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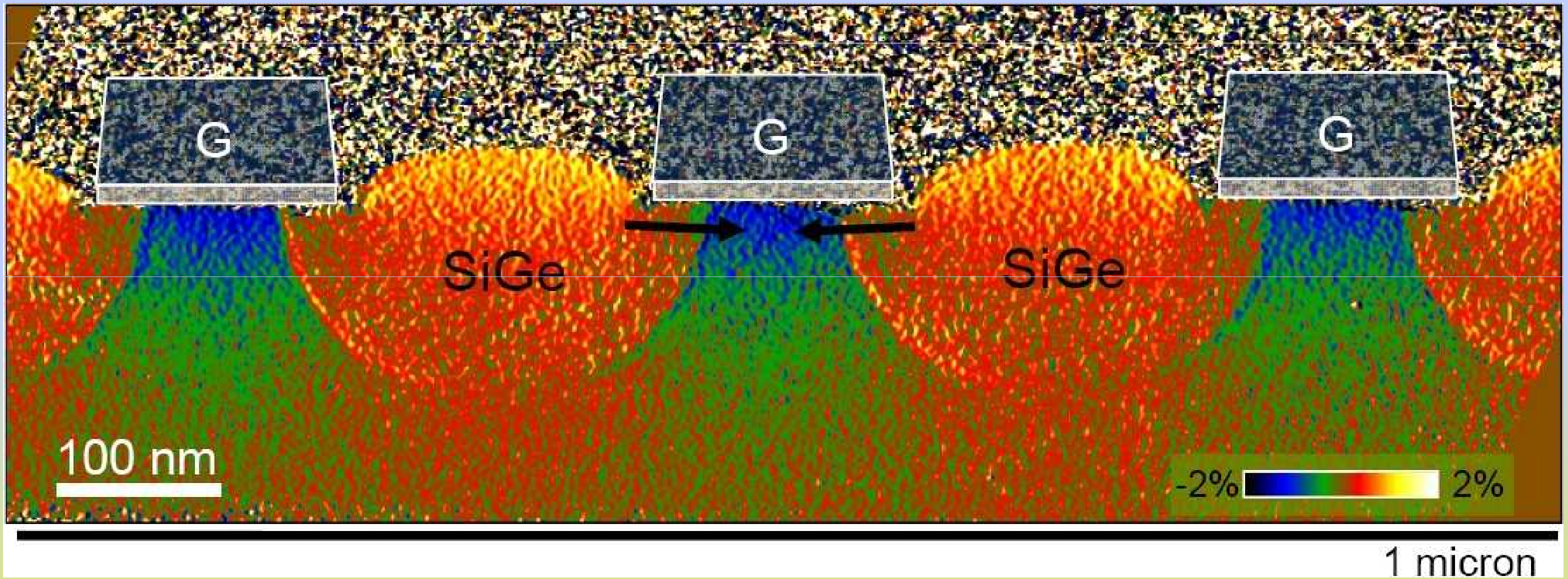
ANR HD STRAIN

CEMES TOULOUSE

Dark-field holography for the measurement of strain at the nanoscale



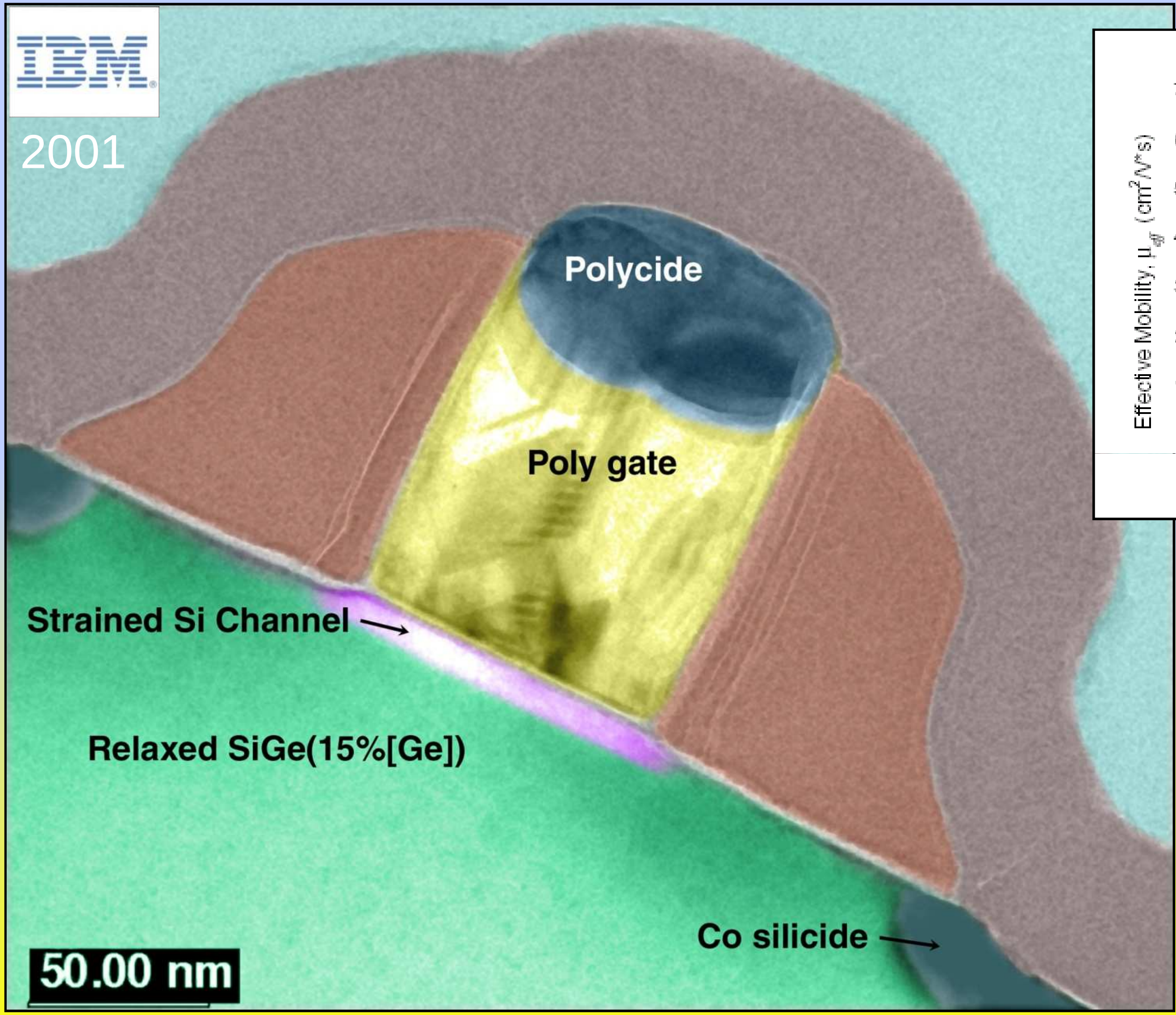
Martin Hÿtch, Florent Houdellier, Florian Hüe*, Étienne Snoeck, Alain Claverie

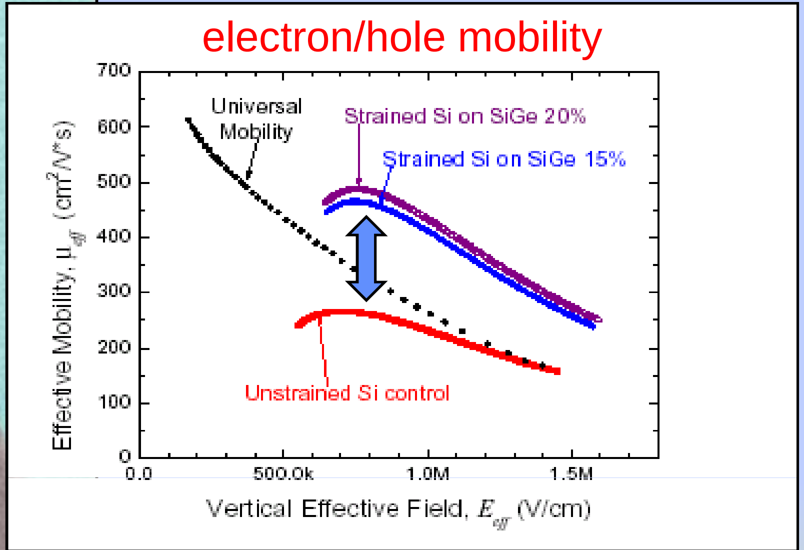
PULLNANO

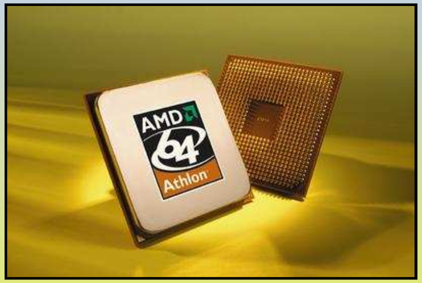
CEMES-CNRS, nMat group ,Toulouse, France

