Precession Electron Diffraction (PED): Si and Si/Ge strain analysis

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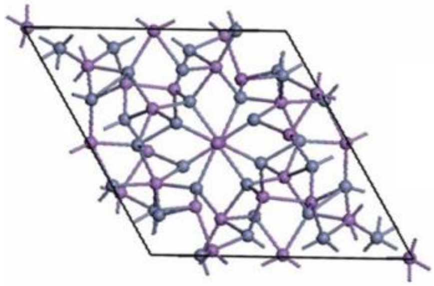
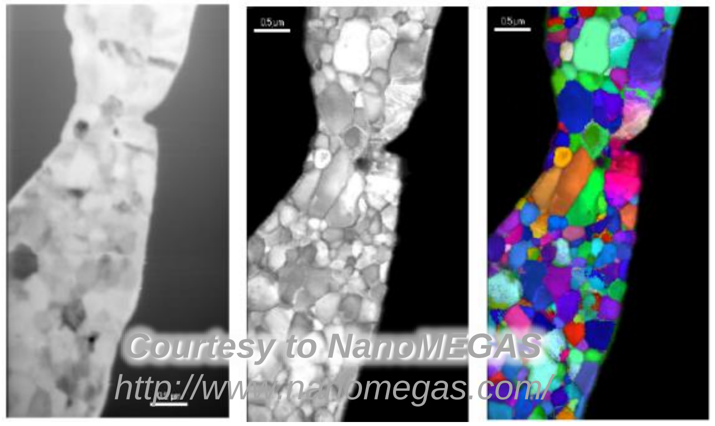
Introduction

__Precession Electron Diffraction (PED)__:
powerful technique that improve the quality of electron diffraction pattern collection in a trasmission electron microscope (TEM).

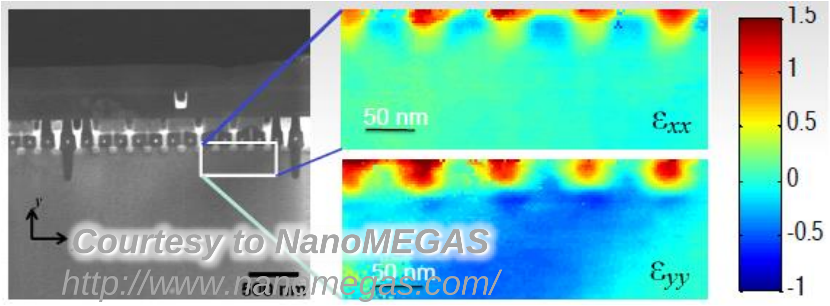


3D Diffraction Tomography

Phase & Orientation Mapping



Courtesy to NanoMEGAS
http://www.nanomegas.com/



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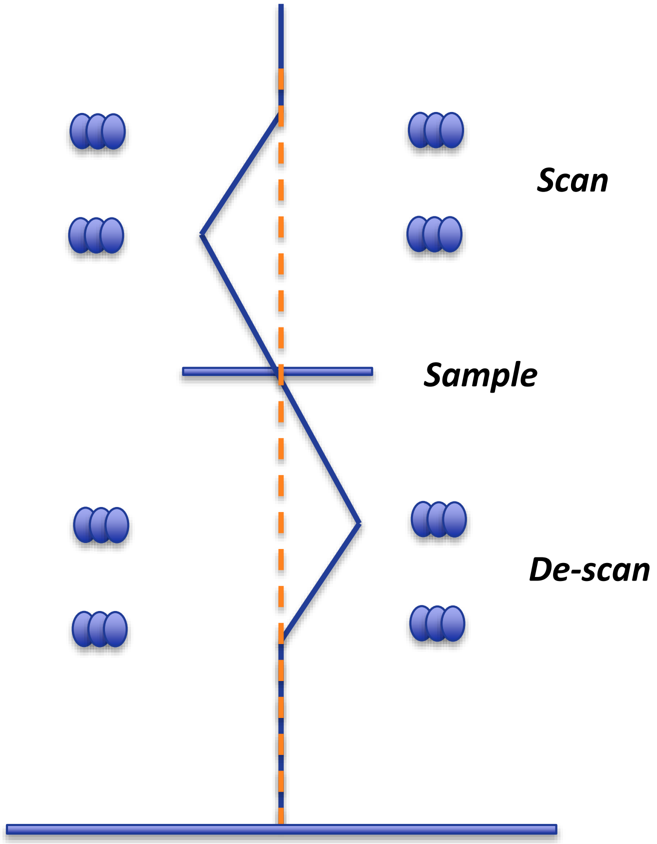
Strain Mapping

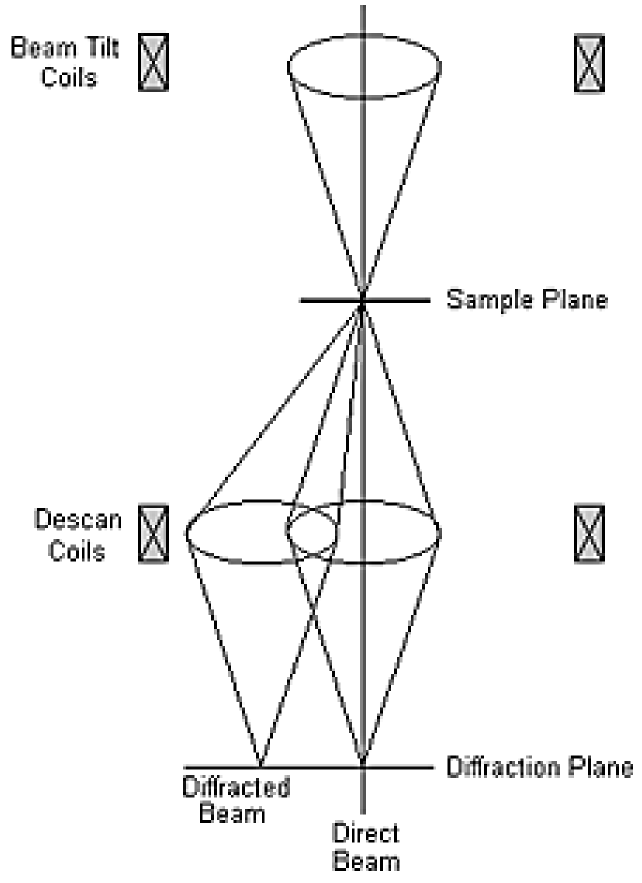
Objective:	We are evaluating if the technique (PED) gives reliable and fast data about strain in real semiconductor devices.

