Focused Ion Beams : A tool for Nanomachining and Advanced Transmission Electron Microscopy

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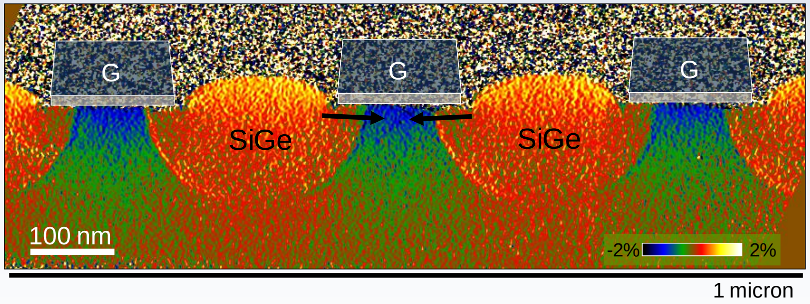
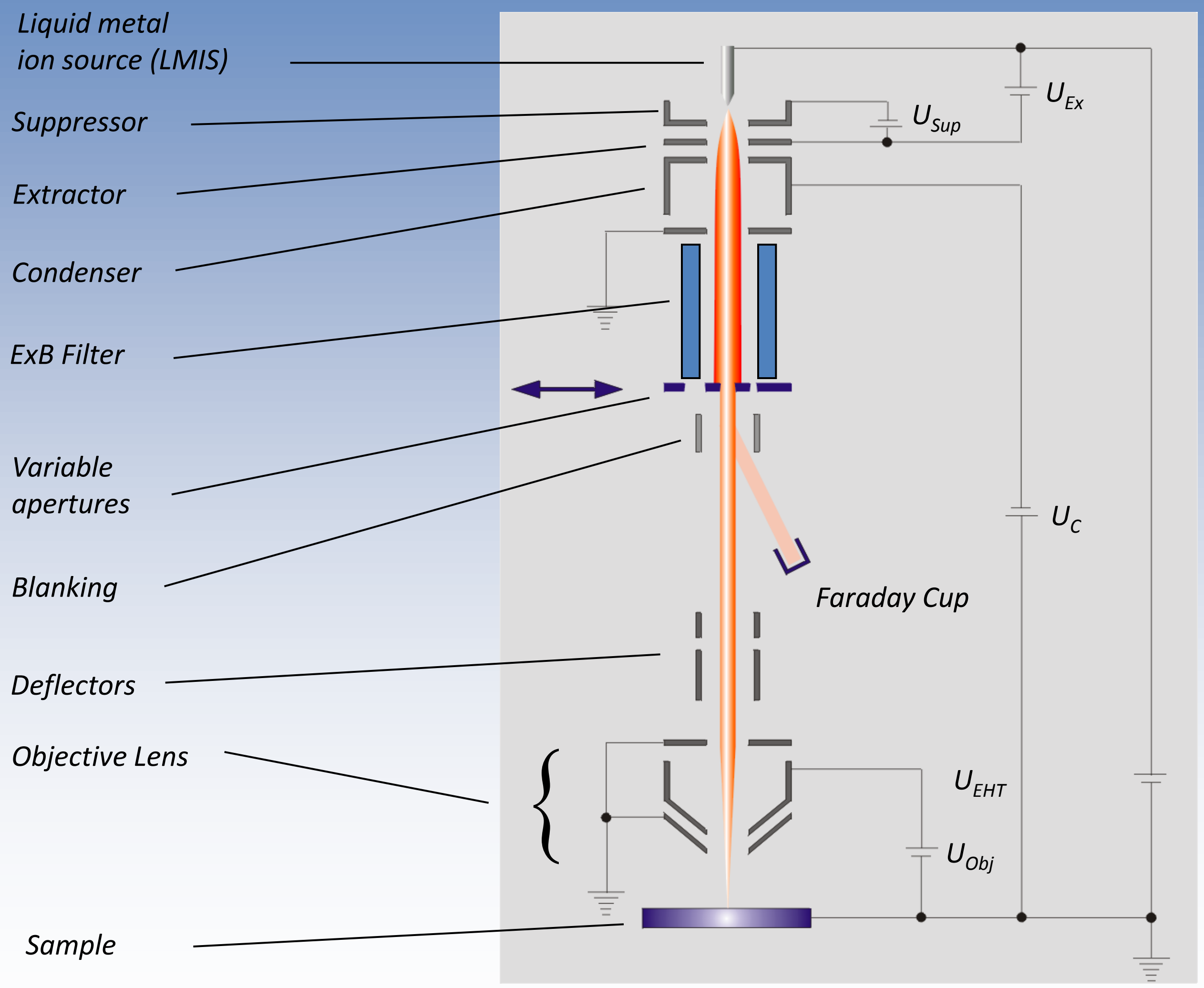


Outline

- ***FIB Optics and Performance***
- ***Thin Samples and New TEM capabilities***
- ***FIB for the Future of TEM ?***

Standard Ion Optics



Liquid metal ion source (LMIS)

