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Stress State Determination in Nanoelectronic Silicon Devices Coupling COMSOL Multiphysics and a Recursive Dynamical CBED Pattern Simulation

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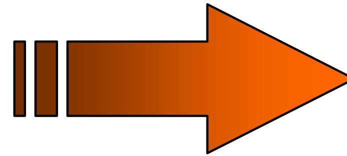
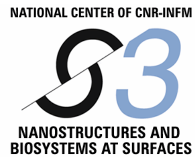
Affiliations





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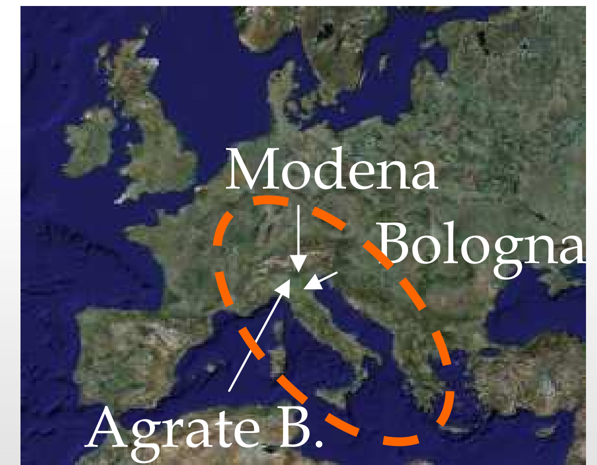

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Outlines

- Introduction on stress
- Experimental part
  - CBED/TEM: a powerful strain measurements tool
- Simulation:
  - Dynamical split HOLZ pattern simulation
  - our recursive method
- An example of application: COMSOL+CBED
- Check by a different technique: COMSOL+LACBED
- Conclusions

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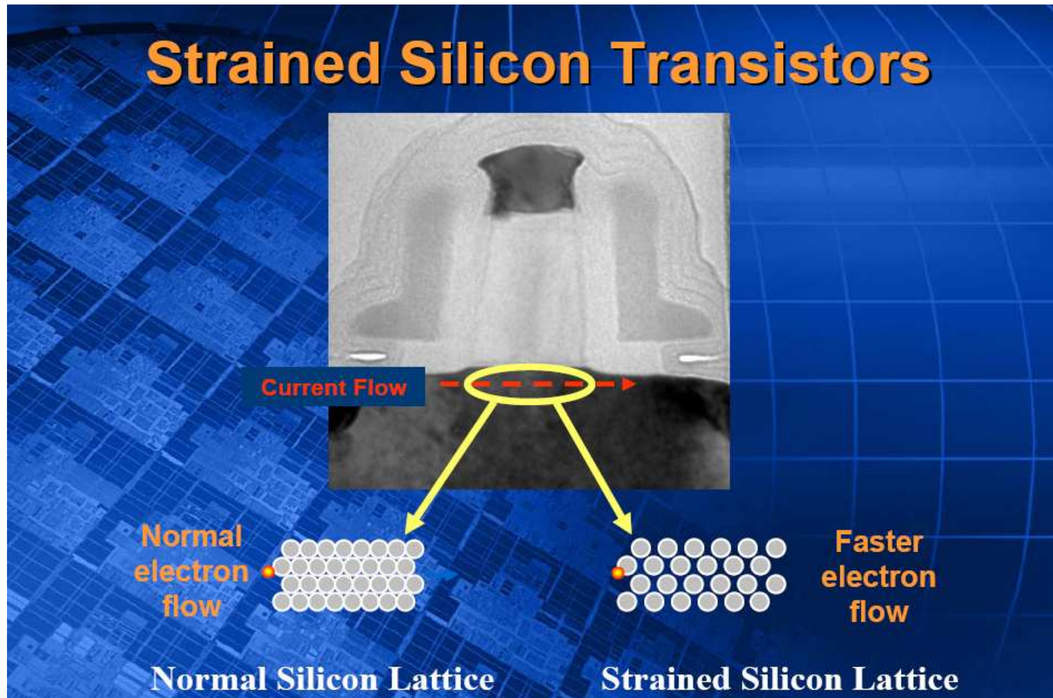
Strain: a way to improve the performance of electronic devices



(*)

Examples of Strained-silicon technology applications:

- Extension of the performance of semiconductor transistors

- Power savings benefit

- Reduced device heat generation

We need methods to map strain at a nanoscale resolution (in order to use it!)

(*) Intel site

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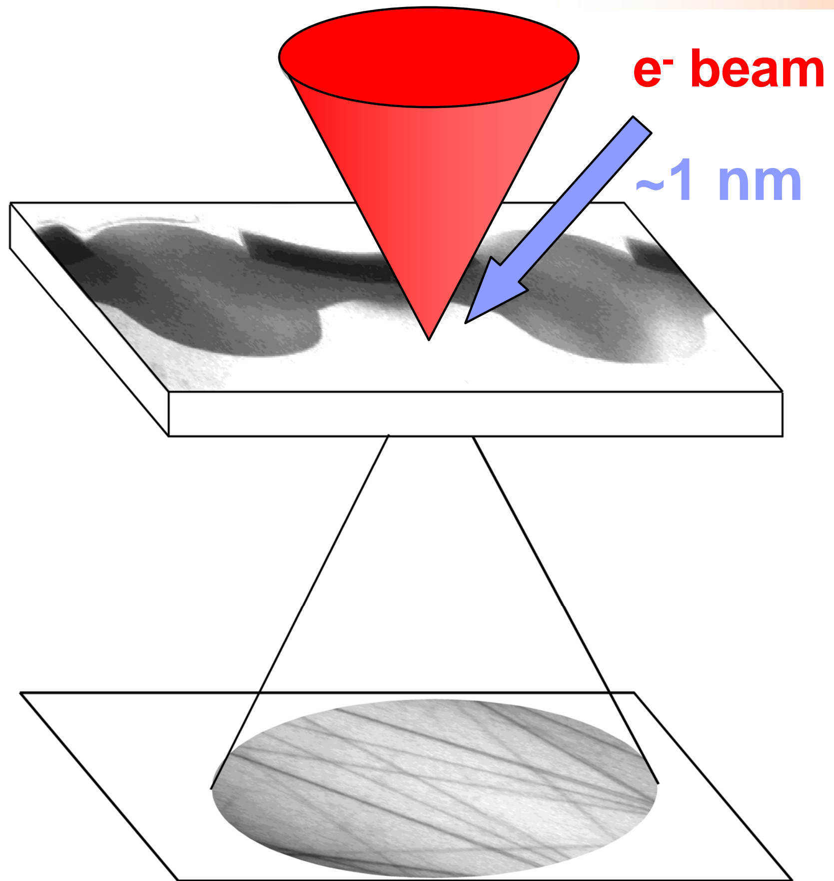
CBED/TEM technique

TEM Convergent electron beam

sample

CBED pattern



Central disk (transmitted beam)