Overview: Geometry

In the usual configuration for ***Precession Electron Diffraction*** (***PED)***, the probe is scanned and descanned symmetrically about the sample plane located at the ***eucentric height***.

- ✓ The beam is precessed around the optic axis while the diffraction pattern is collected over multiple revolutions.
- ✓ The beam tilt coils located pre-specimen (*Scan*) are used to tilt the electron beam off of the optic axis so it is incident with the specimen at an angle, φ.



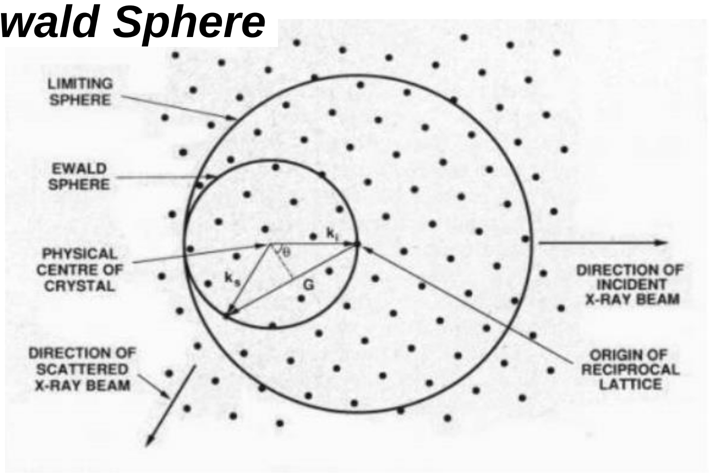


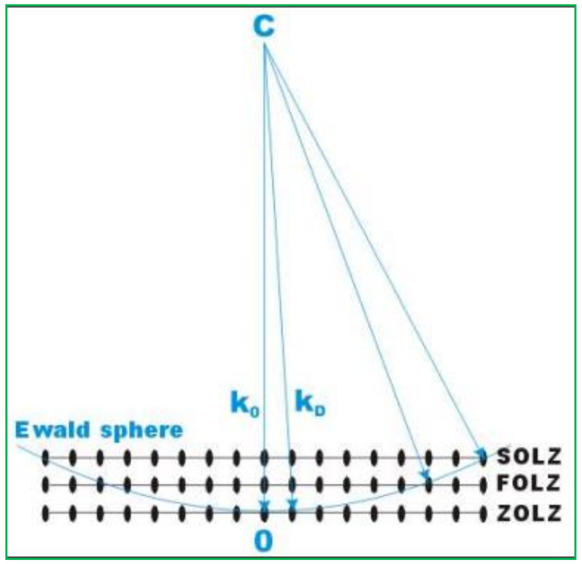
- ✓ With beam precession, Ewald sphere also precess though the reciprocal space.
- ✓ At any moment in time during precession, the diffraction pattern consists of a Laue circle with a radius equal to the precession angle, φ.

Overview: The reciprocal Lattice & Ewald sphere

- The ***Ewald Sphere*** is a sphere in the reciprocal lattice, passing through the origin of the lattice, which radius is equivalent to the incident wave vector.

