Resolving Energy Materials with Transmission Electron Microscopy

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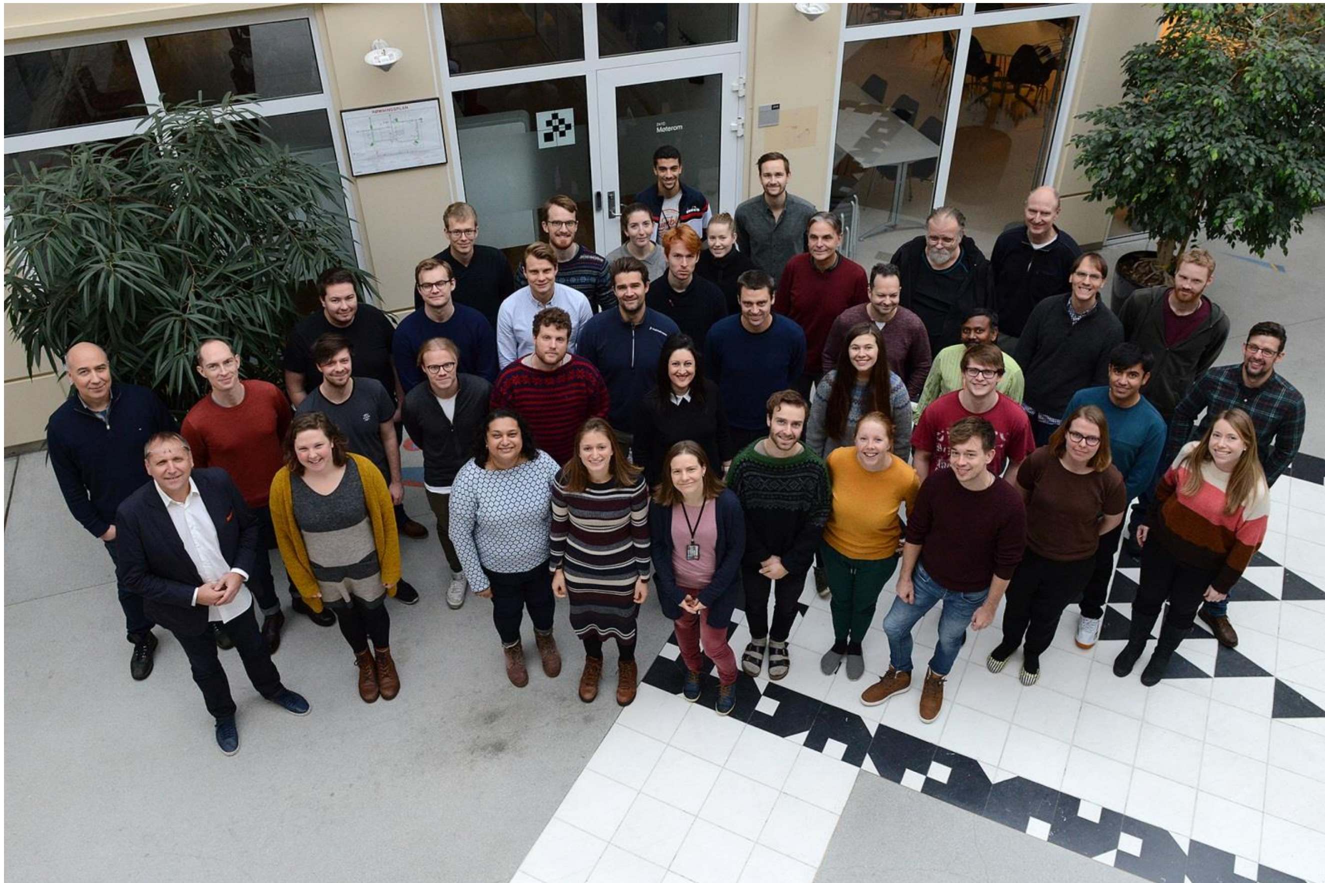
UiO : University of Oslo