Suppressor

Extractor

Condenser

ExB Filter

Variable apertures

Blanking

Deflectors

Objective Lens

Sample

Faraday Cup

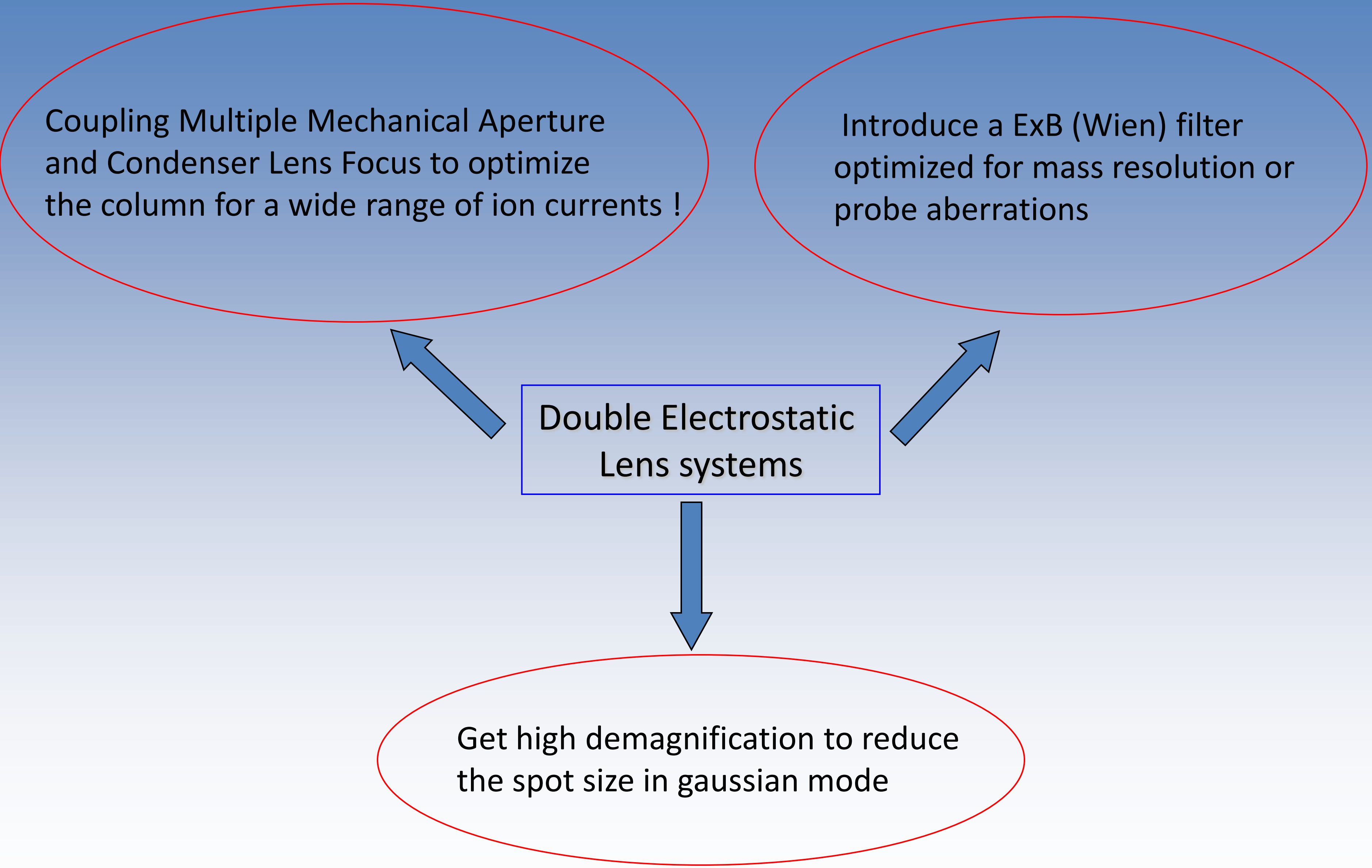
U_{Ex}

U_{Sup}

U_C

U_{EHT}

U_{Obj}



Coupling Multiple Mechanical Aperture and Condenser Lens Focus to optimize the column for a wide range of ion currents !

Introduce a ExB (Wien) filter optimized for mass resolution or probe aberrations

Double Electrostatic Lens systems

Get high demagnification to reduce the spot size in gaussian mode

Essential FIB Specifications

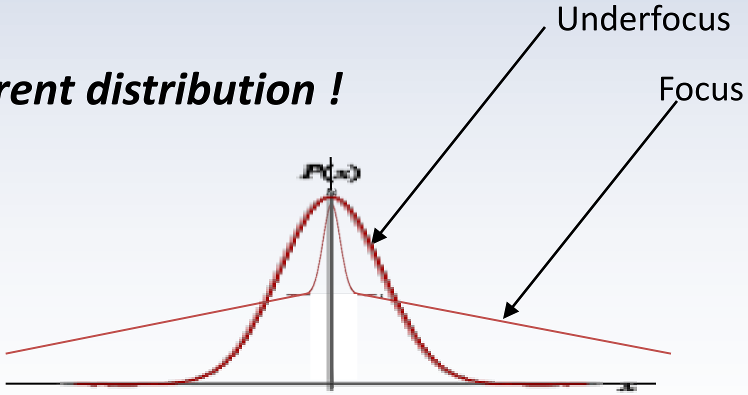
Ip	Resolution	Probe size
1pA	< 3 nm	> 15 nm
>20 nA	< 1µm	Few µm

Resolution : Measurement on images at 20%-80% on edge object
Spot Size : Measurement on a spot machined for 1s on Si

Large discrepancy !!! No agreement !

The question of current distribution !

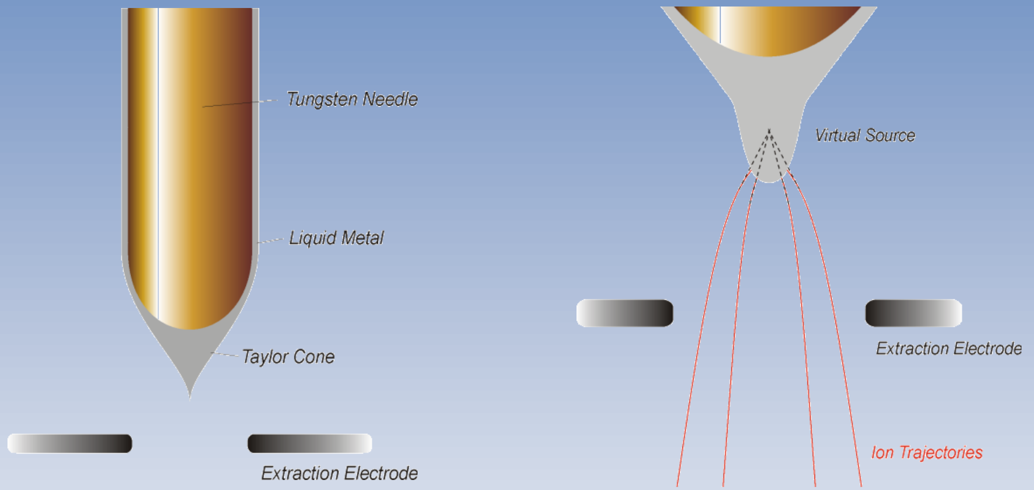
Low Current : Gaussian shape



High Current : Wide Tails depending on focus !

