DESY Summer Student Lectures

Solid State Physics and Nanoscience @ DESY

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Centre for X-Ray and Nano Science CXNS
Deutsches Elektronen Synchrotron (DESY) and
University of Hamburg, Physics Department

HELMHOLTZ
ASSOCIATION

CXNS
Centre for X-Ray
and Nano Science

UHH

DESY

Solid State Physics and Nanoscience @ DESY

Scattering with coherent X-rays
(G. Grübel)

Complex liquids and glasses
Ultrafast magnetization dynamics

X-ray Physics and Nanoscience
(A. Stierle)

Catalytic Reactions on Nanomaterials
Nanoscale Phenomena
Oxide Surfaces and Interfaces

X-ray Crystallography and Imaging
(E. Weckert, I. Vartaniants)

Coherent diffraction from individual semiconductor nanostructures

Magnetism and Coherent Phenomena
(R. Röhlsberger)

Magnetism and magnetic dynamics
Fundamentals of resonant light-matter interaction at x-ray energies

X-ray Nanoscience and X-ray Optics
(C. Schroer)

X-ray imaging: ptychography
Hard X-ray microscopy
X-Ray tomography

Soft X-ray Spectroscopy of Quantum Materials
(Kai Rossnagel)

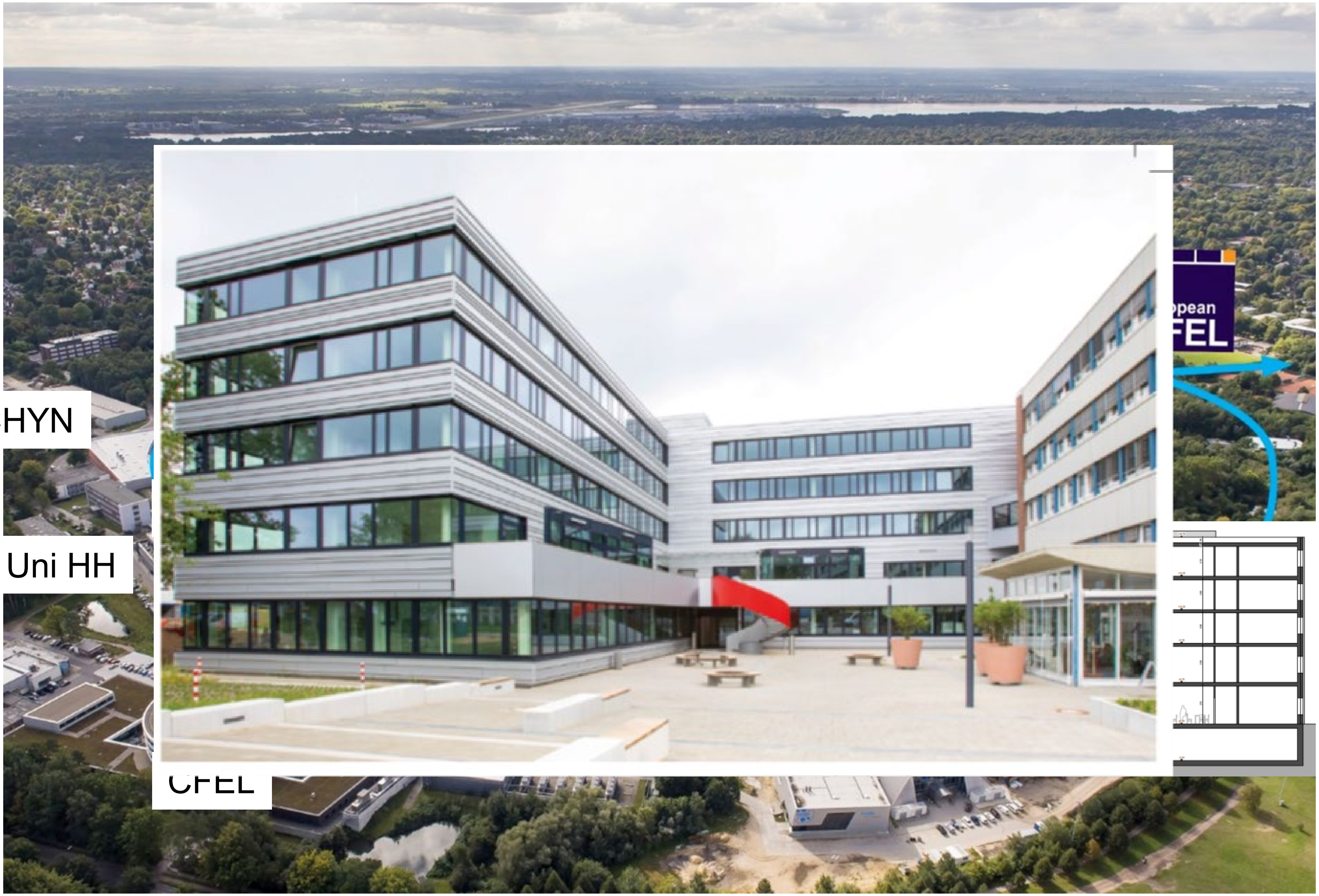
High-Resolution X-Ray Analytics & Physics of Materials
(Patrick Huber)

Spectroscopy of electron dynamics at surfaces and interfaces

https://photon-science.desy.de/research/research_teams/index_eng.html

Correlation structure / composition with functionality
Watch structure formation: In-situ / operando x-ray diffraction experiments

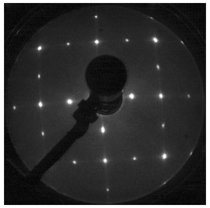
DESY NanoLab Location: CXNS

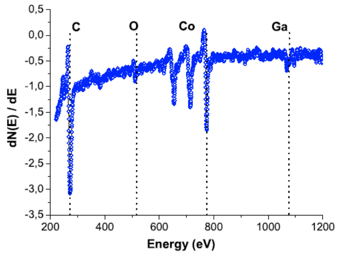


DESY Site – Campus Bahrenfeld

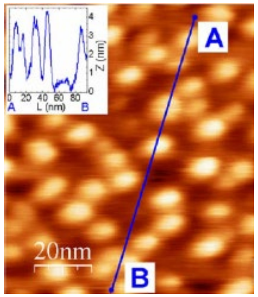
DESY NanoLab Mission

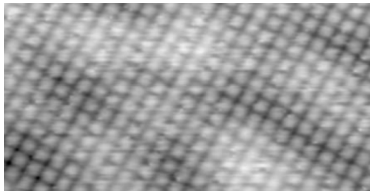
Providing on-site methods for nanoscience complementary to DESY photon science techniques at PETRA III(IV) and FLASH



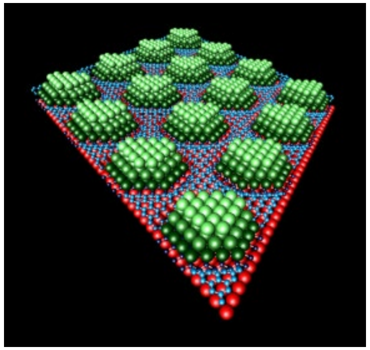


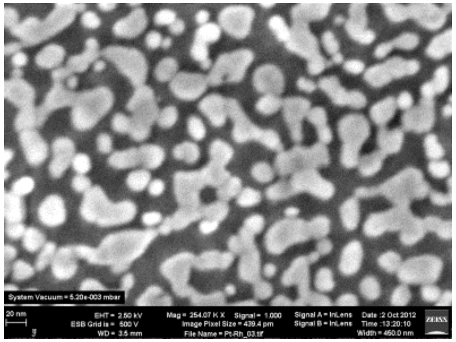
- nano characterization techniques (atomic scale structure, chemistry and magnetism)
- nano structuring techniques
- nano synthesis techniques

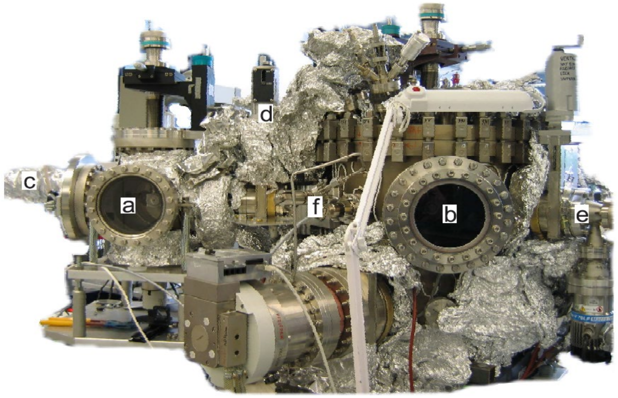




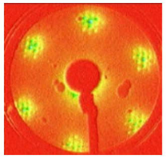
Development of well defined sample transfer protocols between NanoLab and beamlines (nano-PS)

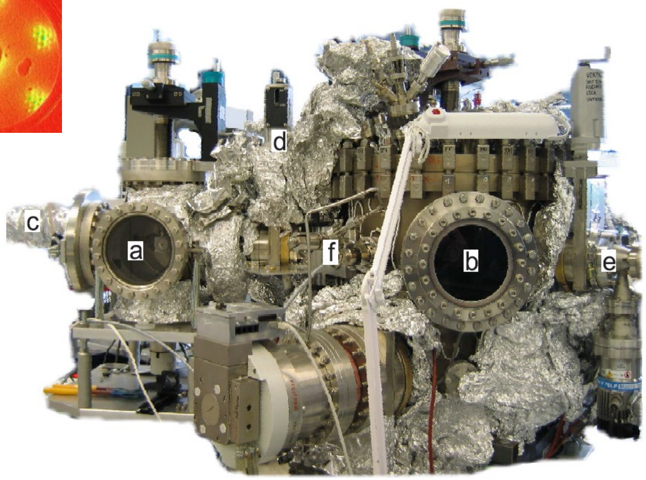






Overview DESY NanoLab Techniques





Spectroscopy & Growth (H. Noei)

- UHV sample preparation chambers with LEED / AES
- XPS, FT-IR, STM

X-ray diffraction (V. Vonk)

- Reflectometer
- Six circle diffractometer
- Sample Environments

Microscopy & Structuring (T. Keller)

- AFM, STM, optical
- SEM + FIB + EBSD + EDX (tomography)
- Lithography (CHyN)
- Scanning Auger Microscope (2021)

Electrochemistry (L. Jacobse)

- Dedicated chemistry lab
- Potentiostats
- Induction oven / gases
- Solid / liquid FT-IR (FAU Erlangen)

Magnetic Characterization (C. Strohm)

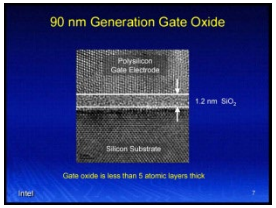
- Physical properties measurement system
- Kerr Microscope

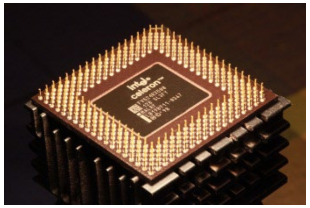
nanolab.desy.de

Introduction

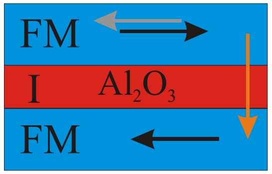
Today's nanotechnology is based on surfaces and interfaces and materials in reduced dimensions

Semiconductor integrated circuits
Topological materials, graphene, vdW materials

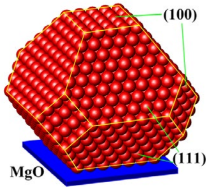


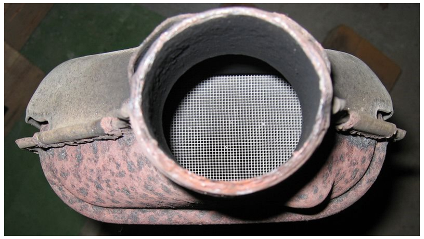


Magnetic sensors (GMR, TMR)
Quantum computers



Heterogeneous Catalysis
Energy harvesting and conversion
Energy storage



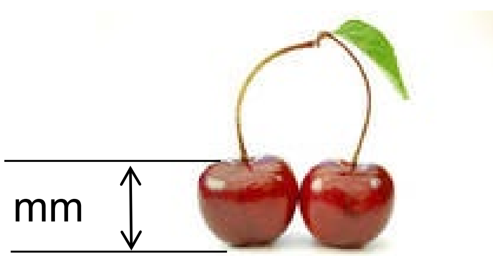


The Nanoworld

Greek: nanos: the dwarf

1 nm = 10^{-9} m is with respect to 1 m as

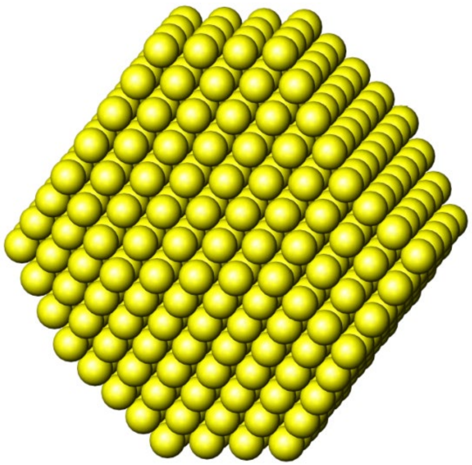
12 mm



12000 km

In the „Dwarf“ World the Rules are Changed

bulk material

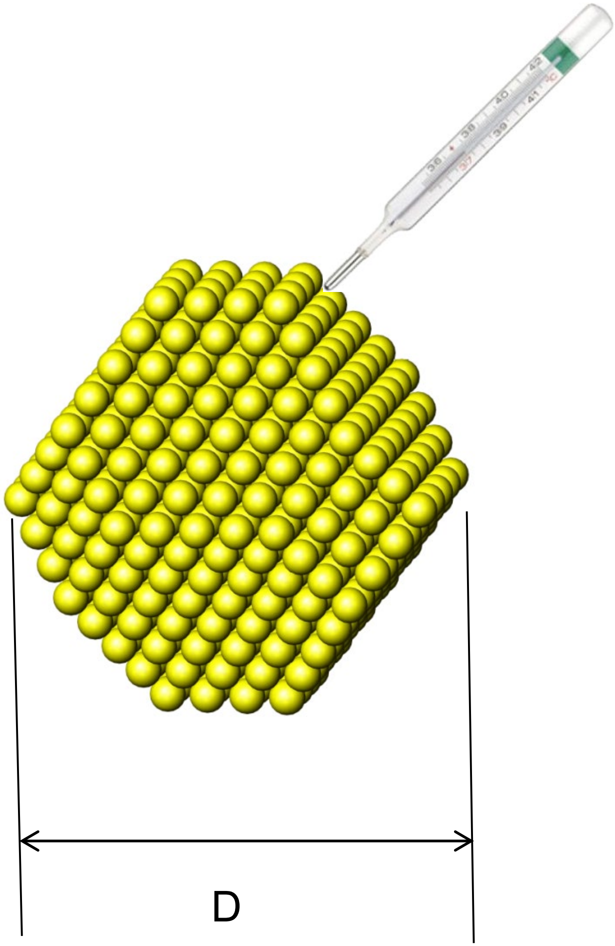


Nanoparticle

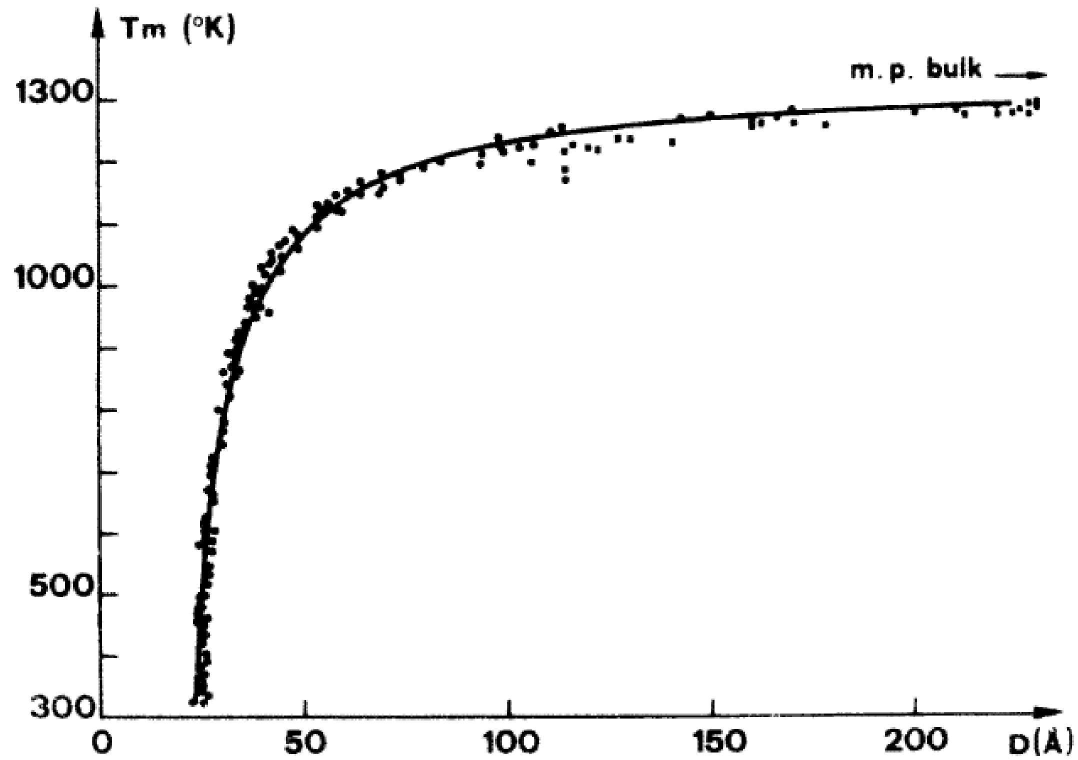
Physical und chemical properties of materials are changed in reduced dimensions

In the „Dwarf“ World the Rules are Changed

Example: Melting of Gold Nanoparticles



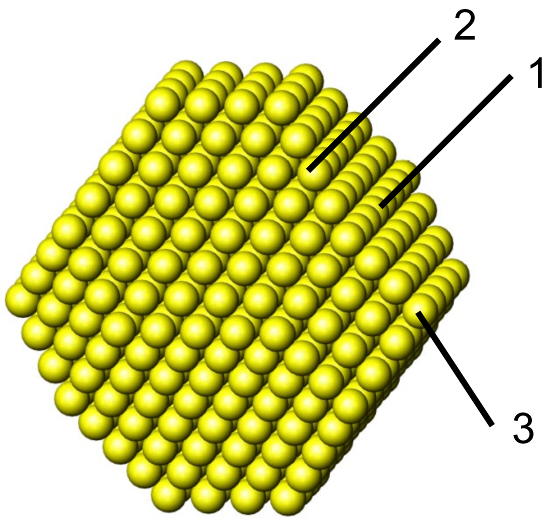
bulk: 1337 K (1064°C)



P, Buffat, J.-P. Borel, Phys. Rev. A 13, 2287 (1976)

