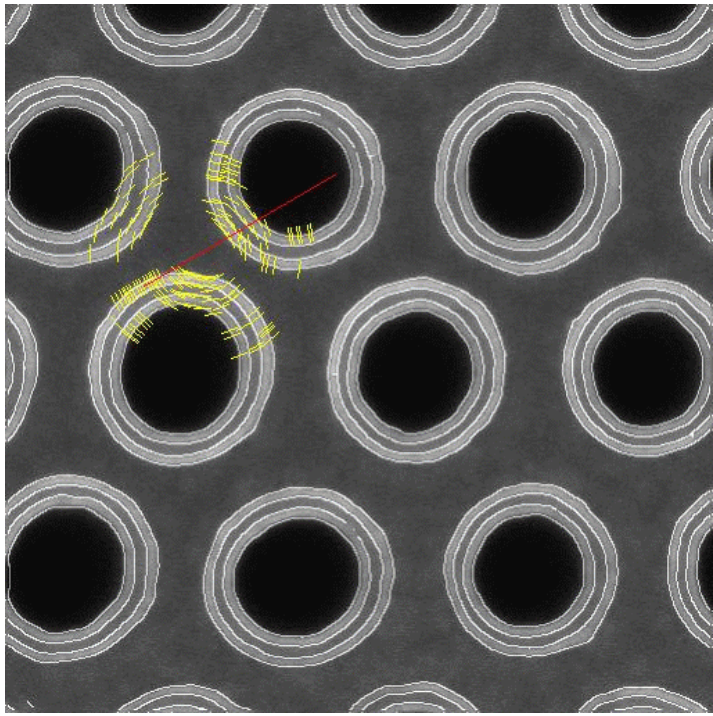
- Low loss EFTEM
- Amorphous material
- Elemental maps
- SEM

Phase contrast is not suitable for metrology

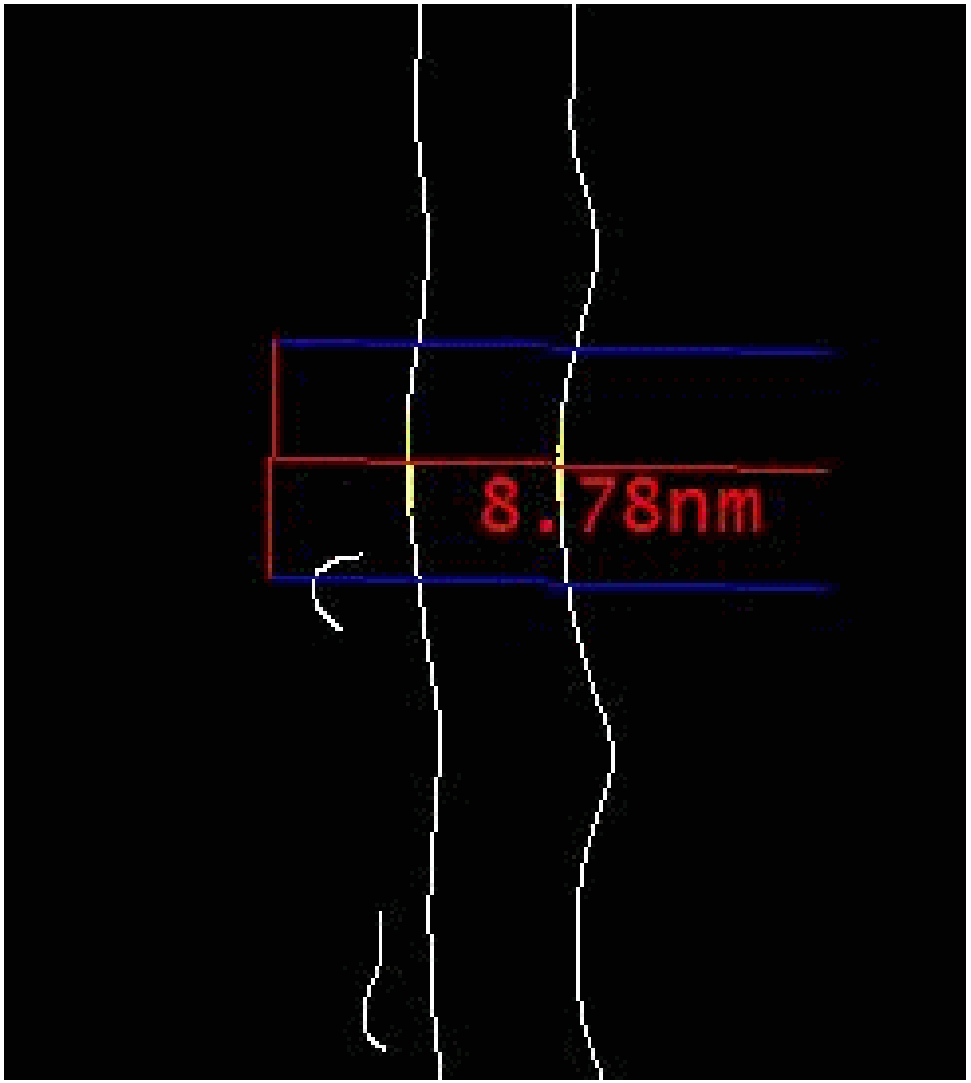
- HREM of crystalline material
- Bright-field of crystalline material