Main Limitations

The ion source : LMIS



Virtual Source Size : 50 nm → (real size 1nm ?)

Brightness : 10^6 ions/cm^2.Sr → CFEG : 10^9 ions/cm^2.Sr

Angular Current Density : 15µA/Sr → 60pA for 1mrad

Energy Spread : 5eV for Ga → Chromatic aberrations

Main Limitations

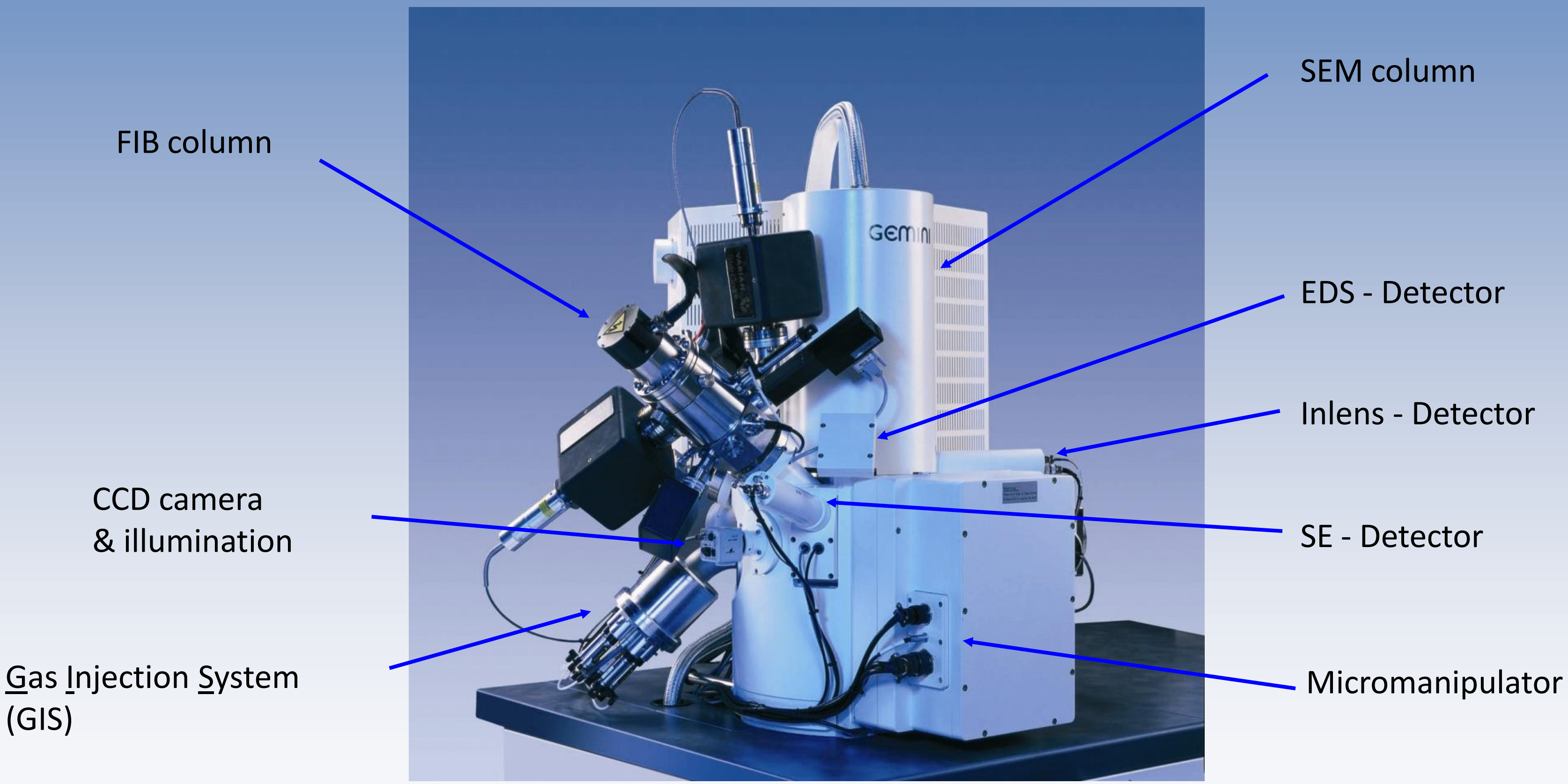
Electrostatic Lenses

Order of Magnitude of Electrostatic Lens System Aberration Coefficients :

- Cs ~ 1m Spherical Aberration
- Cc ~ 100 mm Chromatic Aberration

LMIS source and Lens Properties limit the final performances in Low and High current modes