SMN SENTER FOR MATERIALVITENSKAP OG NANOTEKNOLOGI

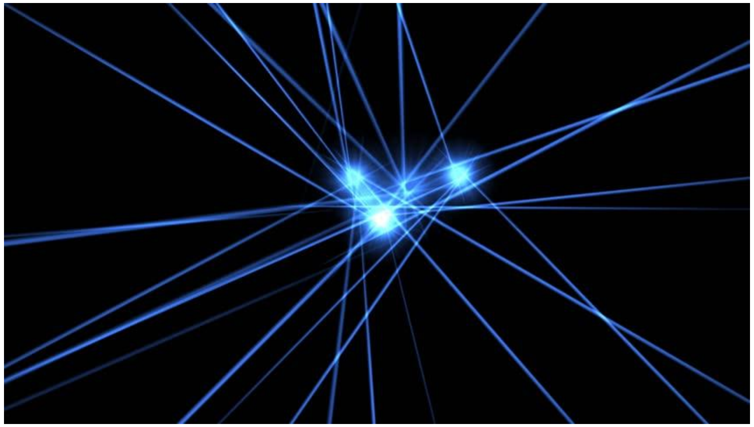


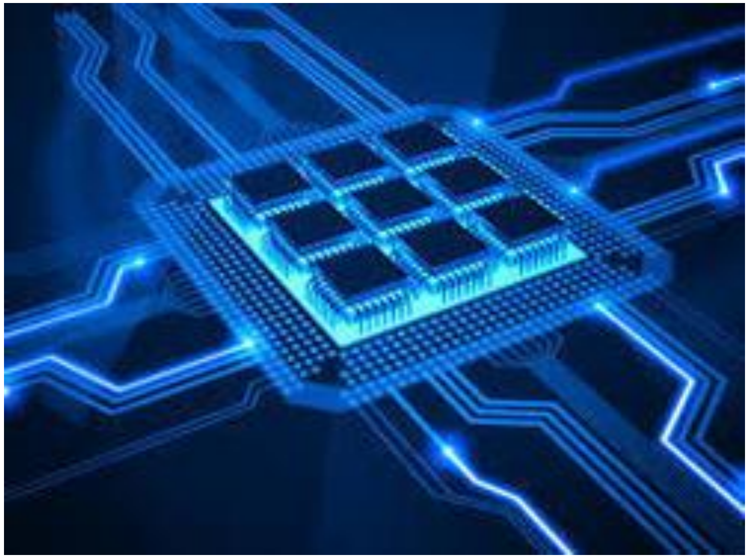
Structure
Physics
group

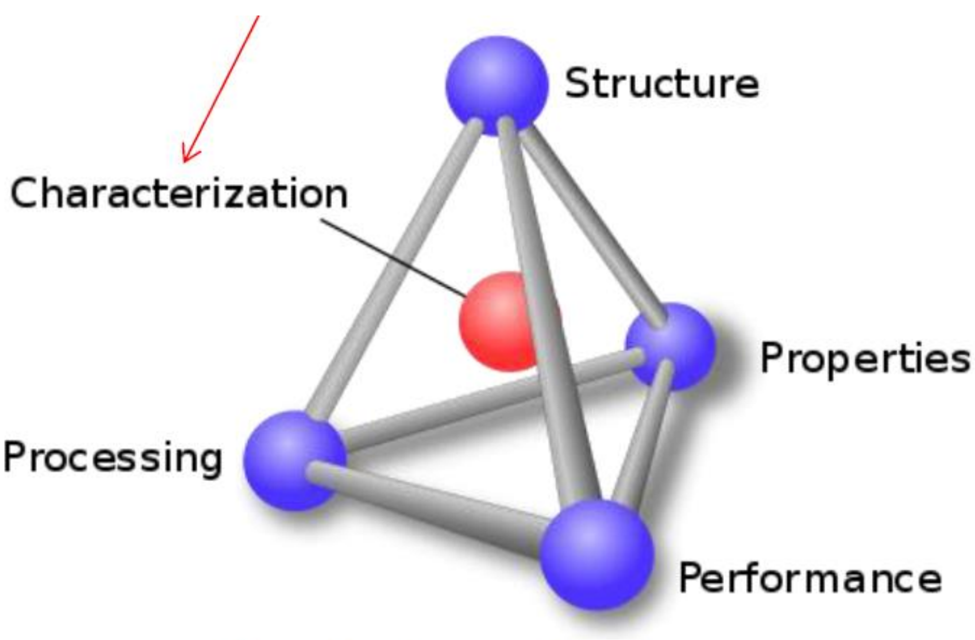
LENS group

UiO : University of Oslo

Materials for applications in solar cells and power electronics







Materials Science Paradigm

local structure and inhomogeneities

Defects

Interfaces

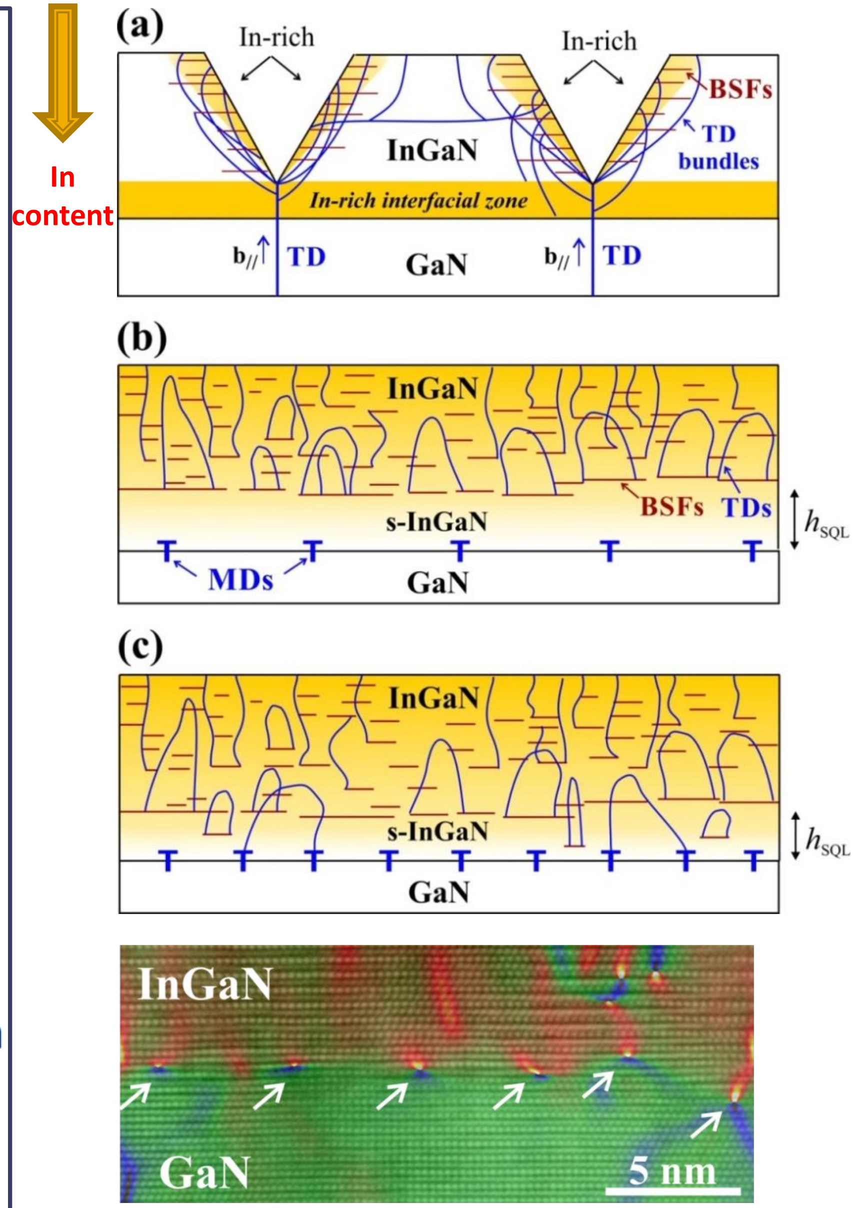
Chemical composition

Precipitates

Chemical bonding

Atomic Structure

Electronic Structure



Bazioti C. at al.
JOURNAL OF APPLIED PHYSICS 118,

Point and extended defects + interaction with dopants

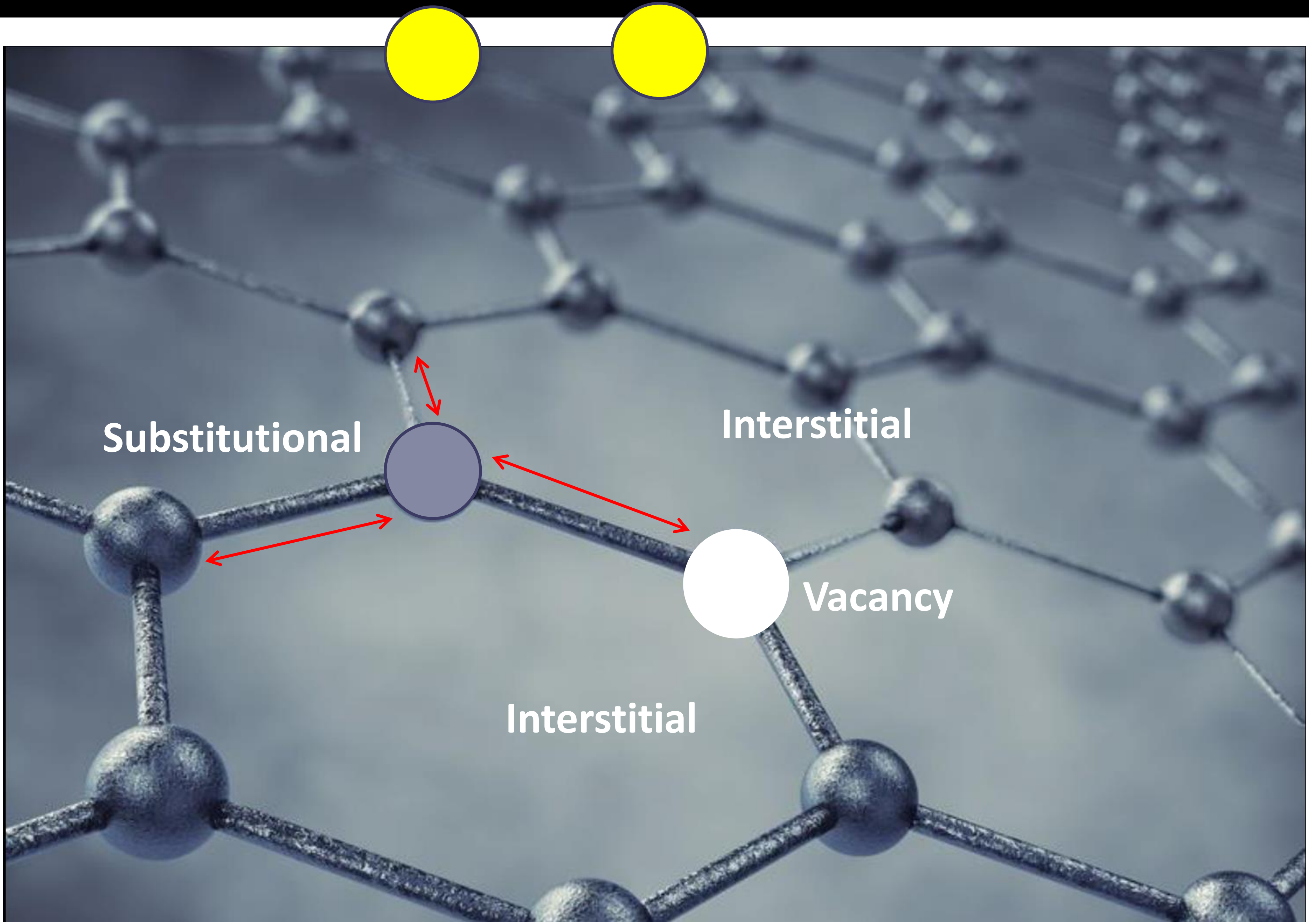
Direct influence on semiconductor properties