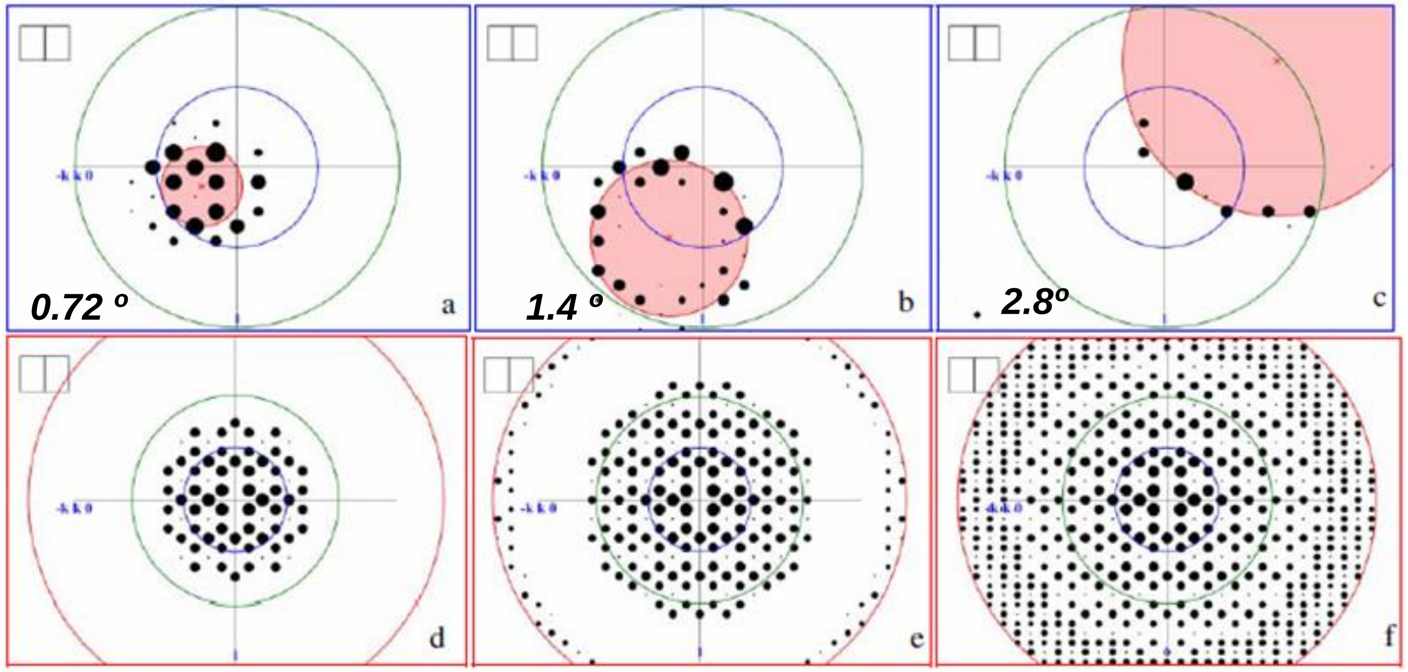
Ewald Sphere





- The reciprocal lattice planes perpendicular to the incident wave vector are the ***Laue Zones – Laue Circle***.

Sketches of PED patterns for silicon, [110] zone axis, calculated under kinematic assumptions.

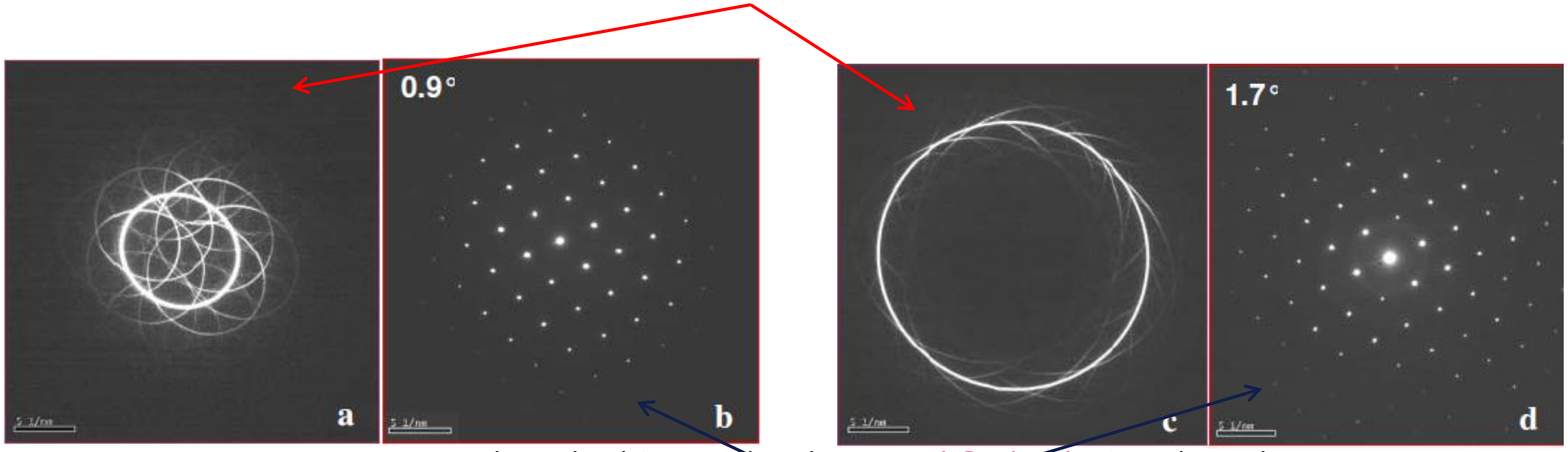


- The radius of the Laue circle is determined by the precession angle.
- It reduces nonsystematic multiple scattering effects significantly.

Peter Moeck *Portland State University*, pmoeck@pdx.edu, Sergei Rouvimov
Z. Kristallogr. 225 (2010) 110–124 / DOI 10.1524/zkri.2010.1162