Patent applications FR 07 06711, FR 08 01662

Strained silicon channel

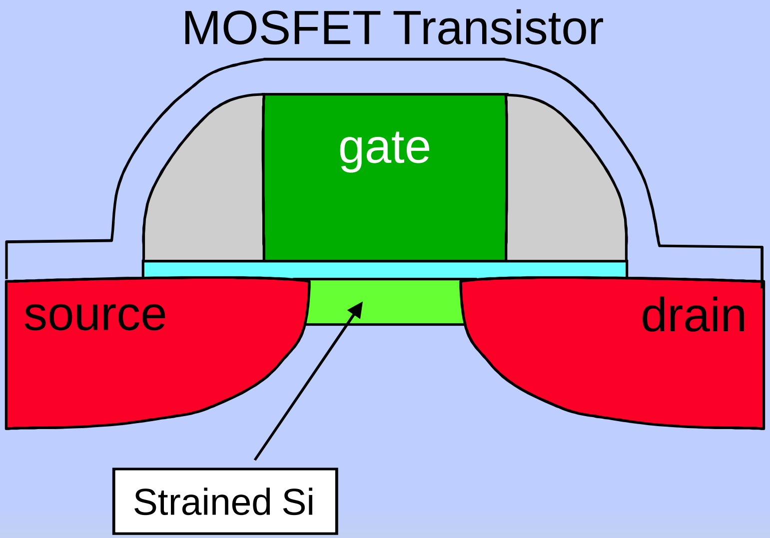


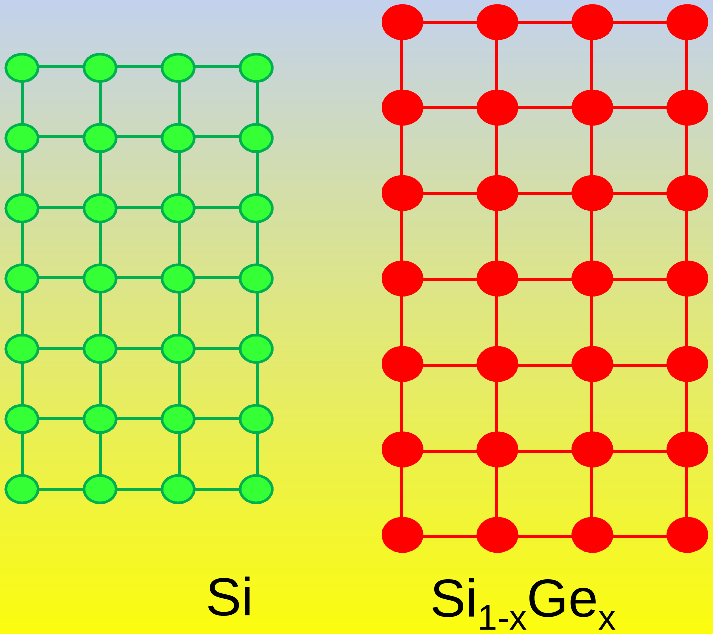


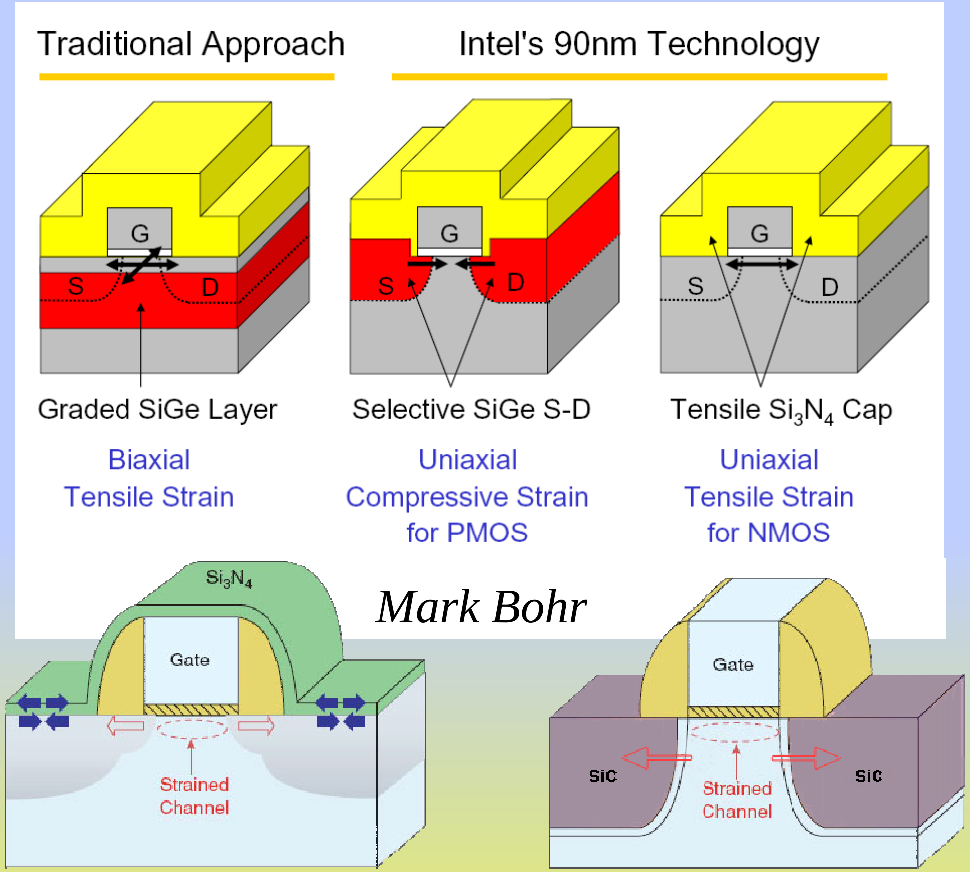


- *strain increases processor speed*

Engineering strain







- need to measure strain
- complex distributions

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Geometric phase

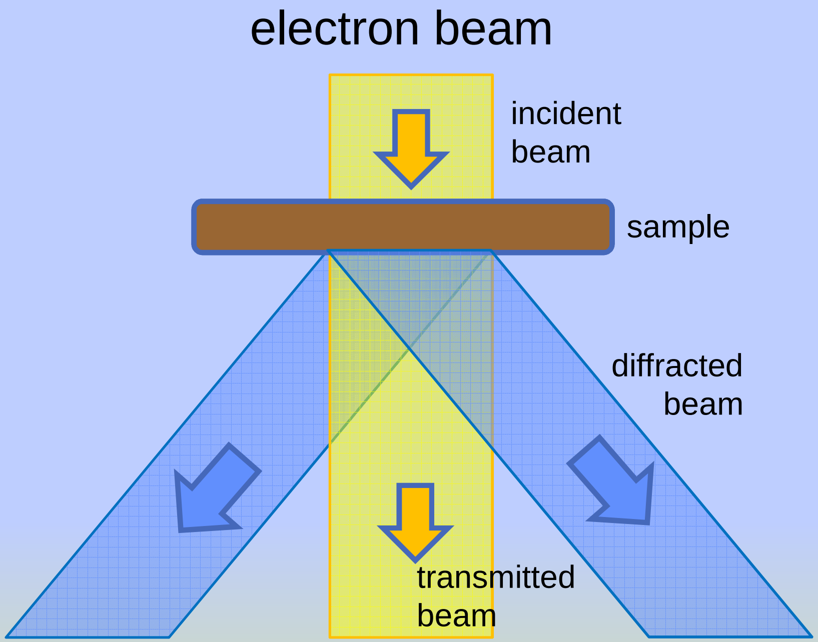
wave function

$$\psi(\mathbf{r}) = \sum_g \tilde{\psi}_g(\mathbf{r}) exp\{2\pi i \mathbf{g}.\mathbf{r}\}$$

diffracted beams

$$\mathbf{r} \rightarrow \mathbf{r} - \mathbf{u}$$ displacement

$$\Rightarrow \tilde{\psi}_g \rightarrow \tilde{\psi}_g e^{-2\pi i \mathbf{g}.\mathbf{u}}$$



geometric phase

$$\phi_g^G = -2\pi \mathbf{g}.\mathbf{u}$$

displacement

$$\Rightarrow \varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

strain

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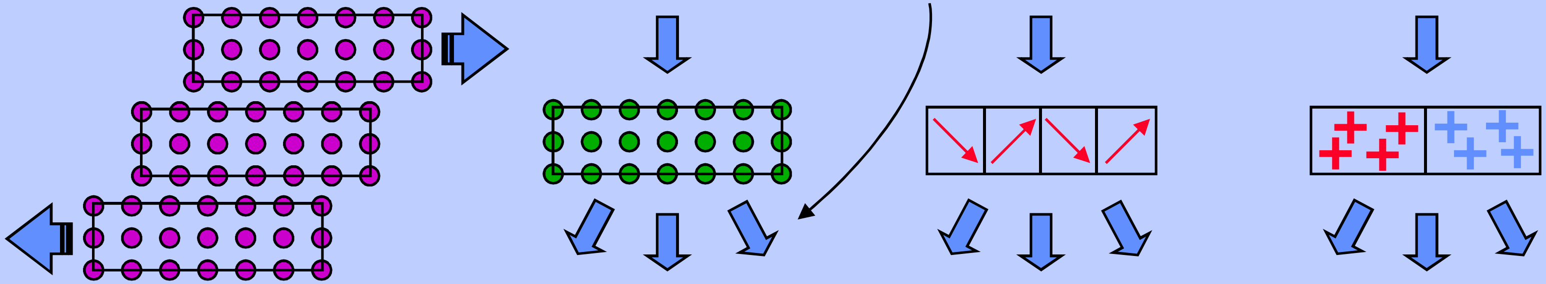
Phase microscopy

interaction electron-matter

$$\psi(\mathbf{r}) = \sum_{\mathbf{g}} \tilde{\psi}_g(\mathbf{r}) e^{2\pi i \mathbf{g}.\mathbf{r}}$$

Fourier space

amplitude and phase



phase shift

G geometric phase

C crystalline potential

M magnetic fields

E electrostatic fields

$$\phi = \underbrace{\phi^G + \phi^C}_{\text{HREM}} + \underbrace{\phi^M + \phi^E}_{\text{EH}}$$