A typical SEM/FIB system for TEM Preparations



FIB column

SEM column

EDS - Detector

Inlens - Detector

CCD camera
& illumination

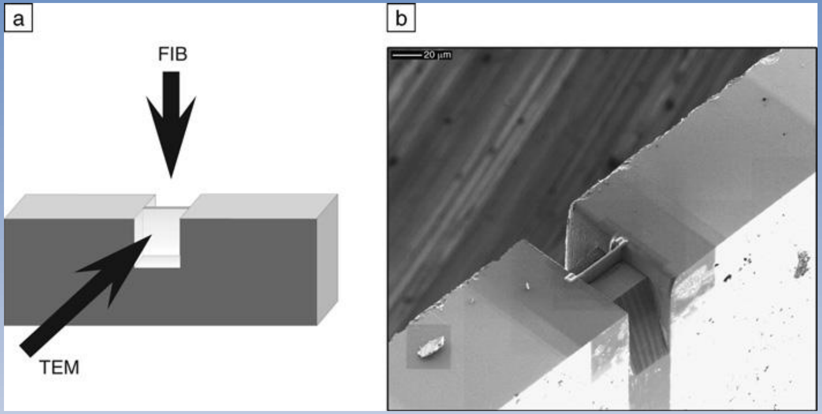
SE - Detector

Gas Injection System
(GIS)

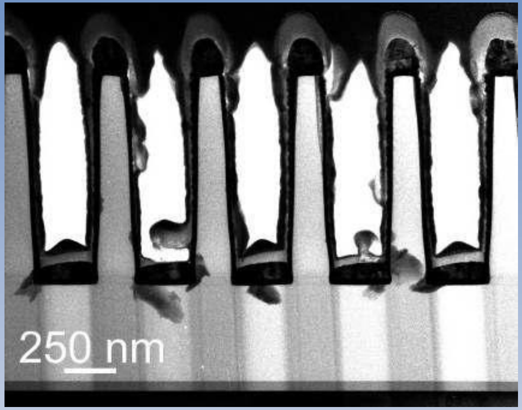
Micromanipulator

Vacuum Clean Room

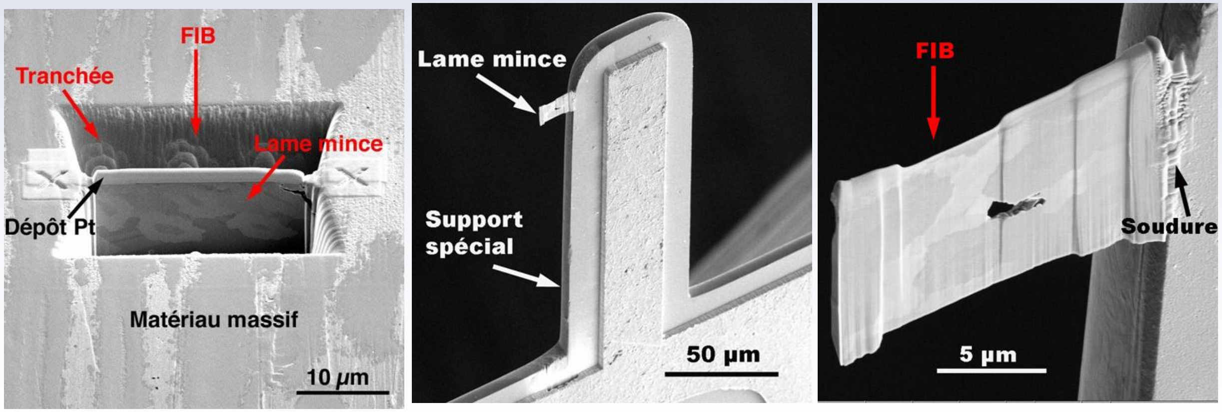
Nanomaching : TEM lamellas



Pre-thinning
Limited tilt
Poor analysis



curtaining

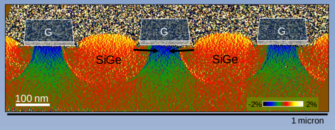


Lamella manipulation
Lamella distortion
Time Consuming

What is new with TEM ?

Cs Correction and/or Monochromator for electron microscopes :

- Image (TEM and EFTEM)
- Probe (STEM and STEM-EELS)

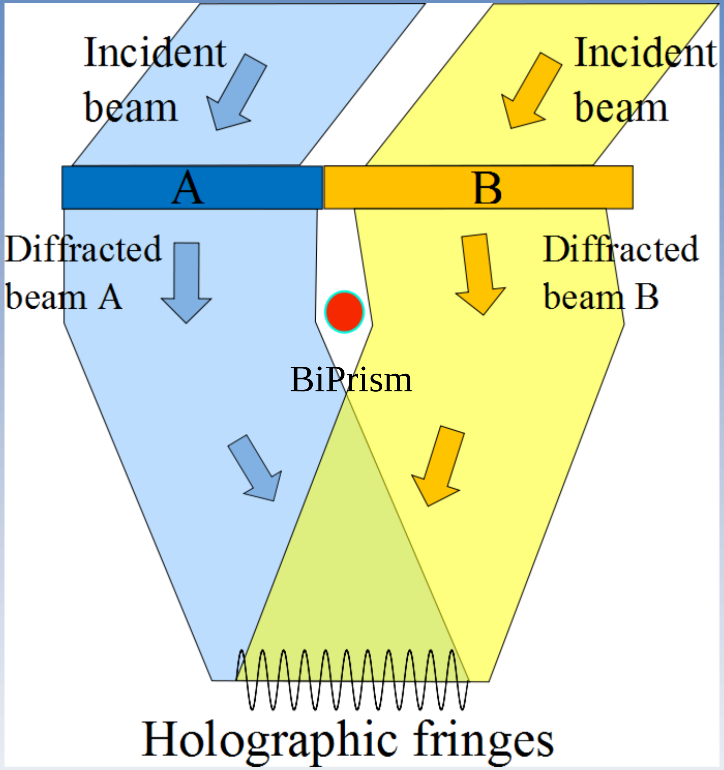


Sub Angström image resolution
0.1 eV EELS resolution

Huge Improvements in Image and Analysis limits

New Thin Sample Preparation Needs

Dark-Field Electron Holography (DFEH)