Need for **precise identification of defect-types**
understanding their **formation and evolution** is crucial for mastering semiconductors.

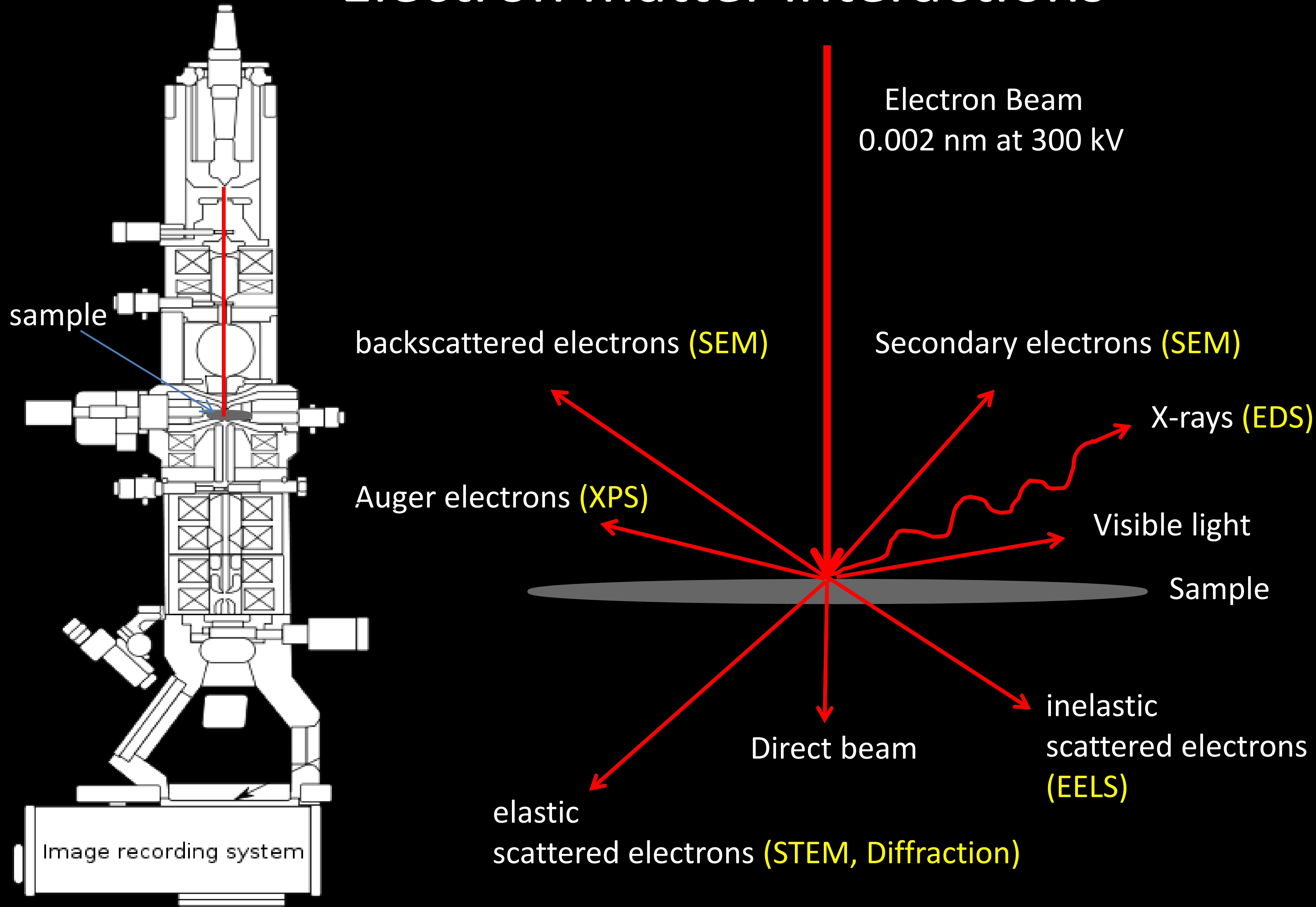
- **ZnO**, a wide direct band-gap semiconductor (3.4 eV at RT) interesting for applications in solar cells.
- **doping with desirable impurities** is a key process in **device fabrication**
- **induced defects**, are detrimental for the **device performance**
- **post-annealing** is typically used to minimize/remove them.

- **Interstitials (Zn_i, O_i)**
- **Vacancies (V_{Zn}, V_O)**
- **complexes with dopants**

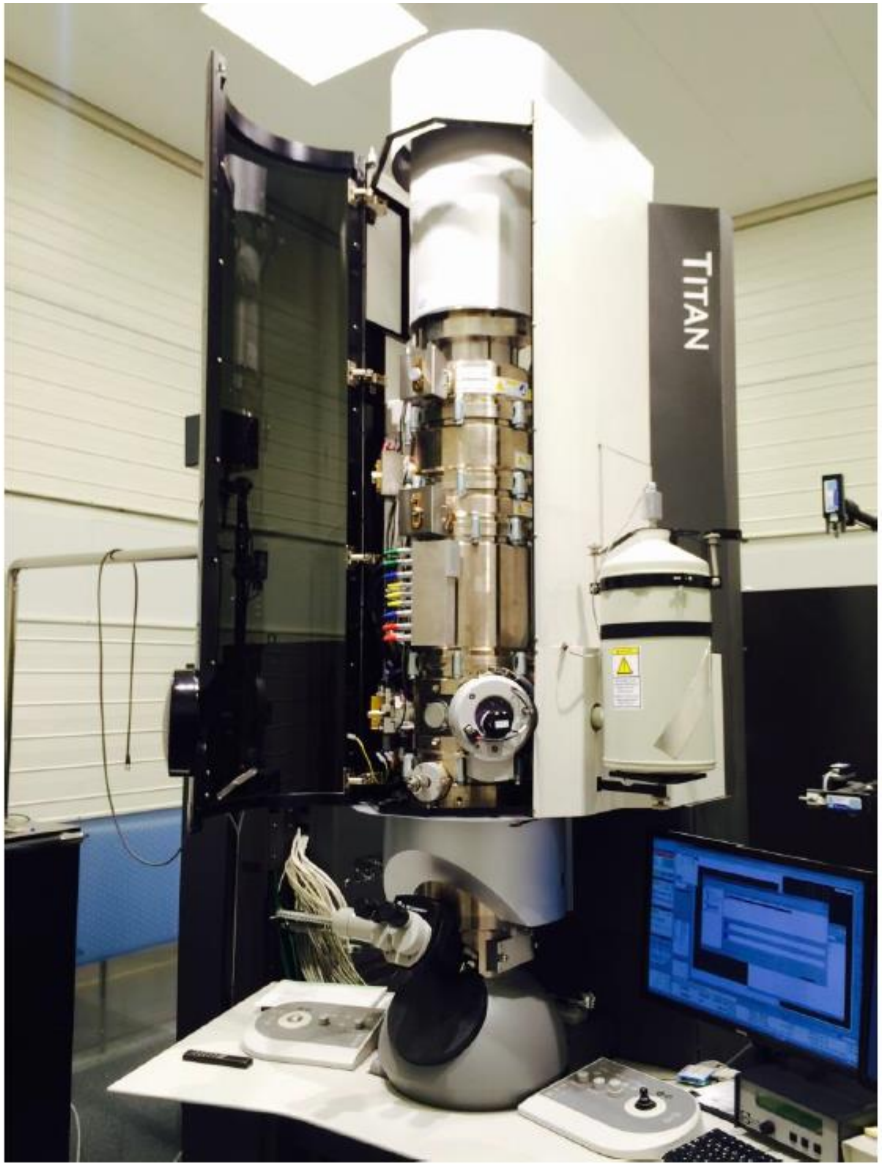
N-implanted ZnO	**p-type** doping
$(ZnO)_{1-x}(GaN)_x$	**Bandgap engineering**