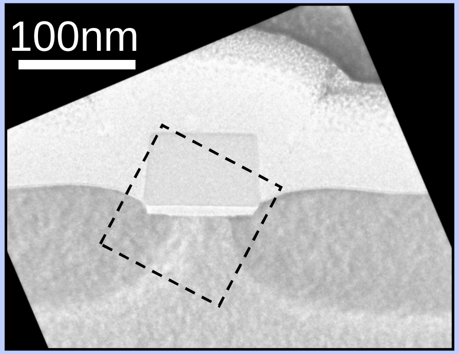
interferometry

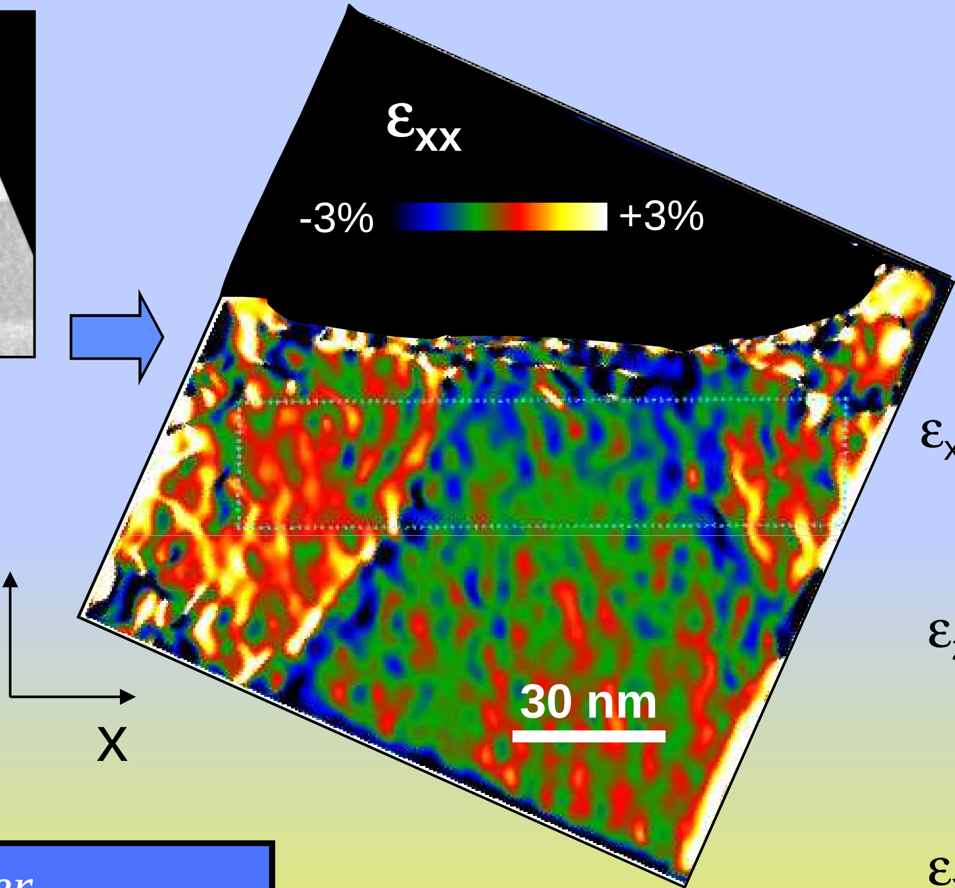
HREM

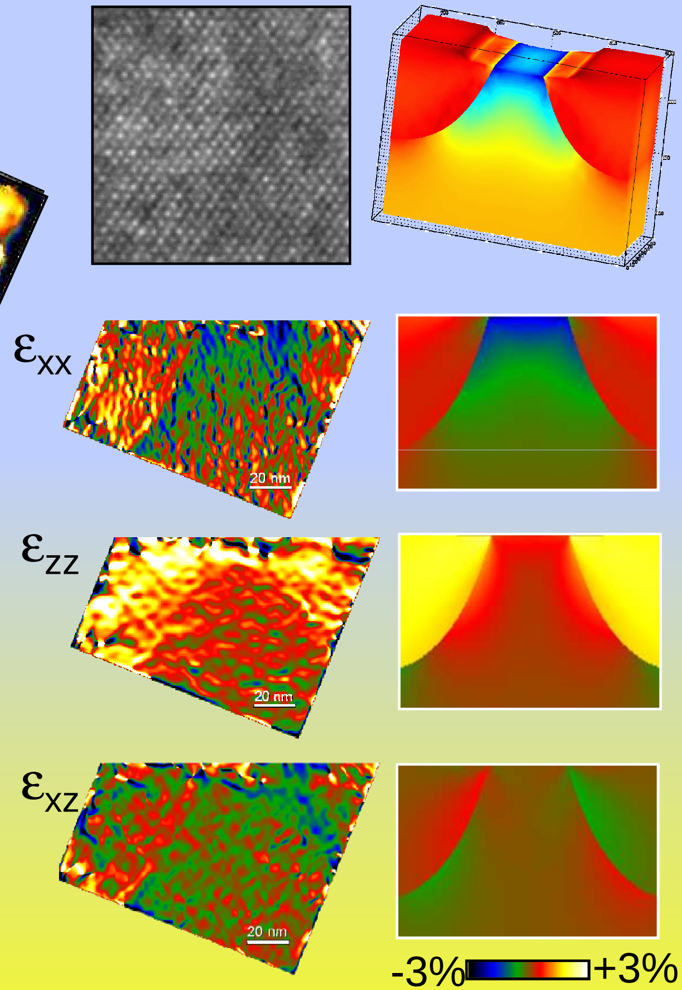
EH

HoloDark

High-resolution TEM



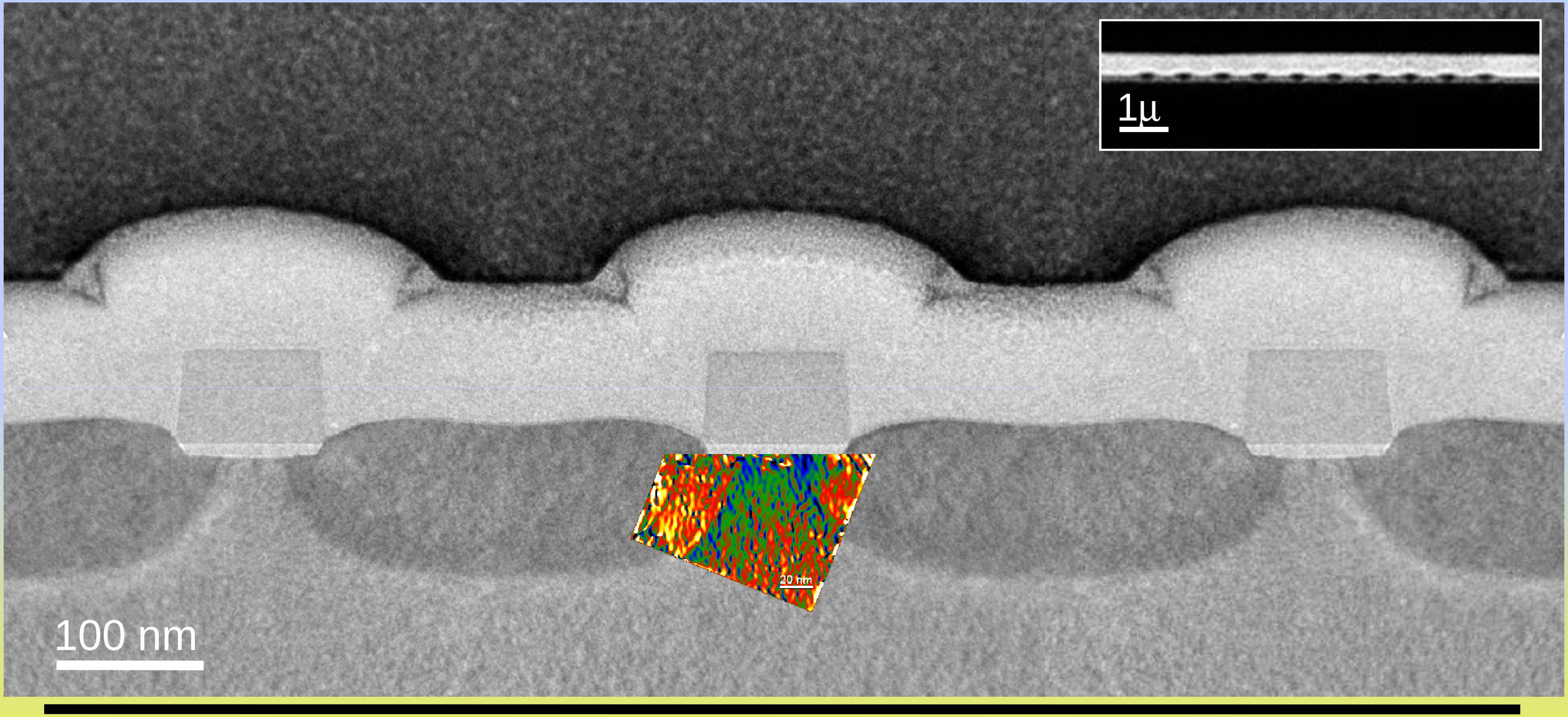




imec
Hugo Bender
IMEC-Leuven, Belgium

cea
Jean-Michel Hartmann
CEA-LETI, Grenoble, France

Need for a new technique



wider field of view
thicker crystals

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Dark-field Holography

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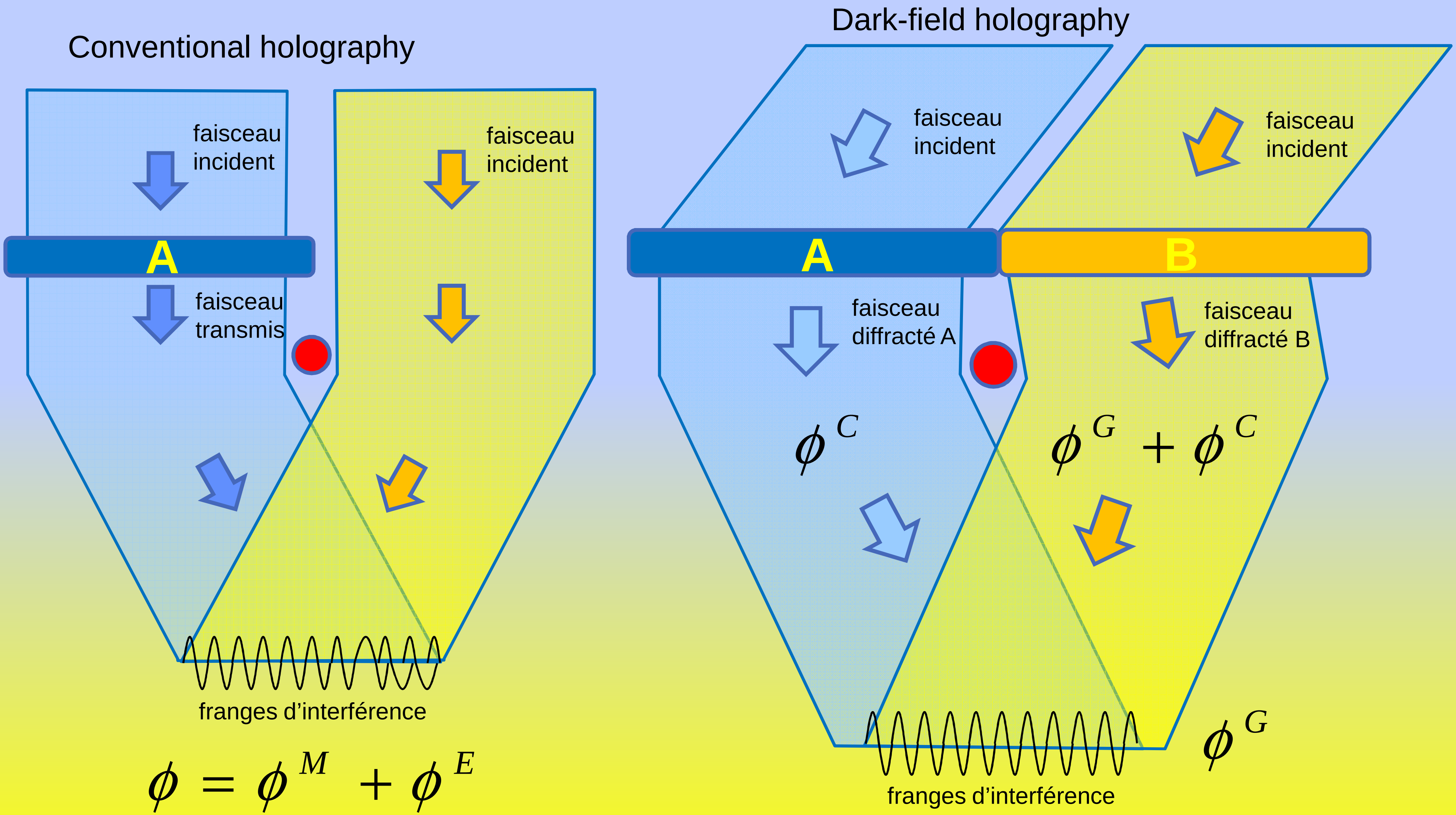