B. Roldan Cuenya, PHYSICAL REVIEW B **84**, 245438 (2011)

In the „Dwarf“ World the Rules are Changed



Atoms with reduced coordination:

1: on facets
2: at edges
3: at corners

Relation surface / volume no of atoms

$$\frac{N_O}{N_V} = \frac{3a}{D}$$

Typical Values for spherical particles

D = 3 nm: $N_S/N_V = 0.25$

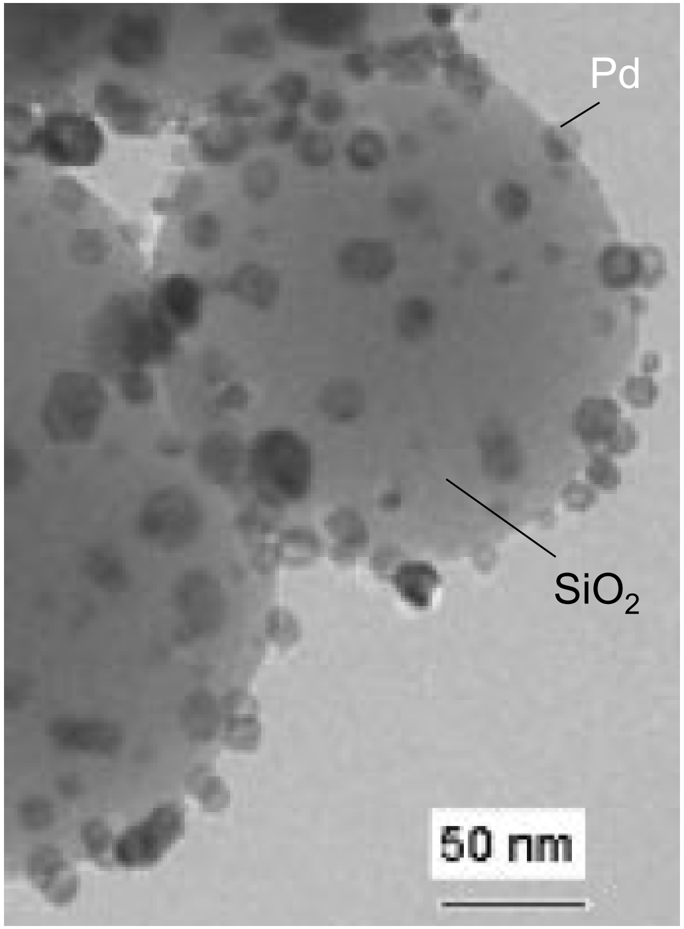
D = 2 nm: $N_S/N_V = 0.375$

D = 1 nm: $N_S/N_V = 0.75$

Reduced dimensions: quantum mechanical effects
box potential for electrons

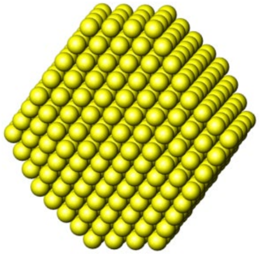
Real Catalysts: The Nanoworld Comes Into Play

„real“ catalyst



A. K. Datye, Topics in Catalysis 13, 131 (2000)

Only surface atoms are „active“



Goal: smaller particles stabilized on an oxide support

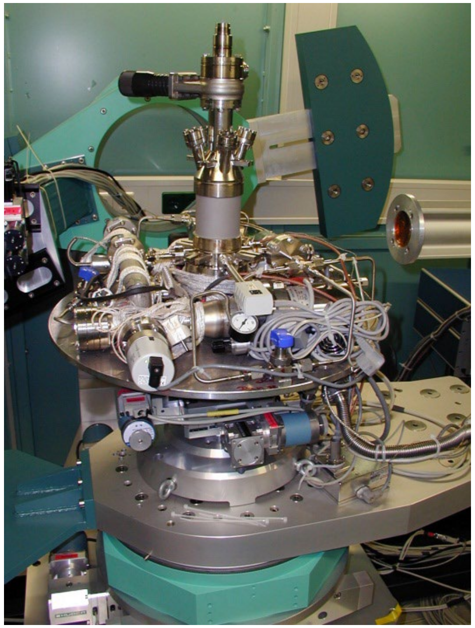
Surface area comparison for 1 kg Pd (expensive !)

Sphere diameter	No of spheres	Surface area
54 mm	1	0.01 m^2
1 mm	159337	0.5 m^2
1 μm	1.58×10^{14}	498 m^2
3 nm	5.85×10^{21}	1.67×10^5 m^2

23 soccer fields !

Introduction

Characterization on the atomic scale desired



- x-rays: λ=0.1 – 0.01 nm
- non-destructive probe
- sample charging not important (oxides !)
- in-situ measurements (high T, high gas pressure, UHV, electro-magnetic fields, in contact with liquids, .) or during their formation (growth)
- probing statistical information, single objects with nanobeams
- allow studying functionality and microscopic structure of the surface / interface / nano-object in the same experiment !

X-Ray Diffraction Techniques for Structural Characterization in Reduced Dimensions

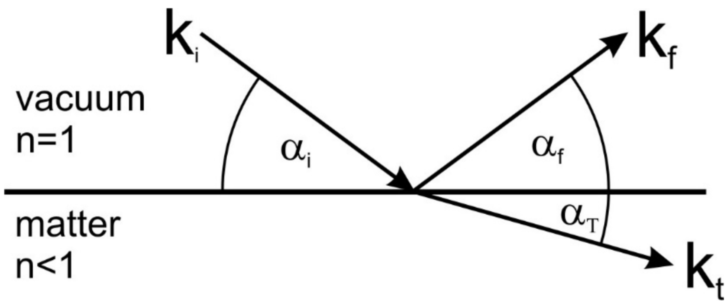
- X-ray reflectivity
- Grazing incidence x-ray diffraction
- (GI) small angle scattering
- Surface x-ray diffraction
- Nanoparticle structural analysis
- Coherent diffraction imaging
- (Extended X-ray absorption Fine Structure (EXAFS)
  (see talk from Christian Schroer)

X-Ray Reflectivity

X-rays: electro-magnetic waves

Fulfill boundary conditions at interfaces

Maxwell's equations are applied
Snell's law:



$$\cos \alpha_i = n \cos \alpha_t$$

For x-rays: refractive index n<1 in matter

Consequence: total external reflection occurs !

X-Ray Reflectivity

$$n = 1 - \delta - i\beta$$

refractive index

$$\delta = \frac{\lambda^2 r_e \rho_e}{2\pi}$$

$$\beta = \frac{\lambda \mu}{4\pi}$$

r_e: classical electron radius (2.82×10^{-15} m)

ρ_e: total electron density

μ: linear mass absorption coefficient

$$\alpha_c = \sqrt{2\delta} = \lambda\sqrt{\frac{r_e \rho_e}{2\pi}}$$

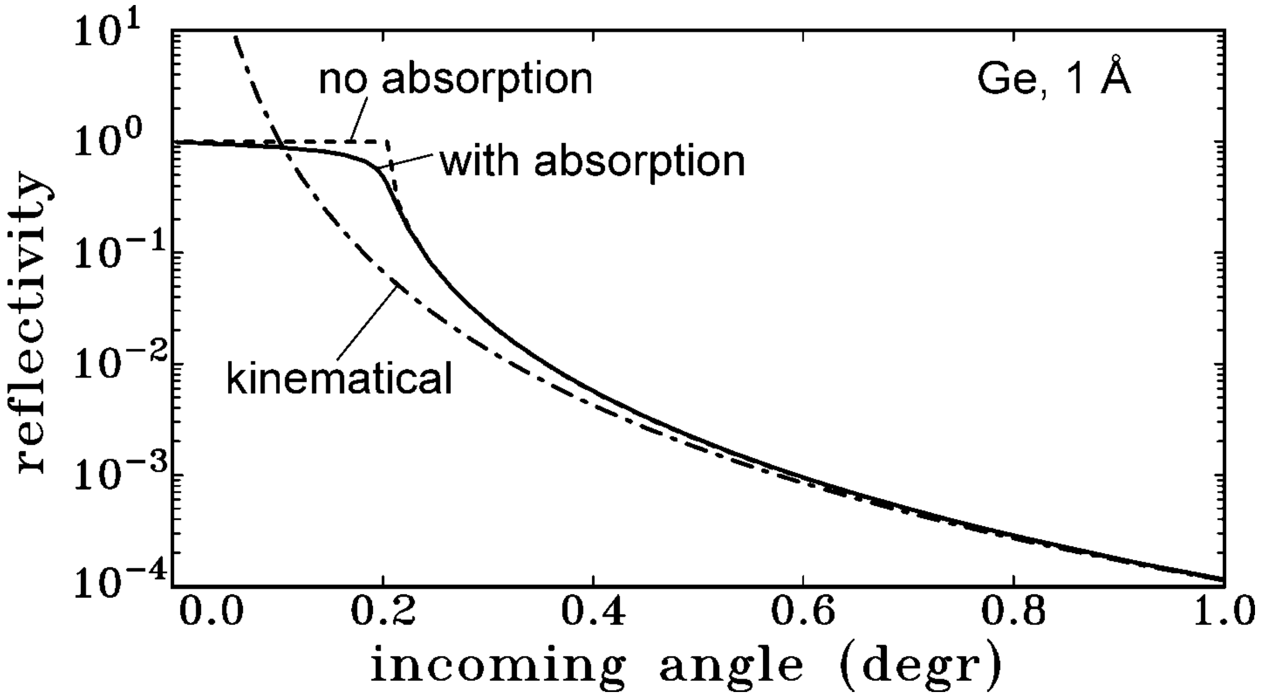
critical angle for total external reflection

X-Ray Reflectivity

Quantitative description:
Fresnel's formulas (sin(α)<<1)

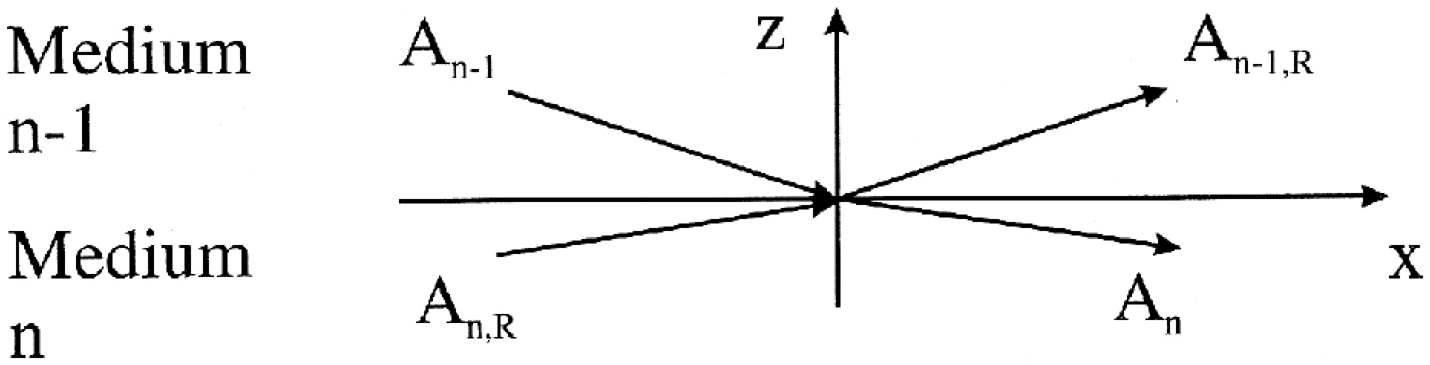
$$T_F = \left| \frac{2\alpha_i}{\alpha_i + \alpha_t} \right|^2 \quad R_F = \left| \frac{\alpha_i - \alpha_t}{\alpha_i + \alpha_t} \right|^2$$

Transmitted (reflected) amplitudes



X-Ray Reflectivity

More complicated case: layered structures



$$R_{n,n-1} = a_{n-1}^4 \frac{R_{n,n+1} + F_{n-1,n}}{R_{n,n+1} F_{n-1,n} + 1} \, . \qquad F_{n-1,n} = \frac{f_{n-1} - f_n}{f_{n-1} + f_n} \, .$$

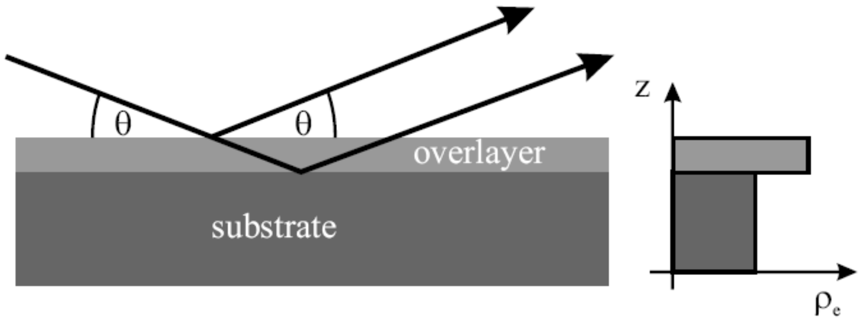
$$R_{n,n+1} = a_n^2 \frac{A_n^R}{A_n} \qquad f_n = \sqrt{\sin^2 \alpha_i - 2\delta_n - 2i\beta_n} \, , \quad a_n = e^{-iQ_n \frac{d_n}{2}}$$

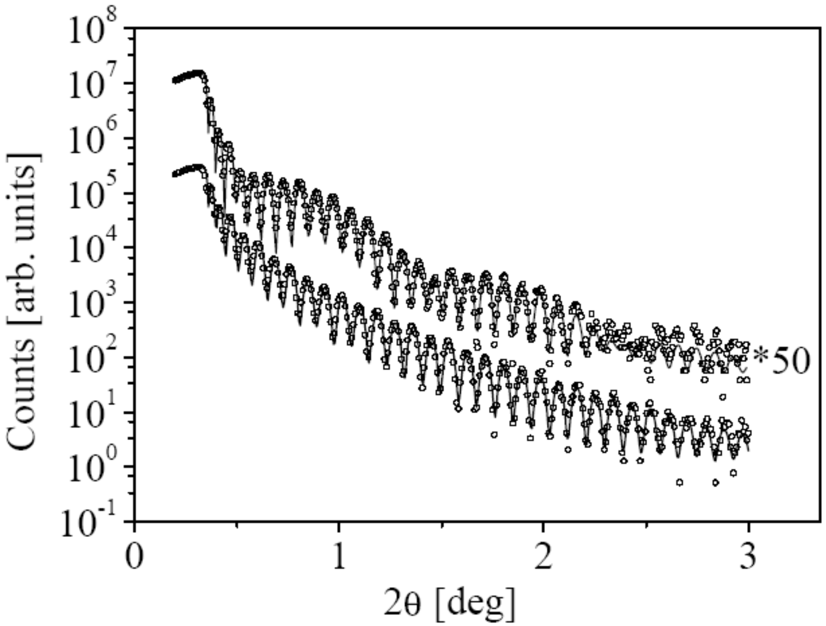
Generalized reflectivity: Parratt formalism

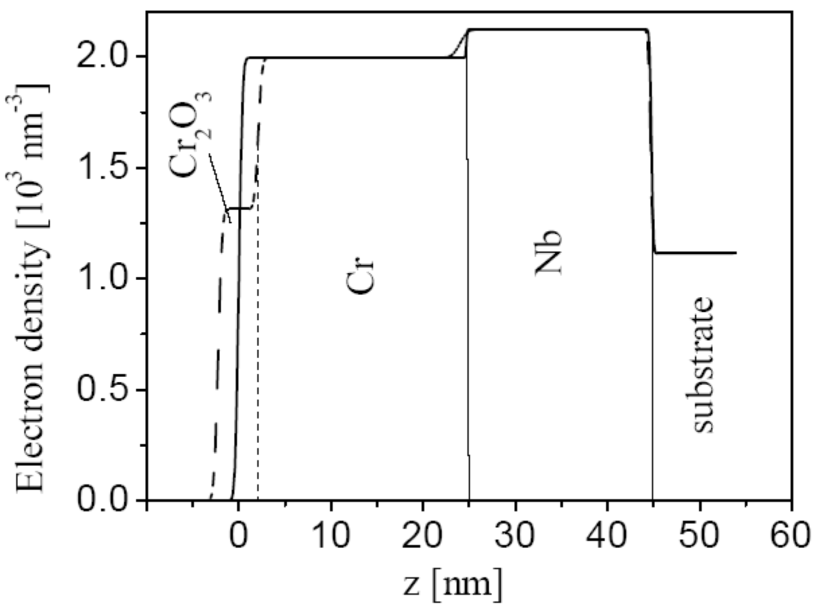
L. G. Parratt, Phys. Rev. 95, 359 (1954)

X-Ray Reflectivity

Example: reflectivity of a Cr film before and after oxidation

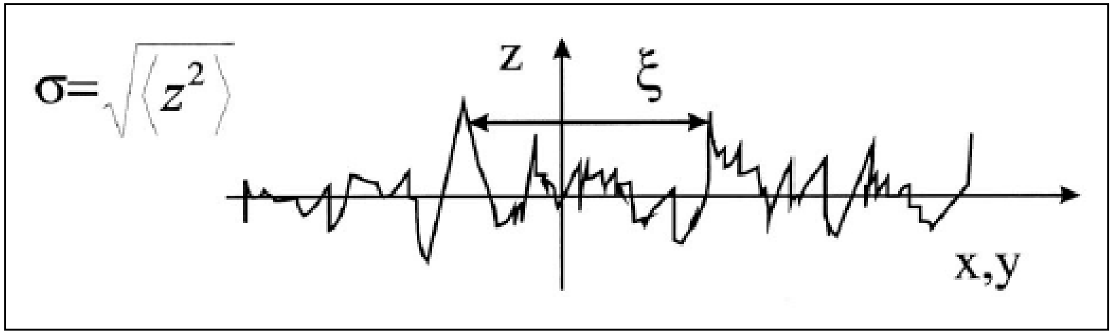






X-Ray Reflectivity

Influence of roughness:



$R = R_F \exp(-\sigma^2 Q_1 Q_2)$

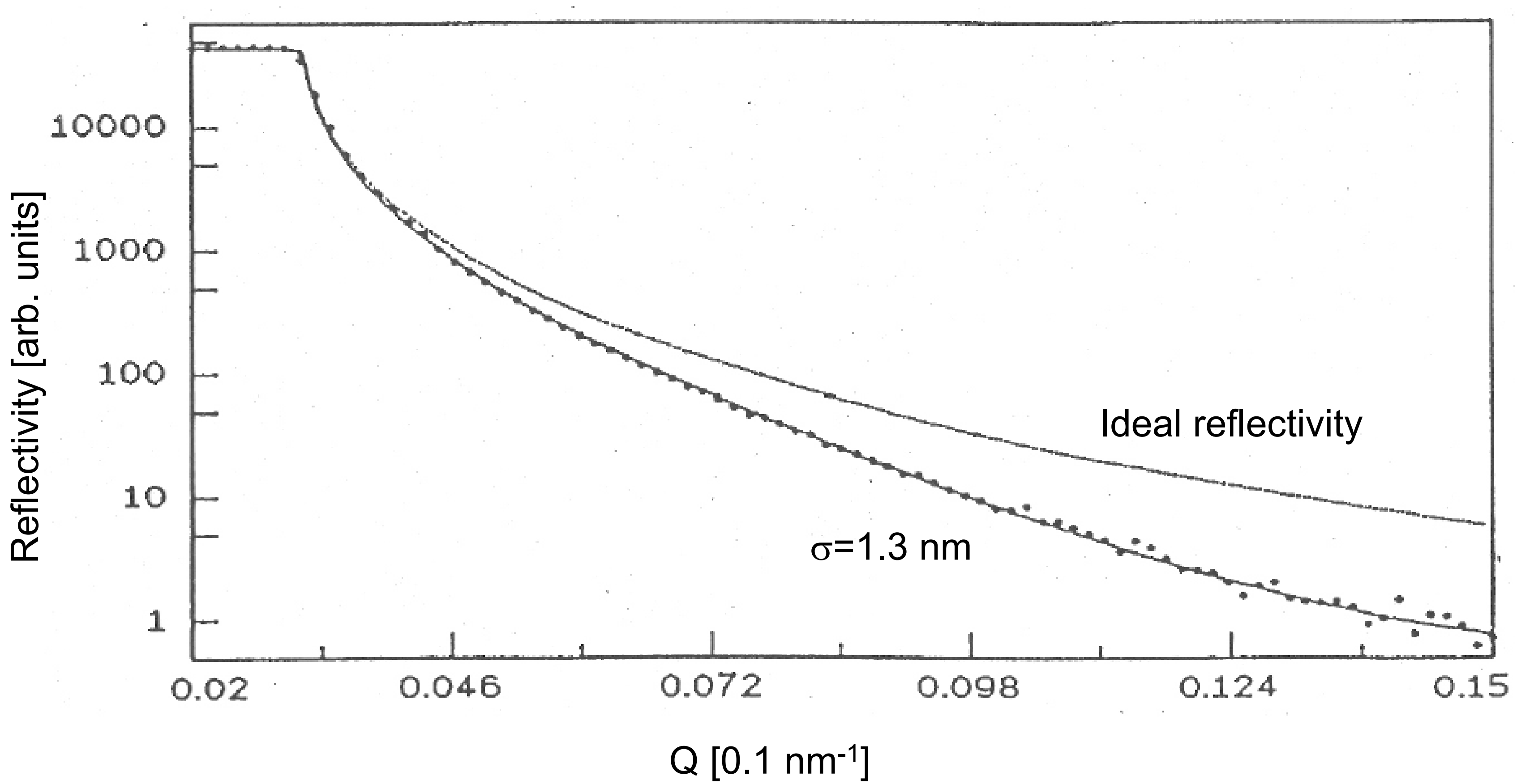
Height fluctuations at an interface

σ: root mean square roughness
from specular reflectivity

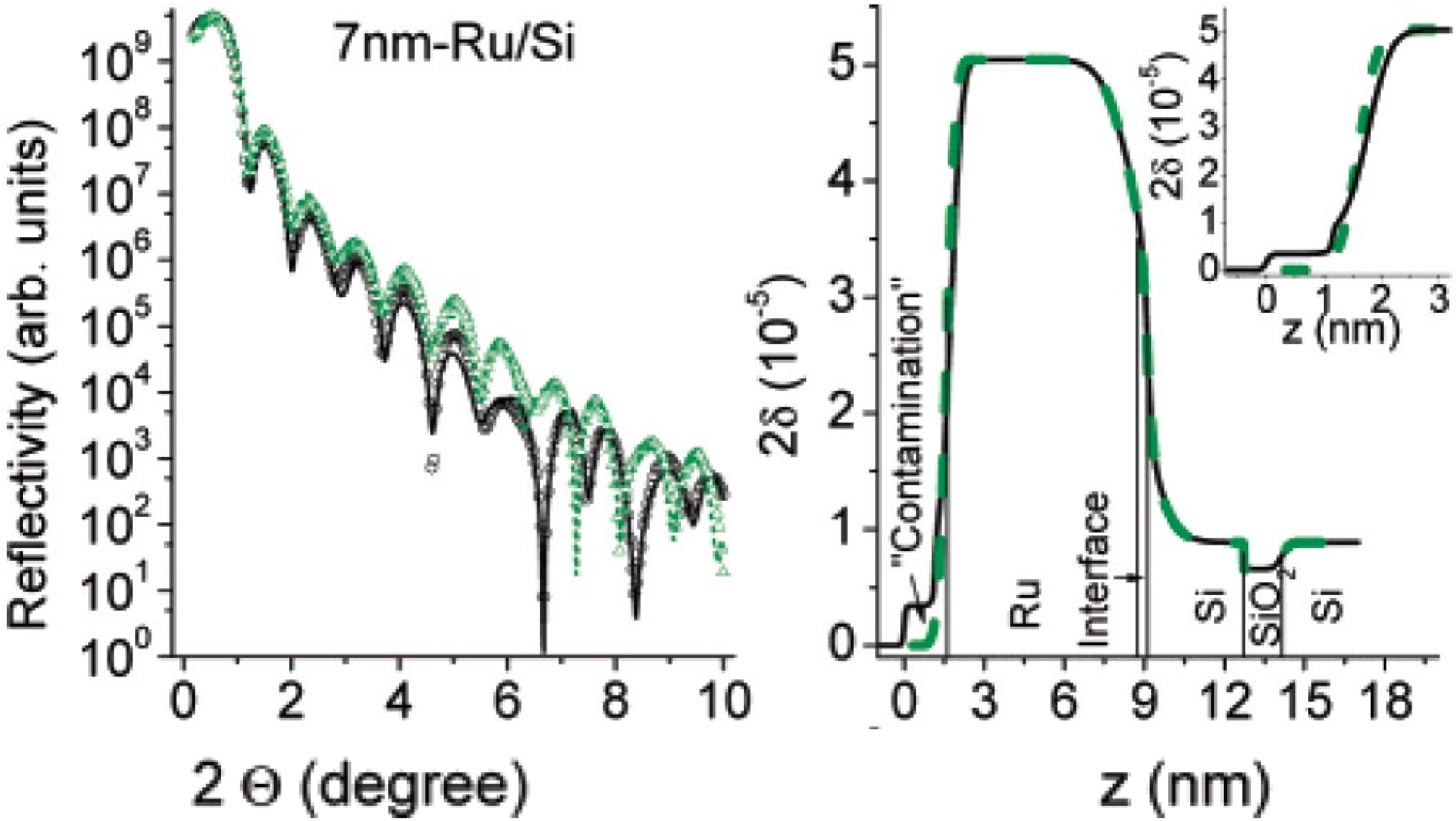
ξ: characteristic length to find same height on the surface
from off-specular scattering, Qx,y≠0, not discussed here