Dark-Field Bragg position

Spatial resolution: 2 - 4 nm

Field of view: 500nm x 2µm

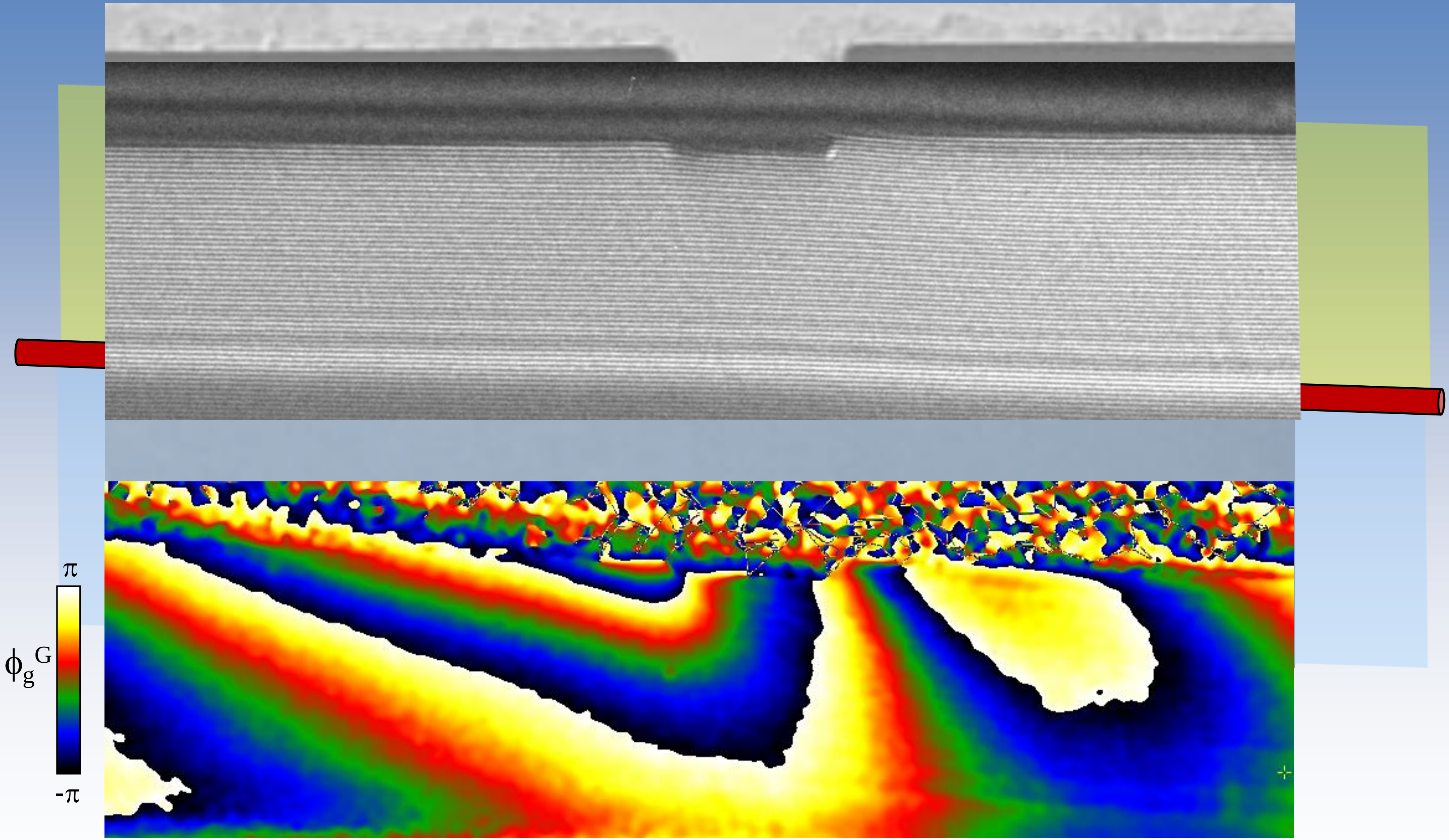
Precision: few 10^{-4}

M.J.Hÿtch, F.Houdellier, F.Hüe and E.Snoeck, Nature ***453*** *1086 (2008)*

M.J.Hÿtch, F.Houdellier, F.Hüe, E.Snoeck, French Patent Application FR N° 07 6711.