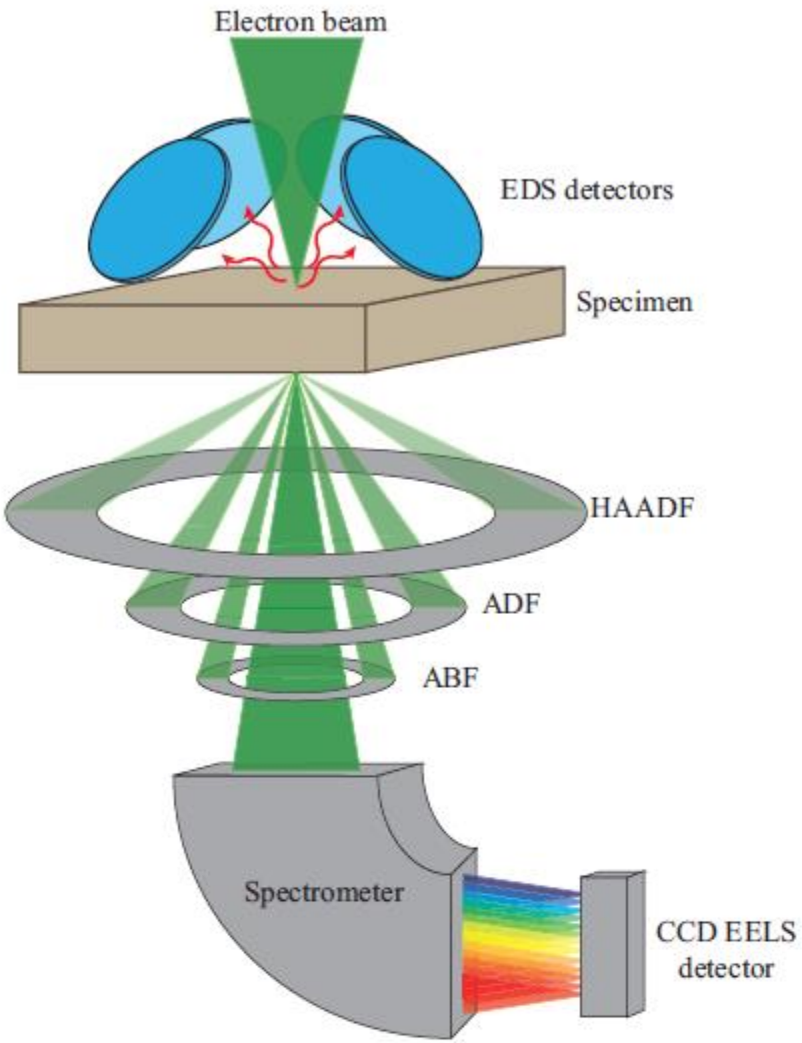

Substitutional
Interstitial
Vacancy
Interstitial

Electron matter interactions



Multiple detectors:
Simultaneous information through different mechanisms of electron-specimen interactions



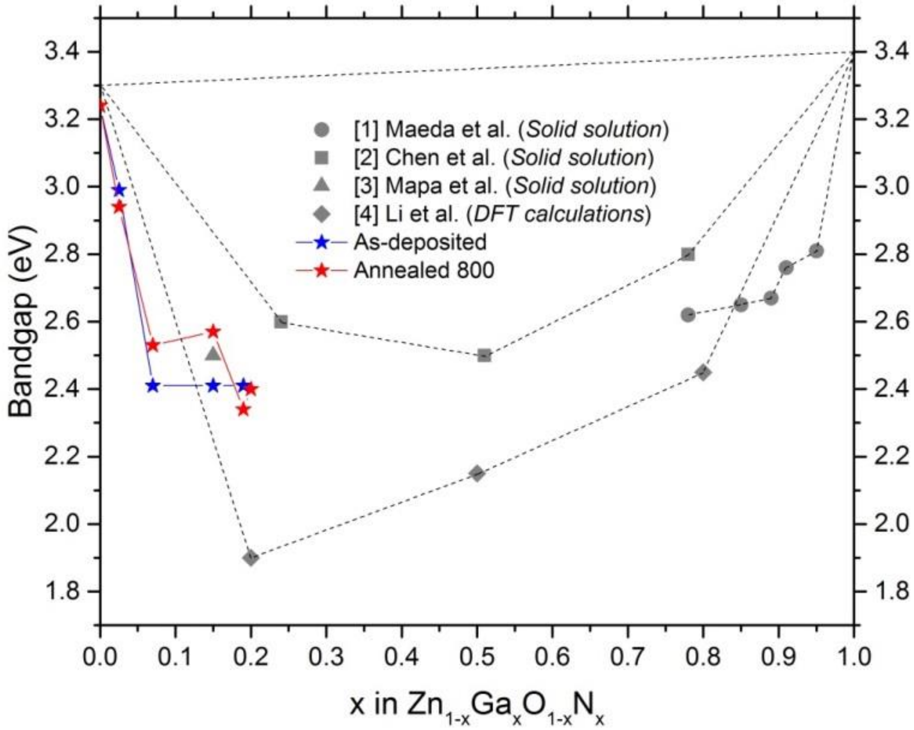


Schematic by V.S. Olsen

FEI Titan G2 60-300 kV, NorTEM facility- UiO
equipped with a **CEOS DCOR probe-corrector** and **monochromator**.