X-Ray Reflectivity

Example: reflectivity from a Si block



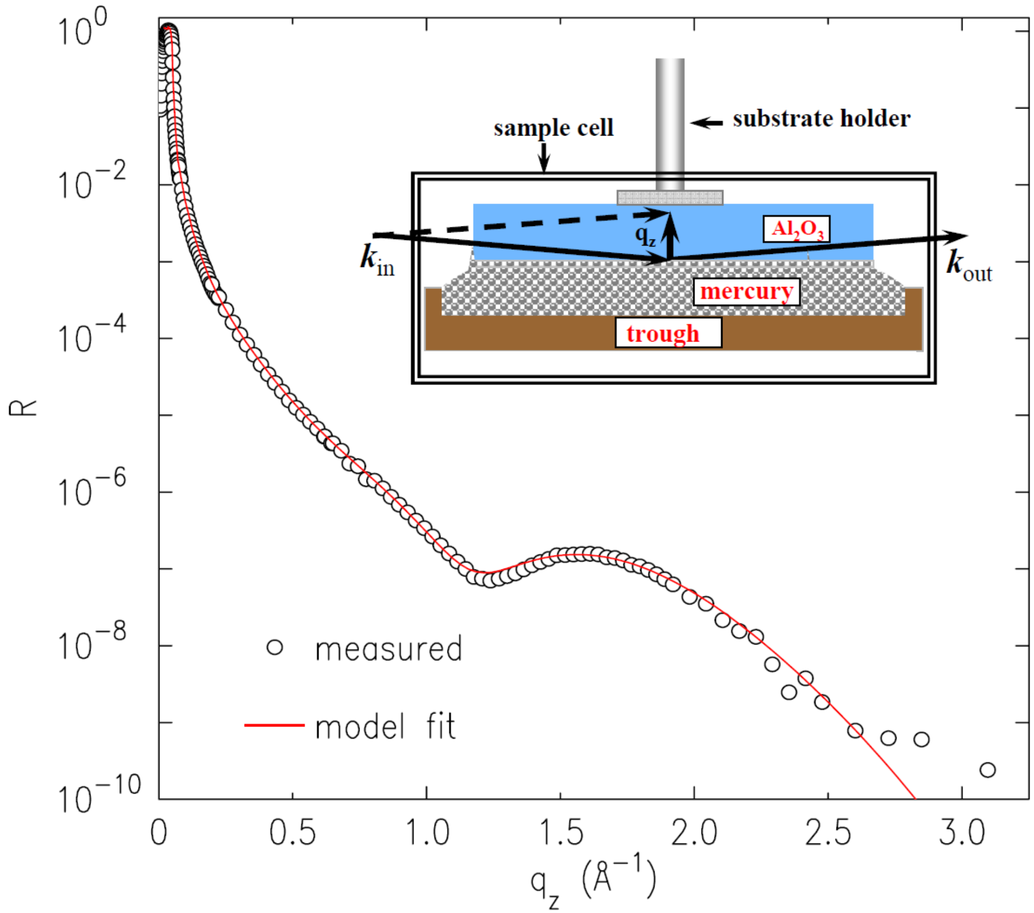
X-Ray Reflectivity from VUV mirrors

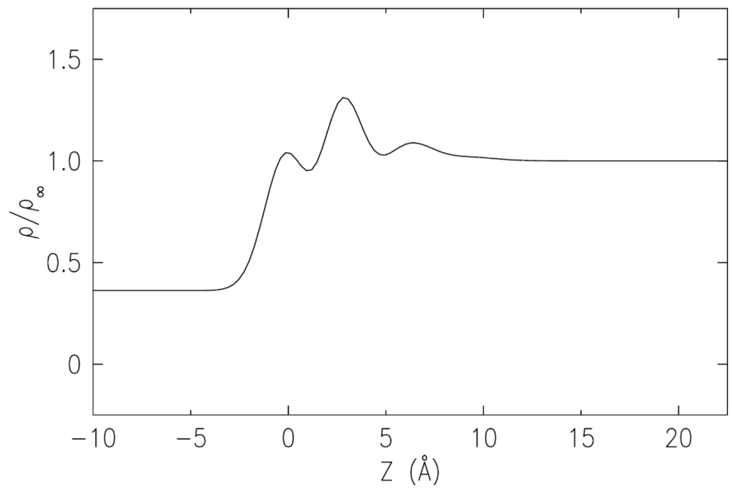


Y. B. He, et al., J. Phys. Chem. C 111, 10988 (2007)

X-Ray Reflectivity

Example: Al_2O_3 in contact with liquid Hg

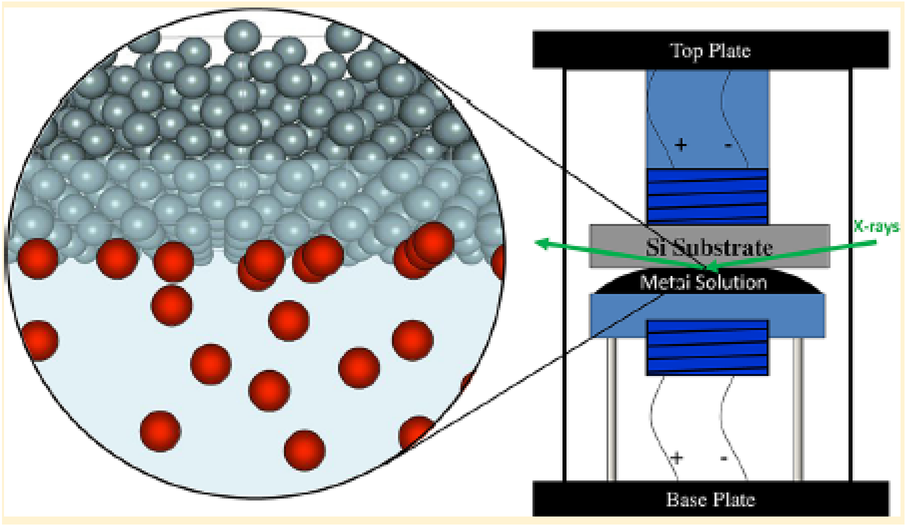


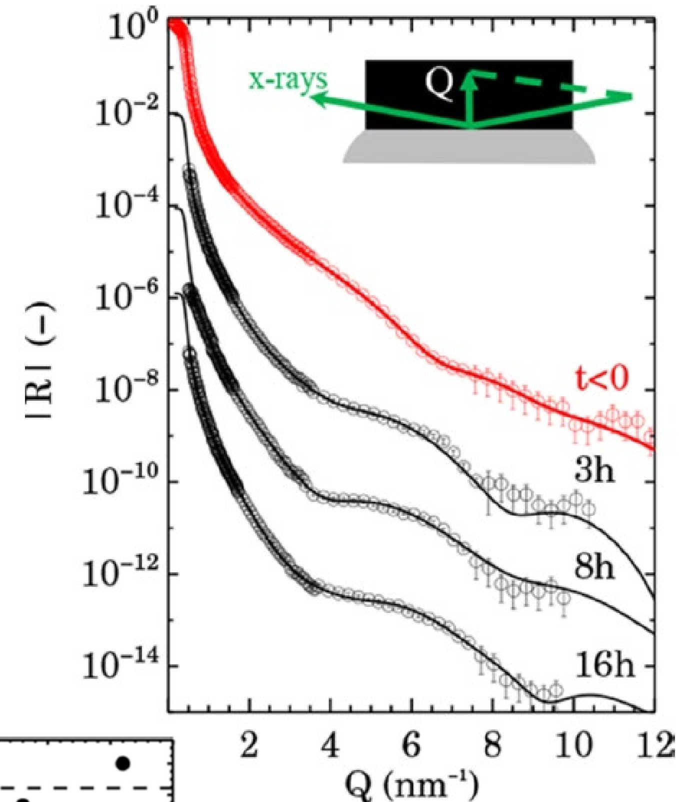


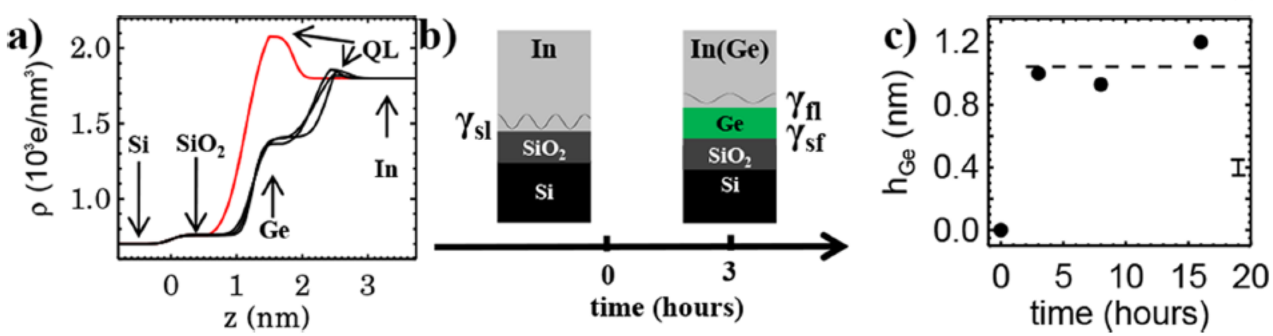
Photon energy: 70 keV

L. Tamam, et. al., J. Phys. Chem. Lett.1 (2010) 1041

High Energy X-Ray Reflectivity: deeply buried interface



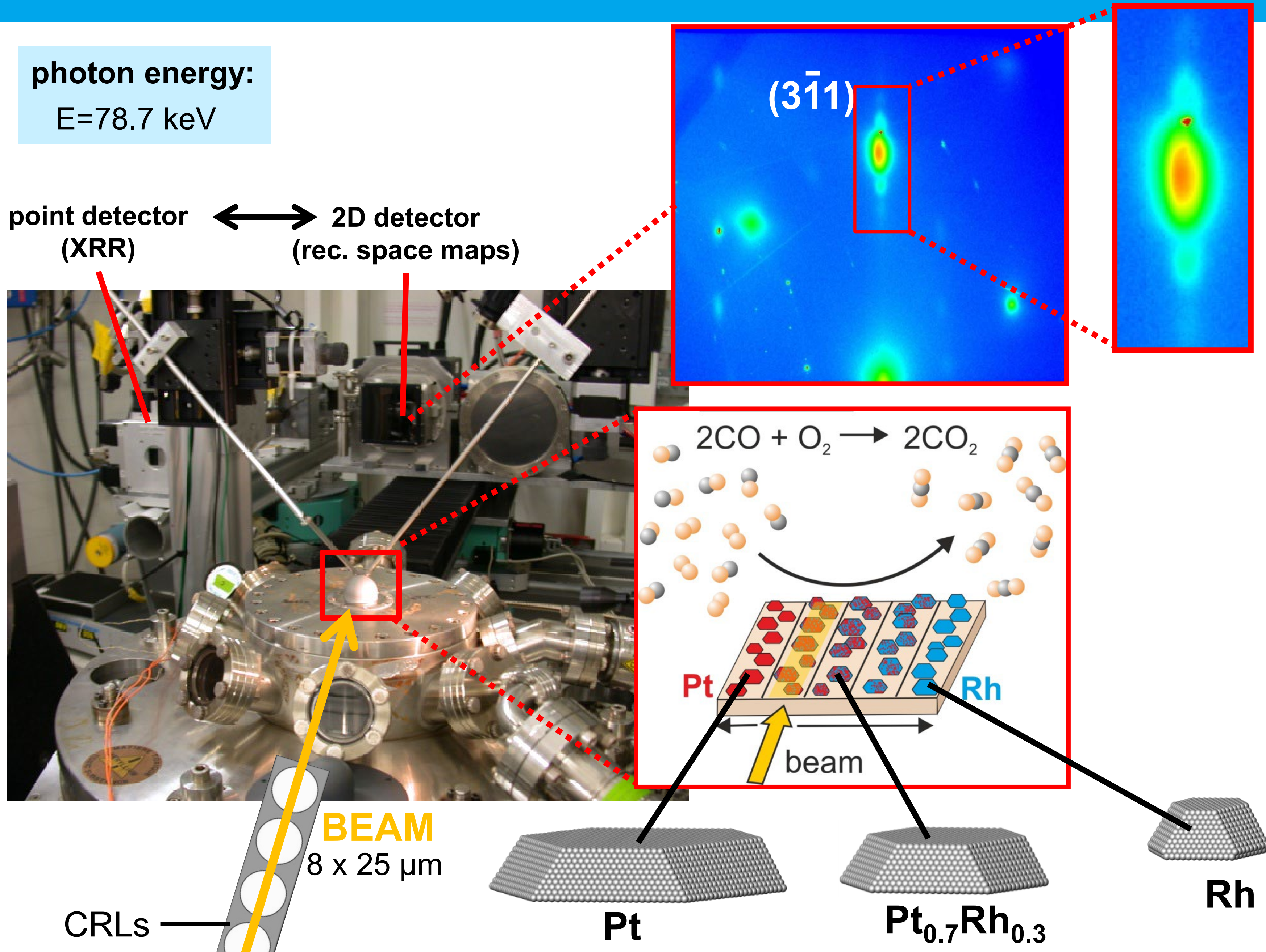




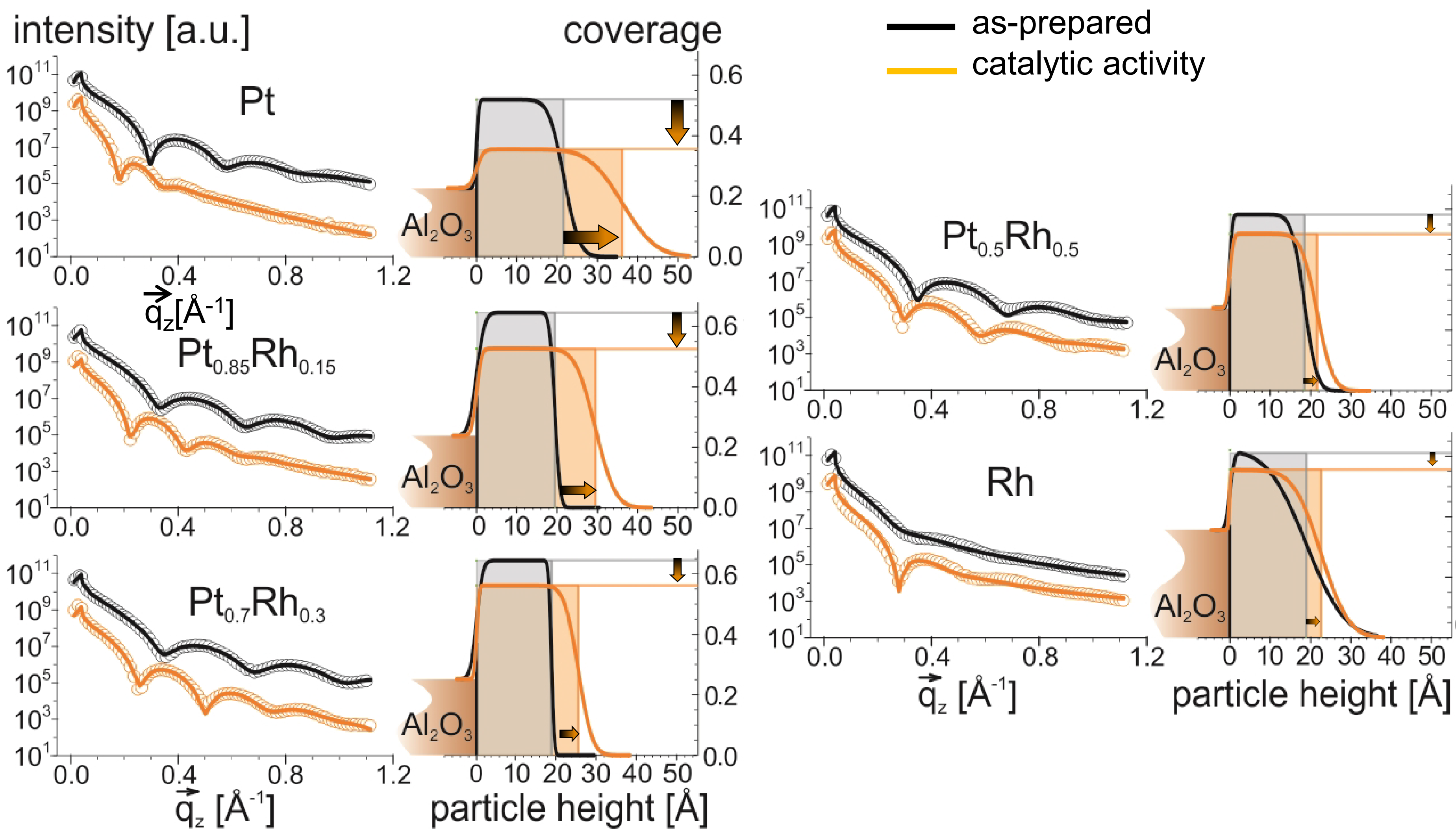
V. Vonk et al., Langmuir 33, 814 (2017).

Pt-Rh Nanoparticles under CO Oxidation Conditions

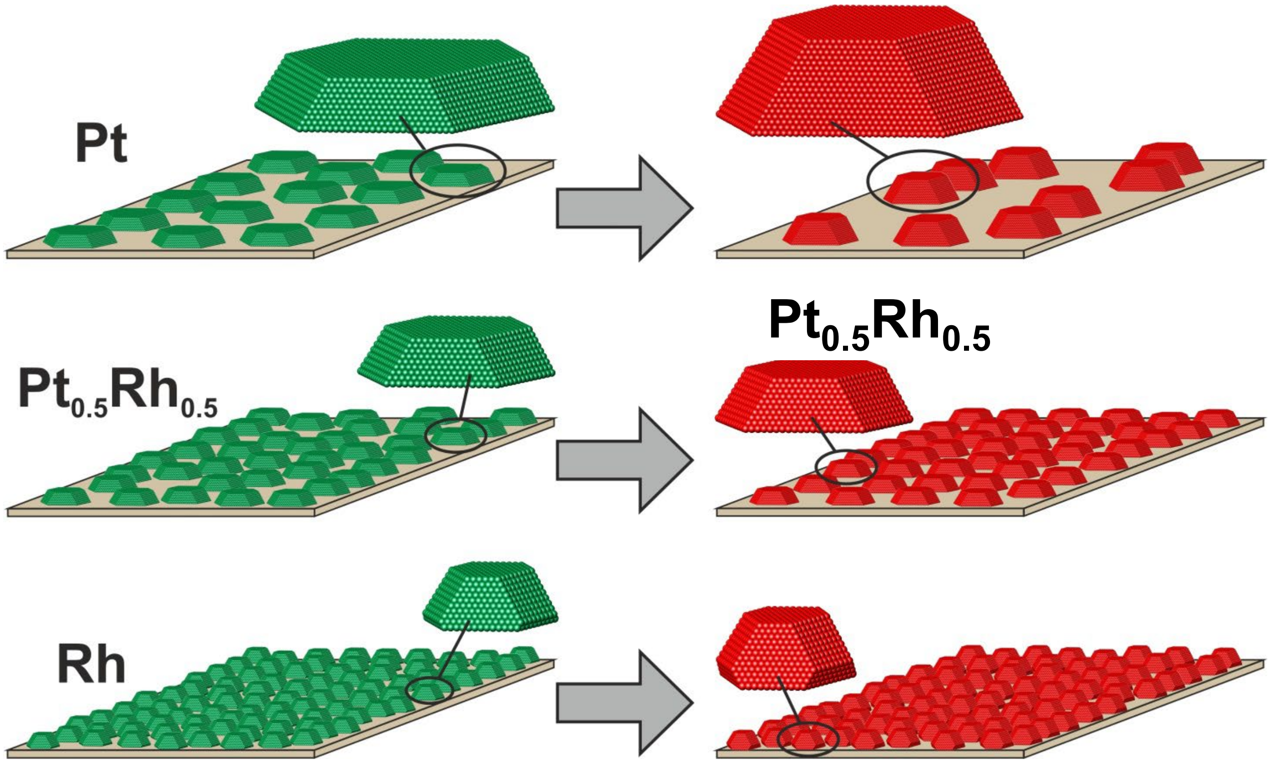
photon energy:
E=78.7 keV



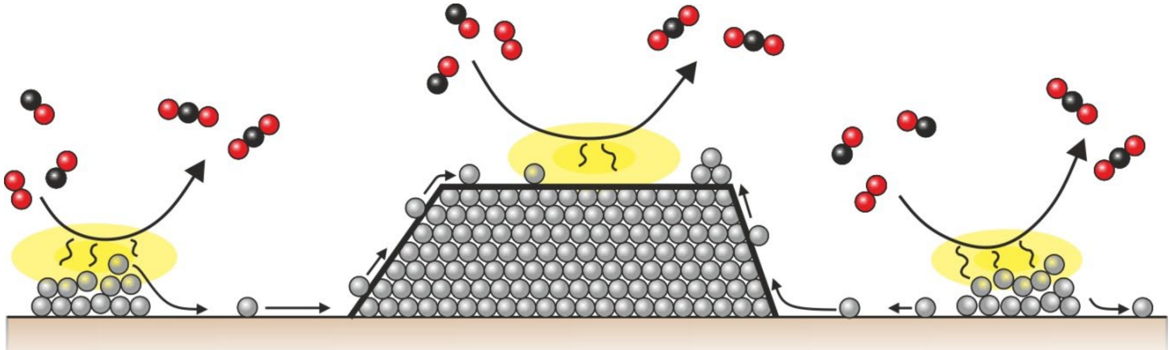
X-Ray Reflectivity Results



Reaction Induced Sintering Mechanism



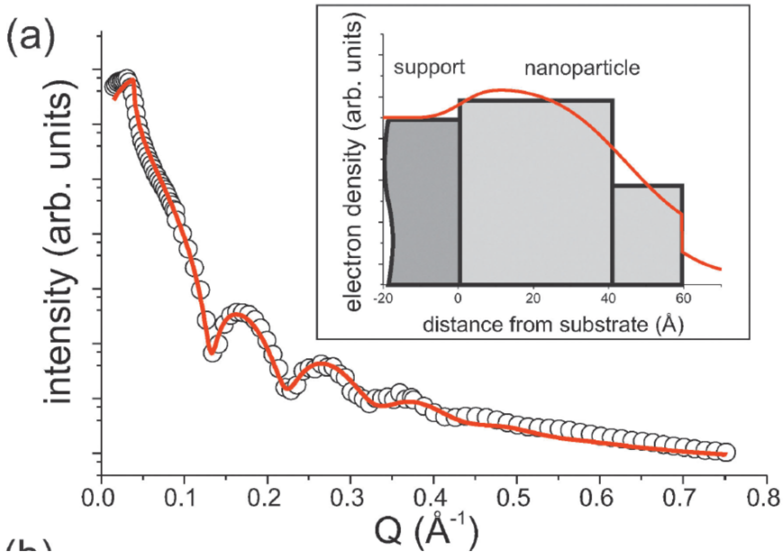
Non-classical Ostwald ripening:

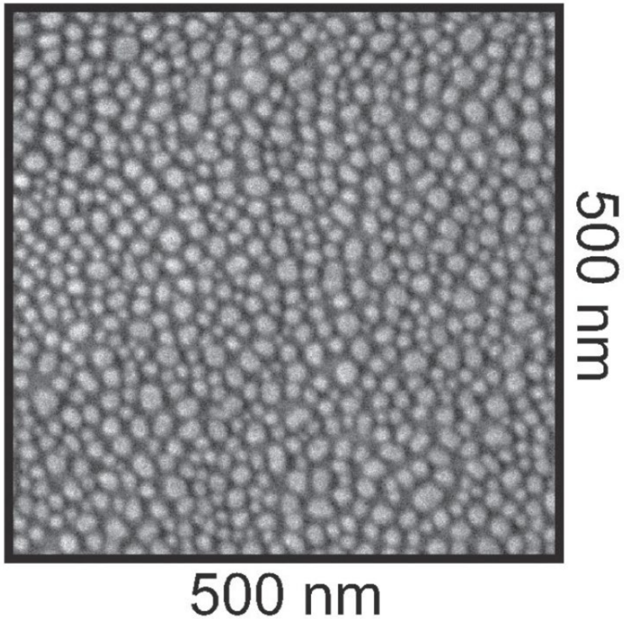


U. Hejral, P. Müller, O. Balmes, D. Pontoni, A. Stierle
Nature Communications 7, 10964 (2016).

Coverage Determination for Nanoparticles

PdRh nanoparticles on $MgAl_2O_4$





SEM after oxidation

Height: 6 nm
Coverage: 36%

P. Müller, et al., Phys. Chem. Chem. Phys. 16, 13866 (2014)

X-Ray Reflectivity

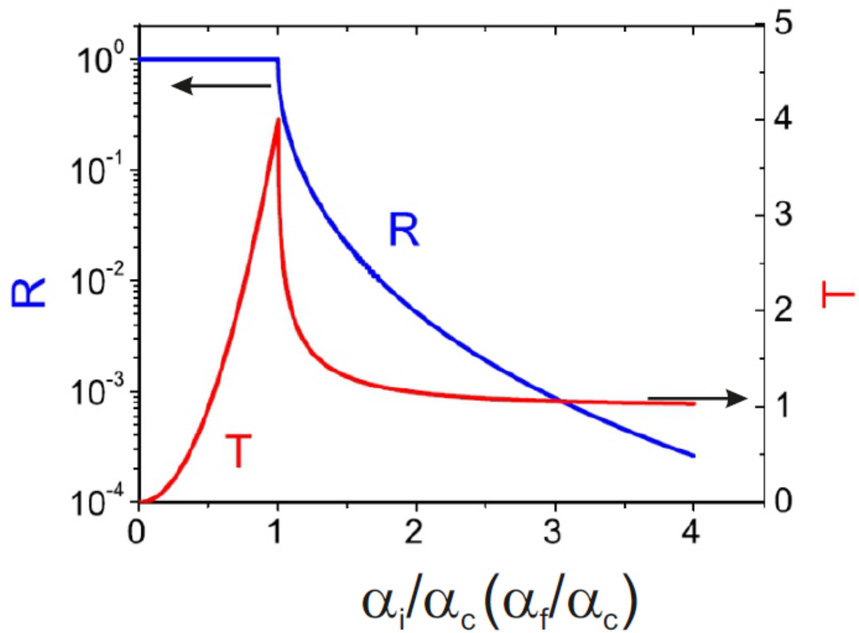
Summary x-ray reflectivity:

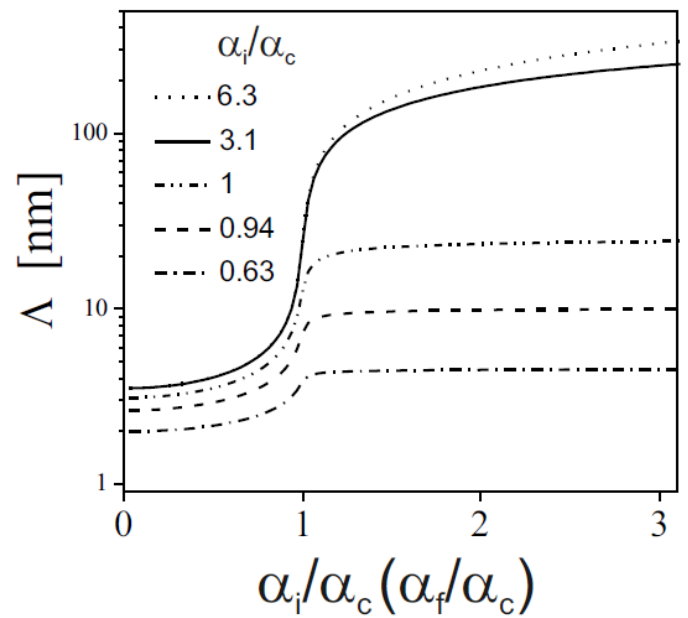
Obtainable Parameters (with sub-nm resolution)

- layer thicknesses
- statistical information on interfacial roughness
- layer density profiles
- limited to stratified media, flat substrate
- independent of crystalline state

Grazing Incidence X-ray Diffraction

Remember: total external reflection induces evanescent wave traveling parallel to the surface.





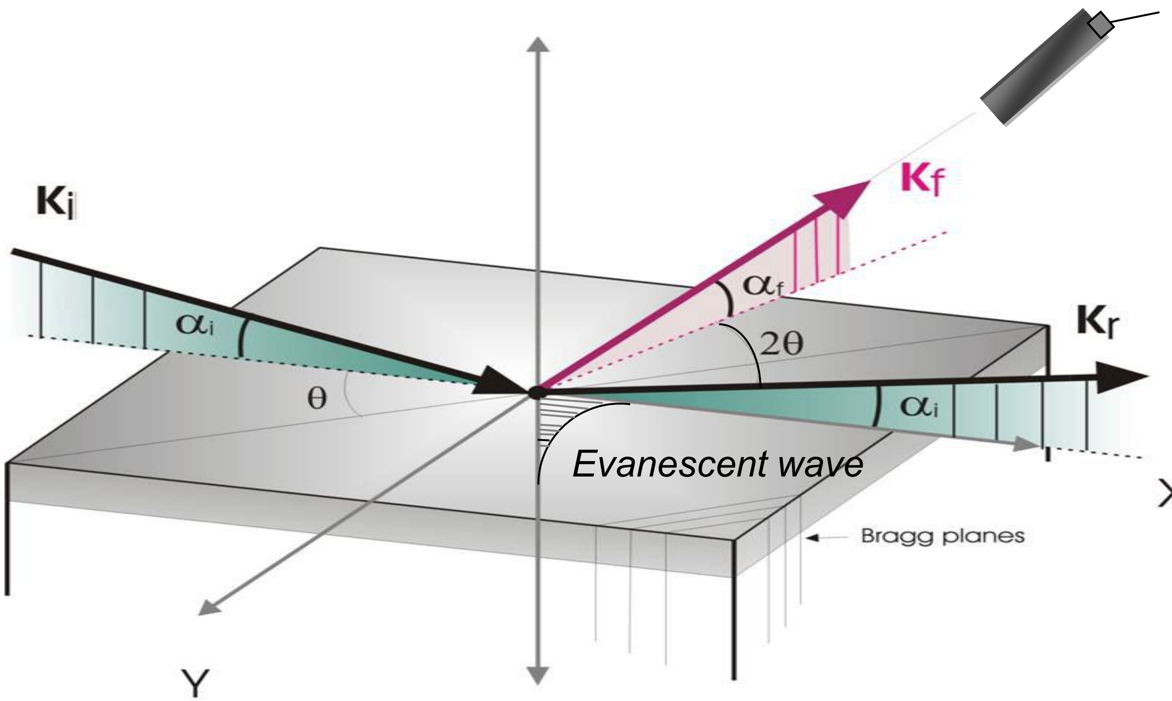
$I(q) \sim T(\alpha_i)S(q') \, T(\alpha_f)$