$$\phi = \phi^{M} + \phi^{E}$$

ϕ^{C} $\phi^{G} + \phi^{C}$ ϕ^{G}

- direct measurement of geometric phase

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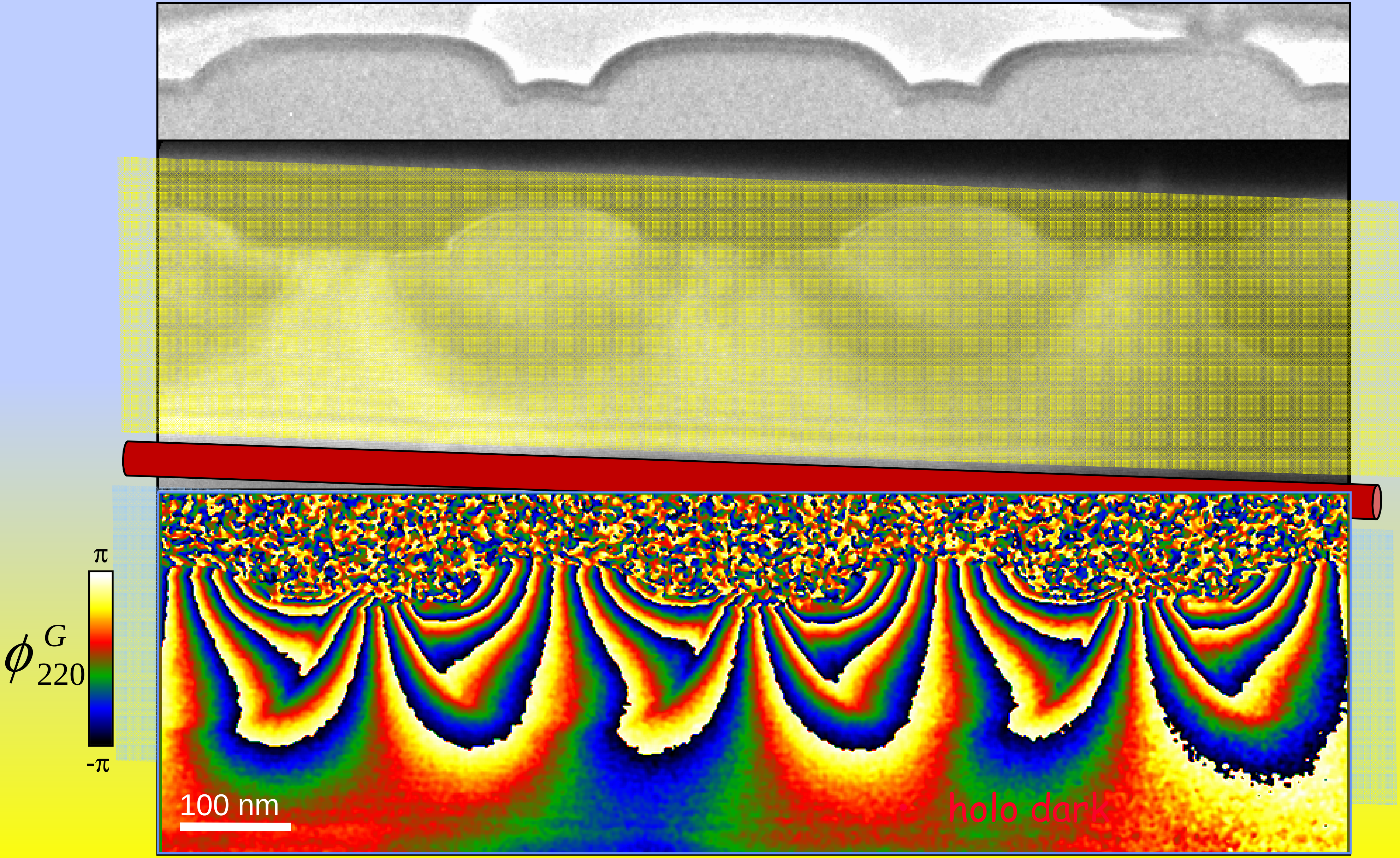
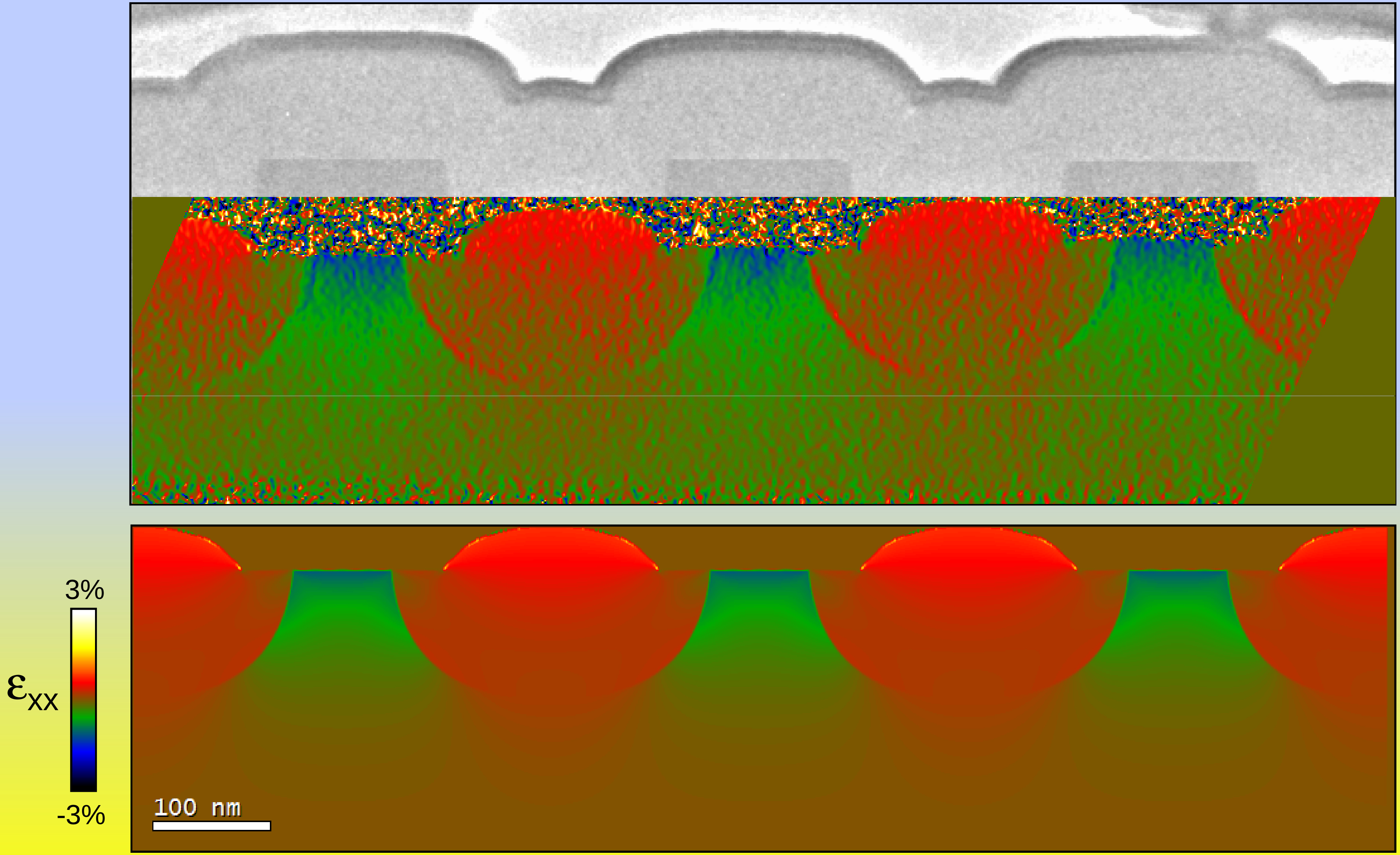
Experiment