- **ZOGN system**. Importance of ***bandgap engineering*** in designing novel functional semiconductor materials

- **ZnO(II-VI) and GaN(III-V)** are wide-bandgap semiconductors

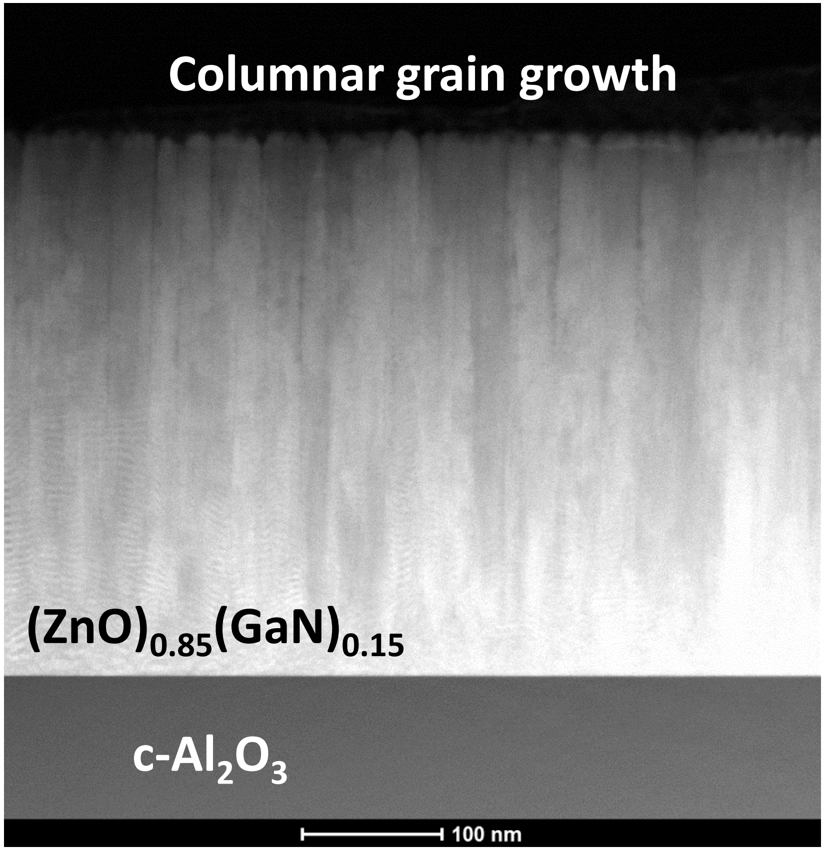


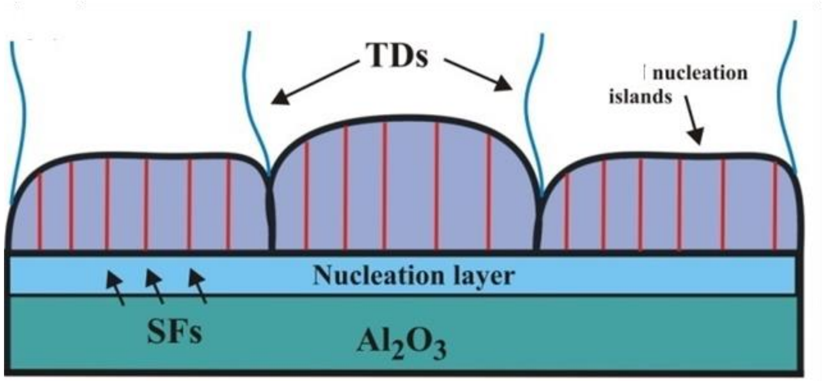
- **Strong band-bowing effect** → **significant bandgap reduction of the alloy**

✓ ***Tailoring optical properties by only changing the composition***

RF magnetron sputtered $(ZnO)_{1-X}(GaN)_X$ thin films deposited on c-Al_2O_3 substrates

primary aim : significant bandgap reduction + good crystal quality





Schematic by: Journal of Applied Physics **115**, 213506 (2014)

electrical and optical performance degraded by the formation of grain boundaries, pores and dislocations, due to charge-carriers and photons scattering.

Olsen V.S., Bazioti C. et al.
Phys. Status Solidi B 1800529, 2019

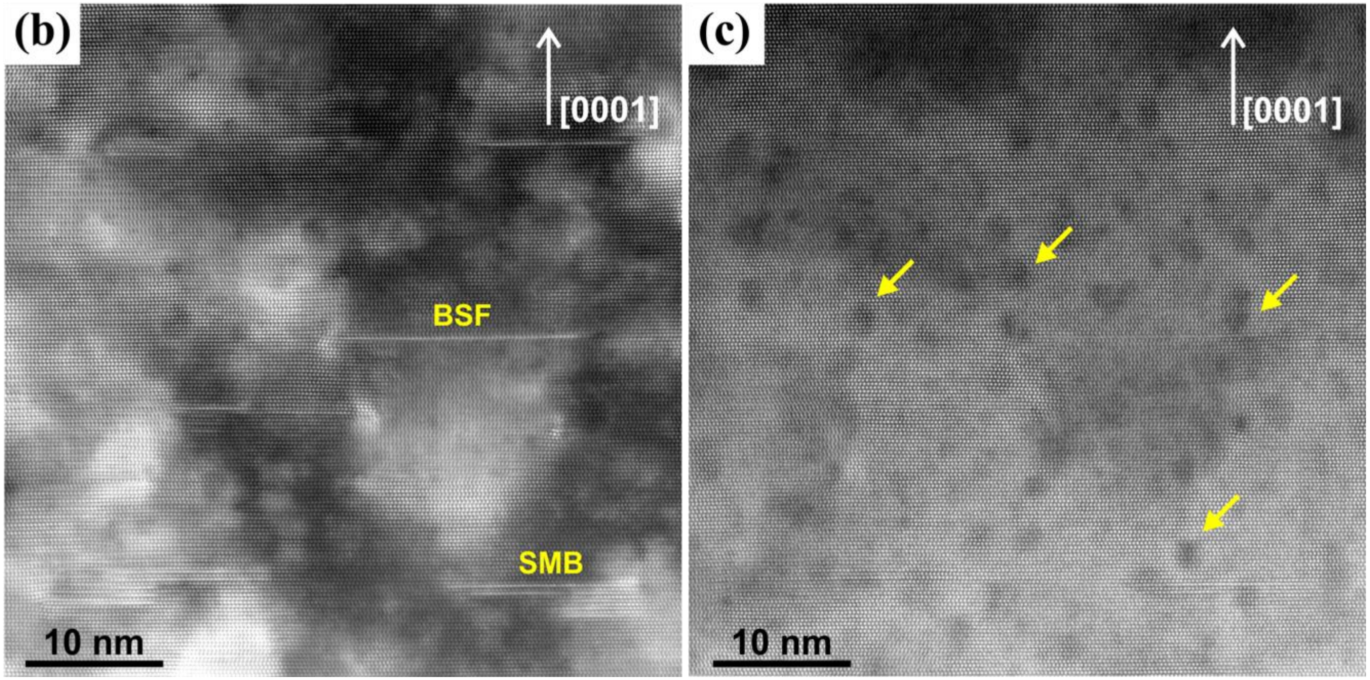
Olsen V.S., Bazioti C et al.
Semicond. Sci. Technol. 10, 1, 2019

Olsen V. S. , Baldissera G. et al.
Phys. Rev. B 100, 165201, 2019

Different STEM detectors help us to have complementary views of the same area

recorded simultaneously

ADF-STEM **HAADF-STEM**



Z-Contrast + Diffraction Contrast

We can easily detect the localization of extended defects

Pure Z-Contrast

We can easily detect clusters of lower atomic density (zinc-vacancy clusters)