S: any type of diffraction / absorption process

q‘: scattering vector inside material

Grazing Incidence X-ray Diffraction

Example: evanescent Bragg scattering



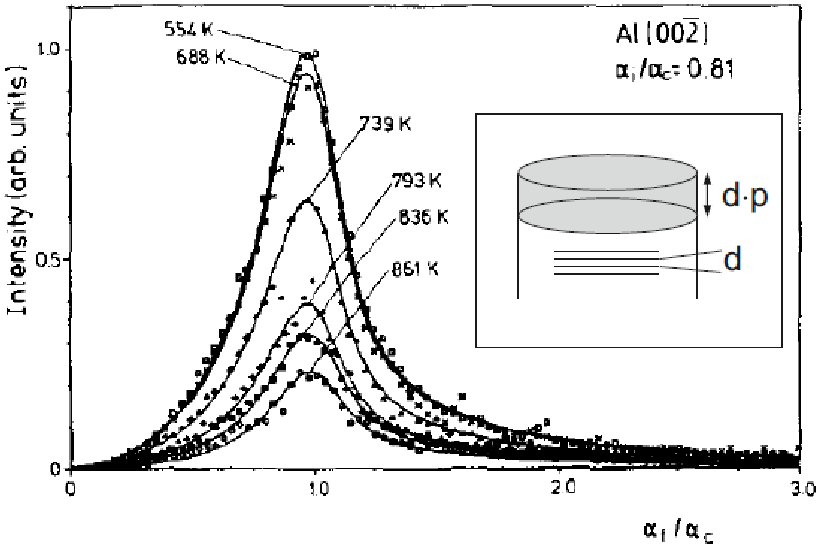
$$S(q') = |F_{hkl}|^2 \, \delta(\mathbf{q}_{\parallel} - \mathbf{G}_{hkl}) \, |1 - \exp(i q'_z a_{\perp})|^{-2}$$

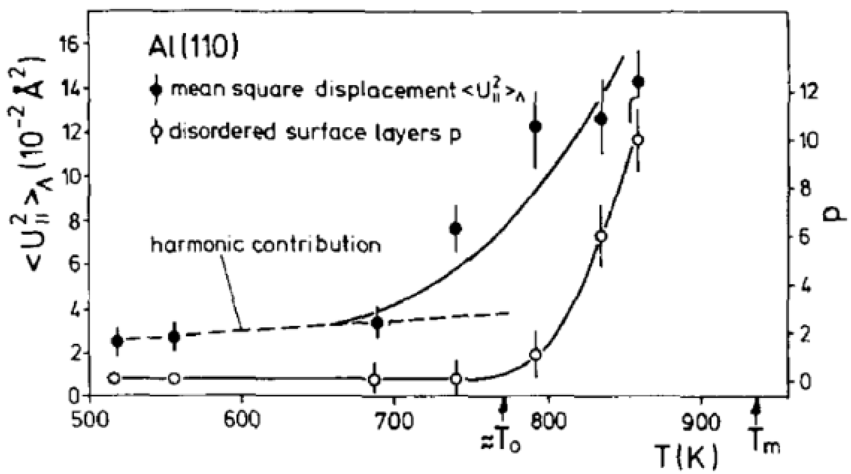
evanescent Bragg scattering law

H. Dosch, Springer Tracts in Mod. Phys. (Springer), Berlin, 1992, p. 126.

Grazing Incidence X-ray Diffraction

Example: surface melting of Al(110)

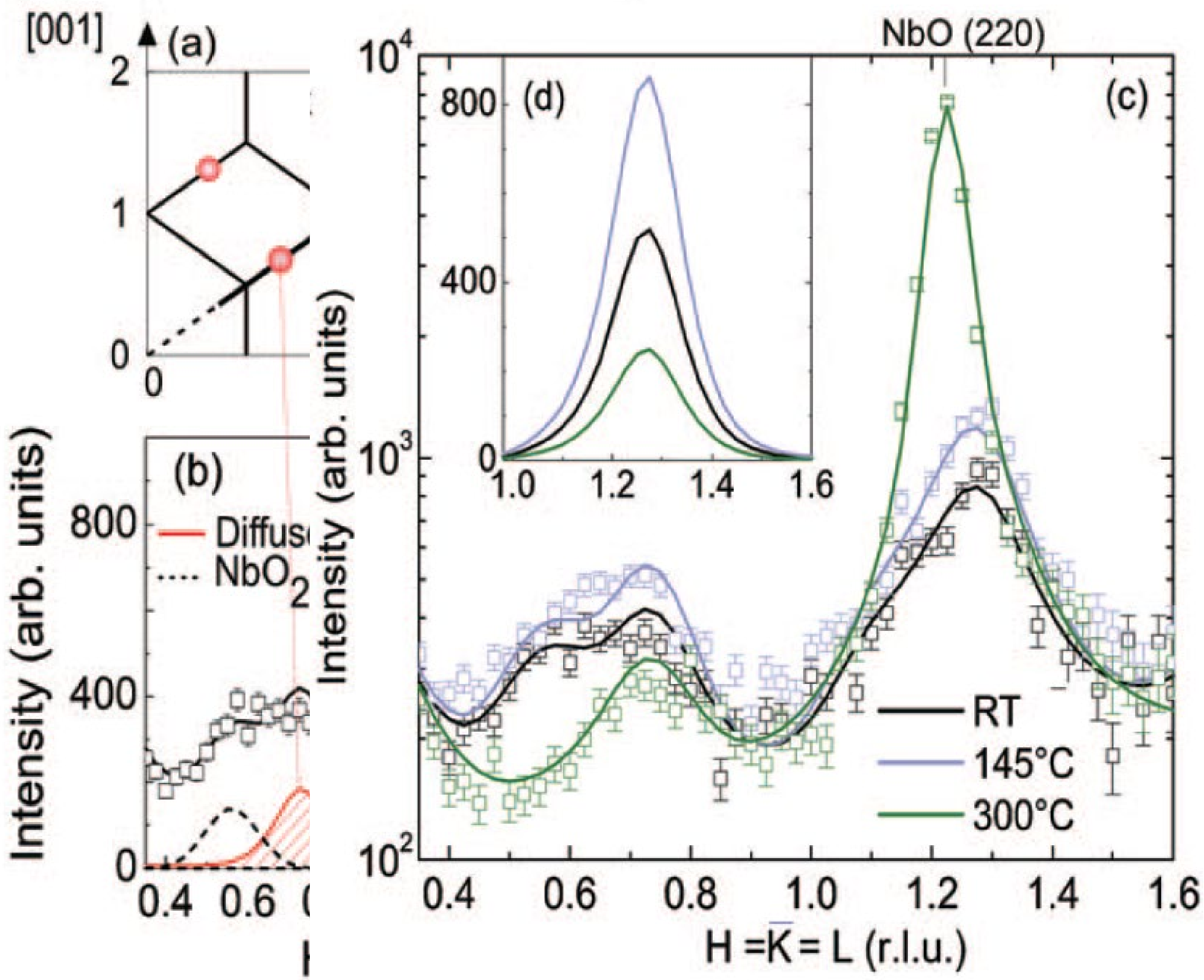


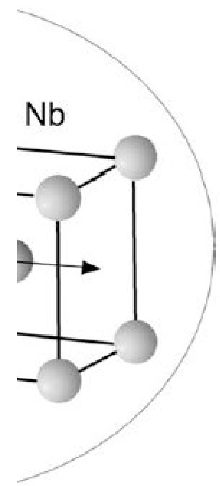


H. Dosch, Physica B 198 78 (1994)

Grazing Incidence X-ray Diffraction

Example: oxidation of Nb(110)





t at Λ=10 nm

M. Delheusy, et al., Appl. Phys. Lett . 92, 101911 (2008)

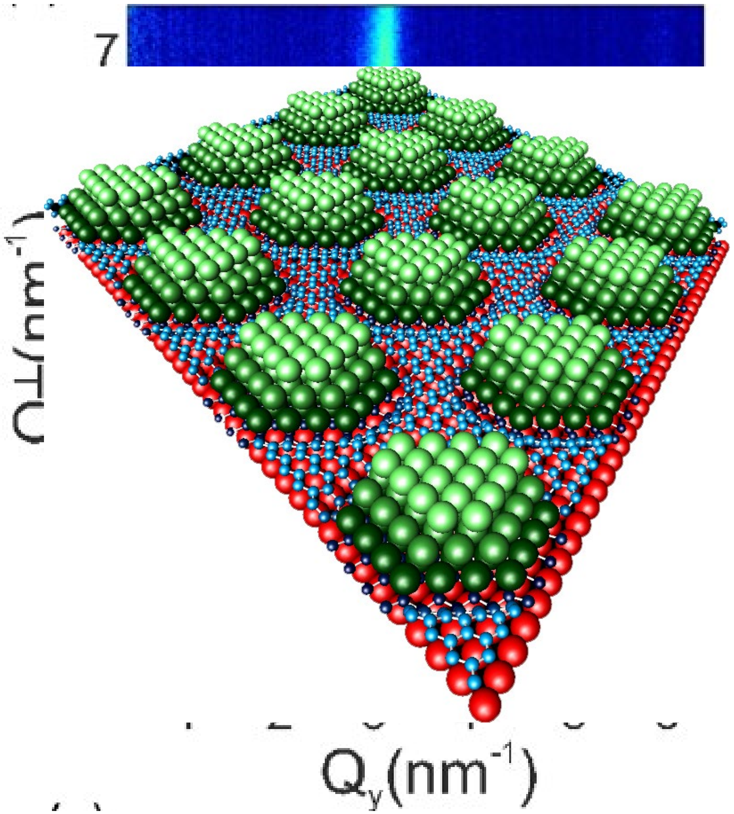
Grazing Incidence X-ray Diffraction

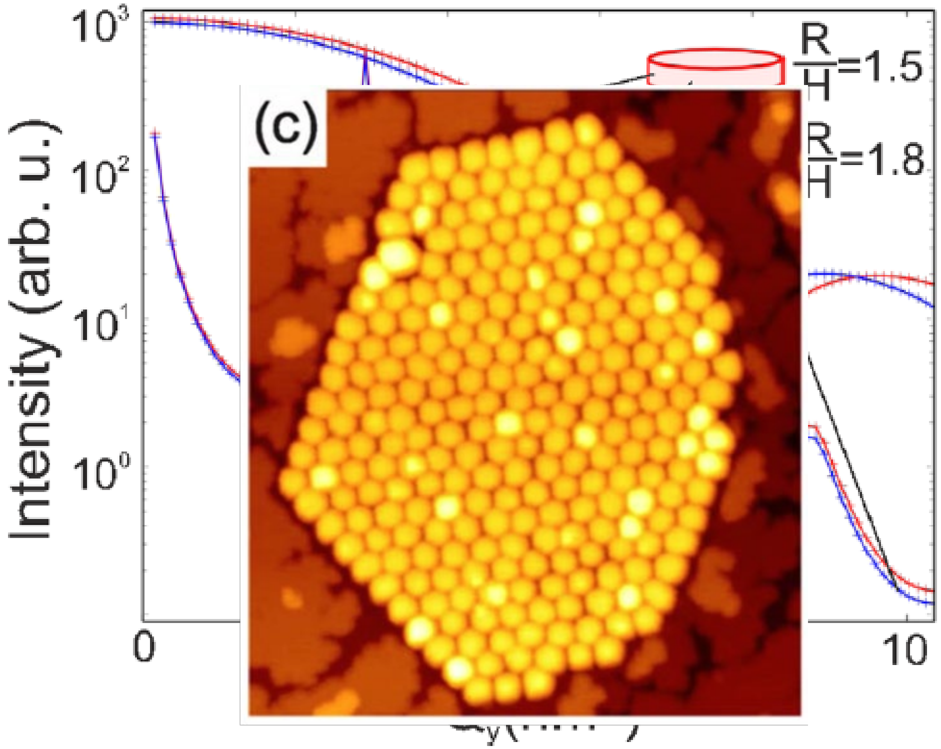
Summary grazing incidence x-ray diffraction:

Obtainable Parameters (with nm resolution)

- all structural parameters and chemical composition with variable information depth, e.g. lattice and order parameters, crystallinity, mosaicity, interstitials,…

Grazing incidence small angle scattering (GISAXS)

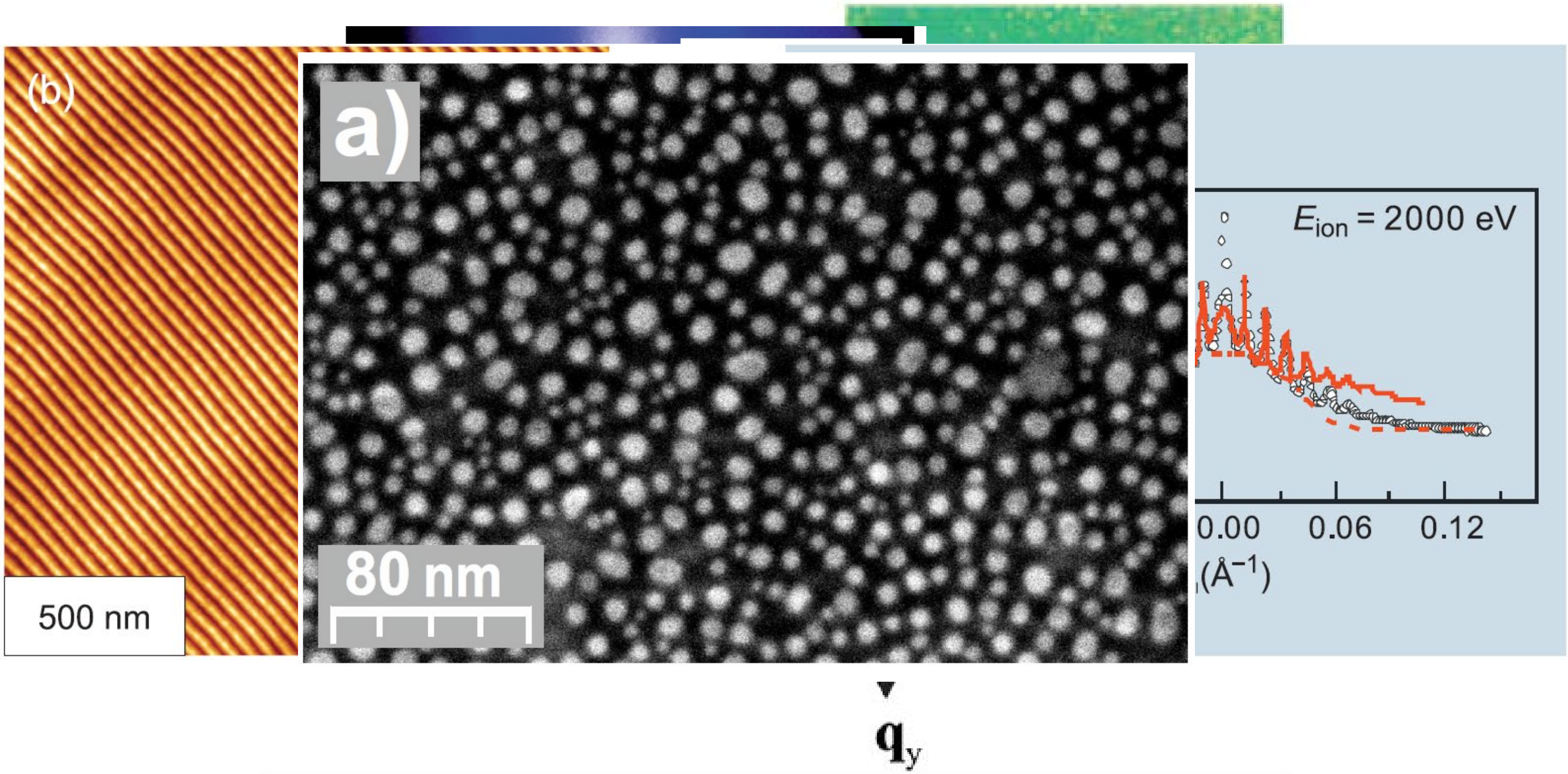




0.8 ML Ir

D. Franz, A. Stierle, et al, Phys. Rev. B 93, 045426 (2016)

Grazing incidence small angle scattering (GISAXS)



J. Oleander, et al., Phys. Rev. B B 76, 075409 (2007)
D. Carbone et al., J. Phys. Cond. Matt. 21 224007 (2009)

Grazing incidence small angle scattering (GISAXS)

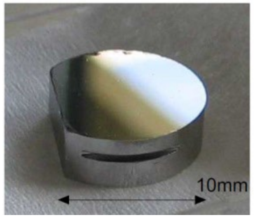
Summary GISAXS

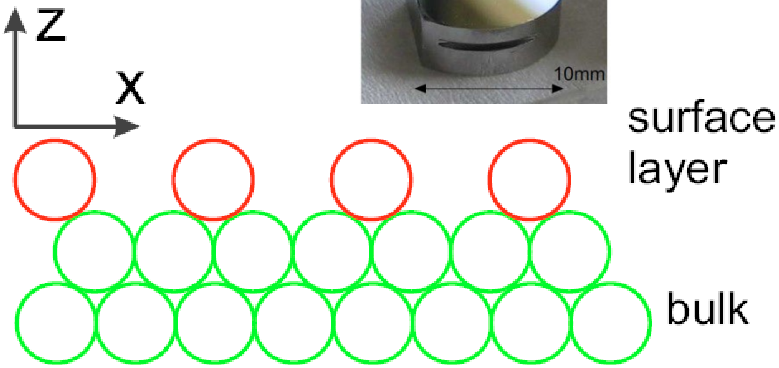
Obtainable Parameters (with nm resolution)

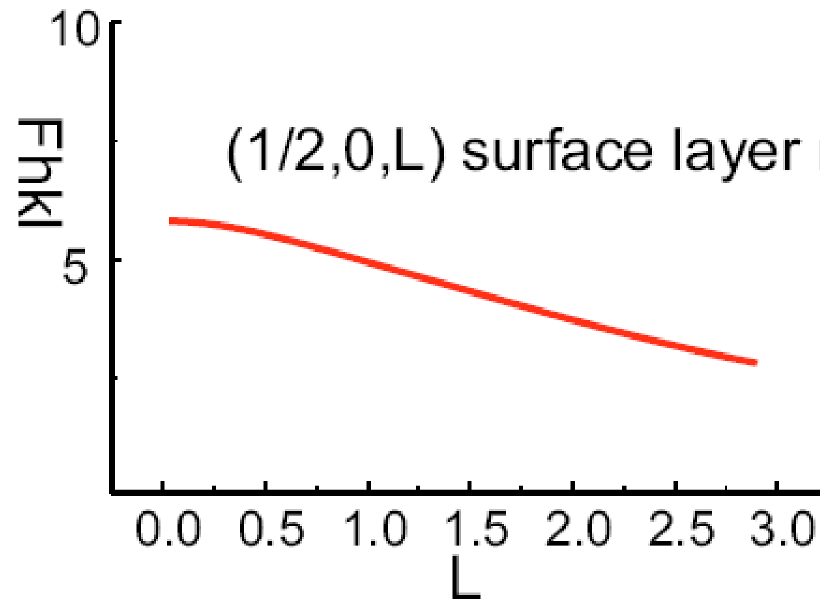
- average nanoparticle / nanostructure size, distance, shape
- lateral morphological information
- independent of crystalline state