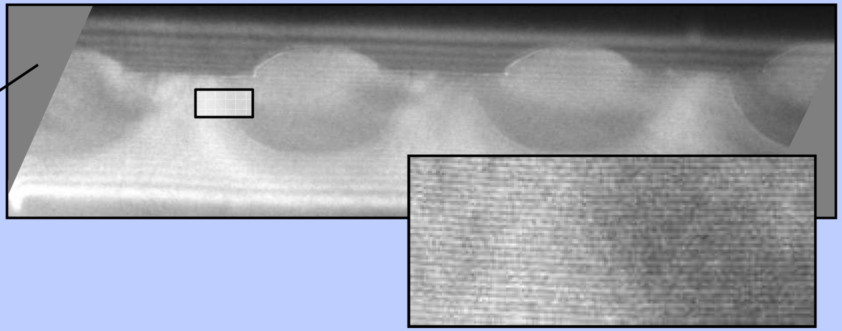
Deformation measurement

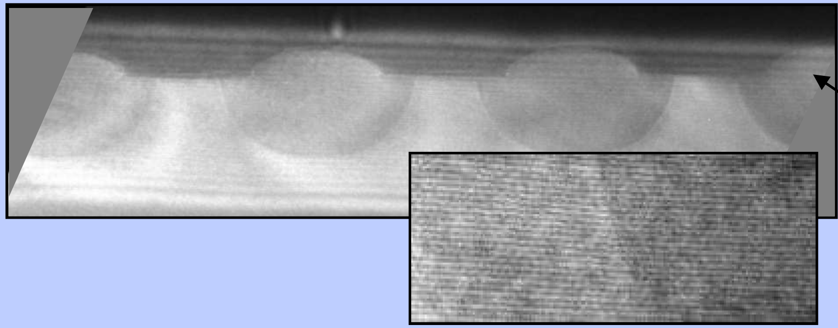


M.J. Hÿtch, F. Houdellier, F. Hüe & E. Snoeck, Nature 453 (19th June 2008) 1086

2D Deformation

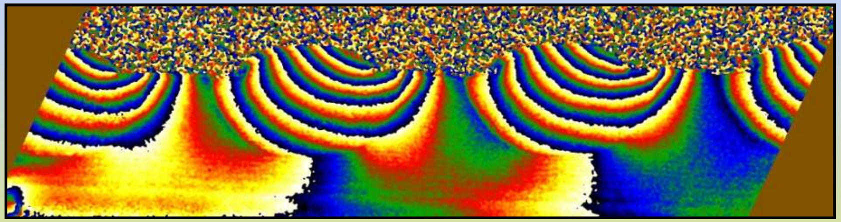
$\mathbf{g}_1$

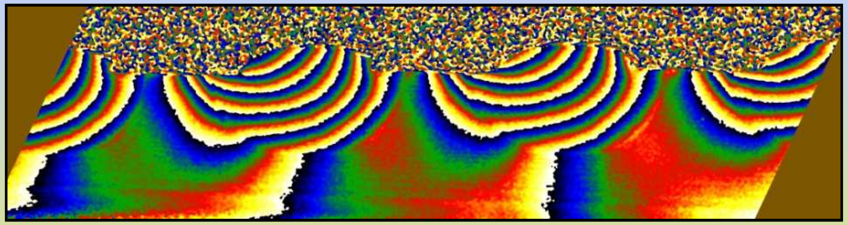




$\mathbf{g}_2$

ϕ^G_{g1}



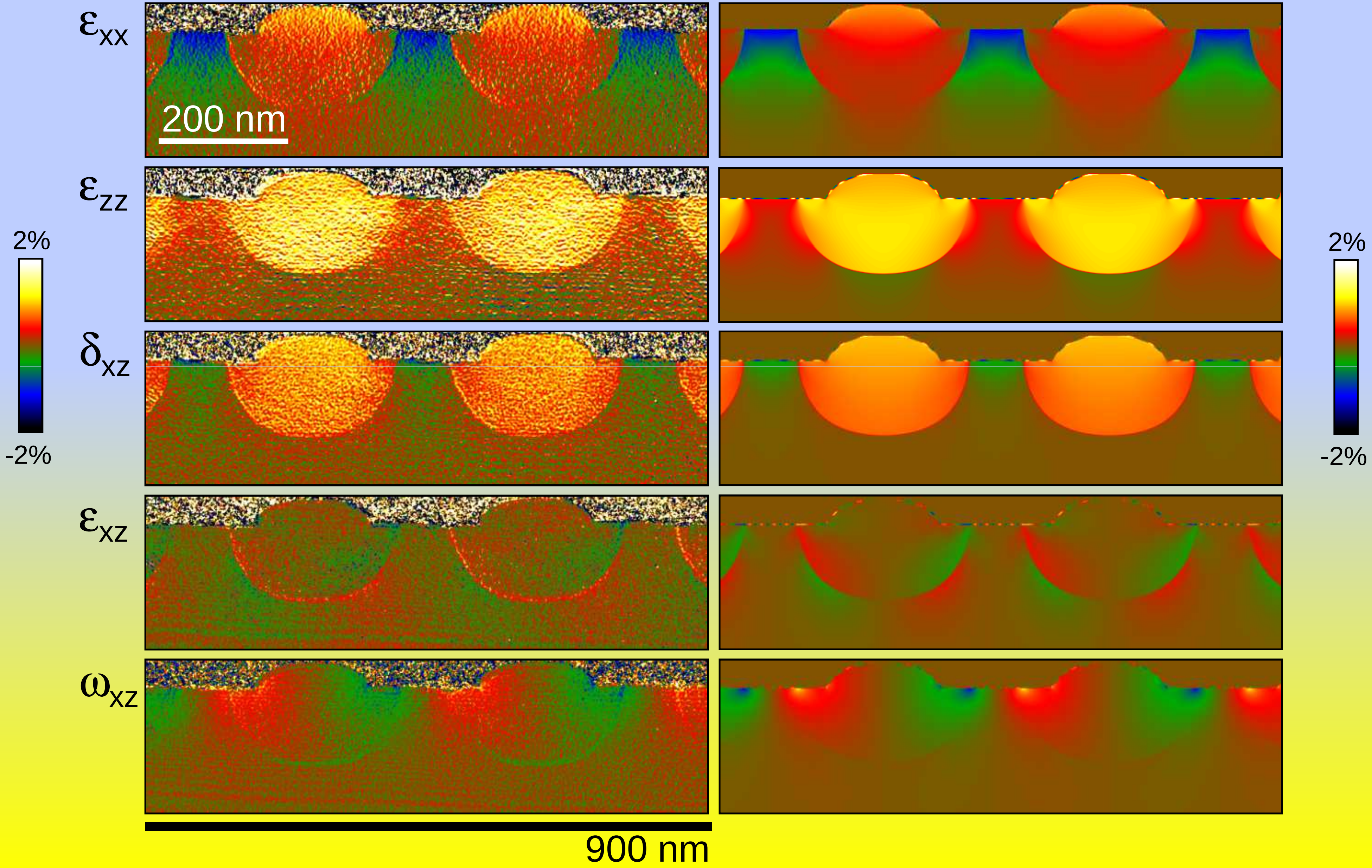


ϕ^G_{g2}

$$\mathbf{u}(\mathbf{r}) = -\frac{1}{2\pi}\left[\phi^G_{g1}(\mathbf{r})\mathbf{a}_1 + \phi^G_{g2}(\mathbf{r})\mathbf{a}_2\right]$$