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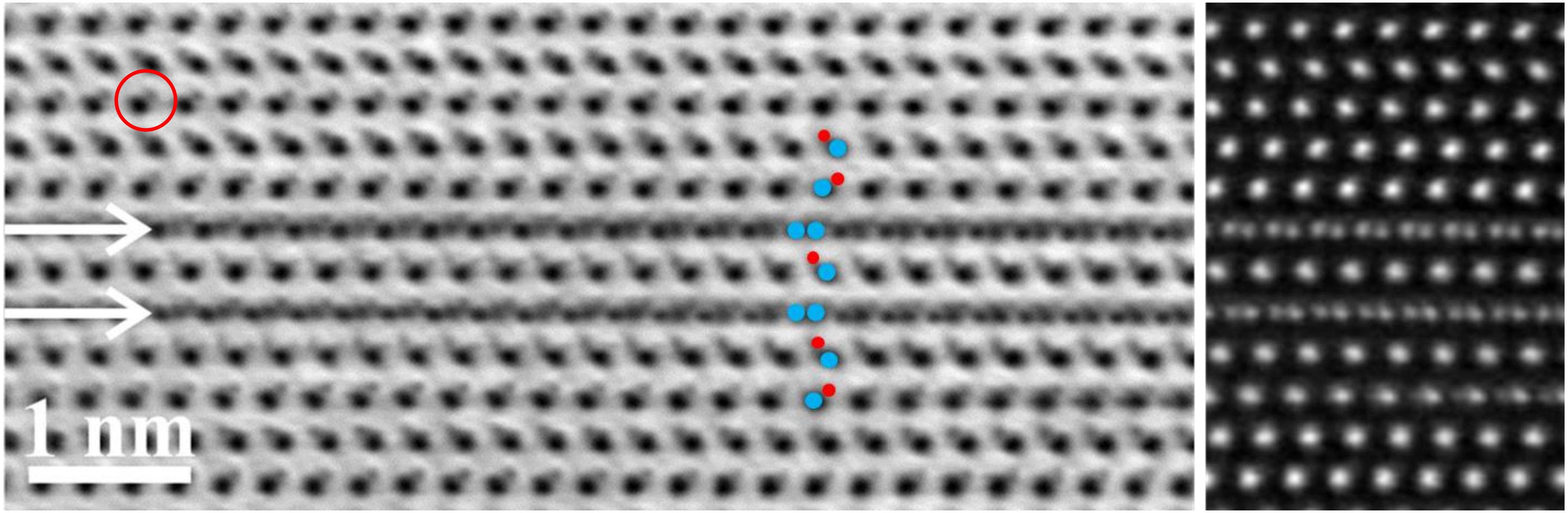
Different STEM detectors help us to have complementary views of the same area

Example of Stacking faults in ZnO

recorded simultaneously

ABF-STEM **HAADF-STEM**



Diffraction Contrast

At low collection angles both heavy and light elements can be visualized.
We see both **Zn** and **O** atomic columns.

Pure Z-Contrast

Only heavy elements scatter at high angles.
We see only **Zn** atomic columns.

We can also identify polarity :)

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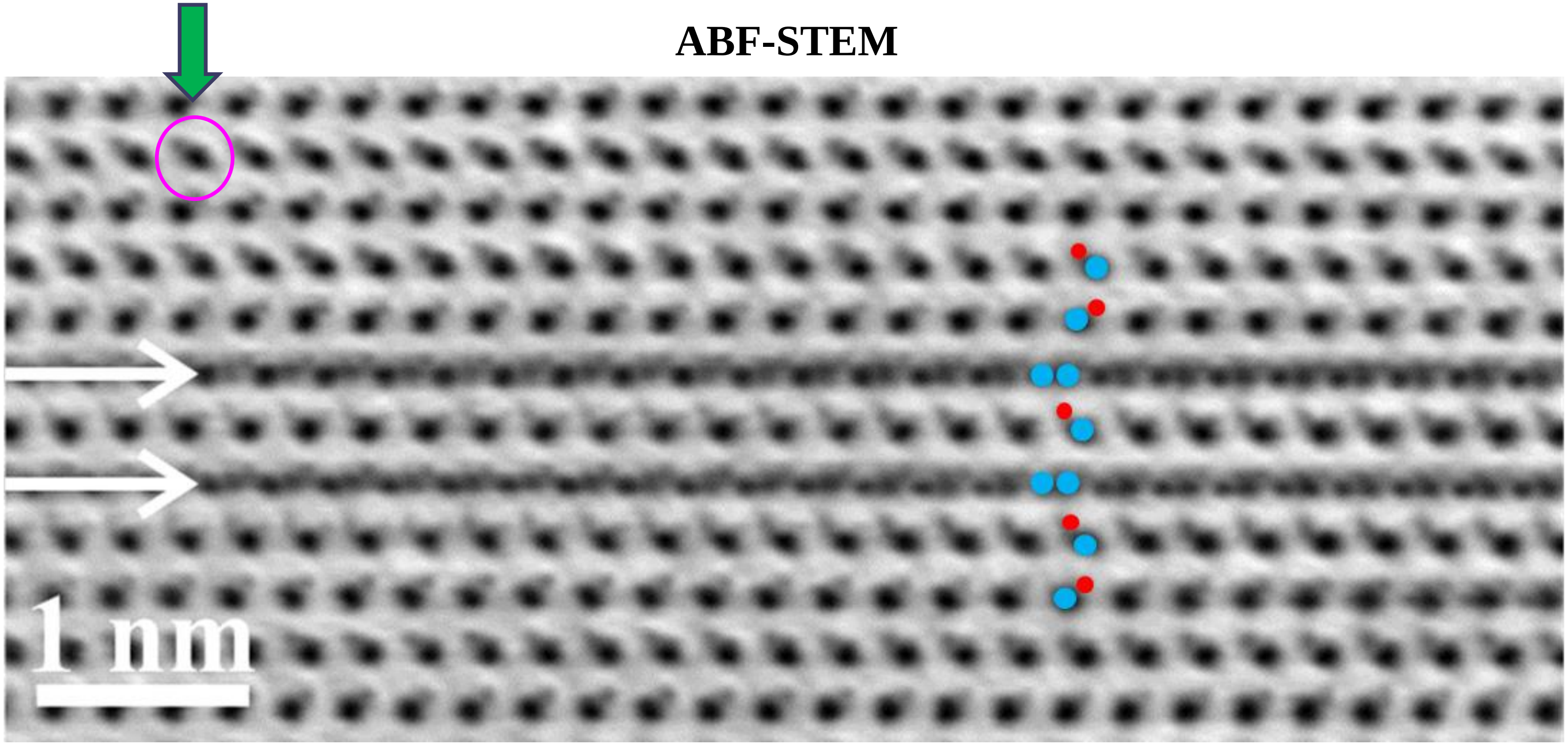
High Spatial resolution (0.08 nm)

We could not resolve Zn-O dumbbells some years ago, before aberration correctors!

ABF-STEM



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Brief History: The state-of-art TEM