Surface X-ray Diffraction

Principles:







$$F_{CTR} = A(\vec{q}) \sum_{n_3=0}^{\infty} e^{i\, q_z n_3 a_3} = \frac{A(\vec{q})}{1 - e^{i\, q_z a_3}} = \frac{A(\vec{q})}{1 - e^{i\, 2\pi\, l}}$$

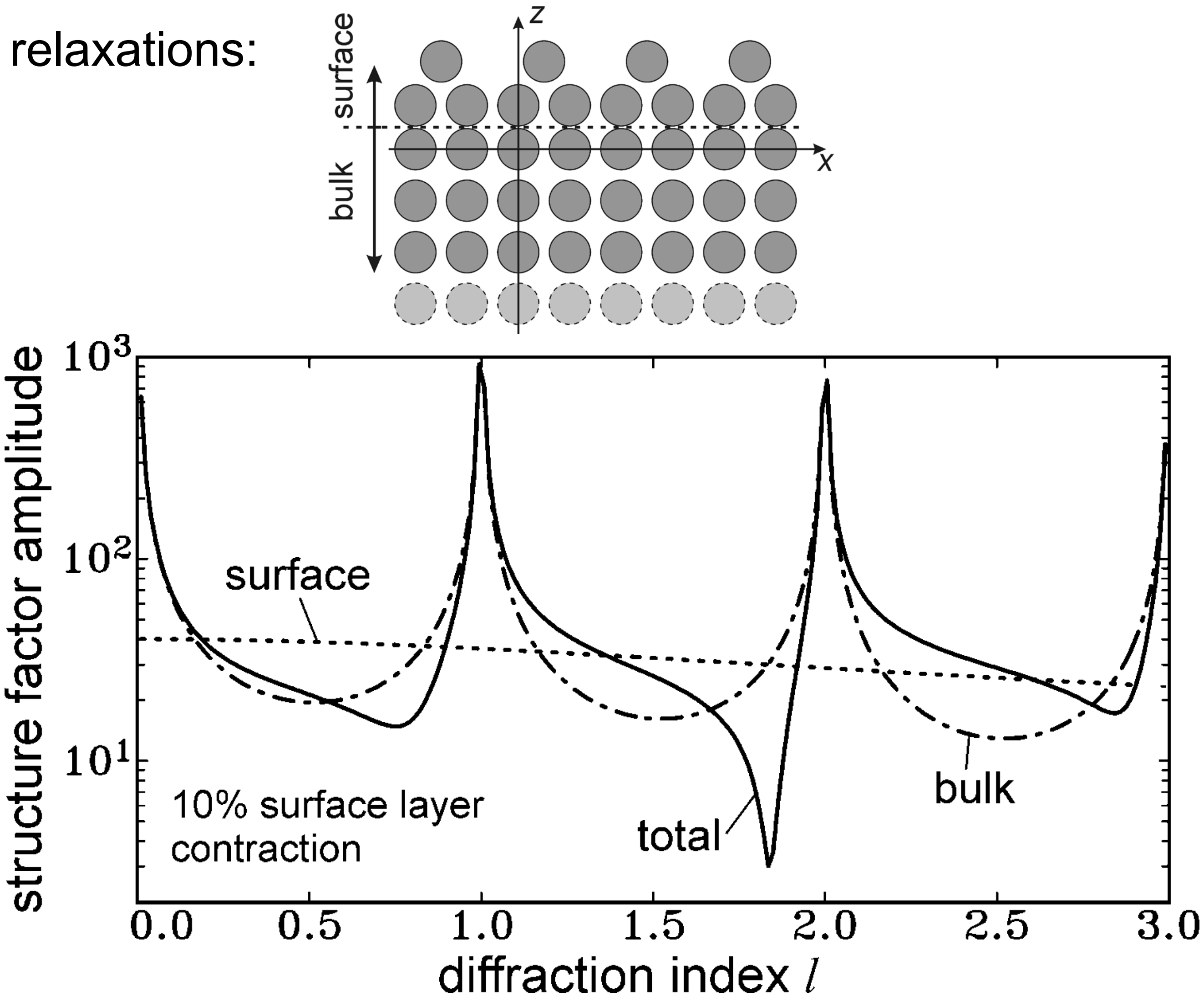
Laue-Stacheln

$$I_{CTR}(\vec{q}) = \left| \frac{r_0}{R} A_0 F(\vec{q}) N_1 N_2 \right|^2 \frac{1}{4 \sin^2(\pi l)}$$

E. Vlieg, J. Appl. Cryst. 33, 401 (2000)
R. Feidenhans'l, Surf. Sci. Rep. 10, 105 (1989)
I. K. Robinsion, D. J. Tweet, Rep. Prog. Phys. 55, 599 (1992)

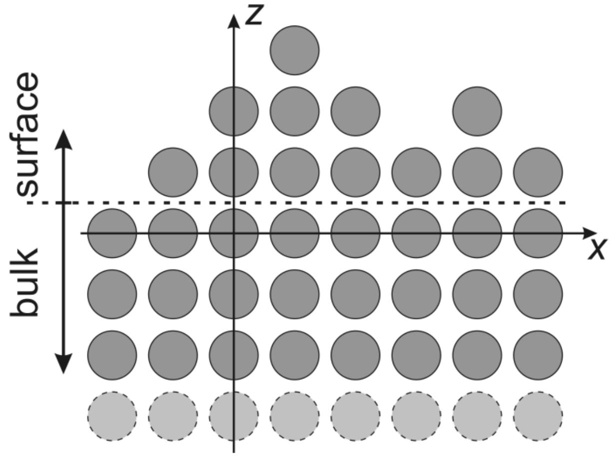
Surface X-ray Diffraction

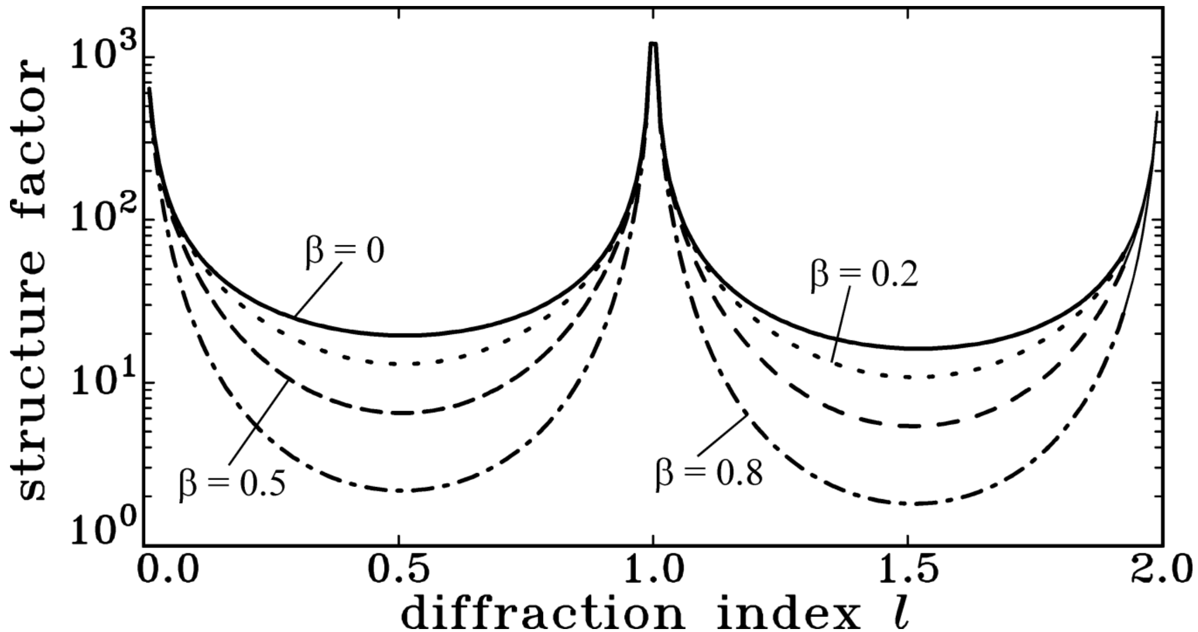
Influence of relaxations:



Surface X-ray Diffraction

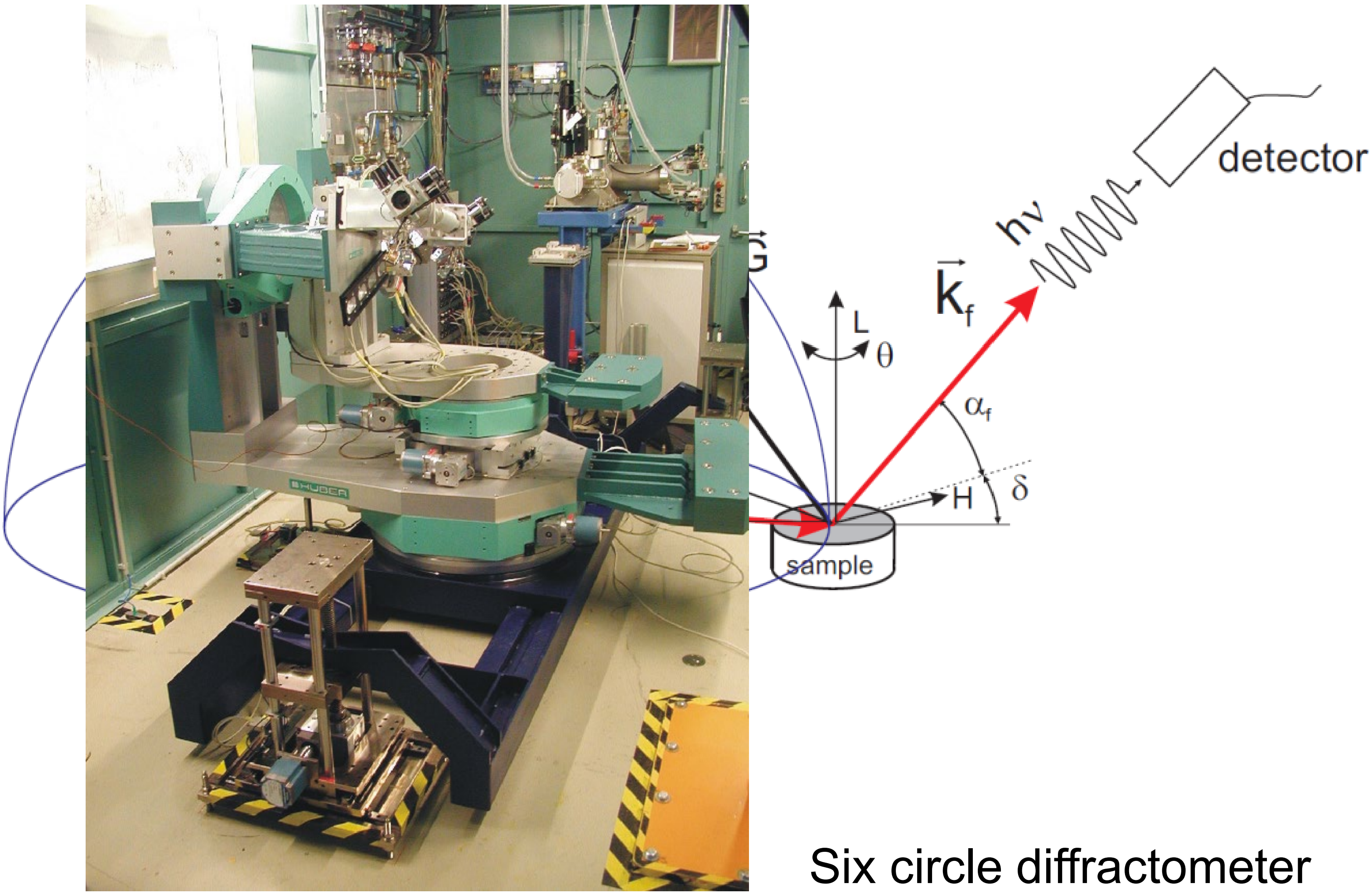
Influence of roughness:





β model: occupation of layer n: β^n

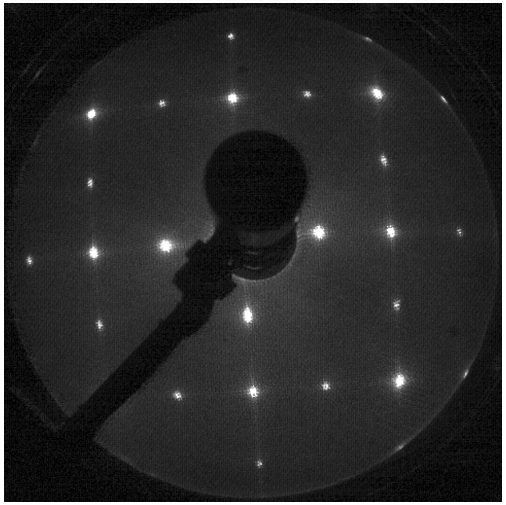
Experimental realization:



Six circle diffractometer

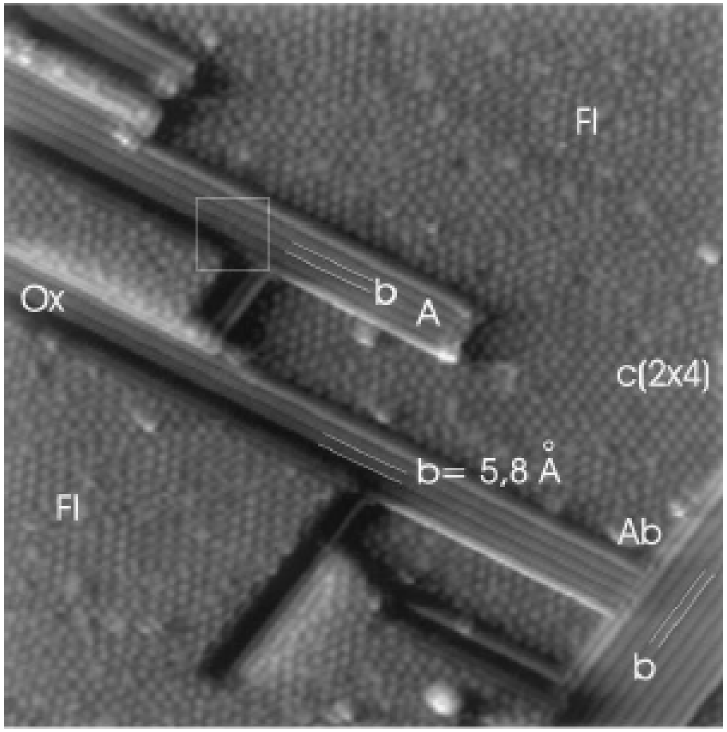
Surface X-ray Diffraction

Oxidation of CoGa(100): Previous Results from LEED and STM



LEED:
(2x1) superstructure

Oxidation at $2x10^{-7}$ mbar, 1260 s at 720 K

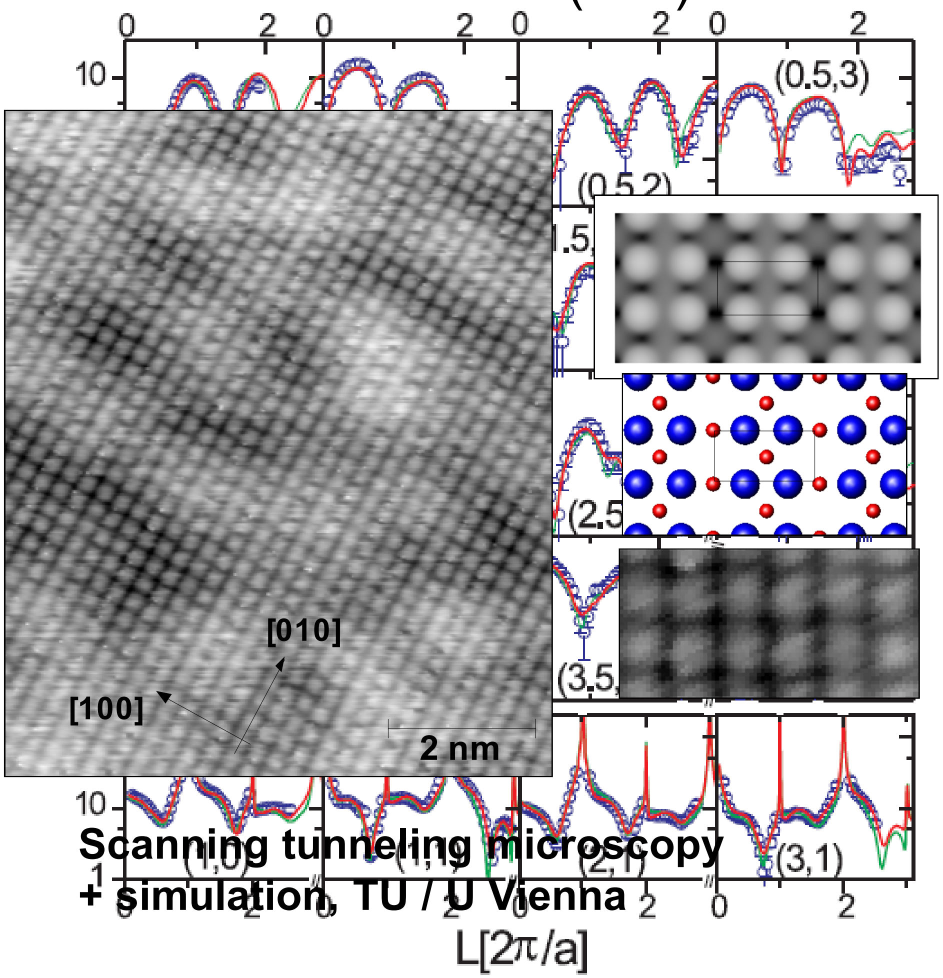


320 x 320 Å²

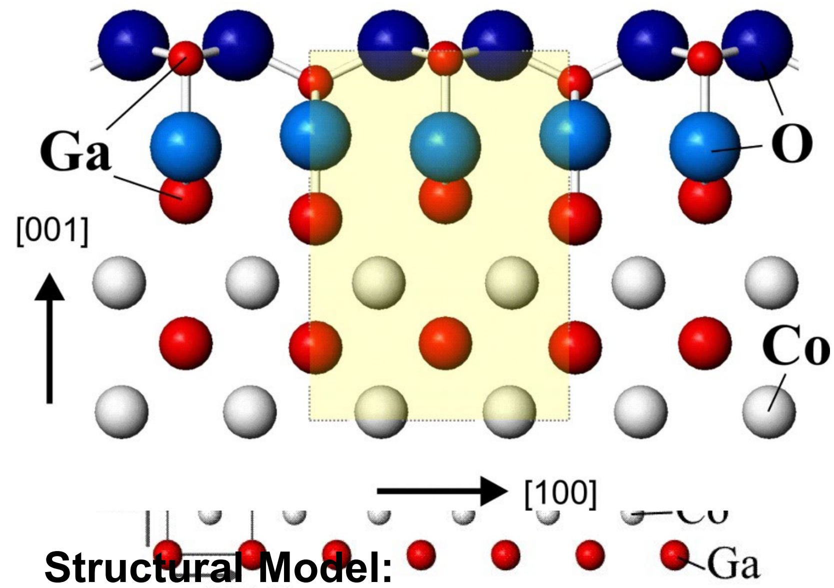
R. Franchy, Surf. Sci. Rep. 38 (2000) 195-294