Zero Order Laue Zones (ZOLZ)		charge distribution
High Order Laue Zones (HOLZ)		Static disorder & lattice displacement

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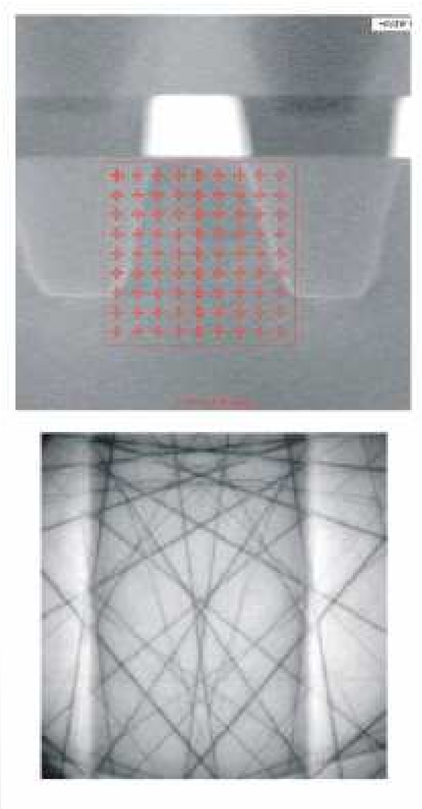
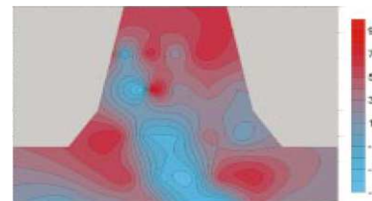
CBED: a powerful tool for strain analysis

STATE OF THE ART: set of patterns analysis



2D strain maps



Determination of the strain tensor in the silicon active regions of deep sub-micron devices with:

- Automatic procedure (no deformation model required)
- very high spatial resolution
- good sensitivity

(*) Armigliato A, Balboni R, Frabboni S, 2005 *Appl. Phys. Lett.* **86**, 63508

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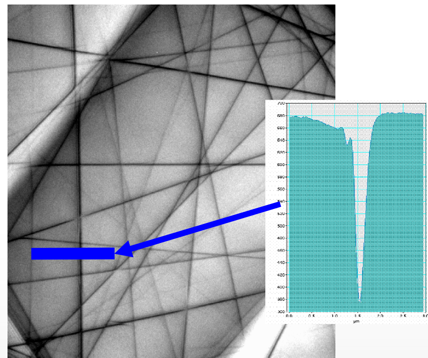
The problem of HOLZ line splitting

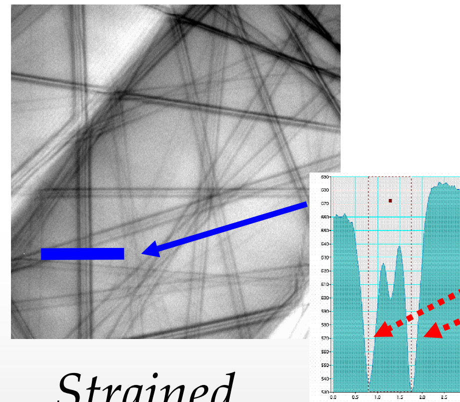
Large strain ***gradients*** **in the electron direction**

Local ***bending*** of the lattice planes

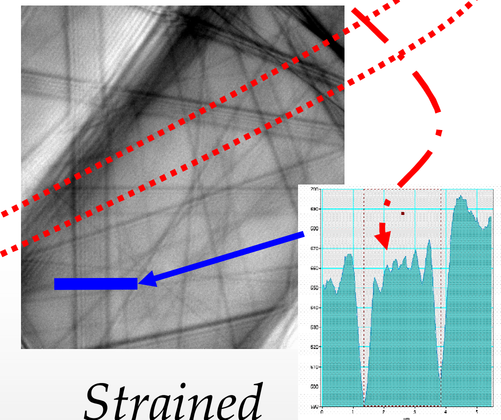
1) the HOLZ lines are *SPLIT* in two components
2) *INTERMEDIATE FRINGES* can be observed



Undeformed silicon *HOLZ profile*



Strained silicon *HOLZ profile*



Strained silicon *HOLZ profile*

New methods are required

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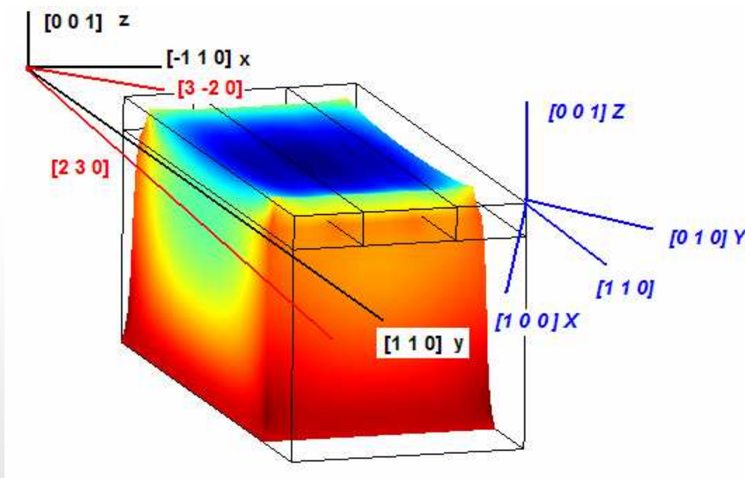
Split HOLZ pattern recursive simulation (1)

1) Parametrized Displacement Field Modelization (from an Analytical Model or Finite Element Method)

FE model

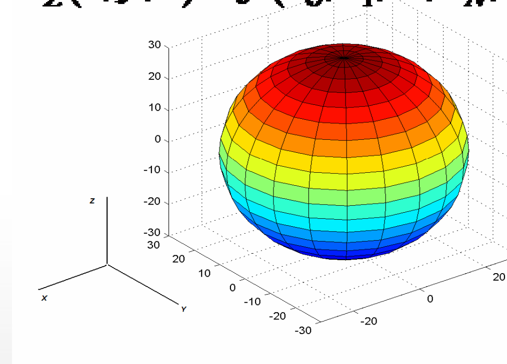


e.g.: Pseudo-thermal relaxation

[example: $(Si_xGe_{1-x}$ / Si)]

Analytical model

$$R_Z(x,y,z) = f(n_0, n_1, ..., n_N, x, y, z)$$



e.g.: Radial deformation

[example: spherical coherent precipitate]

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Split HOLZ pattern recursive simulation (2)

2) Dynamical simulations (column approximation)