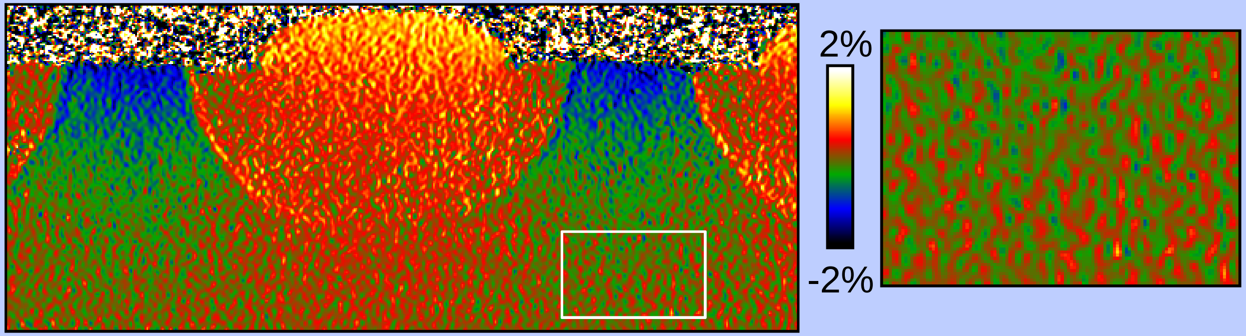
- as with GPA

Strain components



Accuracy and precision

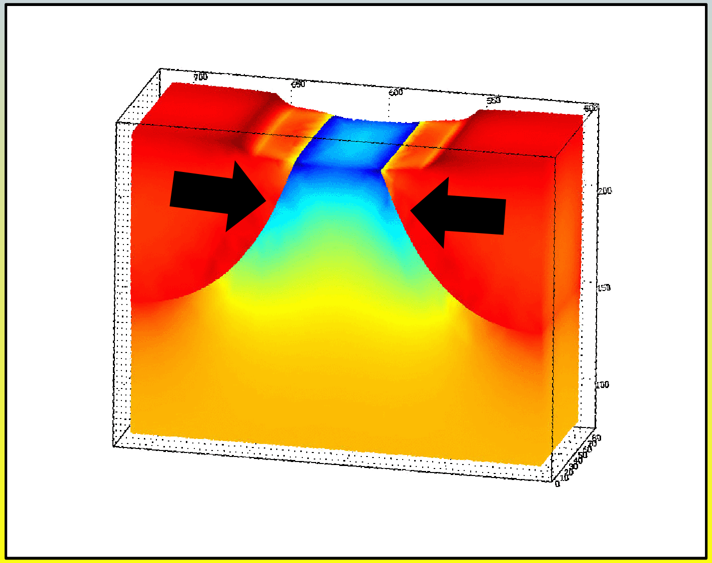
Noise

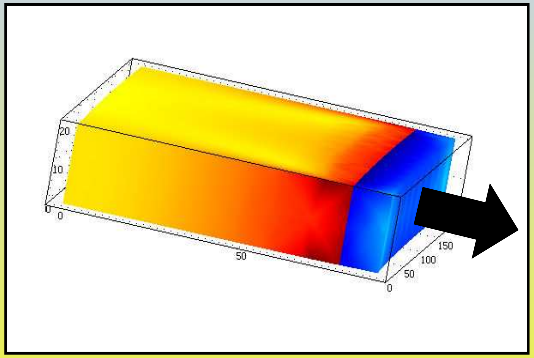


4 nm
0.2%

40 nm
0.02%

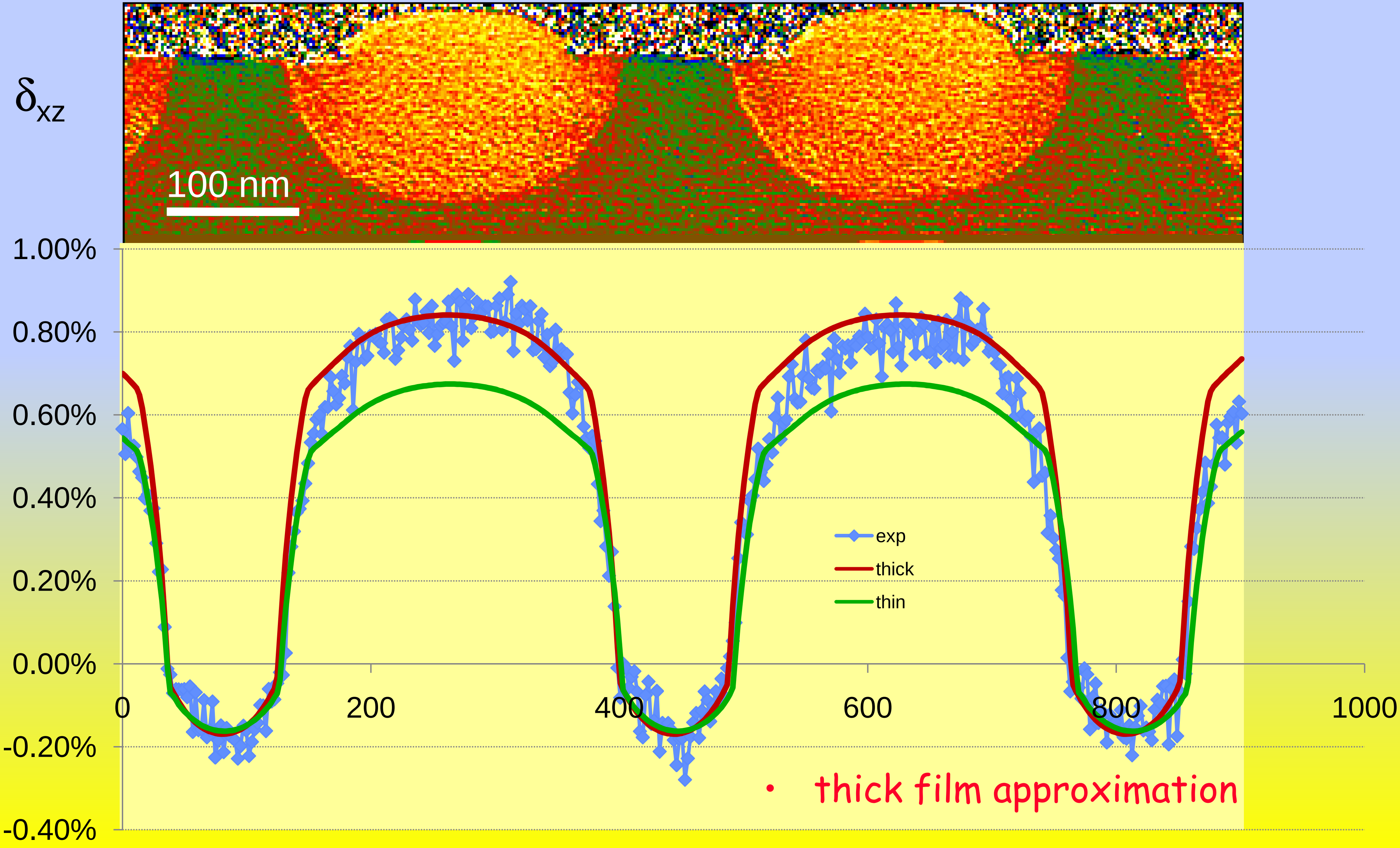
Thin film relaxation





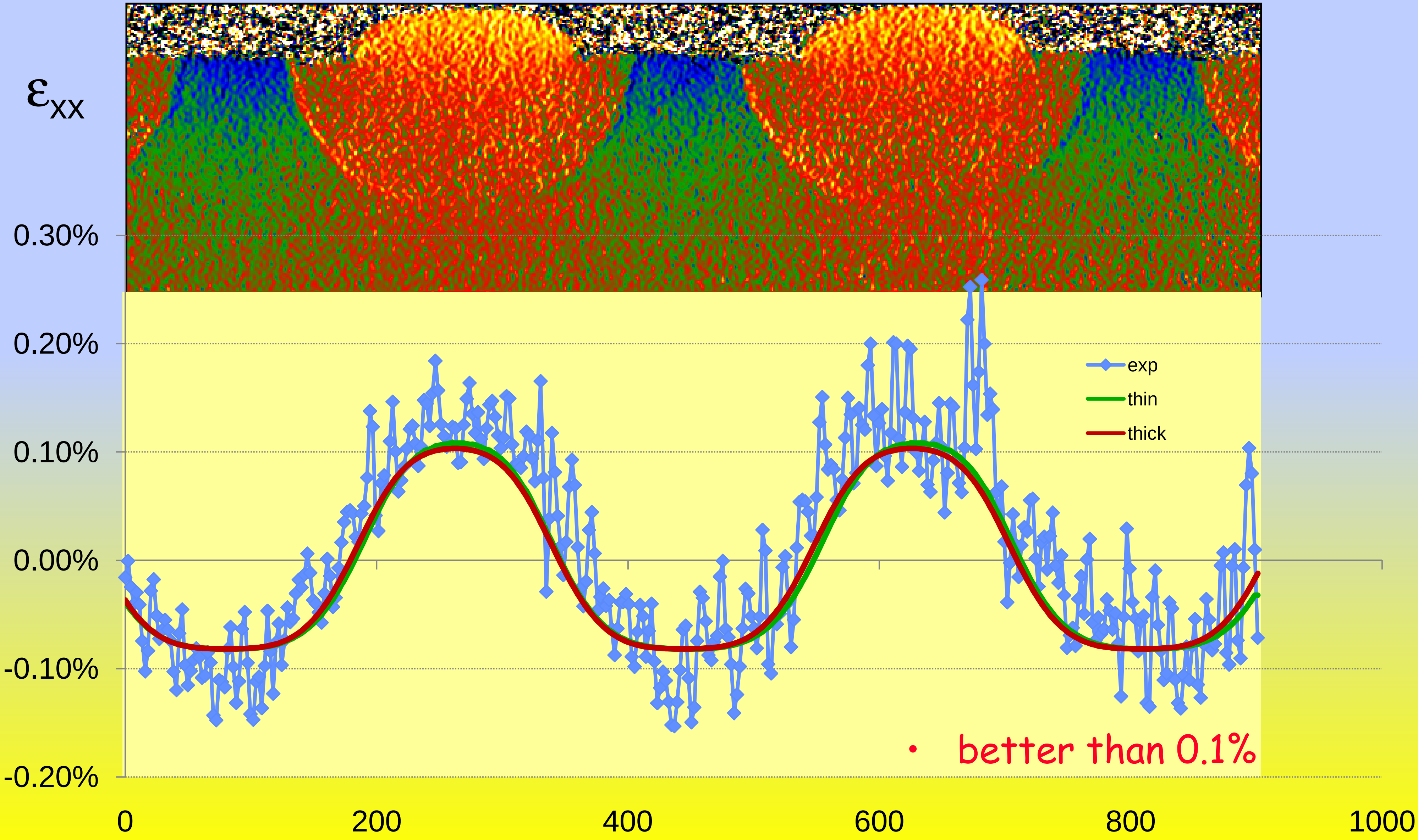
- best and worst
- aspect ratio

Thick or thin ?