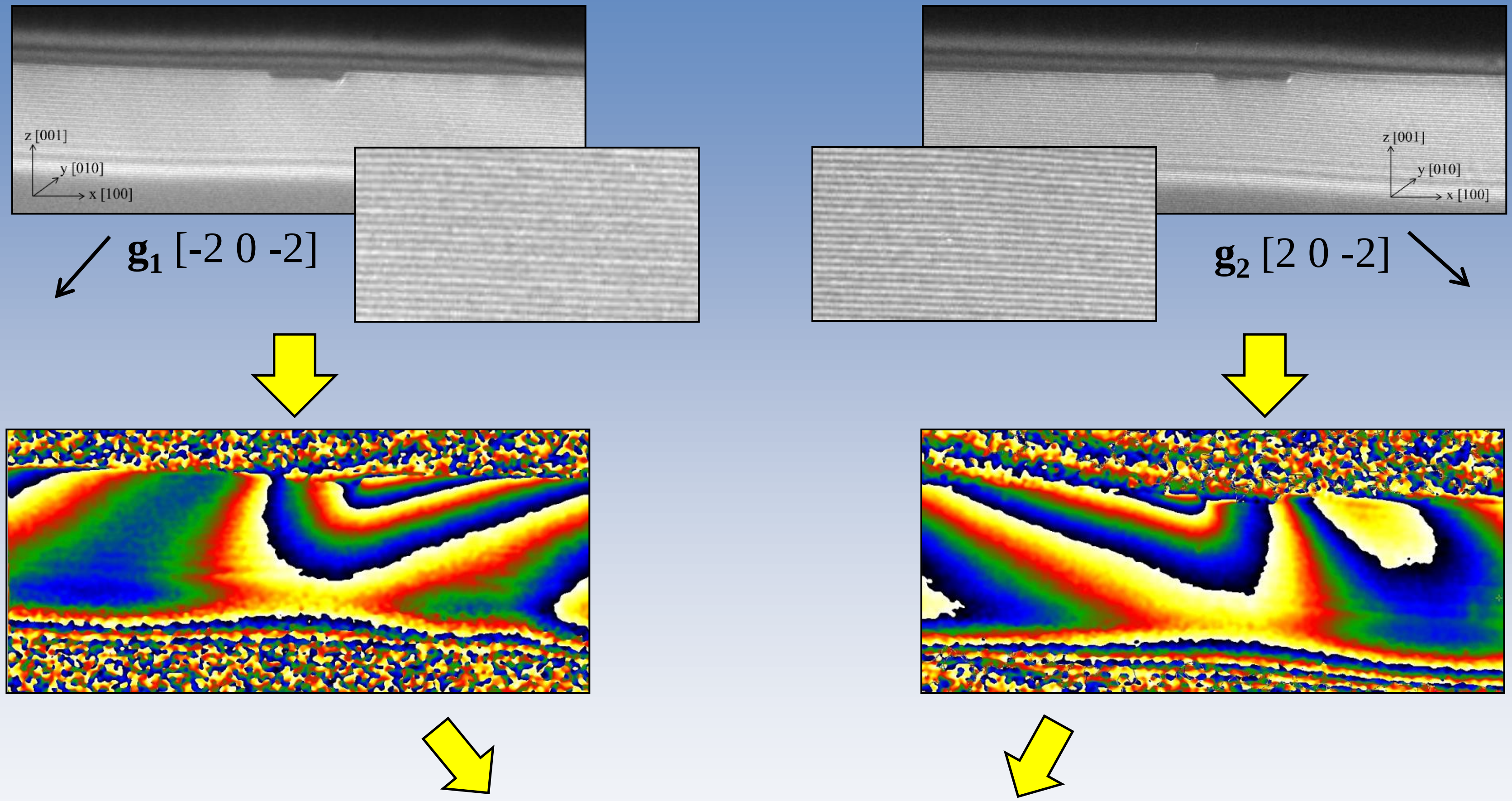
Dark-Field Electron Holography (DFEH)

Experiment



Dark-Field Electron Holography (DFEH)

2D Deformation



$\mathbf{g}_1$ [-2 0 -2]

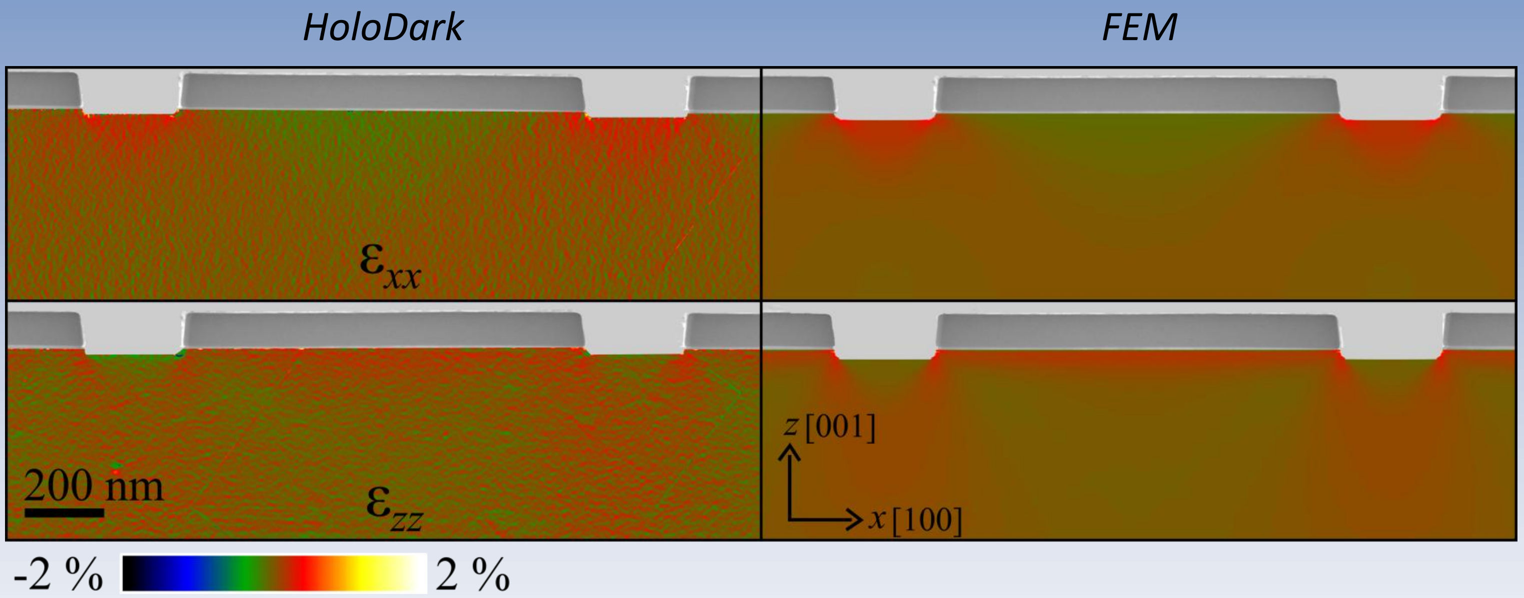
$\mathbf{g}_2$ [2 0 -2]

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

HoloDark 1.0 (HREM Research) by M. J. Hÿtch, C. Gatel & K. Ishizuka

Dark-Field Electron Holography (DFEH)