Computer vision based auto measurements





Increasing data accuracy with linear regression



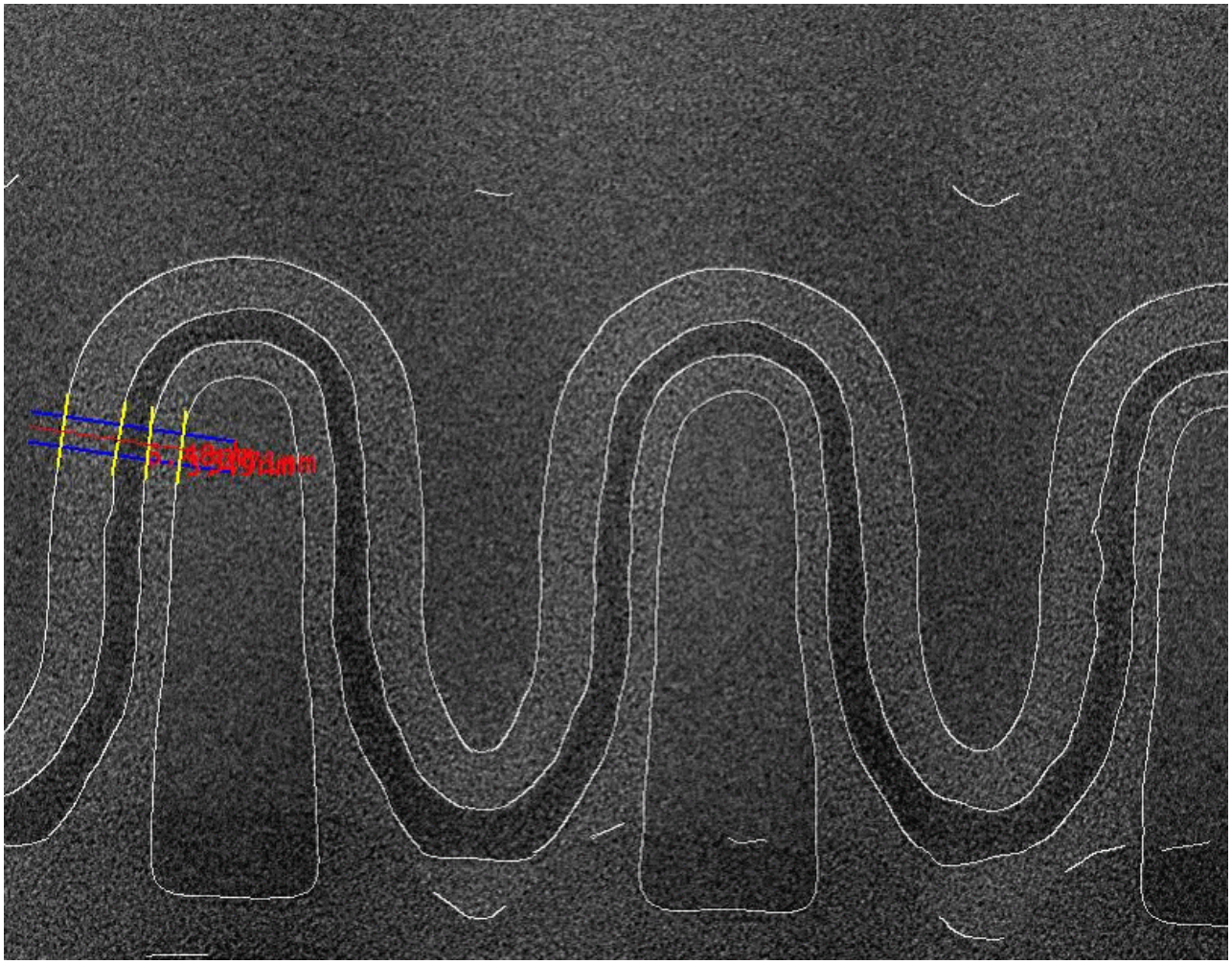
Statistics based CD measurement:

Edge lines are modeled with linear regression lines (Yellow) in localized region (blue).
This is the second step of batch automation.

Benefits:

- Averaging out statistical variation.
- Tolerance of inaccuracy of measuring line (Red) position and orientation.
- Best distance based on mathematical model.
- A certain degree of noise tolerance: “Bad” lines can be filtered out.

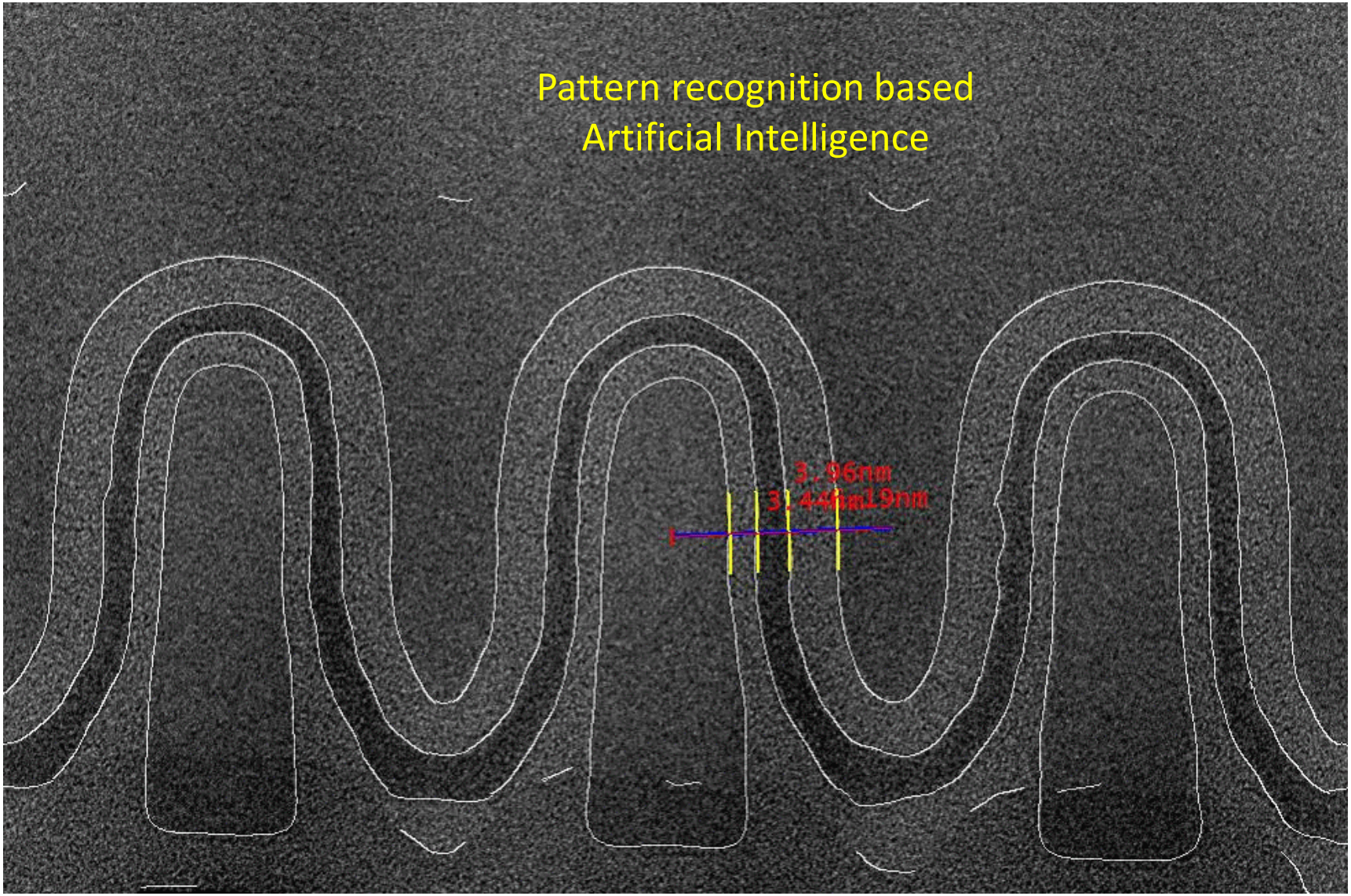
Measurement with linear regression in action