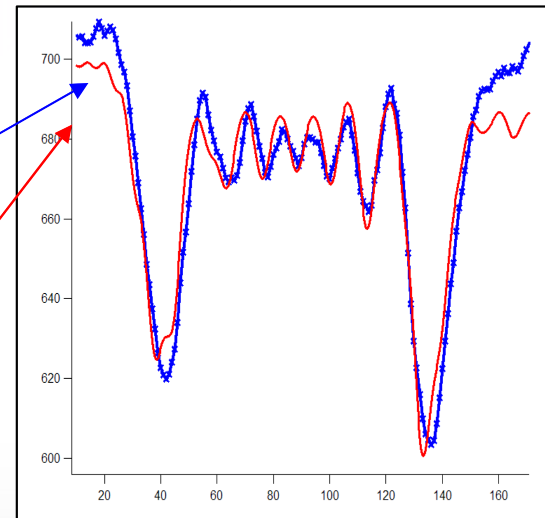
$$\Psi(z)=\prod_{k=1}^{s}[\mathbf{Q}_k\mathbf{P}_k(Z_k)\mathbf{C}_k\gamma_k(t_k)\mathbf{C}_k^{-1}\mathbf{P}_k(-Z_{k-1})\mathbf{Q}_k^{-1}]\cdot\Psi(0) \qquad (*)$$

Displacement

3) Comparison between experimental & simulation pattern (multiple line scan or 2D cross- correlation)

$$\chi^2=\frac{1}{N-f-1}\cdot\sum_{i=1}^{N}\frac{\left(I_i^{(exp)}-cI_i^{(theo)}-I^{(bgr)}\right)}{\sigma_i^2}$$

Exp. (Blu) vs Sim. (Red)
HOLZ Line Profile



4) Best Fit (minimization of χ^2 with iterative simulation)

(*) *Peng & Whelan Many-Beams Matrix Formulation: L.M. Peng and M.J. Whelan, Proc.Roy.Soc. London A* ***431****, 111 (1990)*

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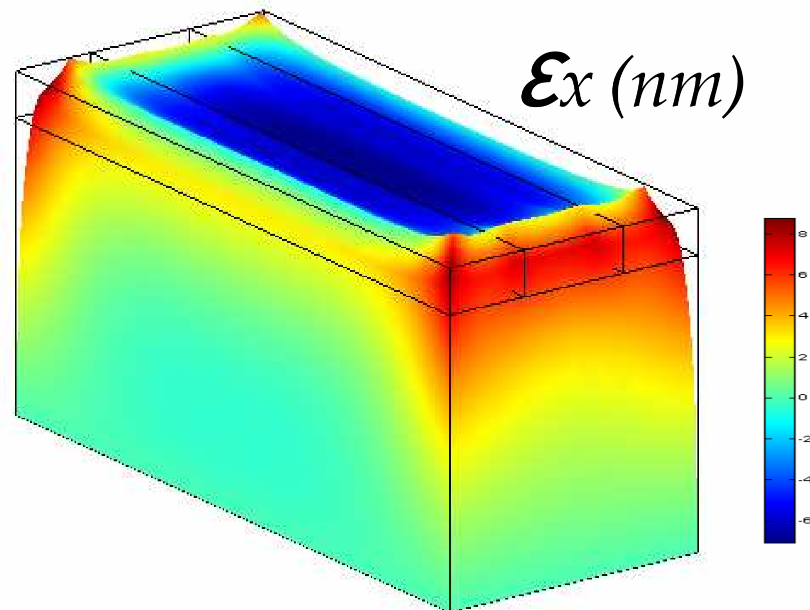
Split HOLZ pattern recursive simulation (3)

DISPLACEMENT FIELD RECONSTRUCTION along z in the (x_i,y_i) surface point

SAMPLING THE DISPLACEMENT FIELD AT DIFFERENT (X_i,Y_i) POSITIONS



STRAIN FIELD MAP

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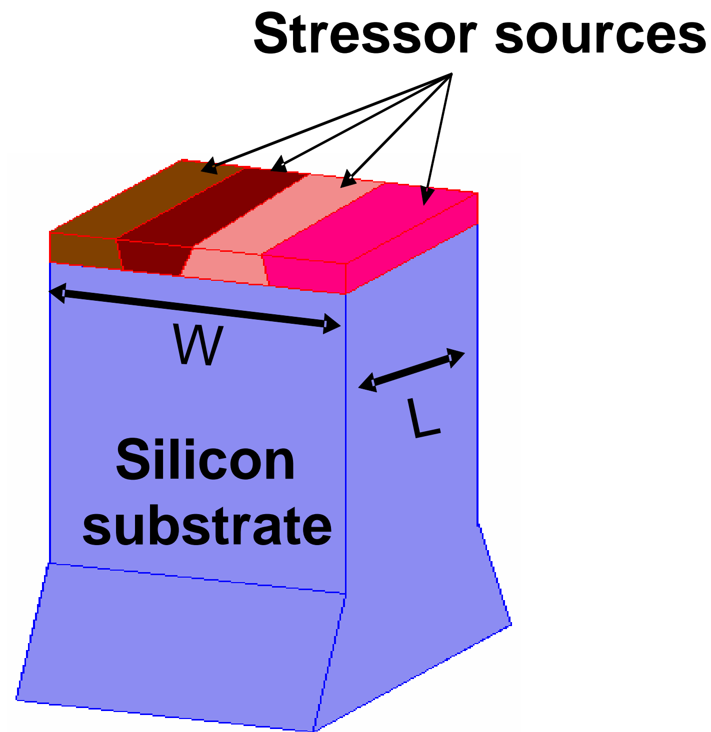
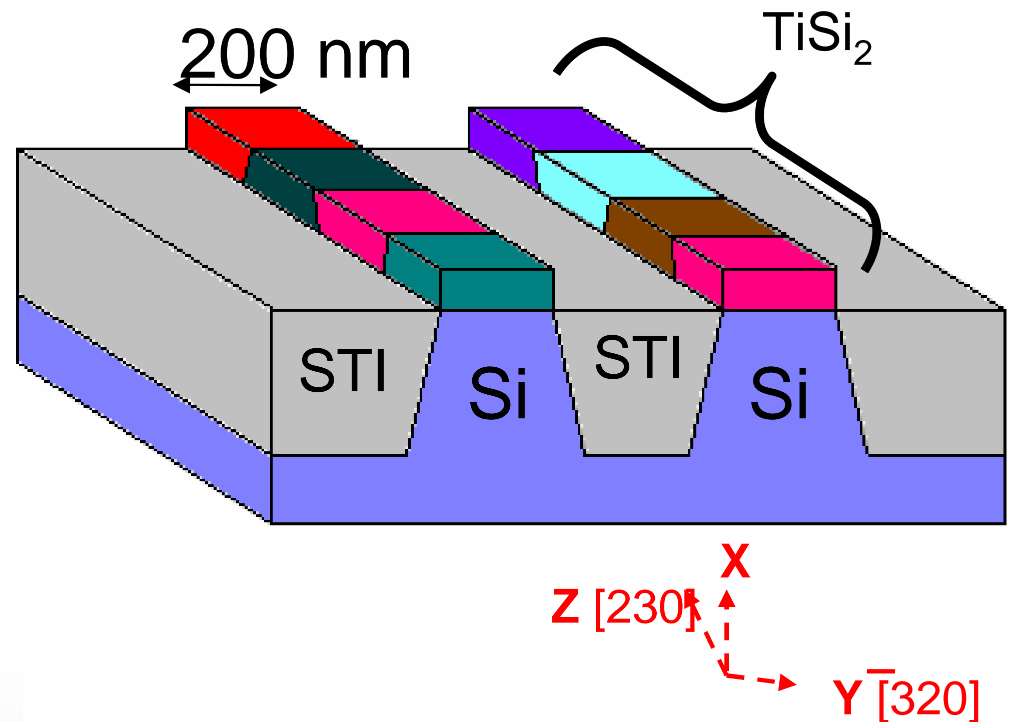
CASE STUDY