- thick film approximation

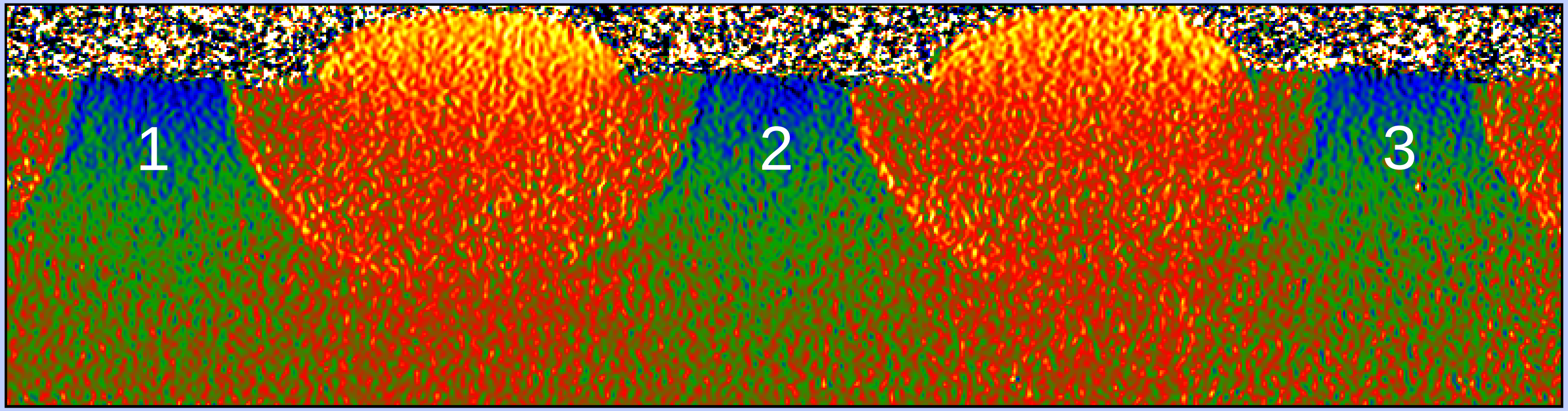
Sensitivity



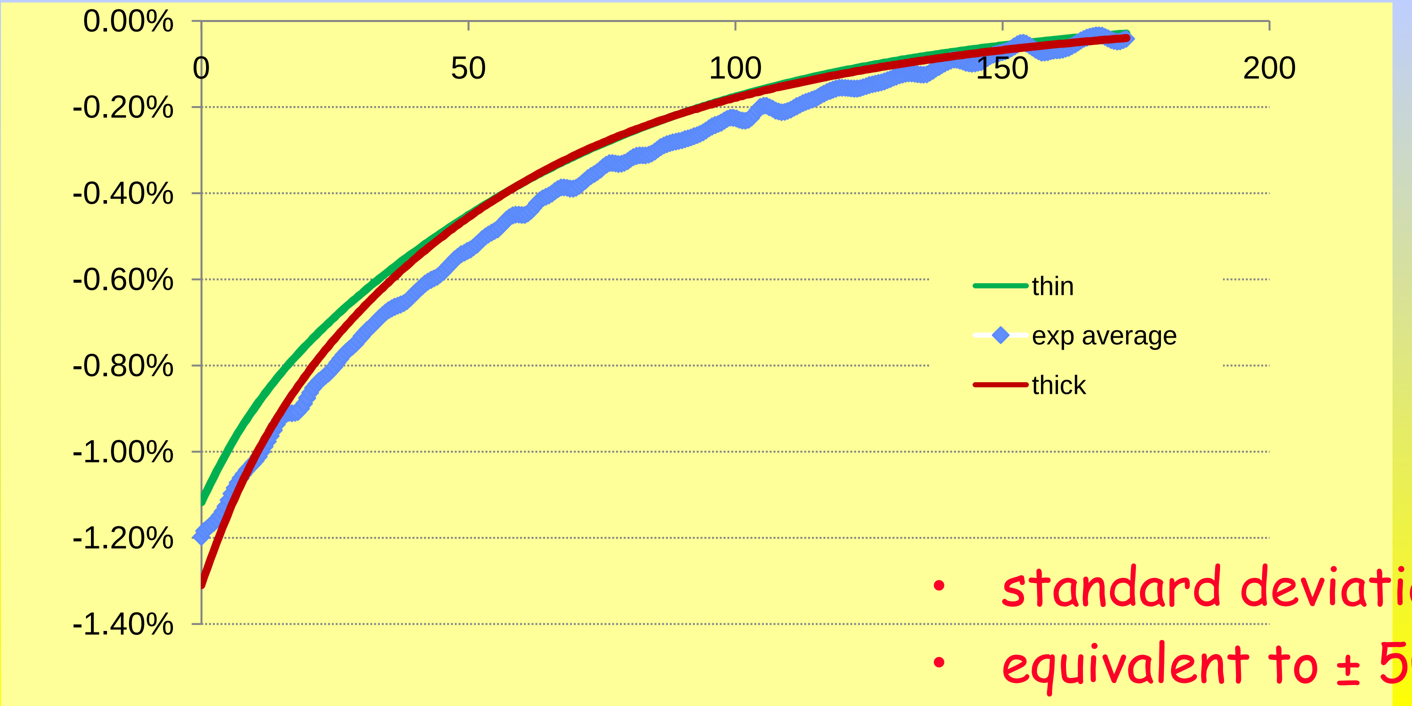
- better than 0.1%

Reproducibility

ε_{xx}



Distance from gate / nm



- standard deviation 0.03%
- equivalent to ± 50 MPa

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nMOSFET with $Si:C_{1\%}$

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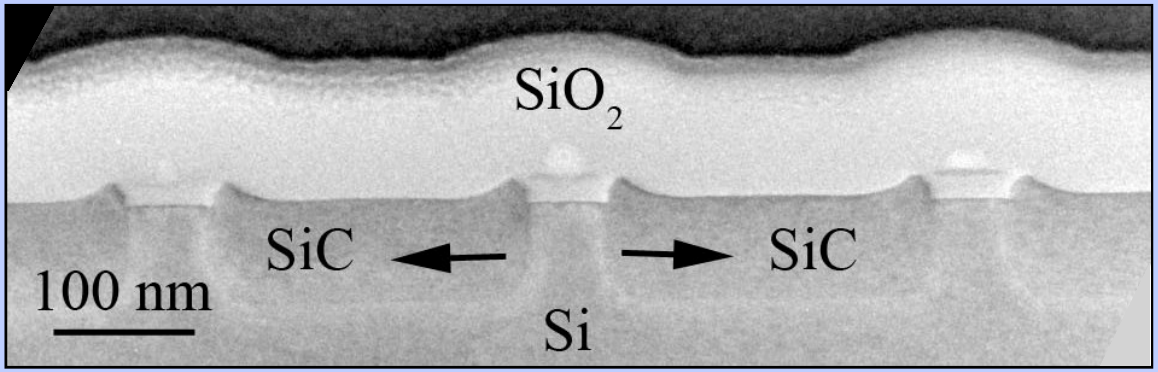
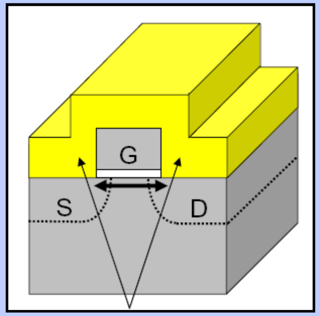
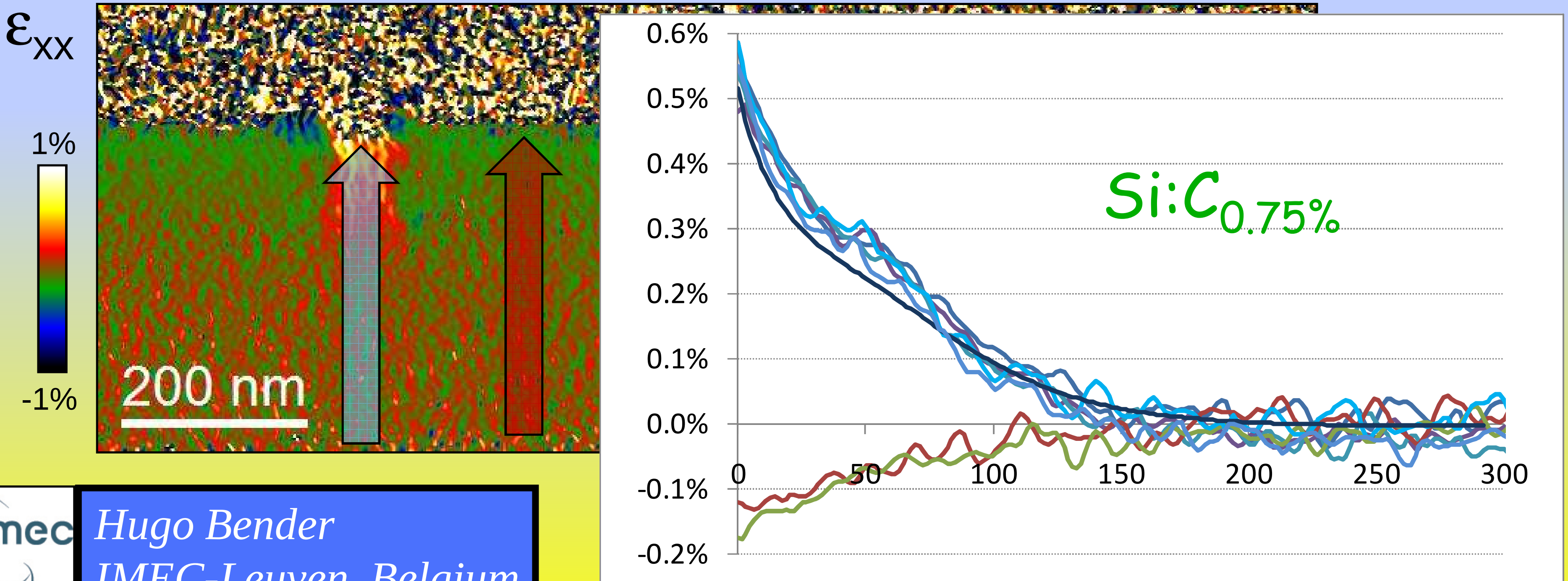




n-MOS

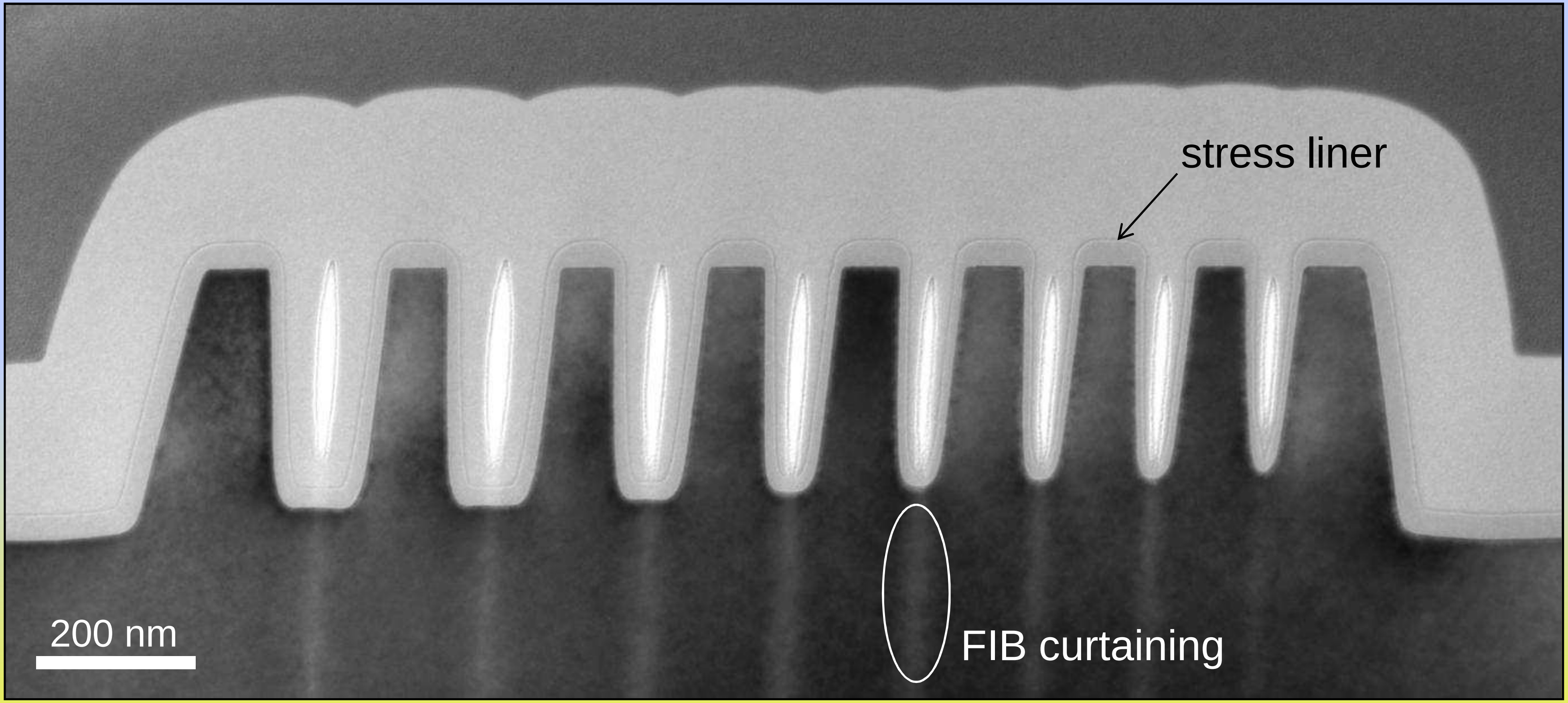


Hugo Bender
IMEC-Leuven, Belgium

- $2\ 10^{-4}$ or 0.02%

N. Cherkashin et al., Appl. Phys. Lett. 94, 141910 (2009)

Flash memory test structure



Aomar Halimaoui
Laurent Clément
Pierre Morin

- CESL applies stress

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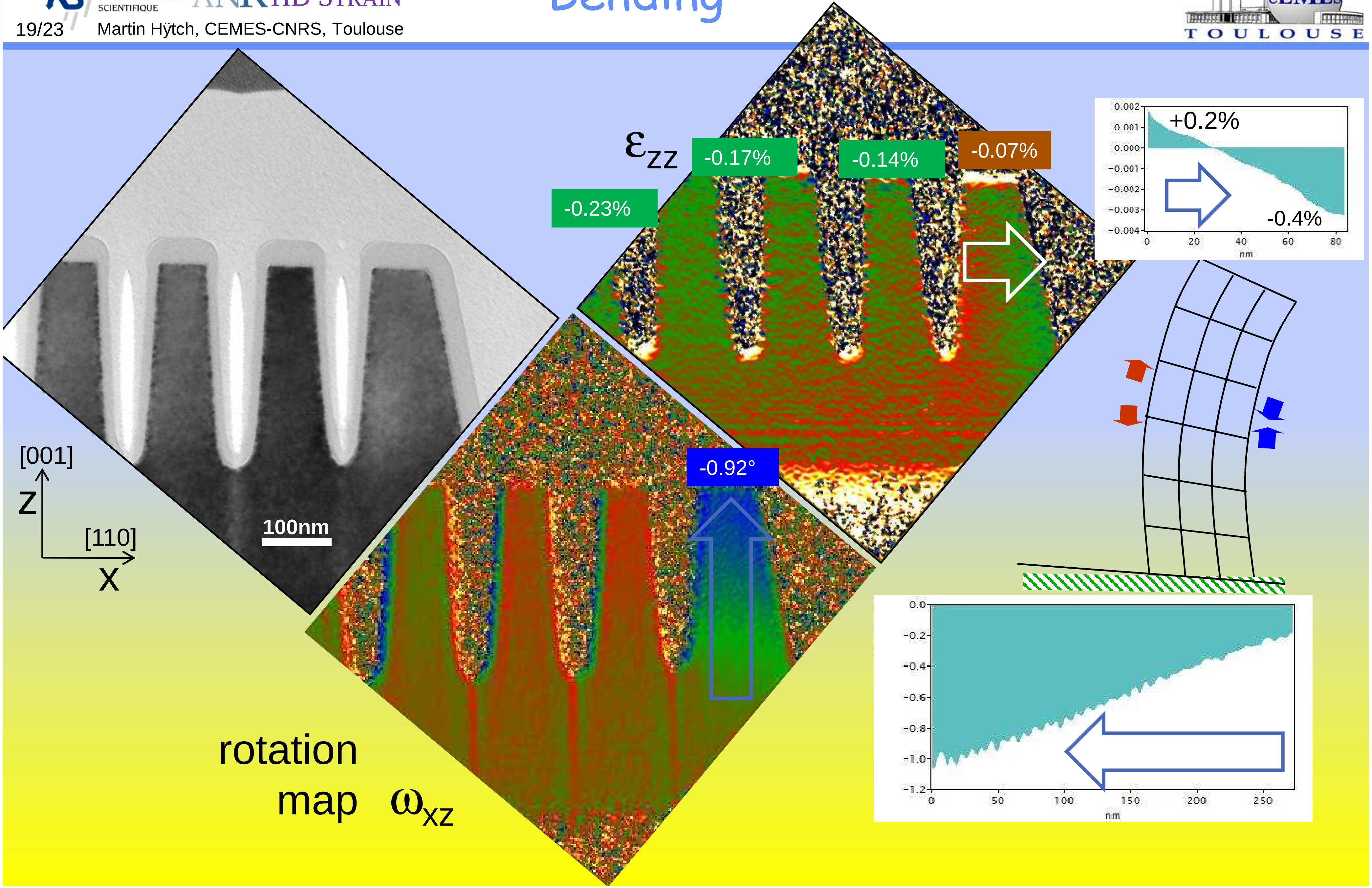
Bending