Overview: The reciprocal Lattice & Ewald sphere

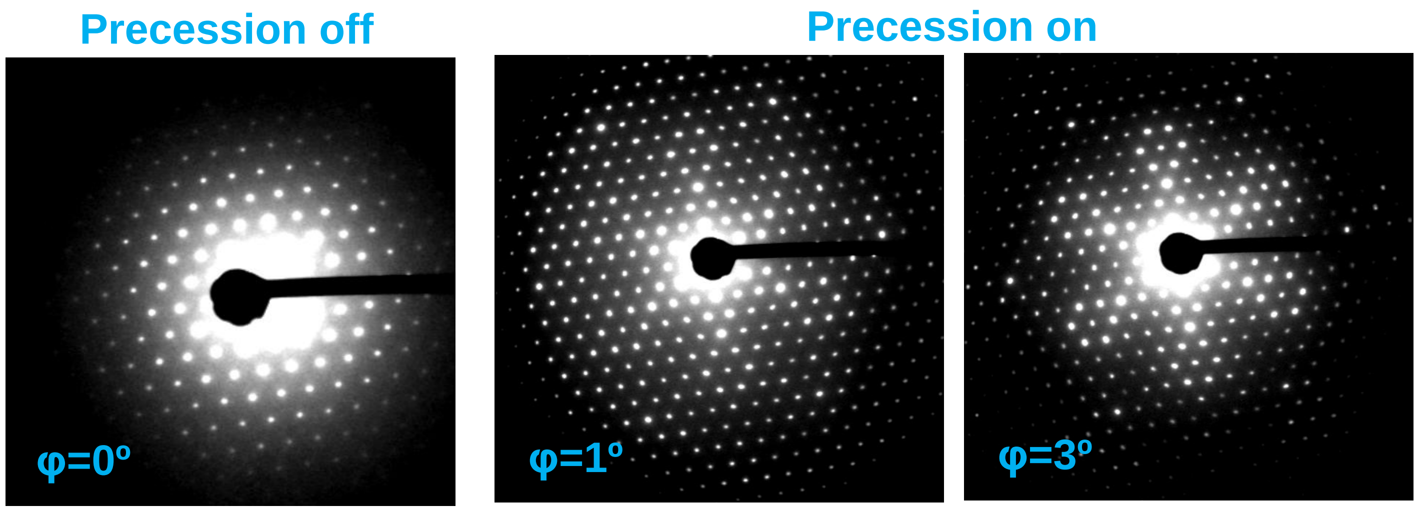
“just precessed” mode



Peter Moeck *Portland State University*, pmoeck@pdx.edu, Sergei Rouvimov

“properly de-scanned” mode so that stationary spot diffraction patterns results

Silicon crystals close to the [110] orientation



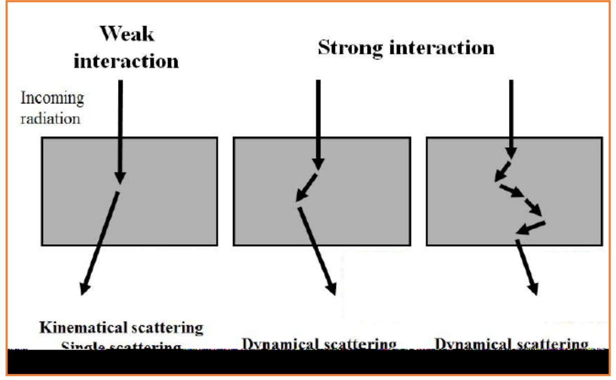
Precession off

Precession on

Courtesy to NanoMEGAS
http://www.nanomegas.com/

- TEM accelerating voltages between 100-400 kV
- Precession frequencies: from Hz to kHz.
  In standard cases 60 Hz has been used.
- Precession angle may vary from 0-3° continuously
- Spot size or beam size (1- 30 nm)
- Precession spatial resolution (1- 10 nm)

Advantage & Practical Considerations



Quasi-Kinematical Diffraction Patterns:

The scan/de-scan procedure (off-axis beam inclination) minimize the dynamical effects because less beams are simultaneously excited.

Broader Range of Measured Reflections:

After integration over multiple precessions, many more reflections in the ZOLZ and in high-order Laue zone (HOLZs) are present.

It can provide more complete information about the three-dimensional nature of reciprocal space.

Single crystal Si - FIB prepared Sample

Position 1 20 nm from Position 1

Practical Robustness:

There is no need for perfect zone orientation during recording of precession pattern.

Since the measurement is an average over many incident beam directions, the pattern is less sensitive to slight misorientation of the zone axis from the optic axis of the microscope.

The patterns obtained are also less sensitive to the thickness of the sample, a parameter with strong influence in standard electron diffraction patterns.

Very Small Probe Size:

Electrons can be used to probe much smaller nano-crystals in a TEM.

Historical Development

- ➢ The first precession electron diffraction system was developed by *Vincent and Midgley in Bristol, UK in 1994*.
- ➢ Over the next ten years, a number of university groups developed their own precession systems and verified the technique by solving complex crystal structures.
- ➢ *In 2004, NanoMEGAS* developed the first commercial procession system capable of being retrofit to any modern TEM. Software methods have also been developed to achieve the necessary scanning and descanning using the built-in electronics of the TEM.

Application: STRAIN mapping

Strain measurement applications in semiconductor and material science require spatial resolution and high precision.

Limitation of Existing TEM Strain Measurement Methods

Technique	Advantage	Limitations
CBED Convergent beam electron diffraction	High spatial, strain sensitivity	Sample thickness >150 nm Sample oriented away from a low index axis Very sensitive to strain relaxation
Dark field holography	High spatial resolution (5nm), large field of view (1umx1um)	Required reference unstrained and with identical crystallographic orientation area closed to strained region
High resolution imaging	High spatial resolution (1nm)	Limited field of view Stringent requirements on specimen quality Dynamical diffraction

- Desired spatial resolution ~ 1 nm
- Strain sensitivity << 0.1%
- Highly automated