Surface X-ray Diffraction

Initial Oxidation of CoGa(100)



Scanning tunneling microscopy + simulation, TU / U Vienna



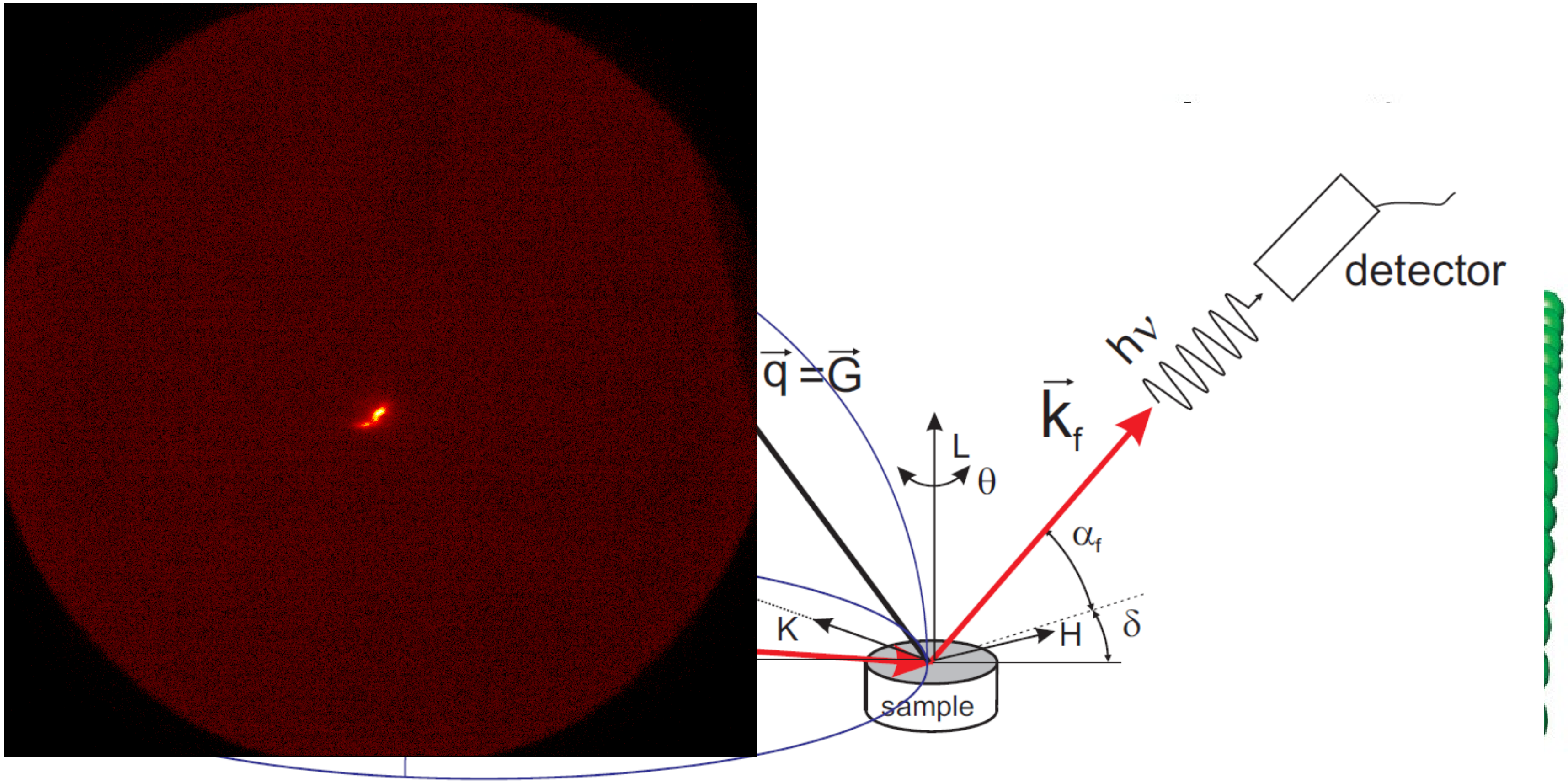
Structural Model:
Ga_4O_4 on CoGa(100)
Starting point: monoclinic Ga_2O_3

Oxidation conditions:
500°C , $p(O_2)$= $5x10^{-7}$ mbar

Crystal Truncation Rod Data
Fit: red line (DFT model: green line)

A. Vlad, et al., Phys. Rev. B 81, 115402 (2010)

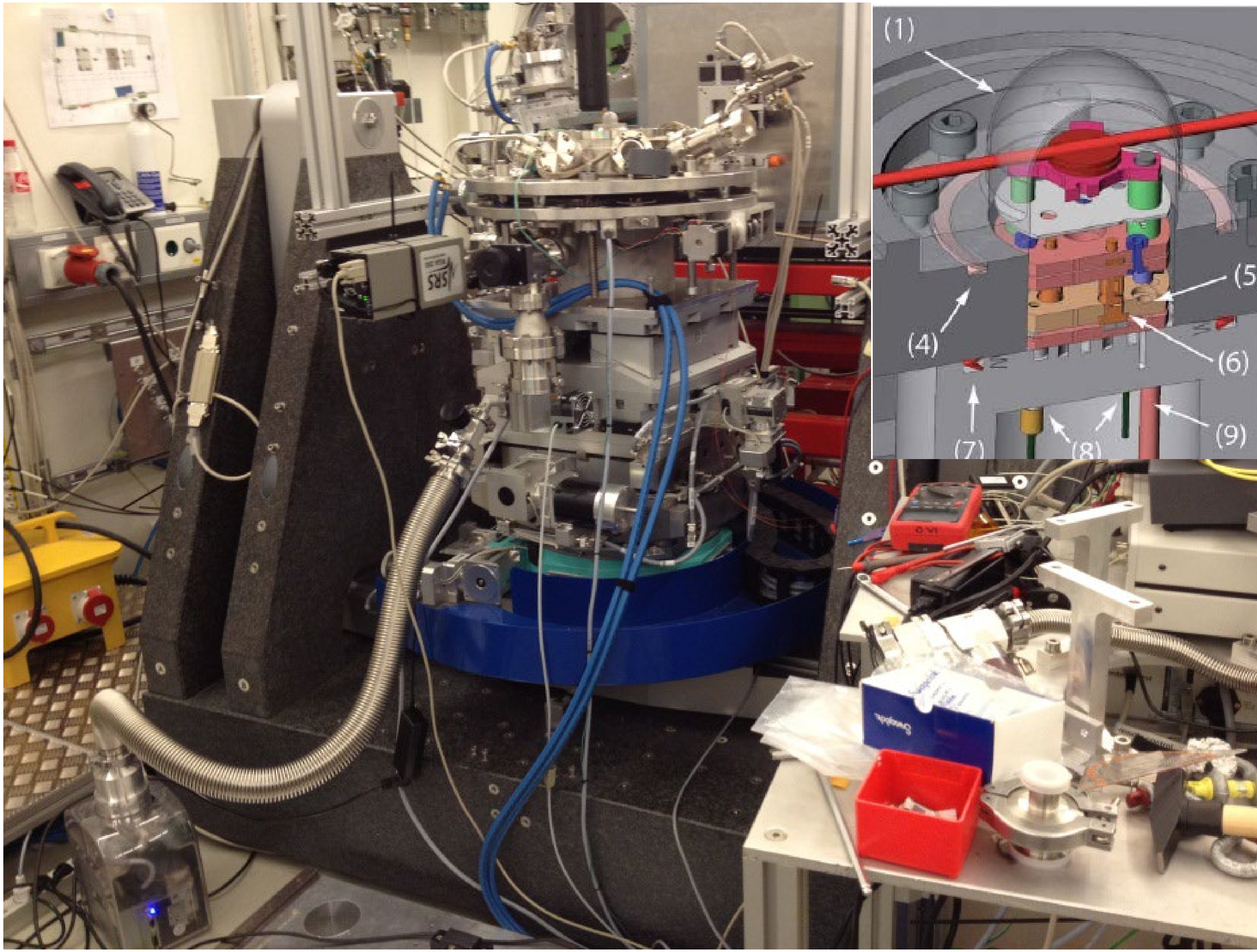
Surface X-ray Diffraction



2D diffraction pattern of growing Ga oxide layer

A. Stierle, et al., New Journal of Physics 9, 331 (2007)

Method: In-situ high energy x-ray reciprocal space mapping (E=85 keV)



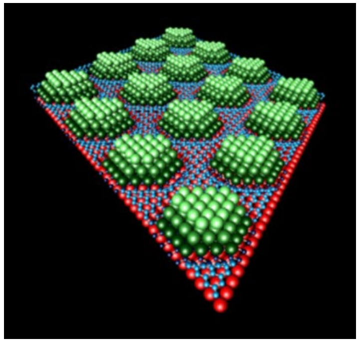
P07
PETRAIII

X-ray movie of Rh(111) surface during CO Oxidation (P07, PETRA III)

2D Detector
40 cm x 40 cm

RA Kollaboration E. Lundgren, J. Gustafon, U. Hejral, A. Stierle

Surface X-ray Diffraction



Summary surface x-ray diffraction

fit: kinematical diffraction theory

parameters:

overlayer structure+registry, thickness,

relaxations, roughness

Structure of ultrasmall nanoparticles

near surface composition

thermal vibrations

In-situ observation of surface processes

Surface Sensitive X-ray Diffraction

Surface Sensitive X-Ray Diffraction Methods

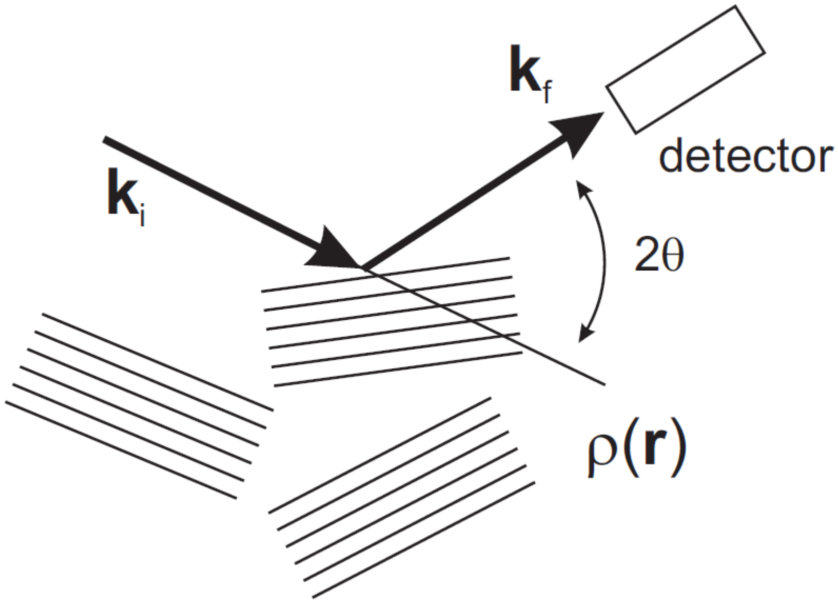
Andreas Stierle, University of Siegen, Germany; Elias Vlieg, Radboud University Nijmegen, The Netherlands

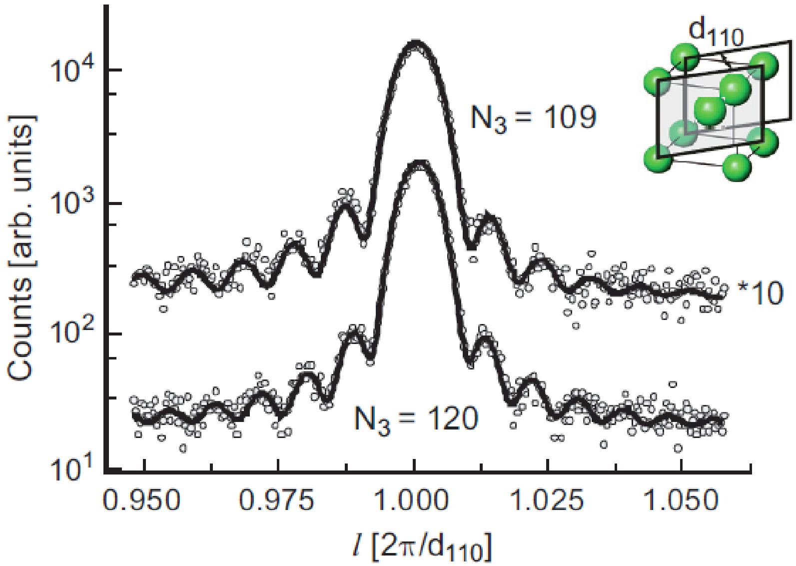
1 Introduction

Since the first demonstration in 1912 [1], X-ray diffraction (XRD) has become the dominant technique to determine the bulk structure of crystals. In fact, many crystals are grown with the sole purpose of determining the structure of their building blocks. This is especially relevant for

A. Stierle, E. Vlieg, in *Modern Diffraction Methods*, edited by E. J. Mittemeijer and U. Welzel, Wiley VHC Weinheim, 2012.

Nanoparticle Structural Analysis





q= $4\pi/\lambda \sin(\theta)$: scattering vector

epitaxial film diffraction

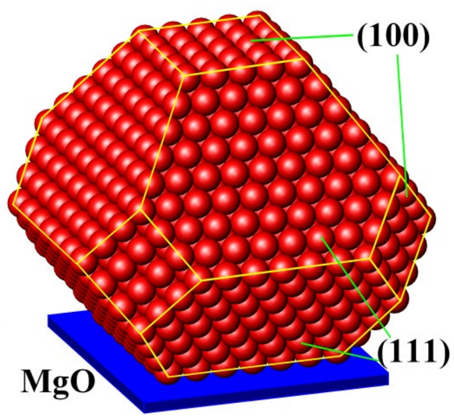
$$\propto \left|F(\boldsymbol{q})\right|^2 \prod_{j=1}^{3} \frac{\sin^2\left(\frac{1}{2} N_j \boldsymbol{q}\cdot\boldsymbol{a}_j\right)}{\sin^2\left(\frac{1}{2}\boldsymbol{q}\cdot\boldsymbol{a}_j\right)}$$

- Surface information lost for powder diffraction
- Small particles produce wide peaks in reciprocal space

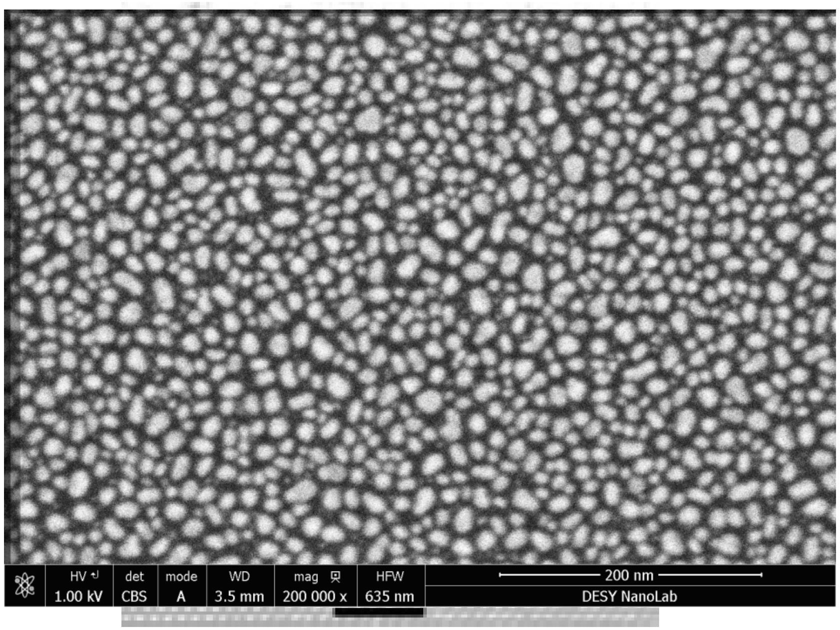
Interference function for single crystalline film

Our Approach: Epitaxial Nanoparticles

Model system: epitaxial nanoparticles supported by oxide single crystals



Pd, Rh, Pt/MgO(100)
PtRh, PdRh /$MgAl_2O_4$(100)
cube-on-cube epitaxy



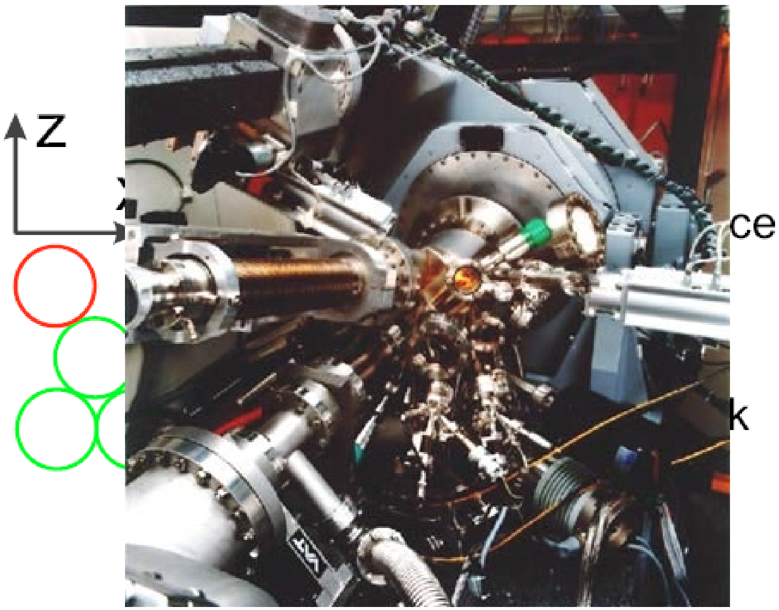
FEI Nova Nano, E= 1 keV
HRTEM, ARM 1.2 MeV