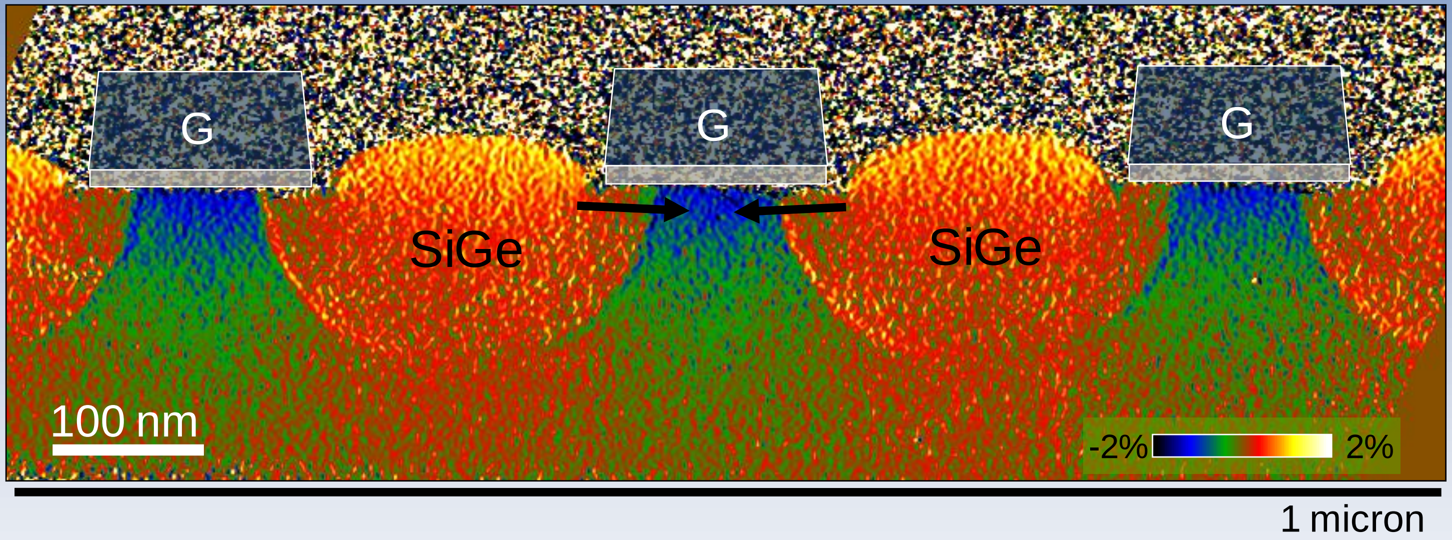
Simulation Vs Experiment



Simulations with σ_i=1.2 GPa and E=300 GPa

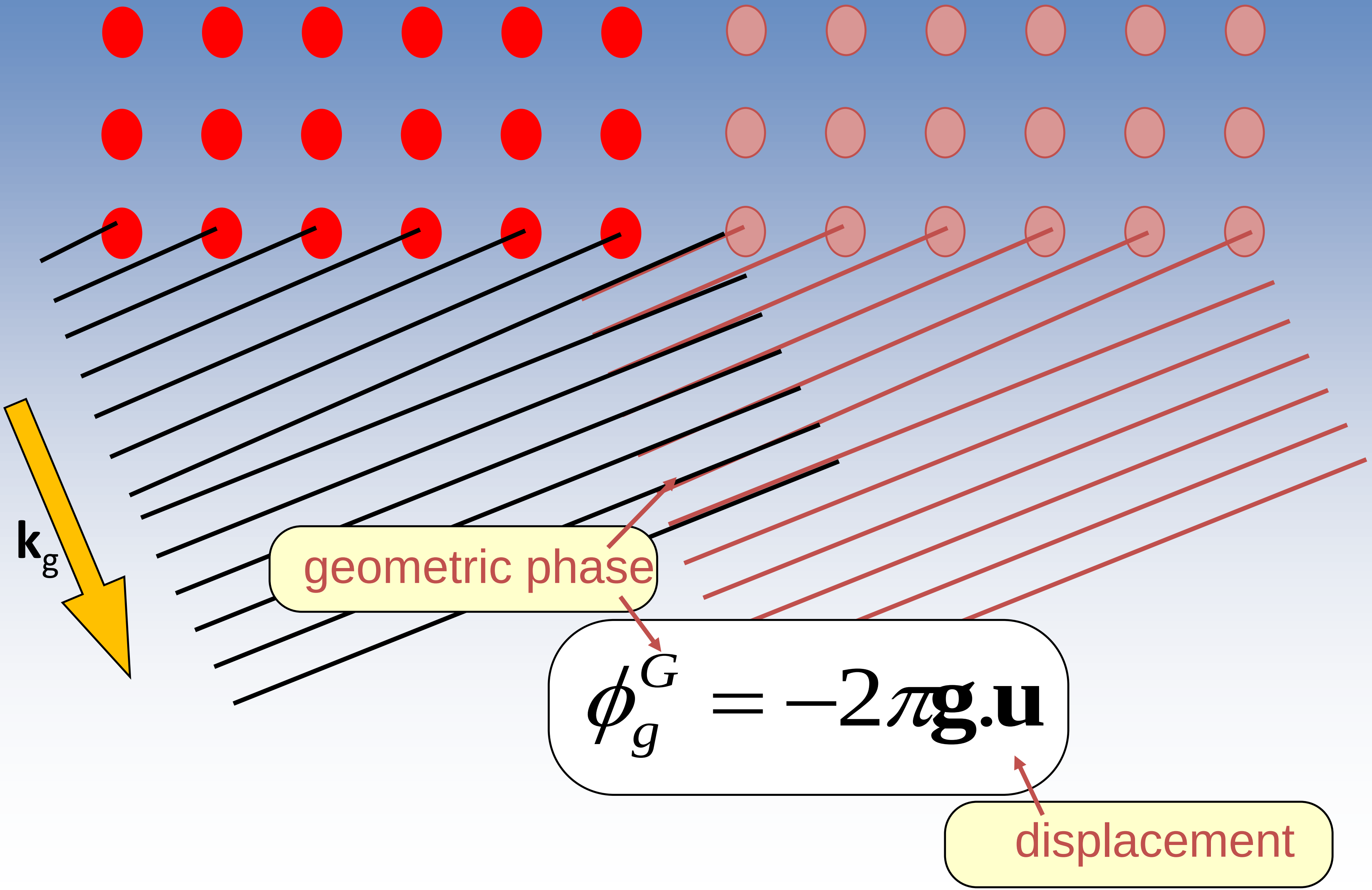
Dark-Field Electron Holography (DFEH)