Application: STRAIN mapping

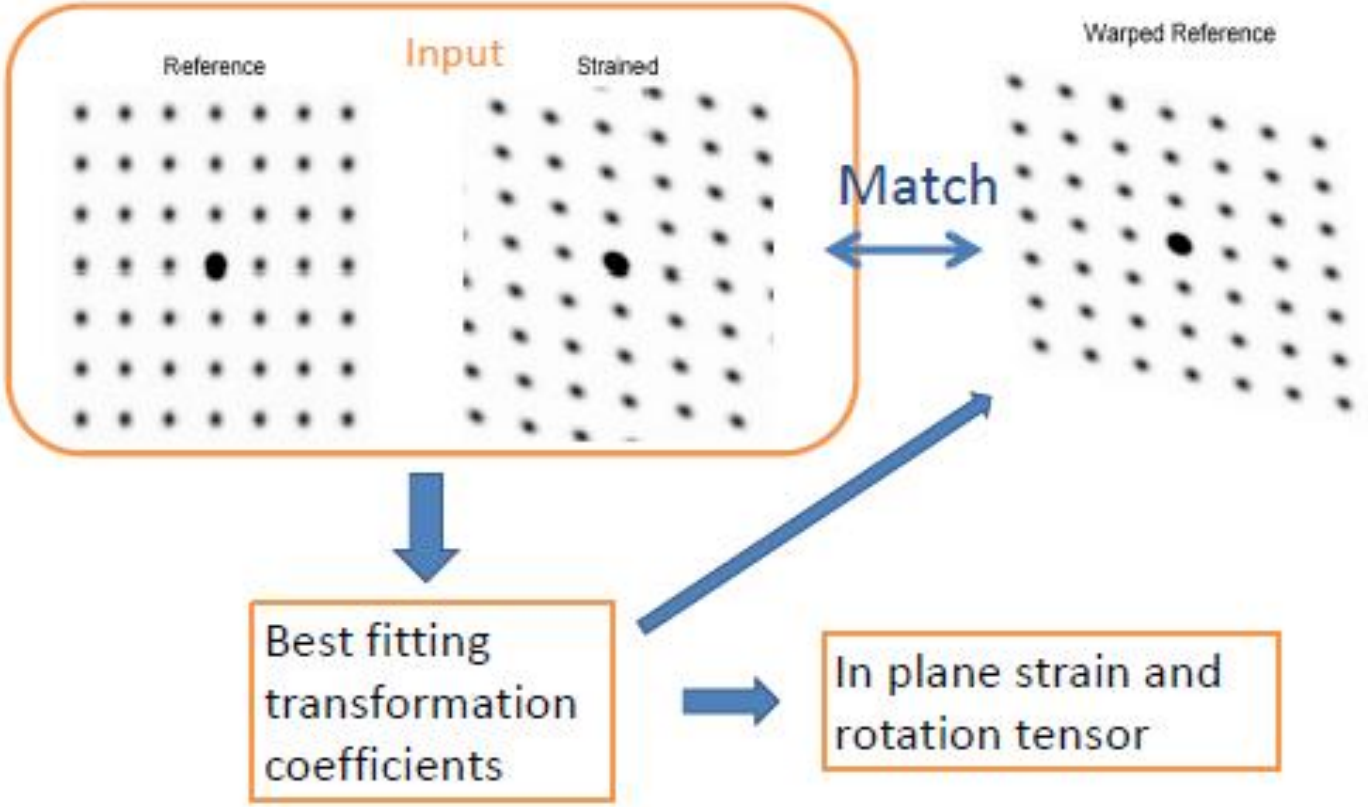
Strain - determined by measuring shift spot position.

Acquisition - Reference pattern from unstrained region.

Diffraction patterns from strained region are matched against a reference pattern.

Correlation distance - used as the metric for fitting reference to strained patterns.