$TiSi_2$ self-aligned silicides ("salicide") overlayers onto the 200 nm wide active silicon areas of STI (Shallow Trench Isolation) structures

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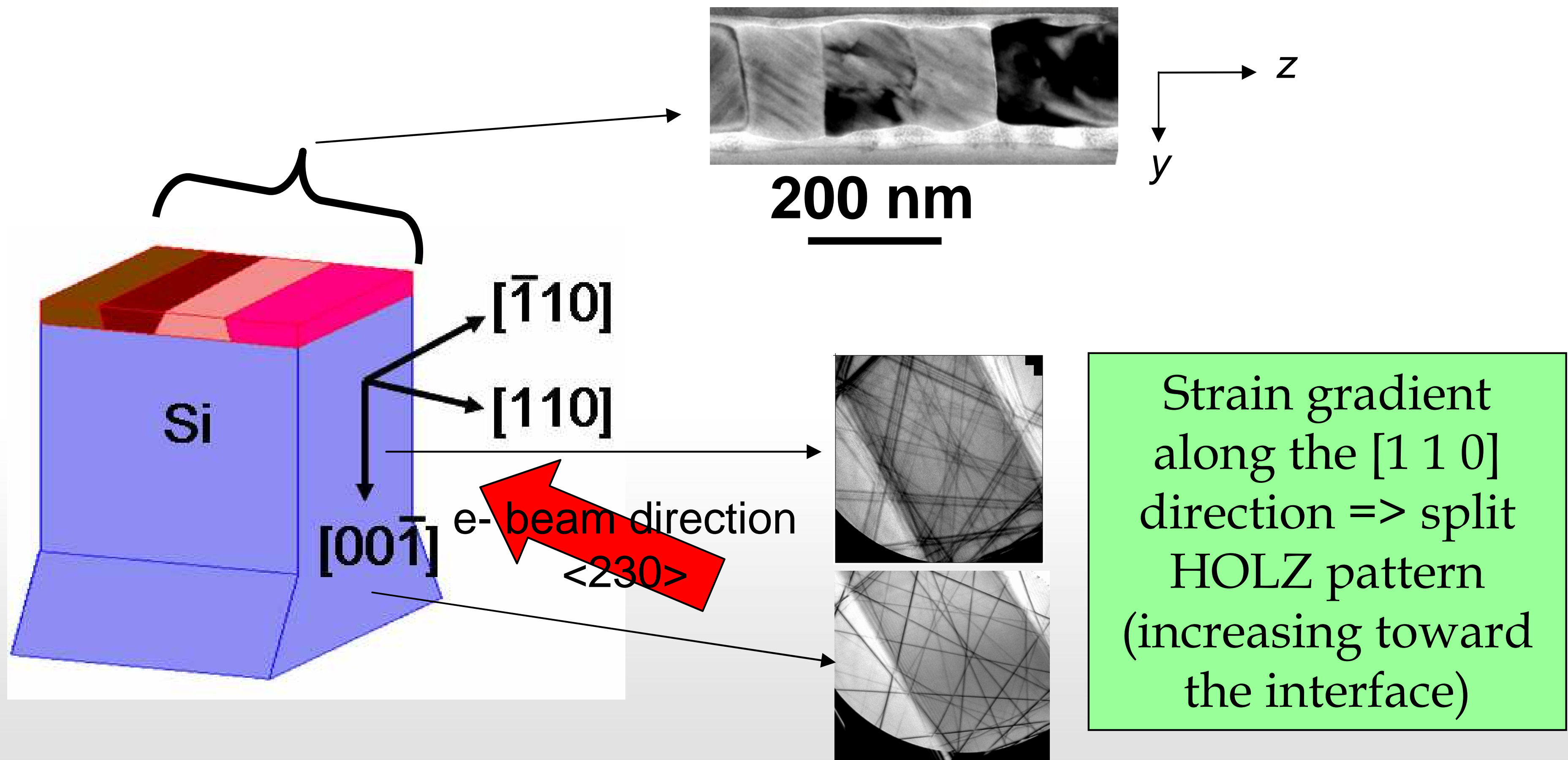
Experimental Details

Bamboo-like distribution of grain boundaries (grain size: ~100 nm)



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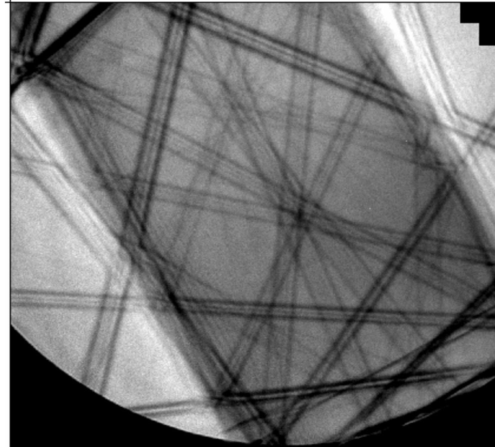
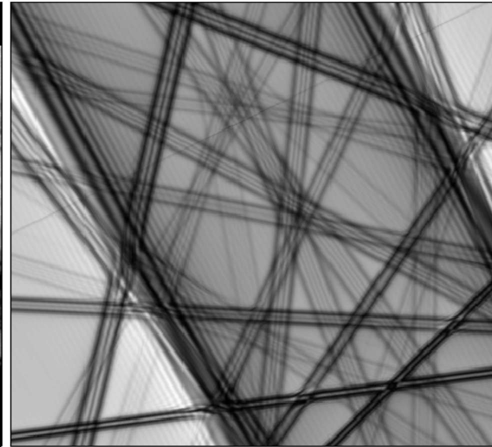
Results: Example of strained pattern simulations