On a real MOSFET



2D Strain measurements on a set
of MOSFETs

Geometric Phase Analysis

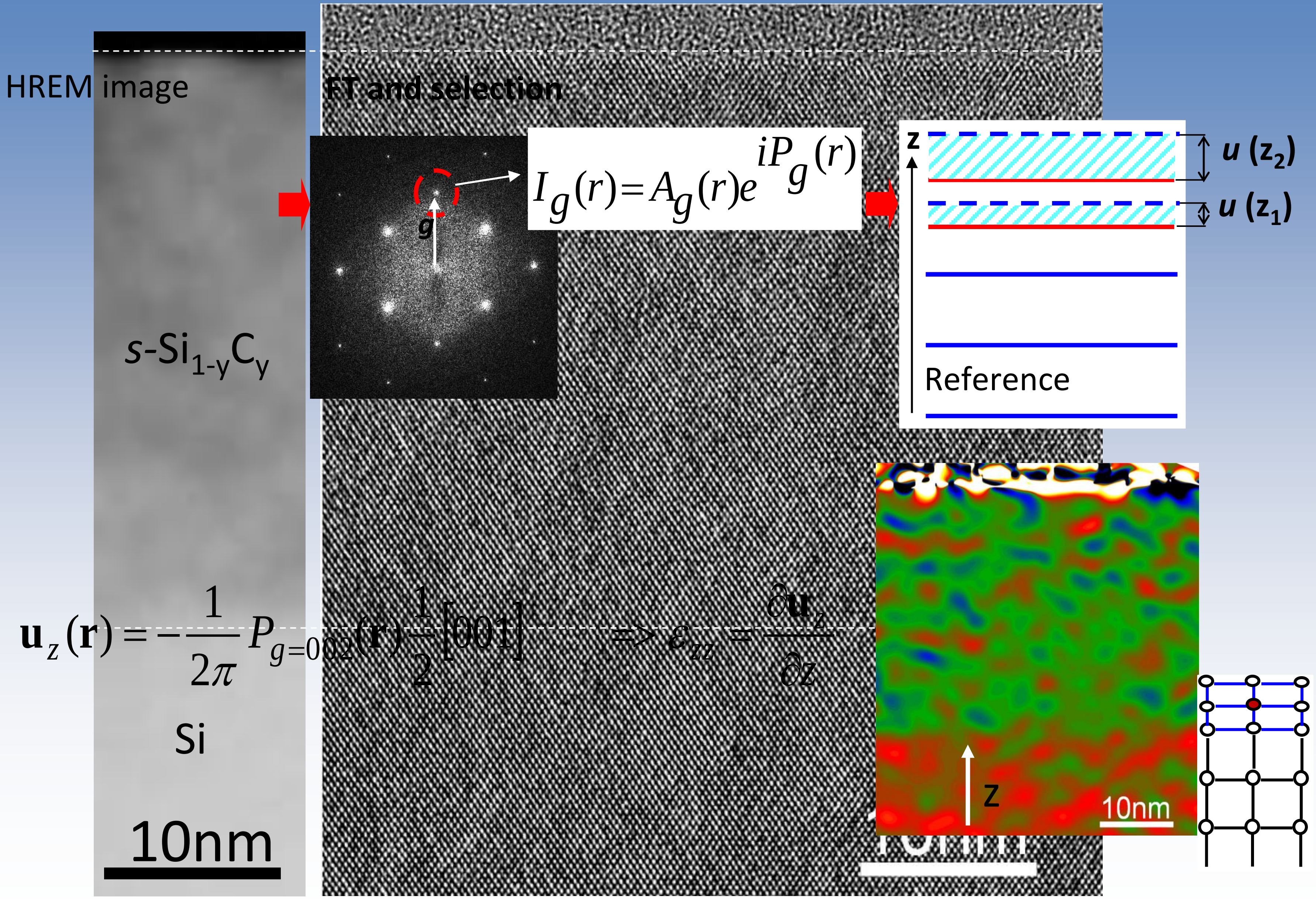


geometric phase

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

displacement

1D strain: GPA



$$I_g(r)=A_g(r)e^{iP_g(r)}$$

$$\mathbf{u}_z(\mathbf{r})=-\frac{1}{2\pi}P_{g=002}(\mathbf{r})\frac{1}{2}[001] \Rightarrow \varepsilon_{zz}=\frac{\partial \mathbf{u}_z}{\partial z}$$

The Perfect lamella

- Parallel face lamella on a long range (few micron)
- Perfectly flat sample → No Curvature
- Ultrathin sample (less than 10 nm) for HREM
- No amorphous layer to reduce phase artefacts
- High speed preparations

Conclusions and perspectives for lamellas and advanced TEM methods

- Steep ion beam distributions for High current (Plasma Sources, Cold Ions, Cs Corrector ?)

- High resolution at very low voltage (GFIS Ne, Cold Ions ?)

- New strategies for ultraflat samples (Backside)

- No Dopant ions for field and doping measurements (Neutral Gas, Si in Si/SiGe ?)

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