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Rotation, ω_{xz}

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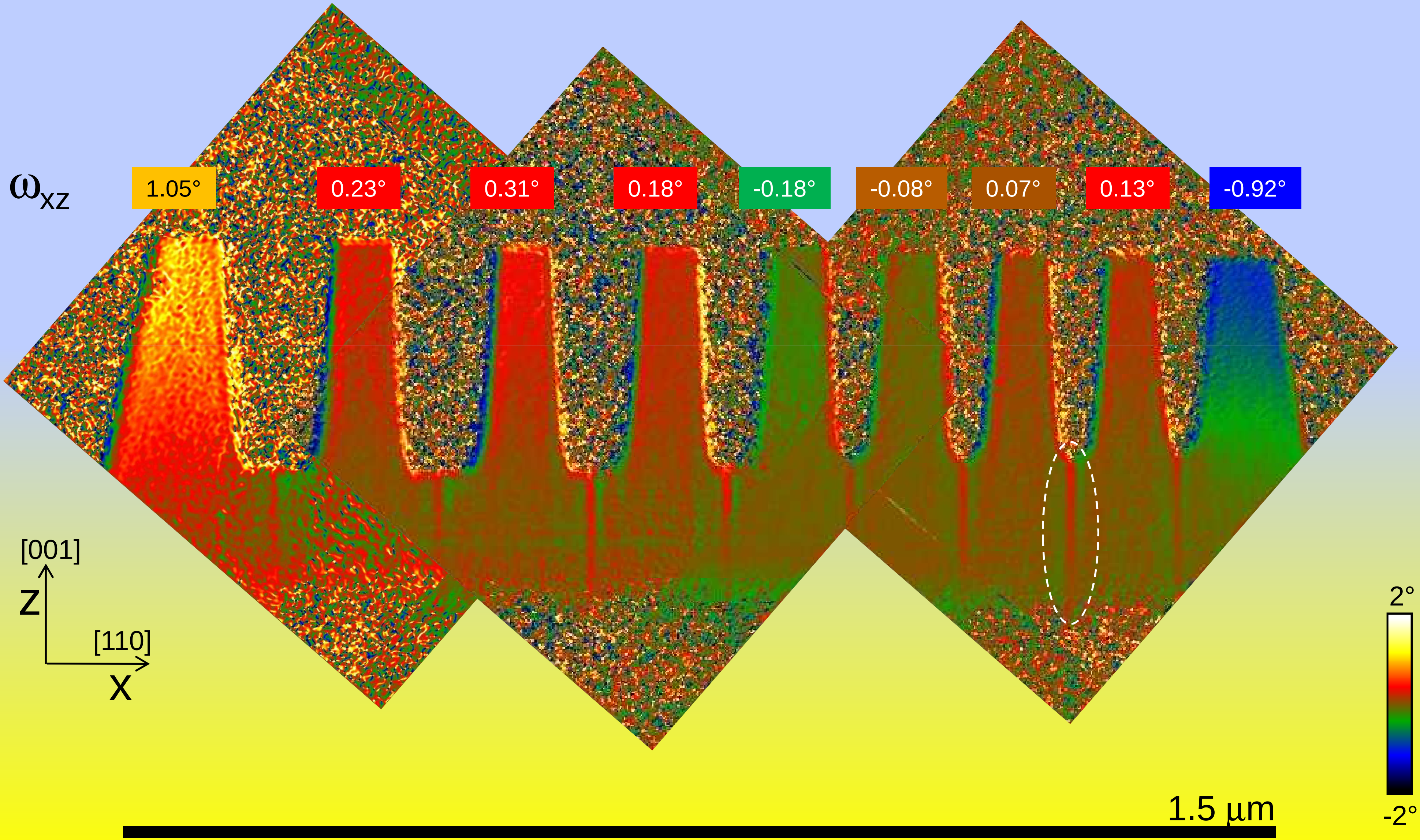
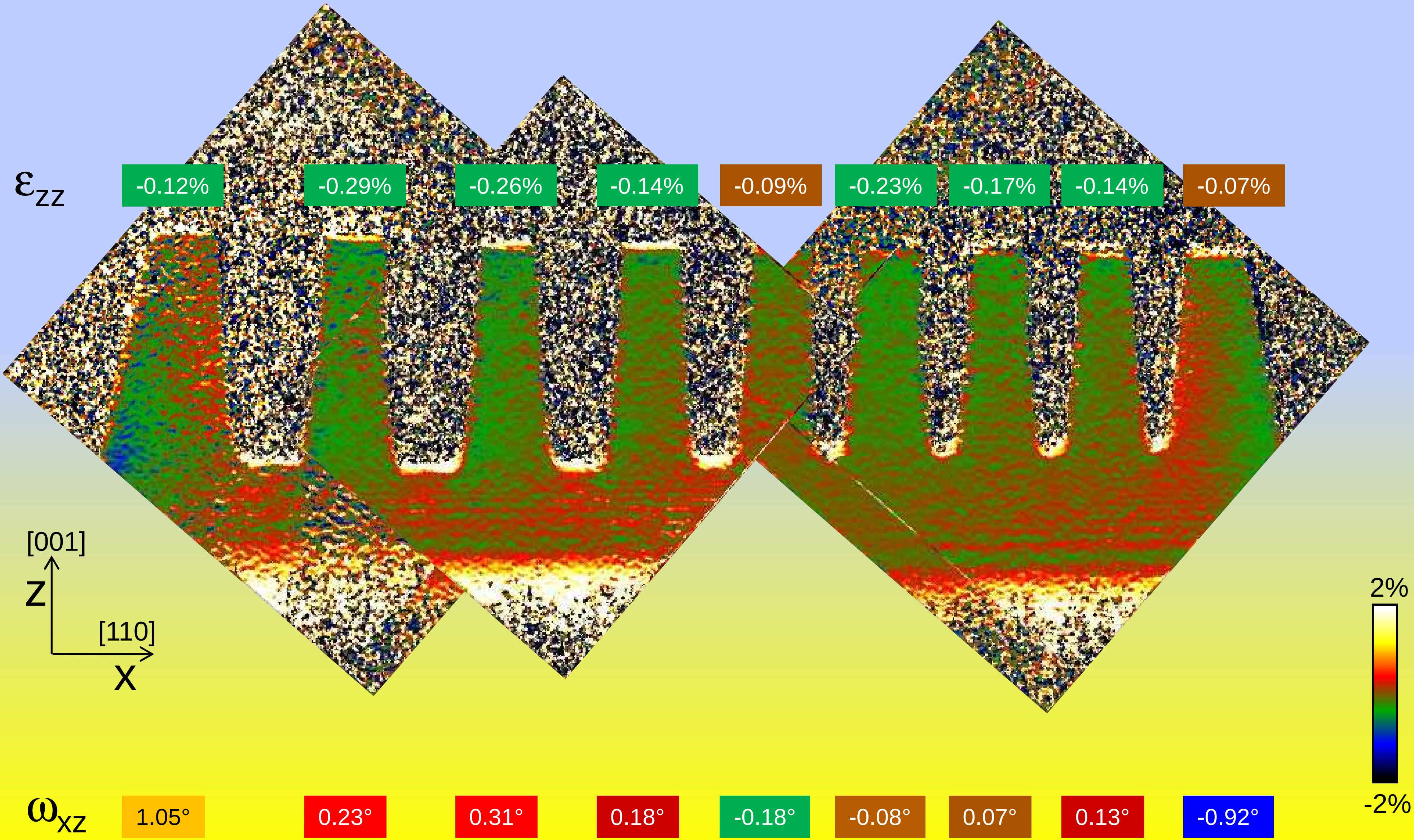


Vertical strains, ε_{zz}



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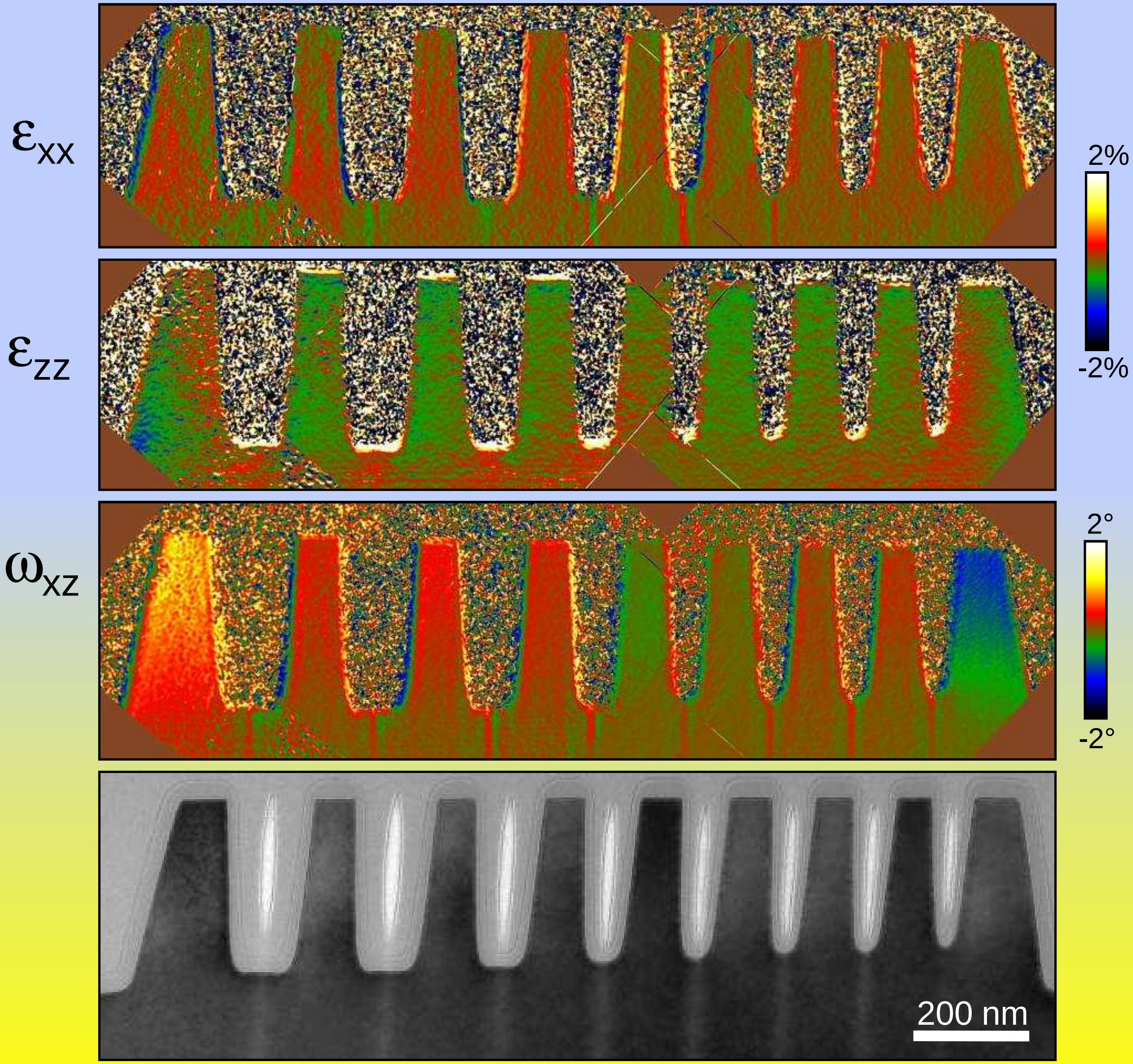
Summary of CESL results



ε_{xx}, ε_{xz} = 0.00%-0.09%

ε_{zz} = -0.19% ± 0.07%

ω_{xz} = 0.1°, ±1°

→ σ_{zz} = -300 MPa ± 100 MPa

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Requirements and Summary

- large fields of view
- thick crystals
- high precision
- high success rate
- easier than HREM ?

- equipment
- software
- microscopist

- thickness
- composition
- crystal bending

→
- dedicated equipment