Z = 150 nm



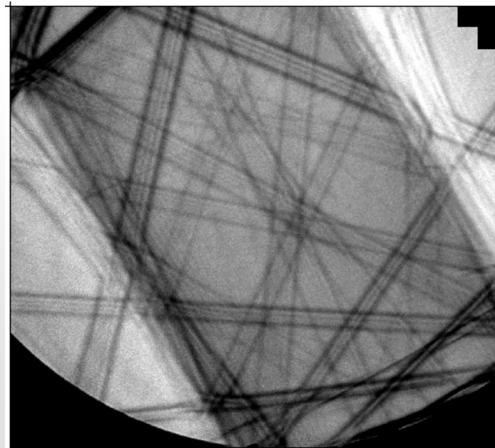
Exp



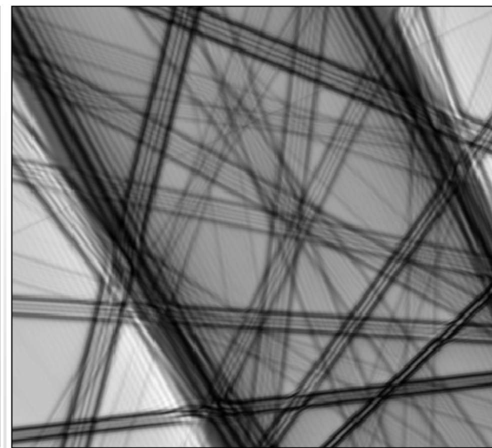
Sim

Matching

Z = 110 nm



Exp



Sim

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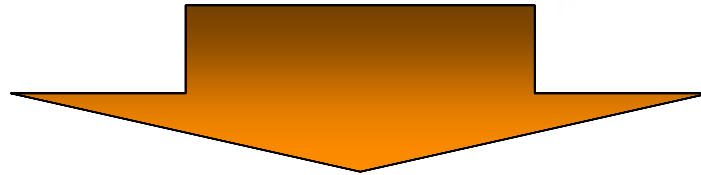
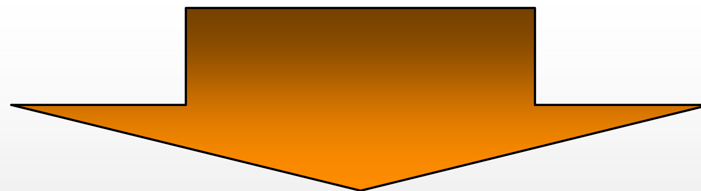
Results: Discrimination between different deformation models (I)

Best fit deformation model in a CBED pattern



Test of the model in a sequence of CBED patterns



Discrimination between various models

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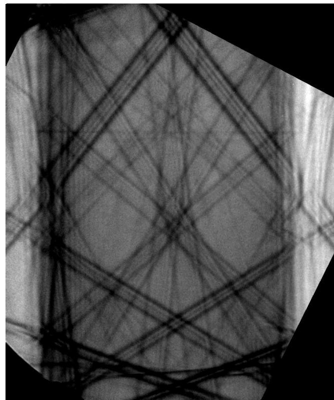
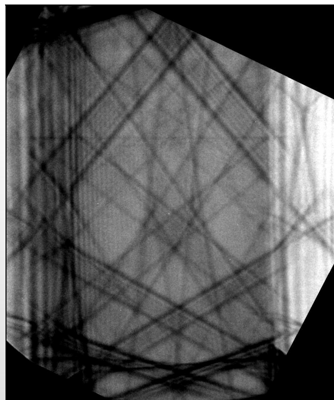
Results: Discrimination between different deformation models (II)

Exp.