Resolution limit

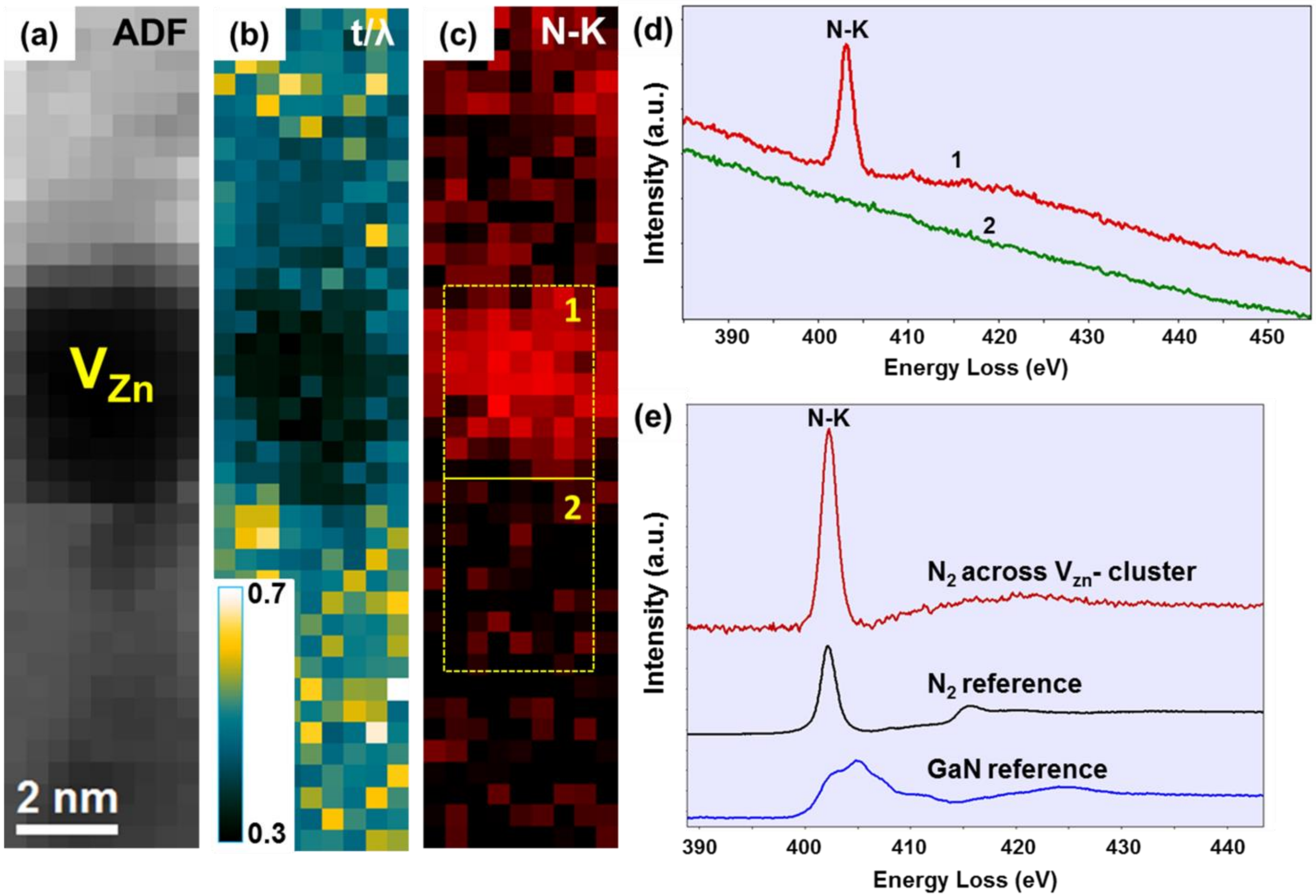
Year	Resolution
1940s	**~10nm**
1950s	~0.5-2nm
1960s	0.3nm (transmission) ~15-20nm (scanning)
1970s	0.2nm (transmission) 7nm (standard scanning)
1980s	0.15nm (transmission) 5nm (scanning at 1kV)
1990s	0.1nm (transmission) 3nm (scanning at 1kV)
2000s	**<0.1 nm (Cs correctors)**

Core of the M100 galaxy seen through Hubble (source: NASA)

Different STEM detectors help us to have complementary views of the same area

STEM + EELS at a zinc vacancy cluster

Monochromated spectra, Dual-EELS



Simultaneous information of: structure + chemical info + bonding

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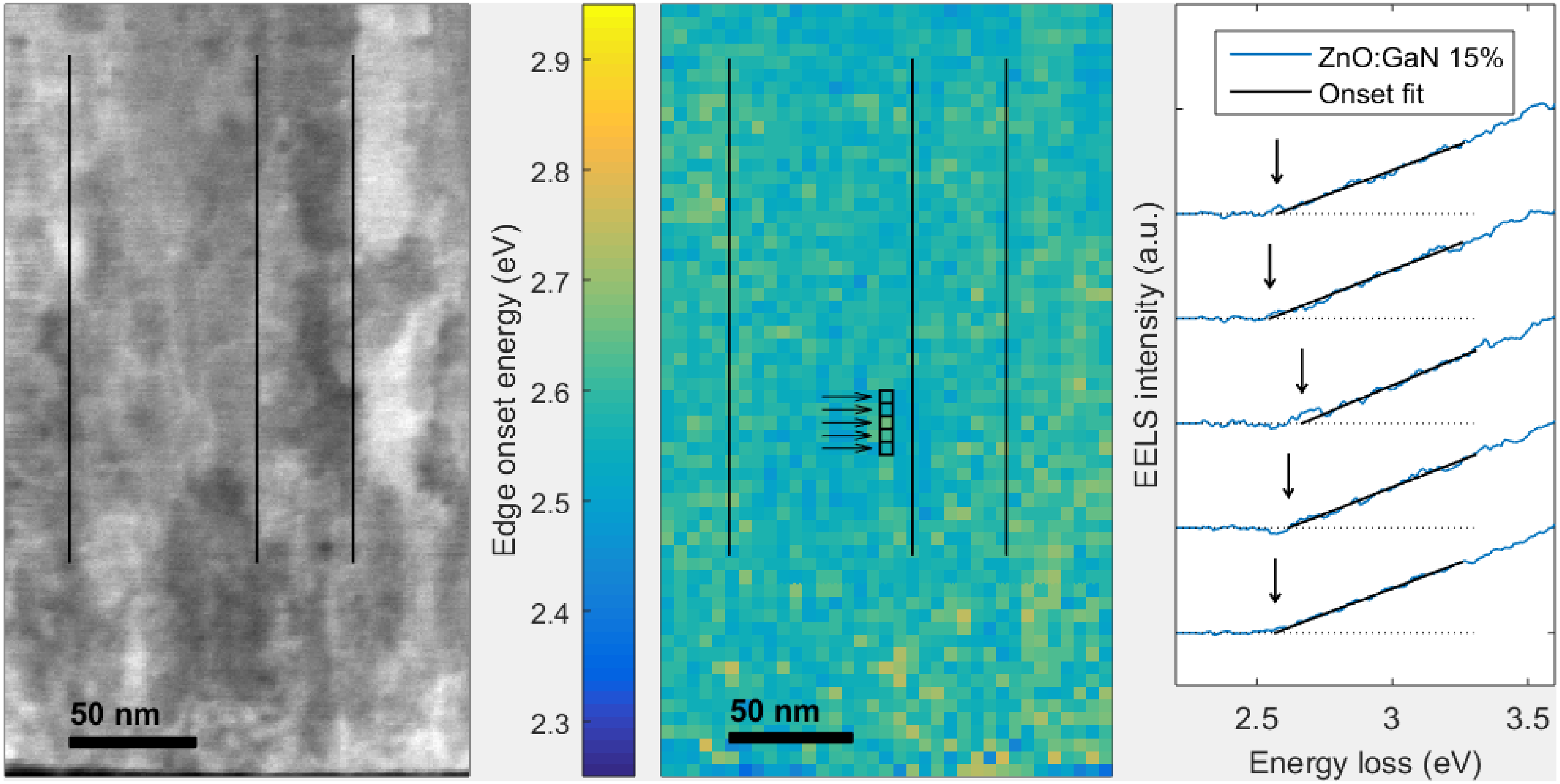
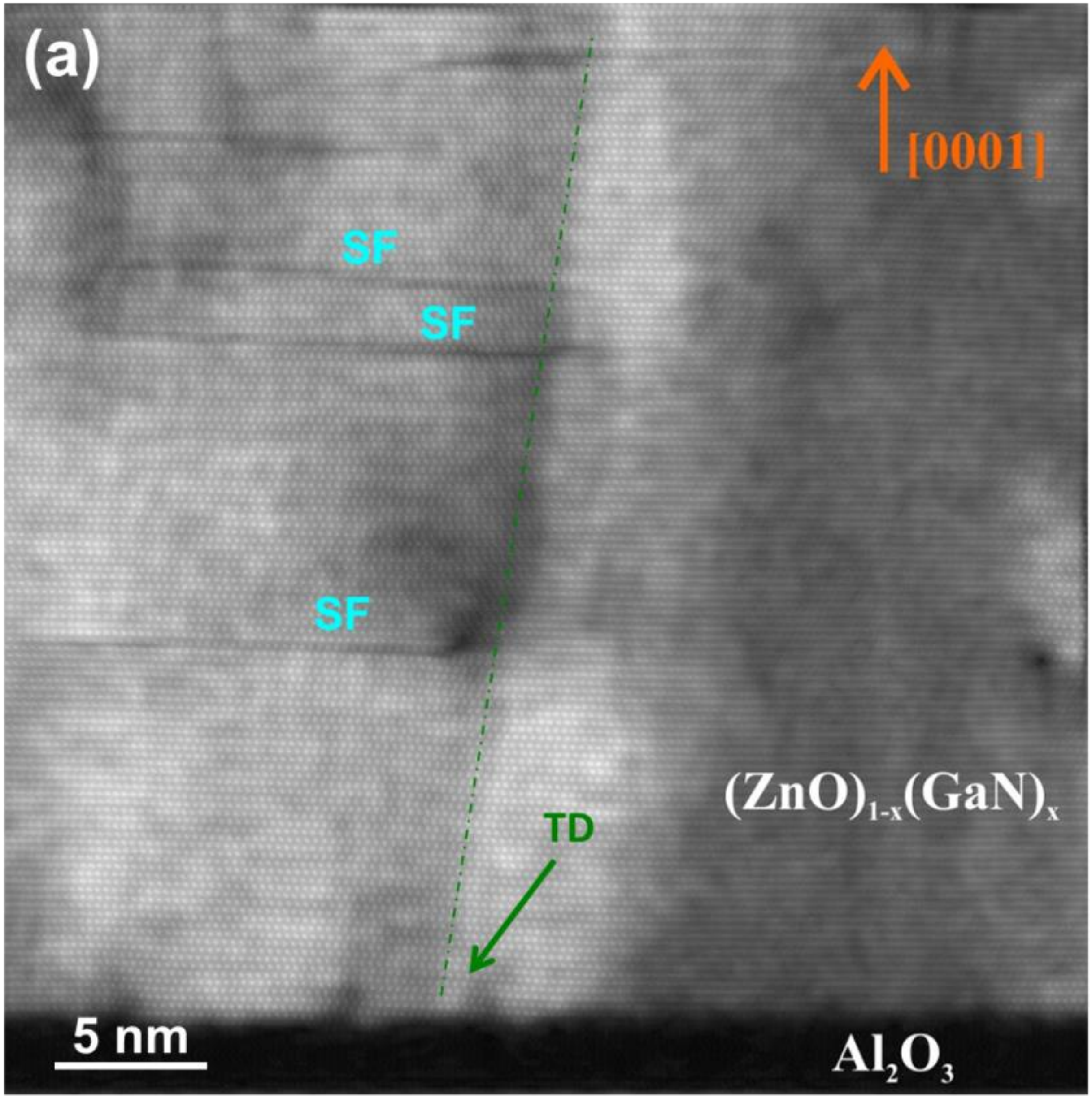
Bandgap measurements on the nanoscale using STEM-EELS