Results include strain in *x and y-directions.*

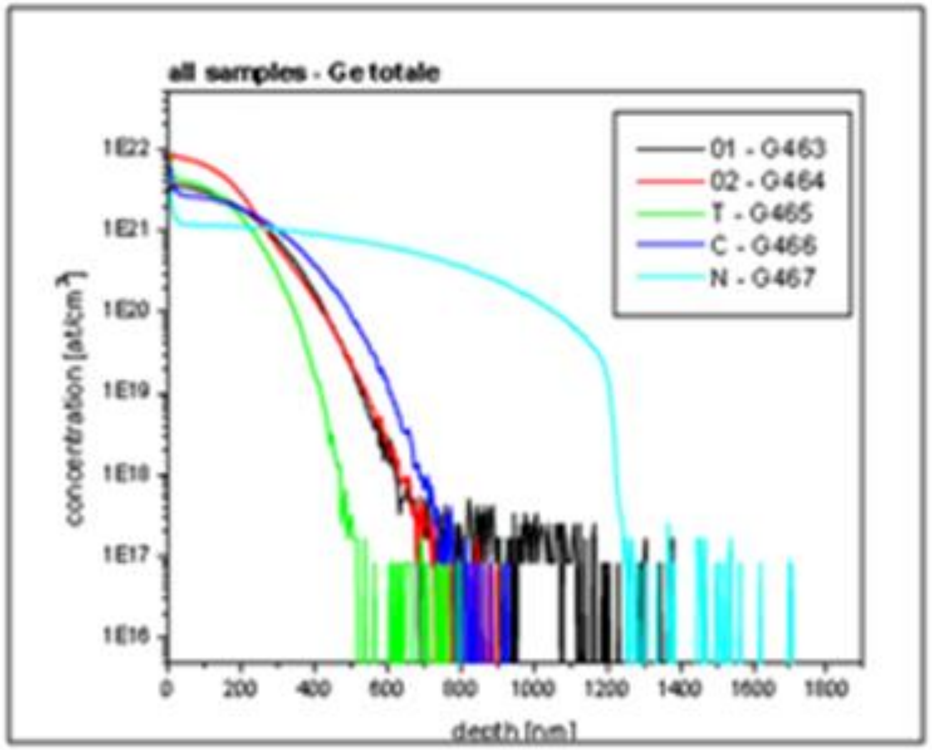


Best fitting transformation coefficients

In plane strain and rotation tensor

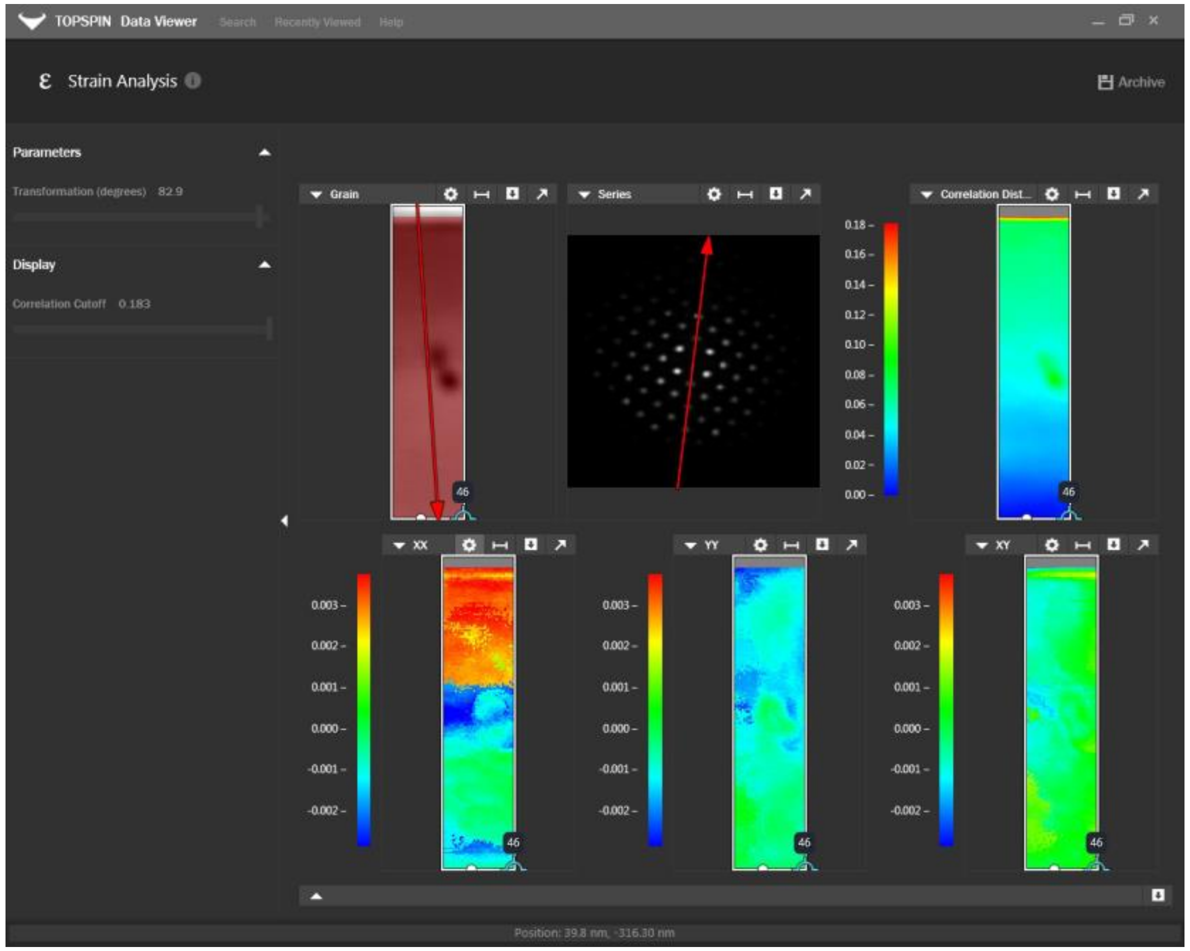
Strain mapping in Silicon sample with Germanium Implanted

Implanted Germanium in Silicon and thermal treatment to homogenize implantation profile of some 5%. (SIMS profile - C sample)



Lamella FIB preparation: Cross sectioned specimen of 60nm thick.

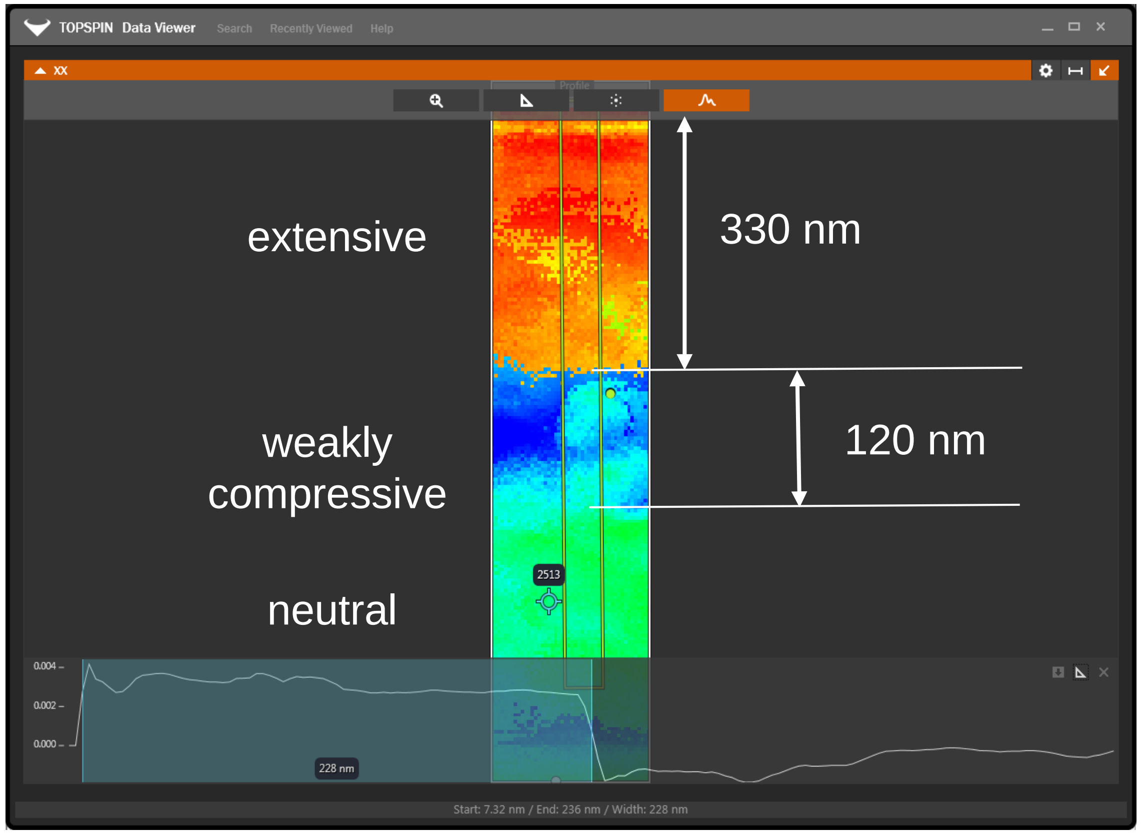
Analysed depth from the top of the sample: 570 nm