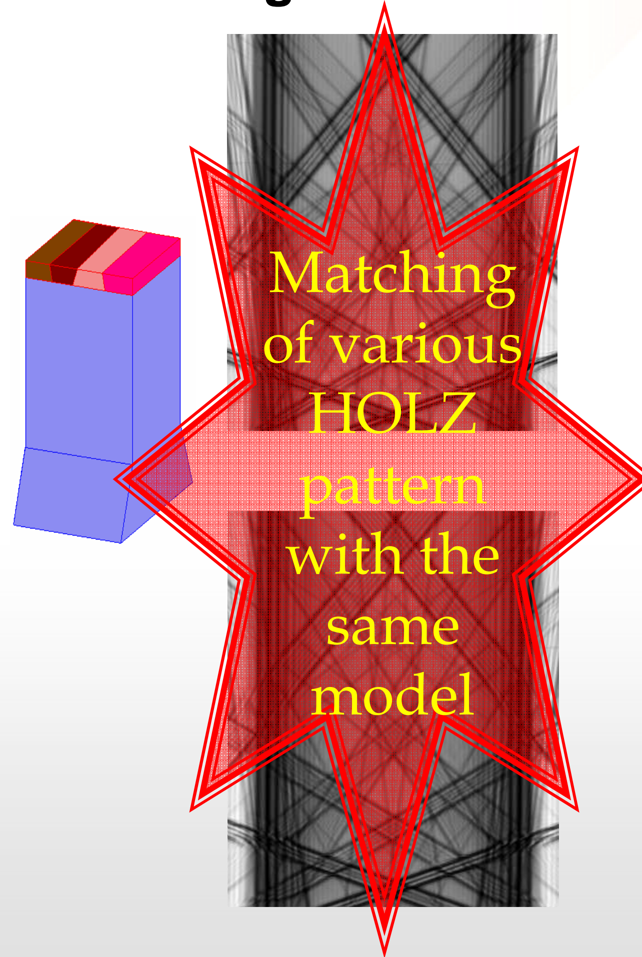
x = 110 nm



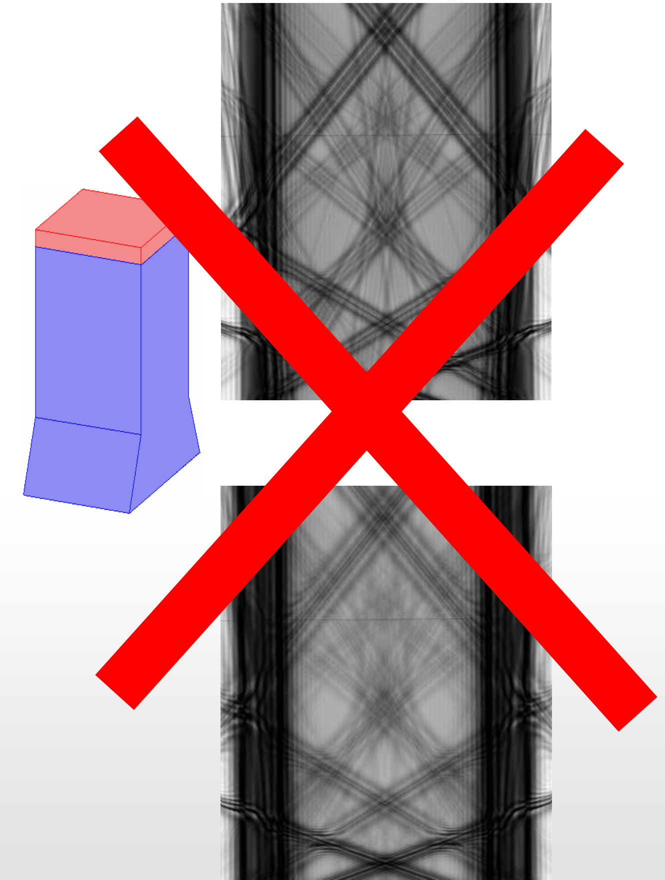
x = 70 nm



Inhomogeneous Model



Homogeneous Model



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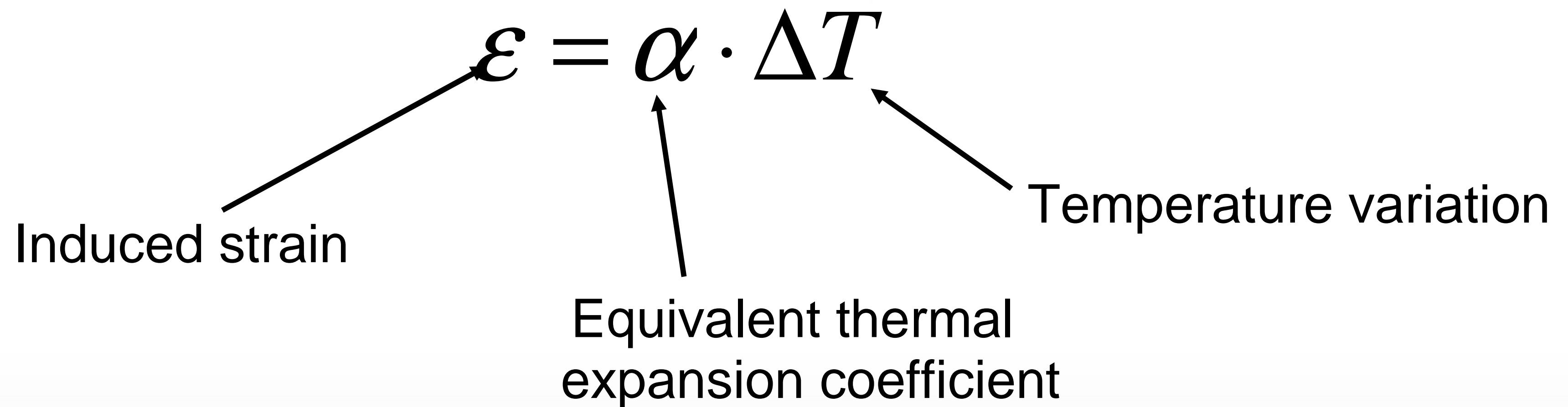
FEA Theory:

- Deformation calculated with a pseudo thermal relaxation
  - Assumption of lattice mismatch between lattice and stressor sources



- Large displacement taken into account
- Extrusion of the 2D deformation into 3D model

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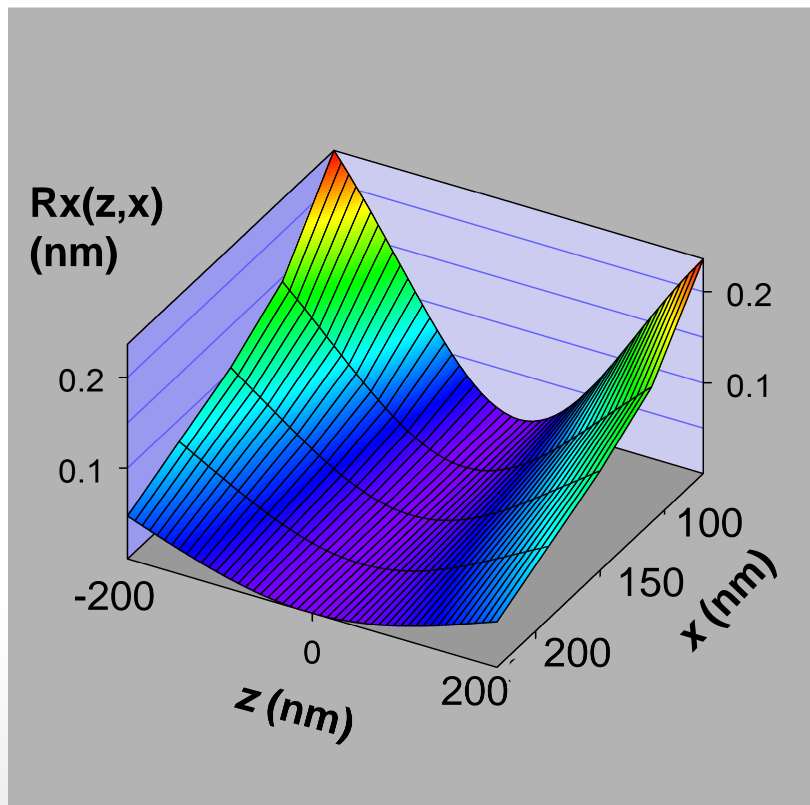
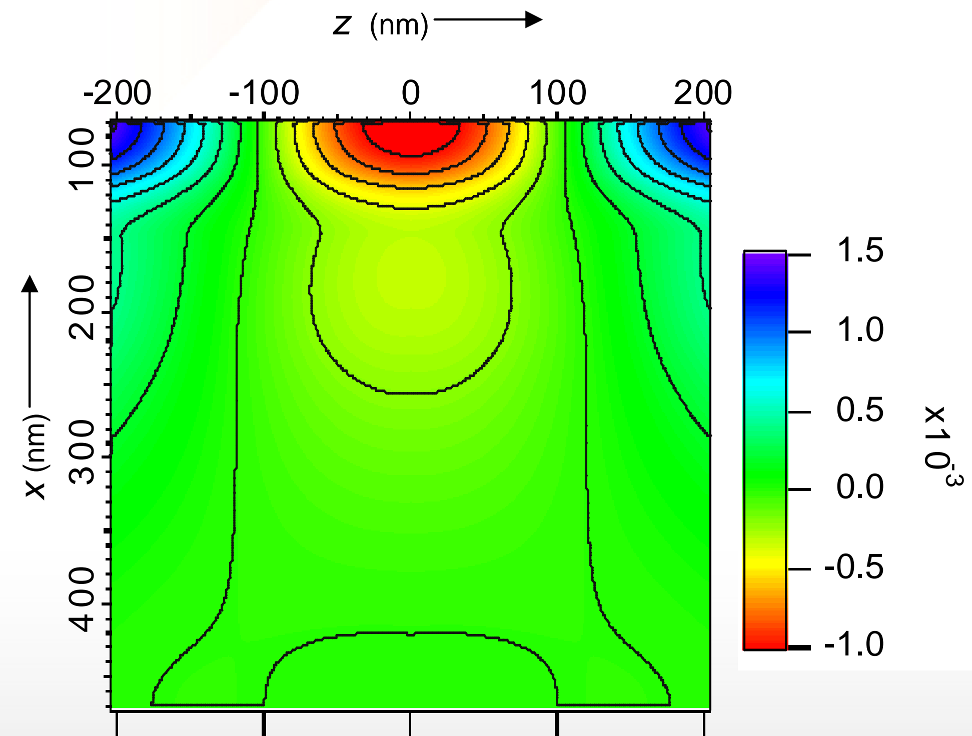
Results: Displacement and Strain Field in the analyzed TEM sample





By numerical interpolation, the strain field can be evaluated in points where the experimental CBED patterns cannot be acquired