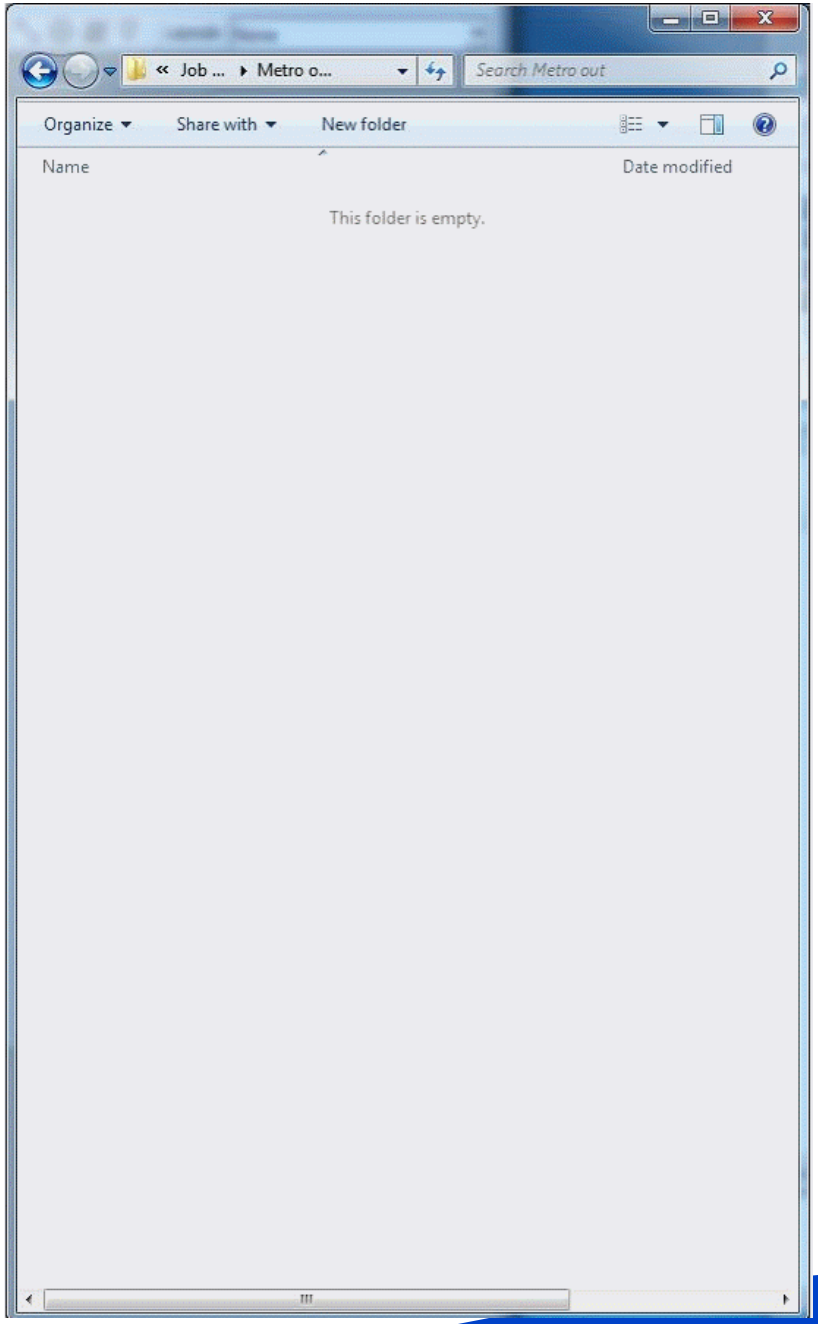
Statistics based CD measurement - demo:

- Spatial average is built in.
- Measuring line does not need to be exact perpendicular to feature.
- Image noise effect is averaged out.
- Certain noise lines are filtered out.

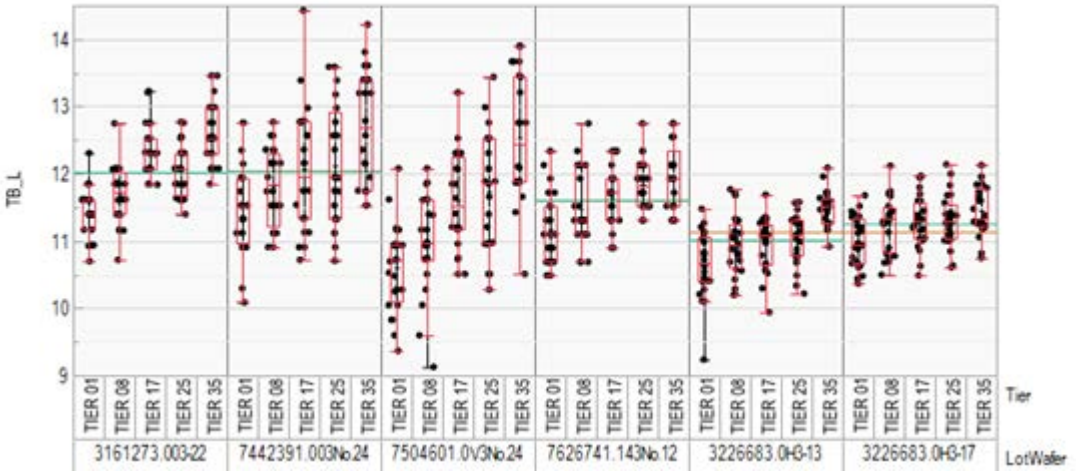
Artificial filtering

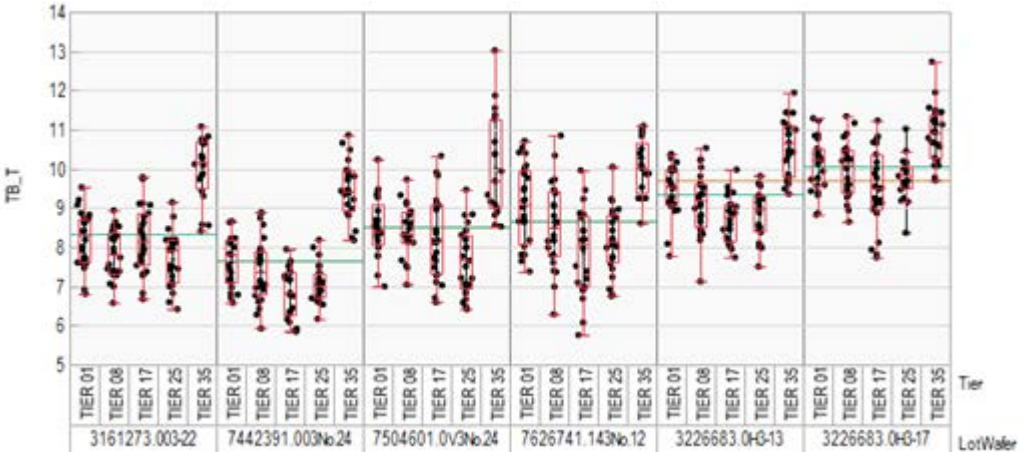


Full-auto batch process

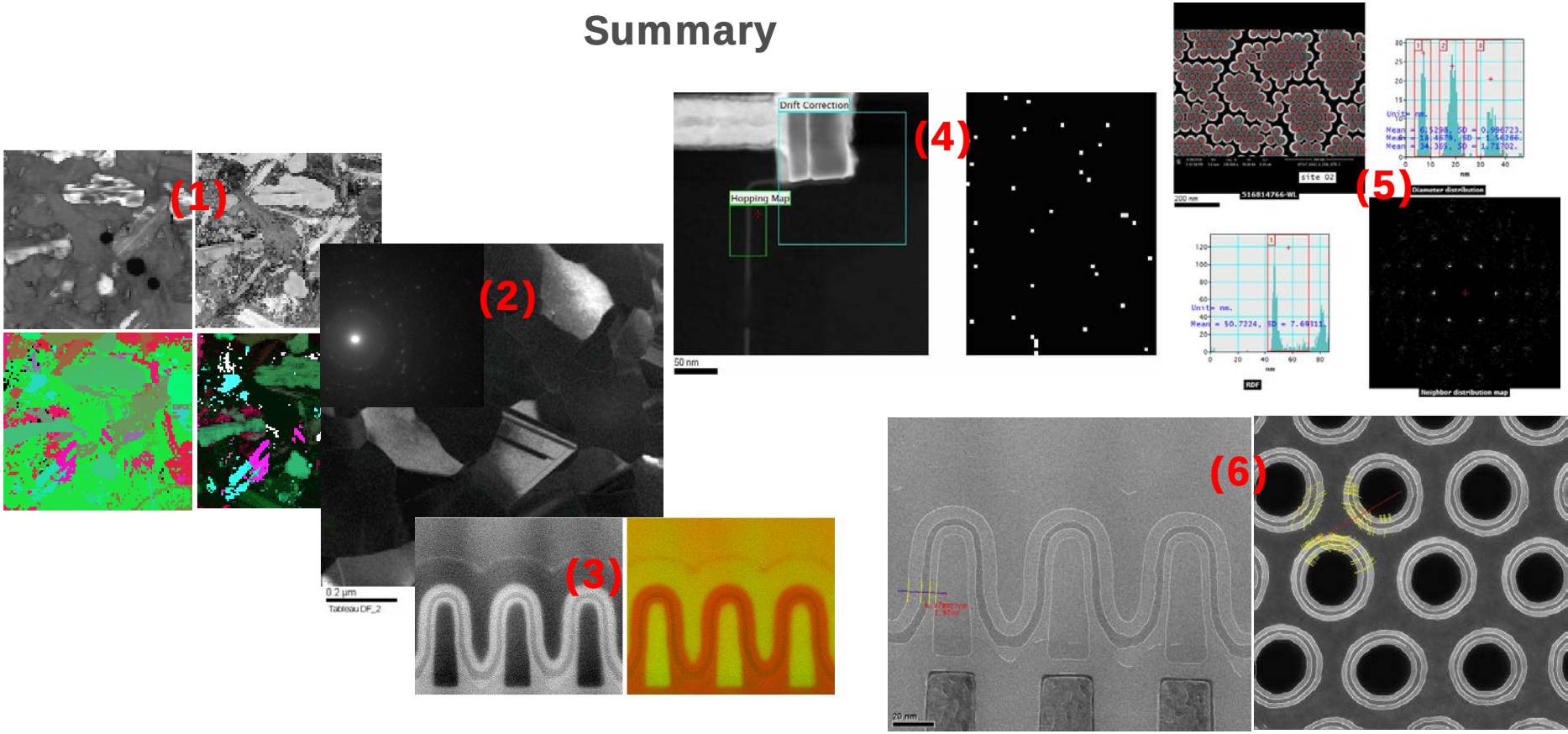


TEM images are turned into quantitative dataset bearing critical info about process control.





Summary



Acknowledgements

- Micron Technology Inc. for its support and supplying the platforms and equipments to test our and implement the applications.
- Dr. Du Li for his suggestions and supports in those projects.
- Engineers in Micron R&D for suggestions and source of initiations.
- Team members in Micron TEM lab for their suggestions and help in sample preparation and software testing.