Transformation (degrees) 82.9

Correlation Cutoff 0.183

Position: 39.8 nm, -316.30 nm

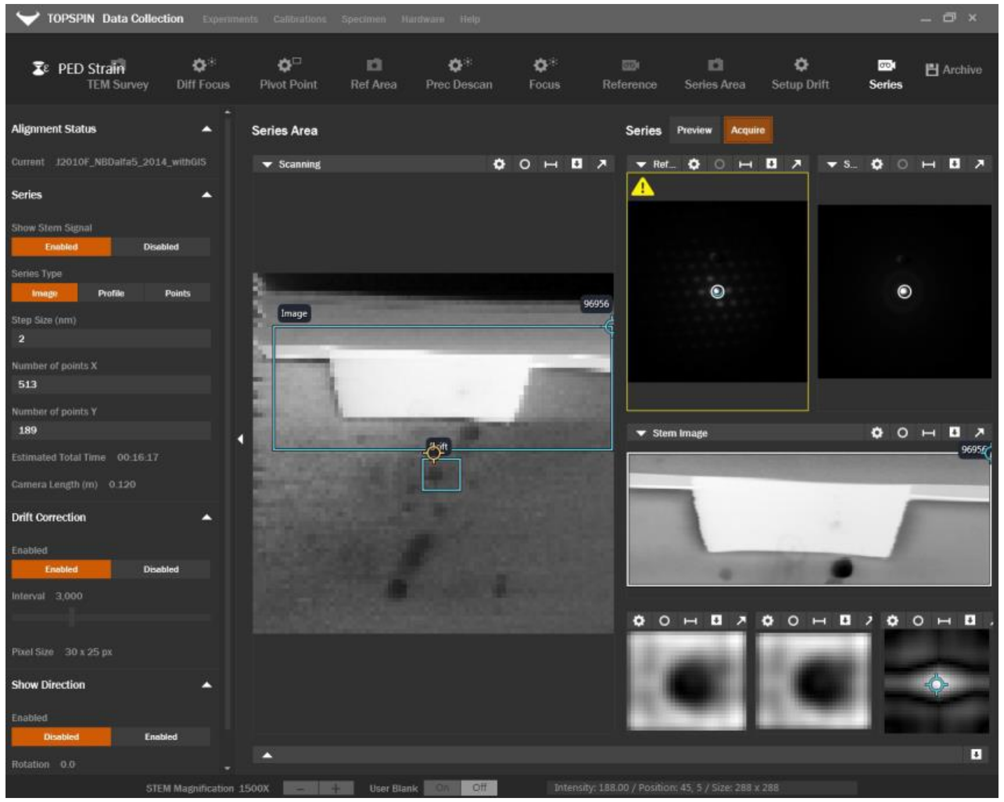


Start: 7.32 nm / End: 236 nm / Width: 228 nm

Corresponding strain value of 0.4% in 300nm thick SiGe layer along XX direction, i.e. <001>.

Data acquisition and elaboration Dr Joaquim Portillo from CciT_UB February, 20th 2016

Si- Nit (Super Low Power)



Alignment Status
Current J2010F_NBDalfa5_2014_withGIS

Series
Show Stem Signal: Enabled
Series Type: Image
Step Size (nm) 2
Number of points X 513
Number of points Y 189
Estimated Total Time 00:16:17
Camera Length (m) 0.120

Drift Correction
Enabled: Enabled
Interval 3,000
Pixel Size 30 x 25 px

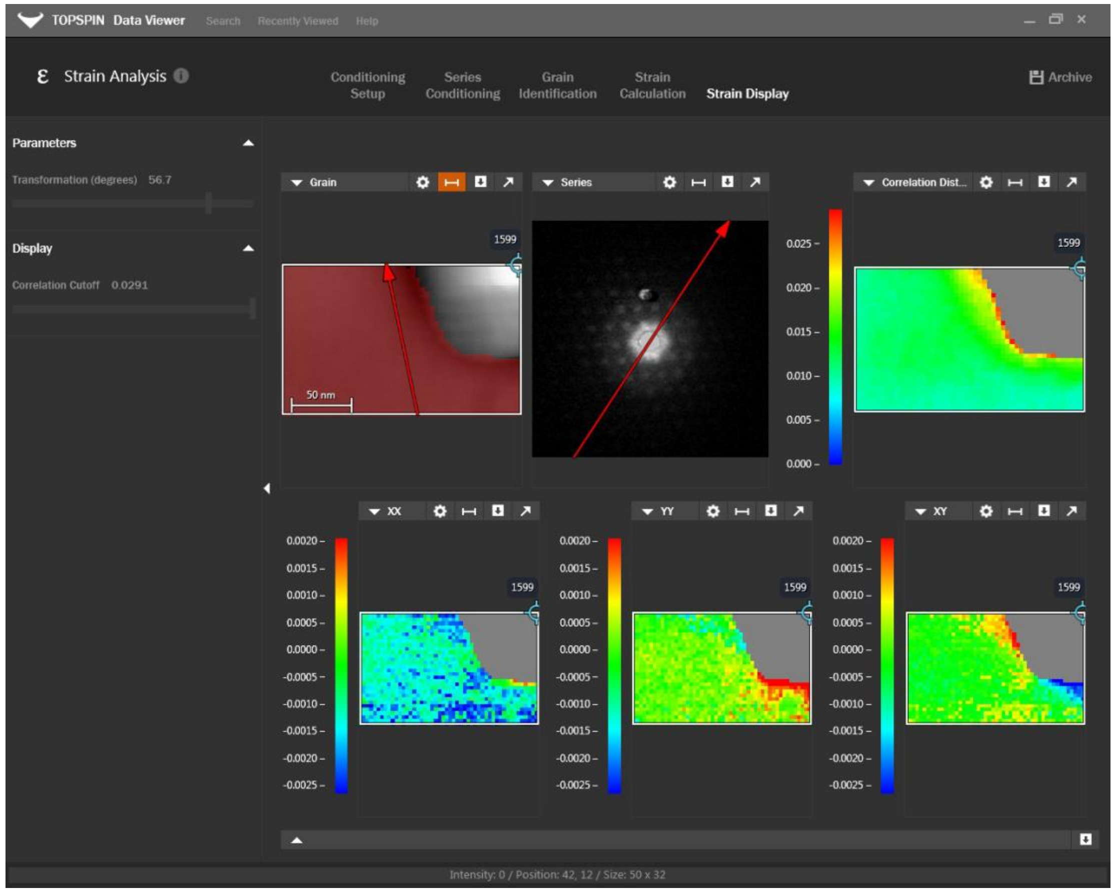
Show Direction
Enabled: Disabled
Rotation 0.0