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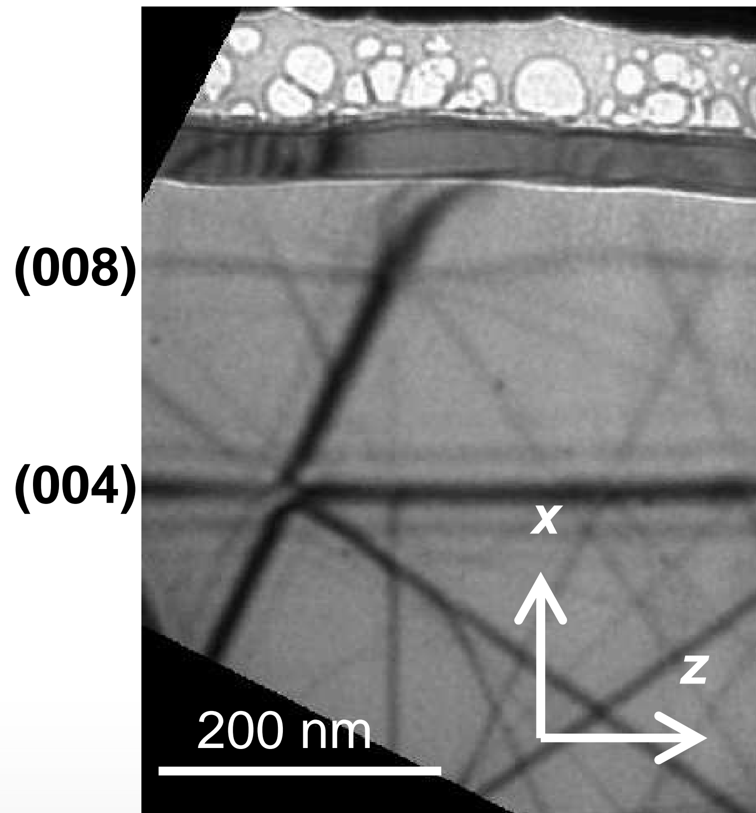
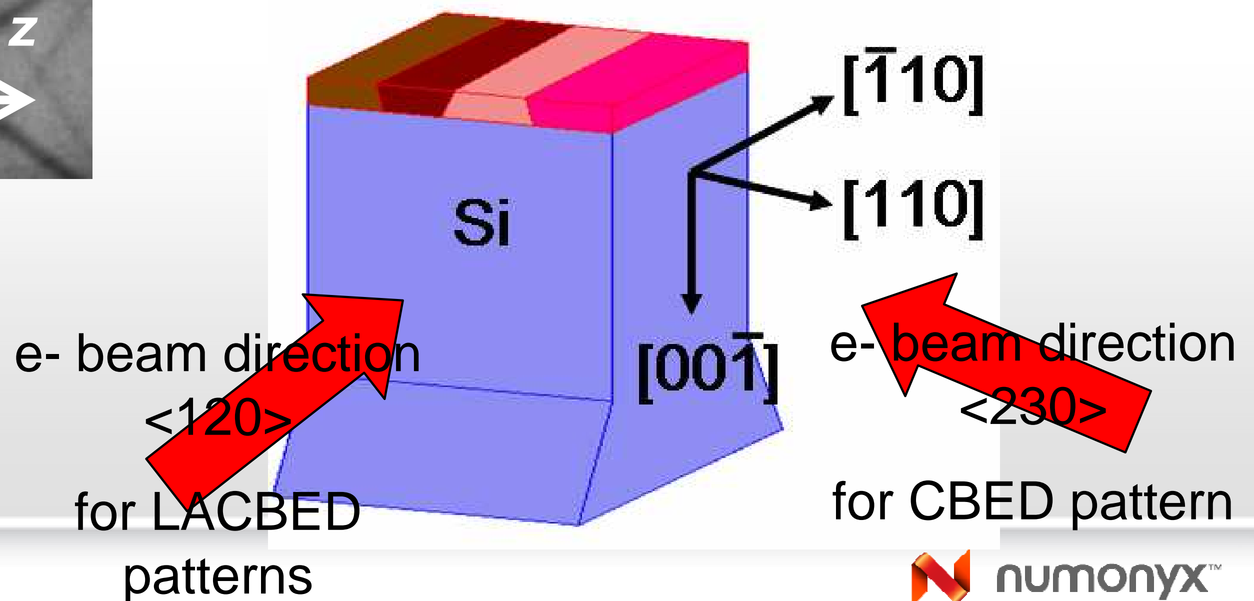
LACBED patterns



-The diffraction pattern is super-imposed to the image

-Every point is connected with the strain state of a different area of the sample



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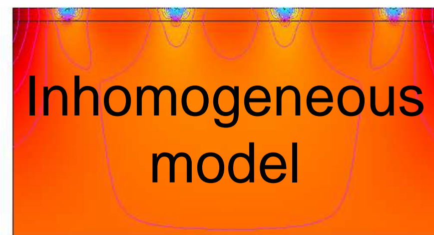
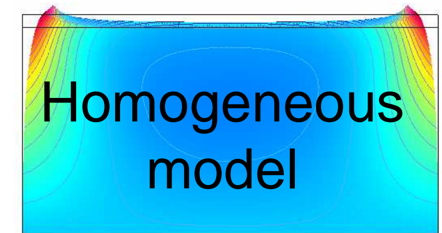
Check of the CBED results by LACBED

Exp.