Olsen V. S. et al. Phys. Rev. B 100, 165201, 2019

Analysis of defect networks



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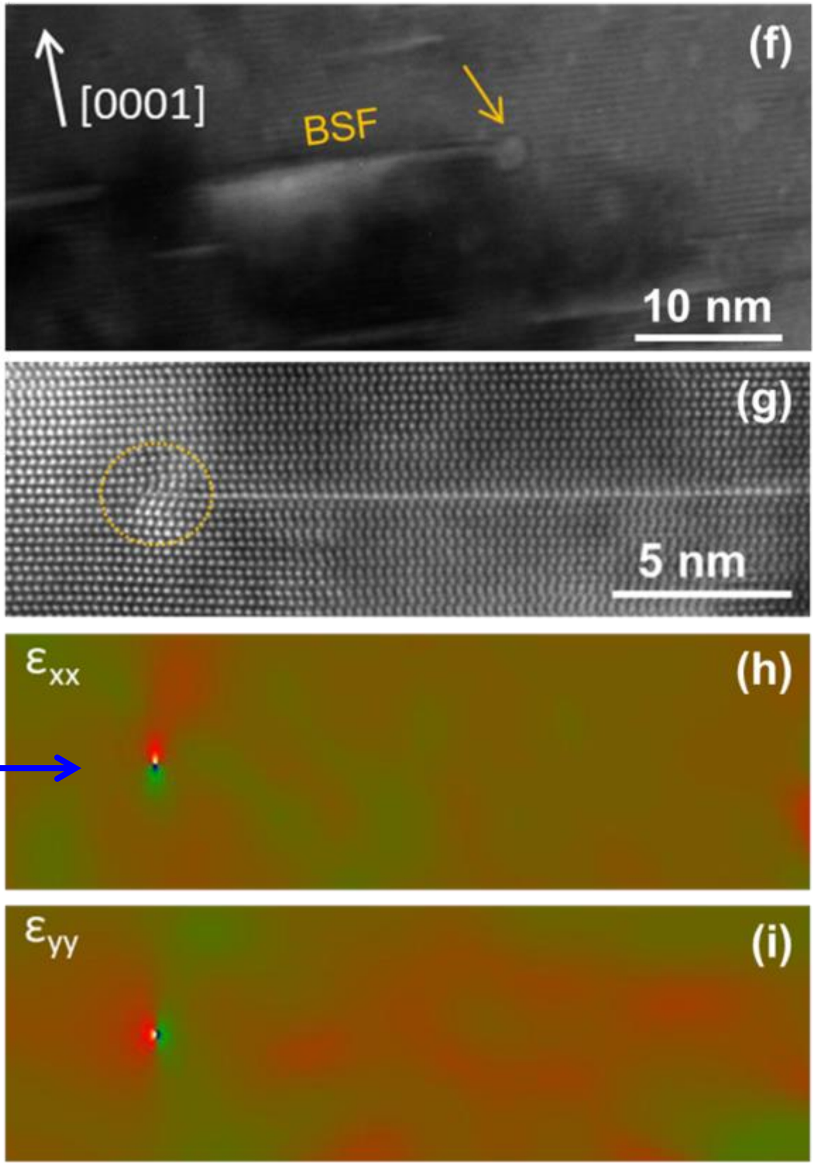
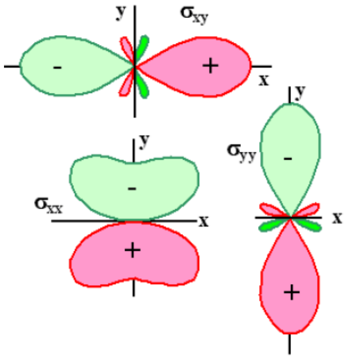
HR(S)TEM images and Geometrical Phase Analysis (GPA)
Strain fields at nanoscale



Dislocations bounding a stacking fault
Visualization of local strain fields



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Thank you for your attention!

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