STEM Magnification 1500X

Intensity: 188.00 / Position: 45, 5 / Size: 288 x 288

Lamella FIB preparation: Cross sectioned specimen of 120nm thick. Regular thickness until 1um in depth from the top.

Cross sectioned device with insulation trenches.

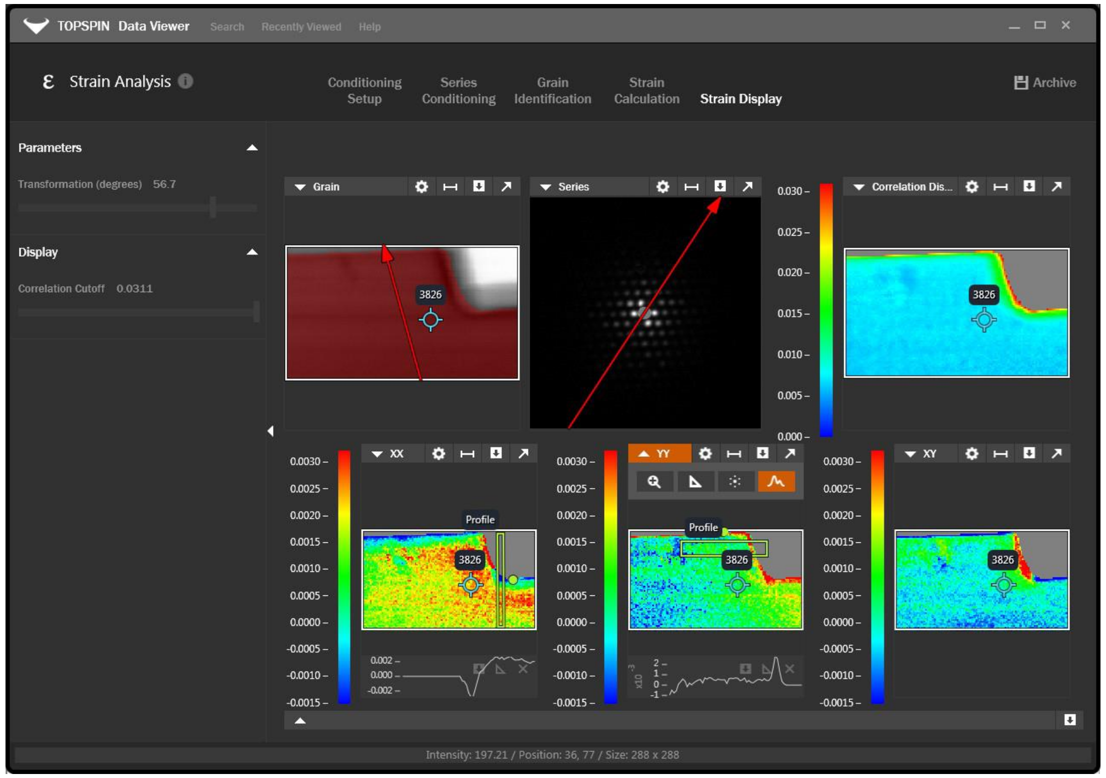


Parameters
Transformation (degrees) 56.7

Display
Correlation Cutoff 0.0291

Intensity: 0 / Position: 42, 12 / Size: 50 x 32

Strain is only seen in value less of 0.3% and not symmetrically on both sides of the insulating trench.



Parameters
Transformation (degrees) 56.7

Display
Correlation Cutoff 0.0311

Intensity: 197.21 / Position: 36, 77 / Size: 288 x 288

Data acquisition and elaboration Dr Joaquim Portillo from CciT_UB February, 20th 2016

Conclusion

- Generally measurement of strain with high spatial resolution and high precision in semiconductor devices is critical.

- PED Technique is made possible by beam precession that improves quality of diffraction patterns to maintain small probe size.

- Strain mapping with PED showed good results for Silicon sampled with Germanium implanted.

- For future development it is interesting to understand the lower limits of sensitivity for strain measurement with PED - compare with data from strain simulation.

References

http://www.nanomegas.com/

Precession Electron Diffraction in theTransmission Electron Microscope: electron crystallography and orientational mapping
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Precession Electron Diffraction Applications in TEM: From Structure Determination To Orientation Imaging and Strain Mapping

Thanos Galanis *Application Specialist*