Sim. 1

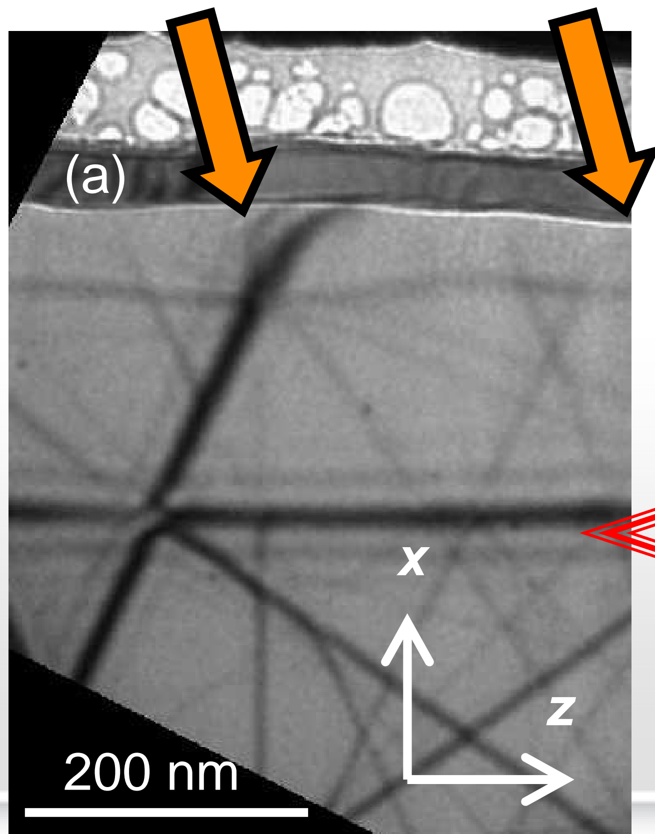
Sim. 2

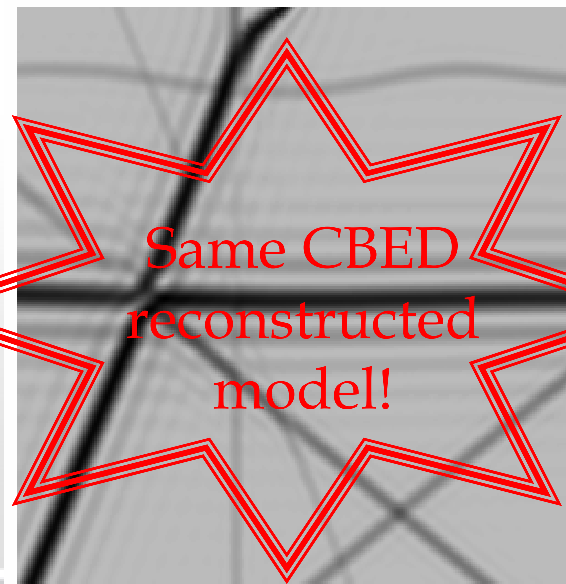


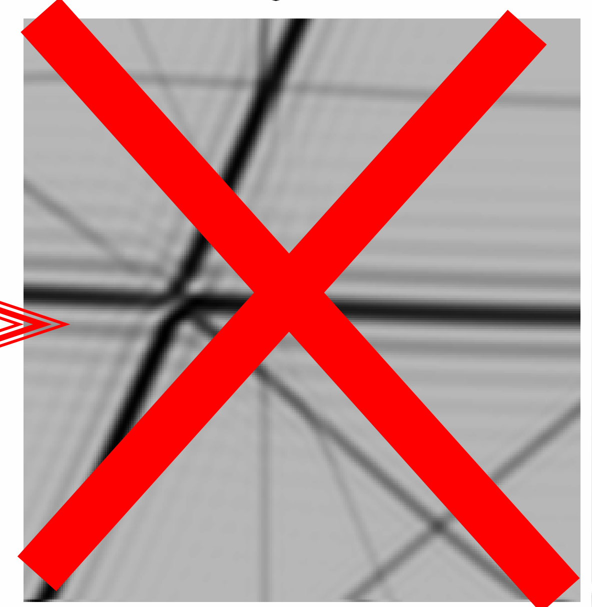


(008)

(004)







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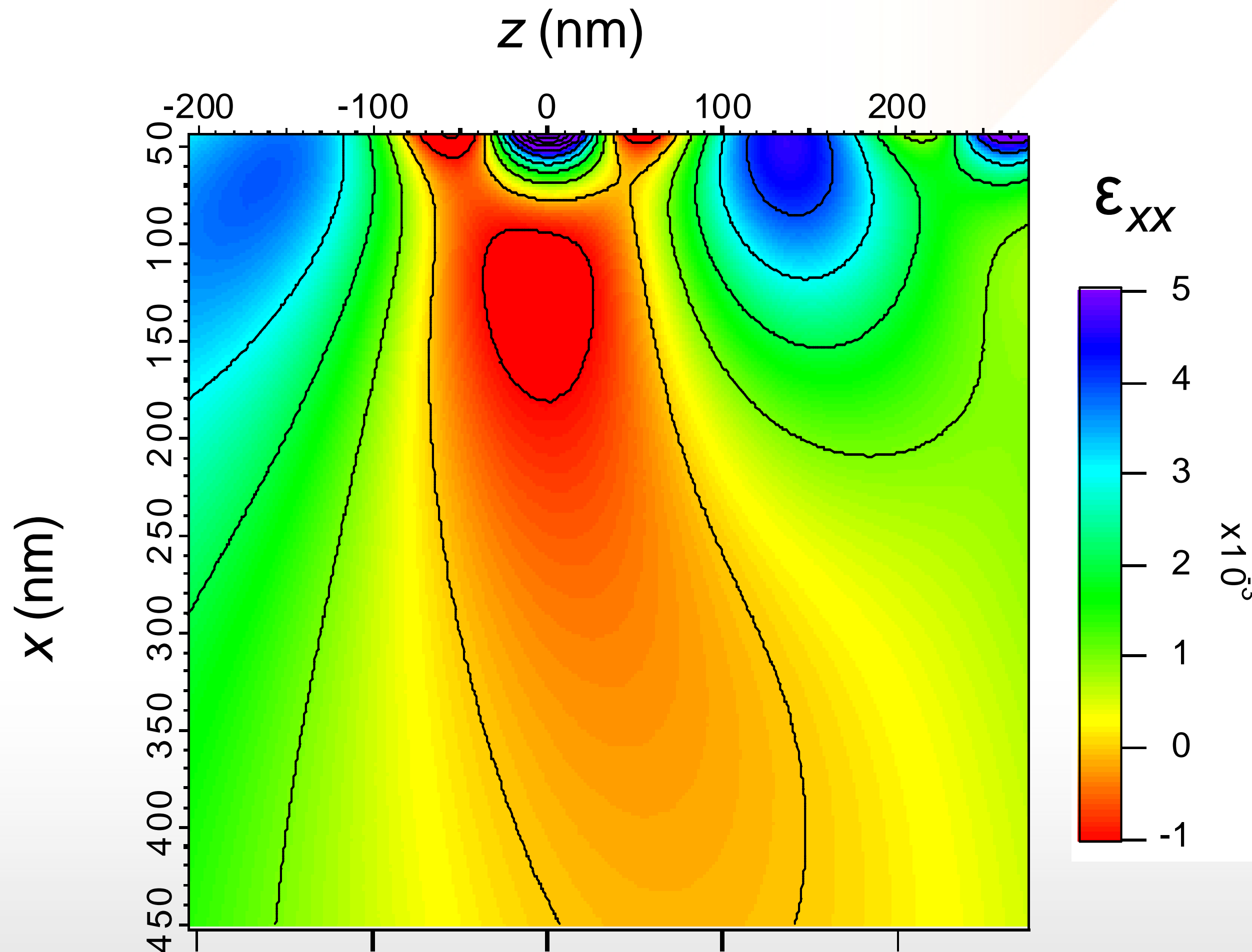
Check of the strain field obtained by CBED in <230>



Stain field obtained in the <120> by LACBED is in agreement with the CBED results

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Conclusions

1) By *CBED* simulation, the displacement field is reconstructed in the TEM sample by the analysis of an experimental database of patterns. Coupling the experimental data with the COMSOL simulation, the strain gradient can be evaluated

2) The strain field can be checked in the LACBED simulation even in the inhomogeneous case, and used to reconstruct the unthinned situation with the help of FEA simulation

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