Sample preparation by MBE growth at T=400°C
Size distribution: 30-60%

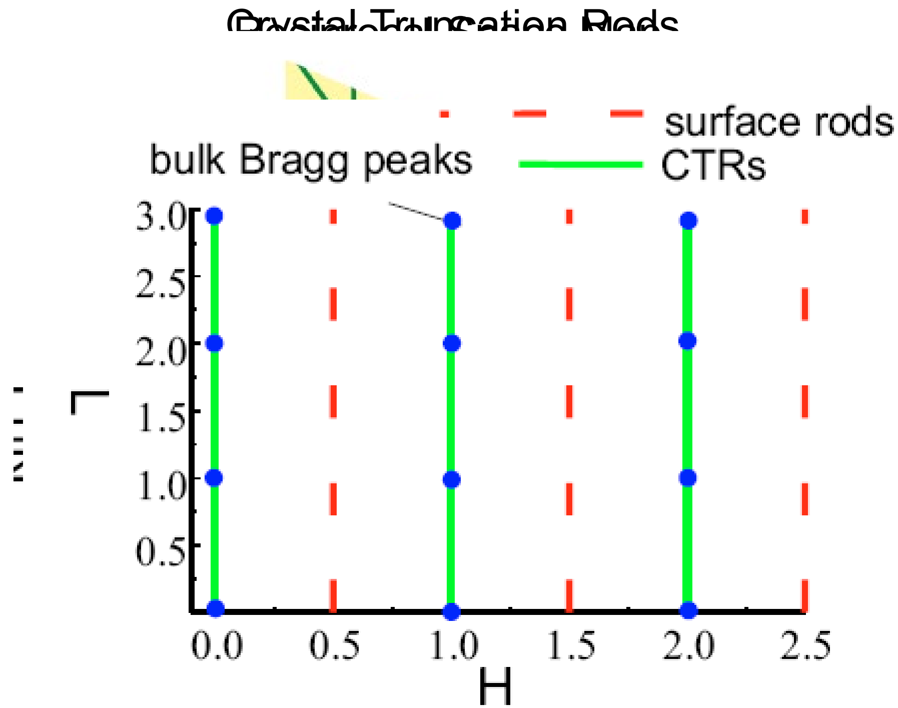
Shape Change of Pd and Rh Nanoparticles on MgO(100)

High resolution reciprocal space mapping

Experimental set-up at BM32, ESRF



UHV surface x-ray diffraction and GISAXS chamber

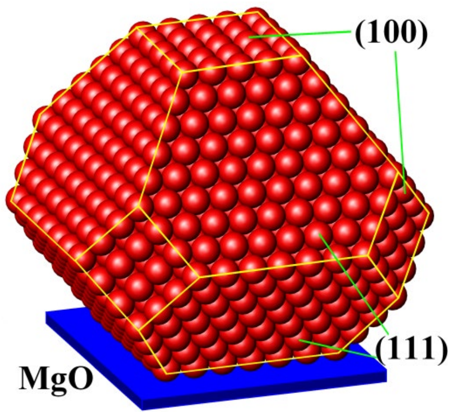


BM32, ESRF
E_p=12 keV

G. Renaud, et al. Nuc. Inst. Meth. B 95, 422 (1995)

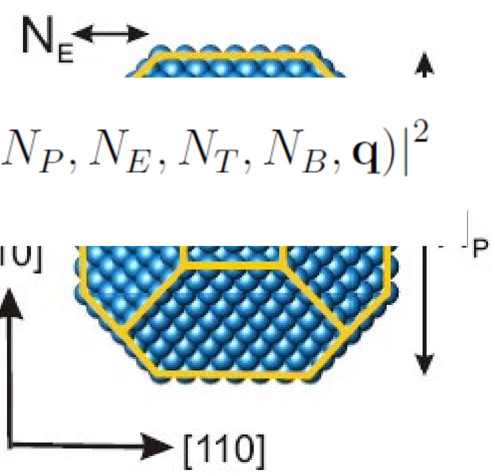
Shape Change of Pd and Rh Nanoparticles on MgO(100)

Particle Size & Shape Variation:

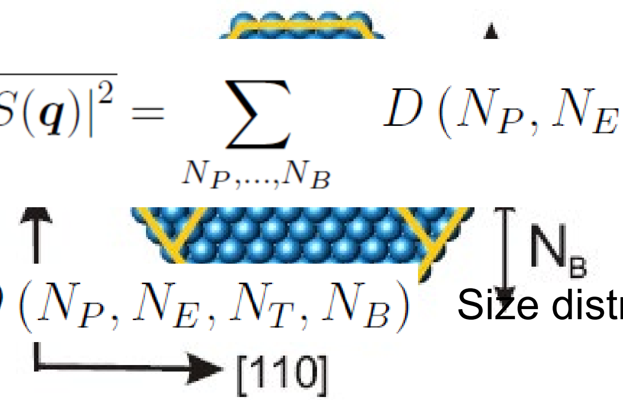


4 parameters for x-ray structure factor calculation

$\{N\} \equiv \{N_P, N_E, N_T, N_B\}$



$$\overline{|S(\boldsymbol{q})|^2} = \sum_{N_P,\ldots,N_B} D\left(N_P, N_E, N_T, N_B\right) \left|S\left(N_P, N_E, N_T, N_B, \mathbf{q}\right)\right|^2$$

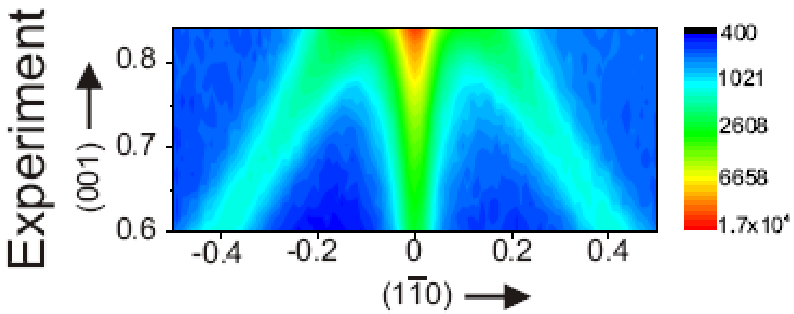


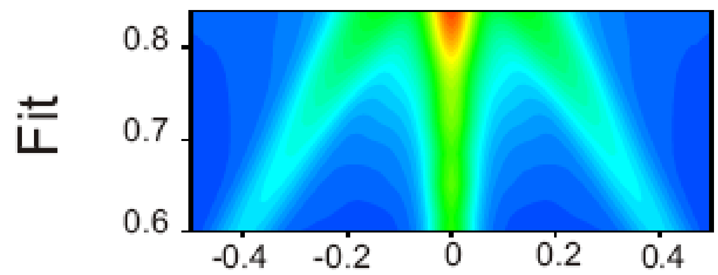
$D\left(N_P, N_E, N_T, N_B\right)$ Size distribution

N. Kasper, et al., Surf. Sci. 600, 2860 (2006)

Shape Change of Rh Nanoparticles on MgO(100)

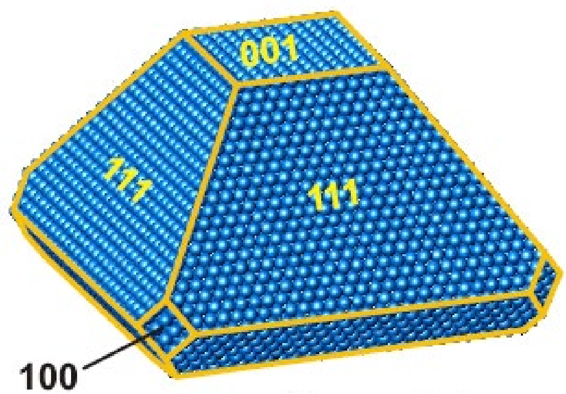
Clean Rh nanoparticles SXRD reciprocal space maps at T=600 K





Fit Results:
NP=31±1,
NT=20±1,
NB=5±1
NE=3±1

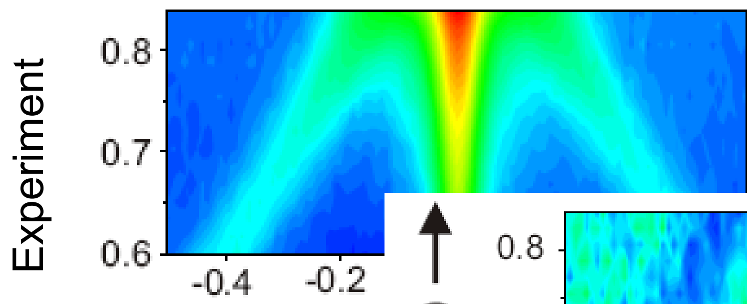
average diameter: 8.3 nm
average height: 4.8 nm

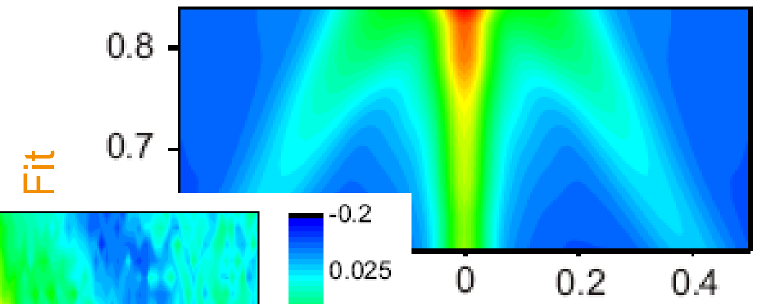


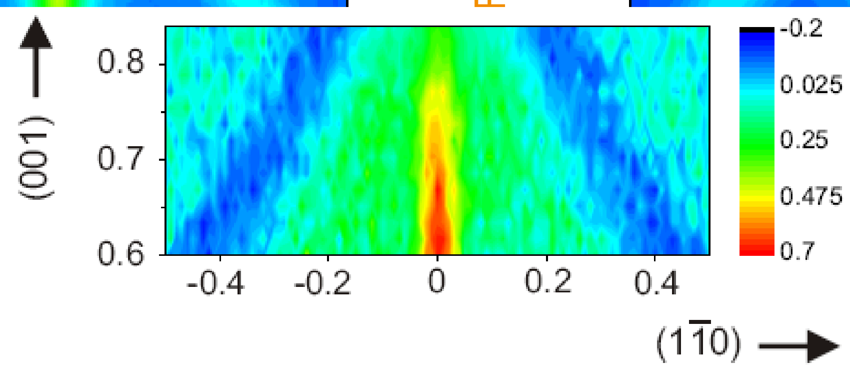
clean Rh particle

Shape Change of Rh Nanoparticles on MgO(100)

Oxidation at T=600 K, $p(O_2)=3x10^{-5}$ mbar

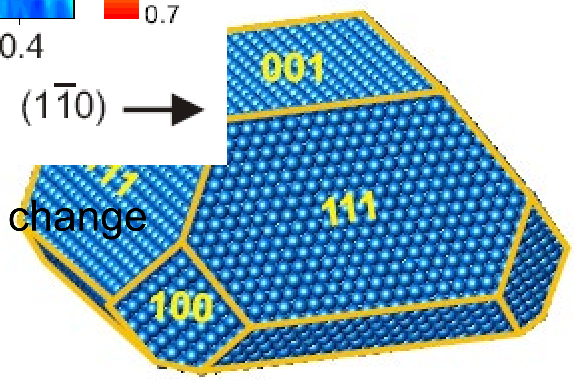






Fit Results:
NP=31±1,
NT=16±1,
NB=5±1
NE=7±1

Oxygen adsorption induced signal change

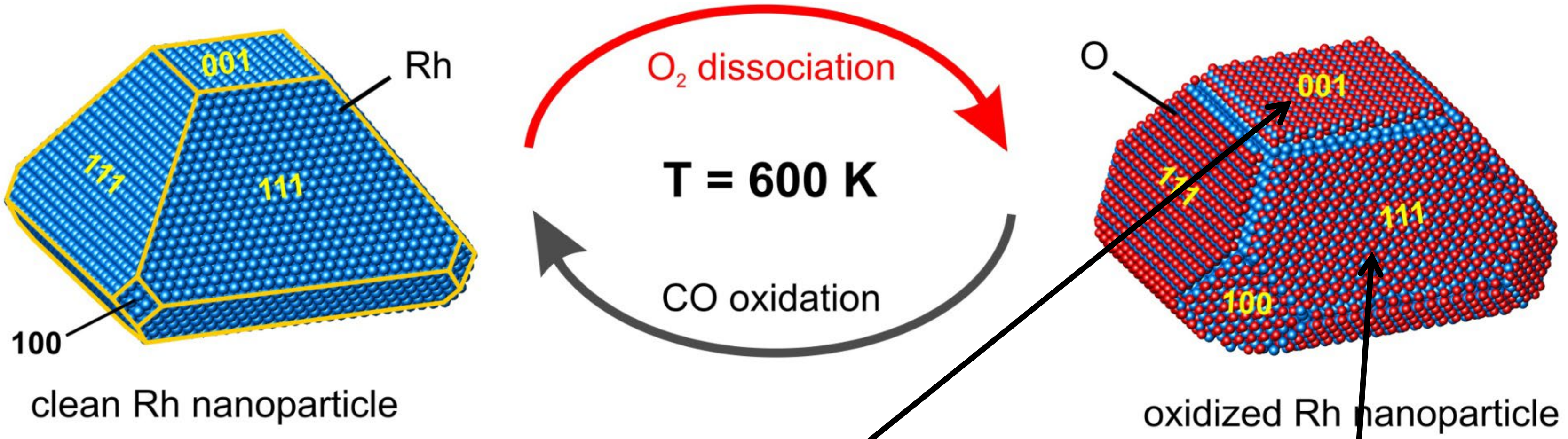


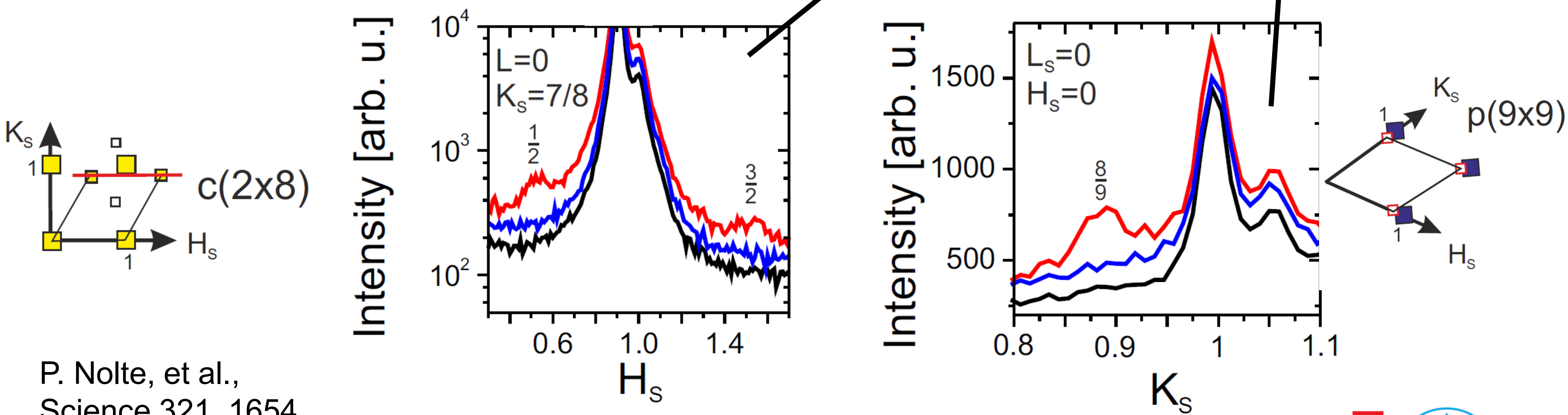
oxidized Rh particle (core)

average diameter: 8.3 nm
Average height: 4.0 nm

Shape Change of Rh Nanoparticles on MgO(100)

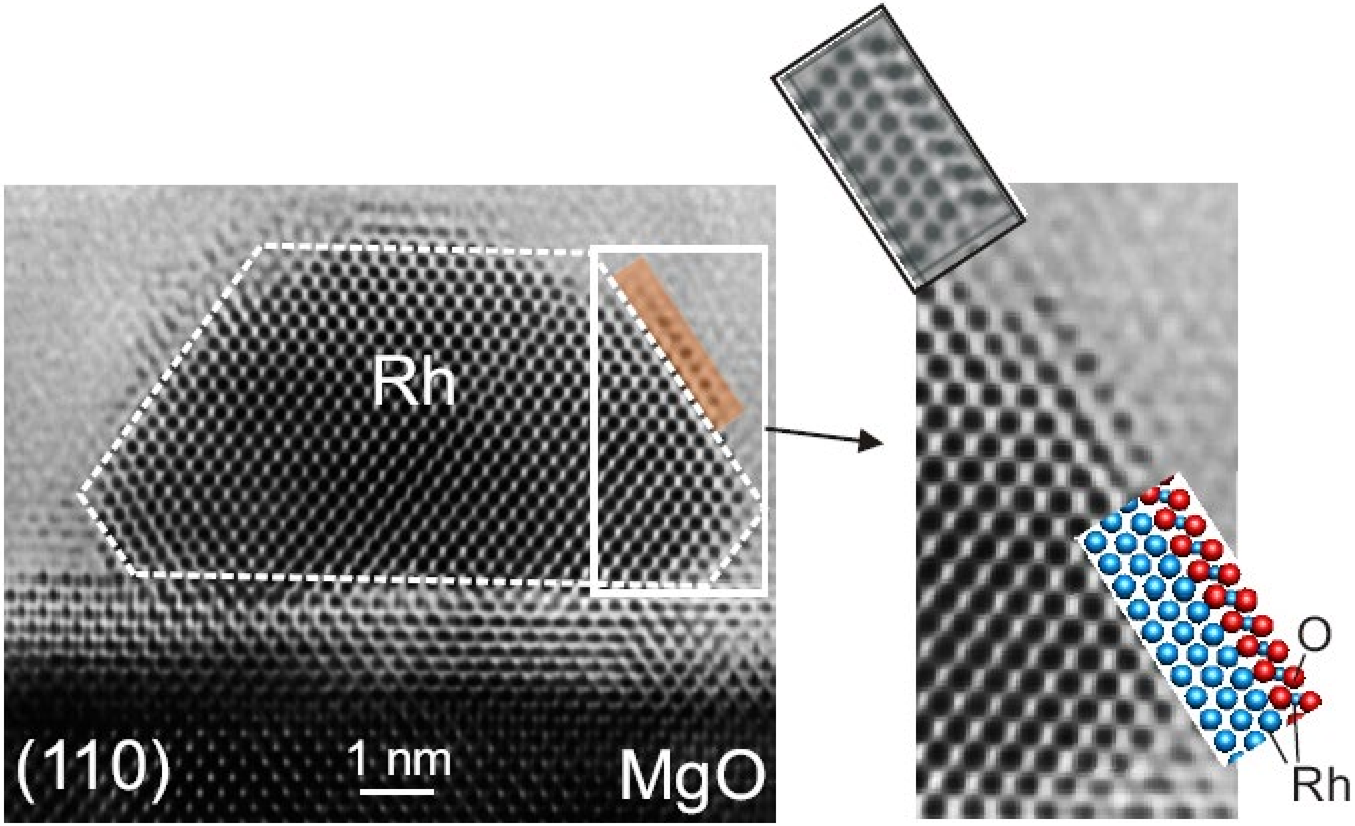
CO Reduction and Reversible Shape Change
T=600 K, p(CO)=3x10^{-5} mbar





P. Nolte, et al., Science 321, 1654 (2008)

Ex-Situ Cross-Section TEM Characterization

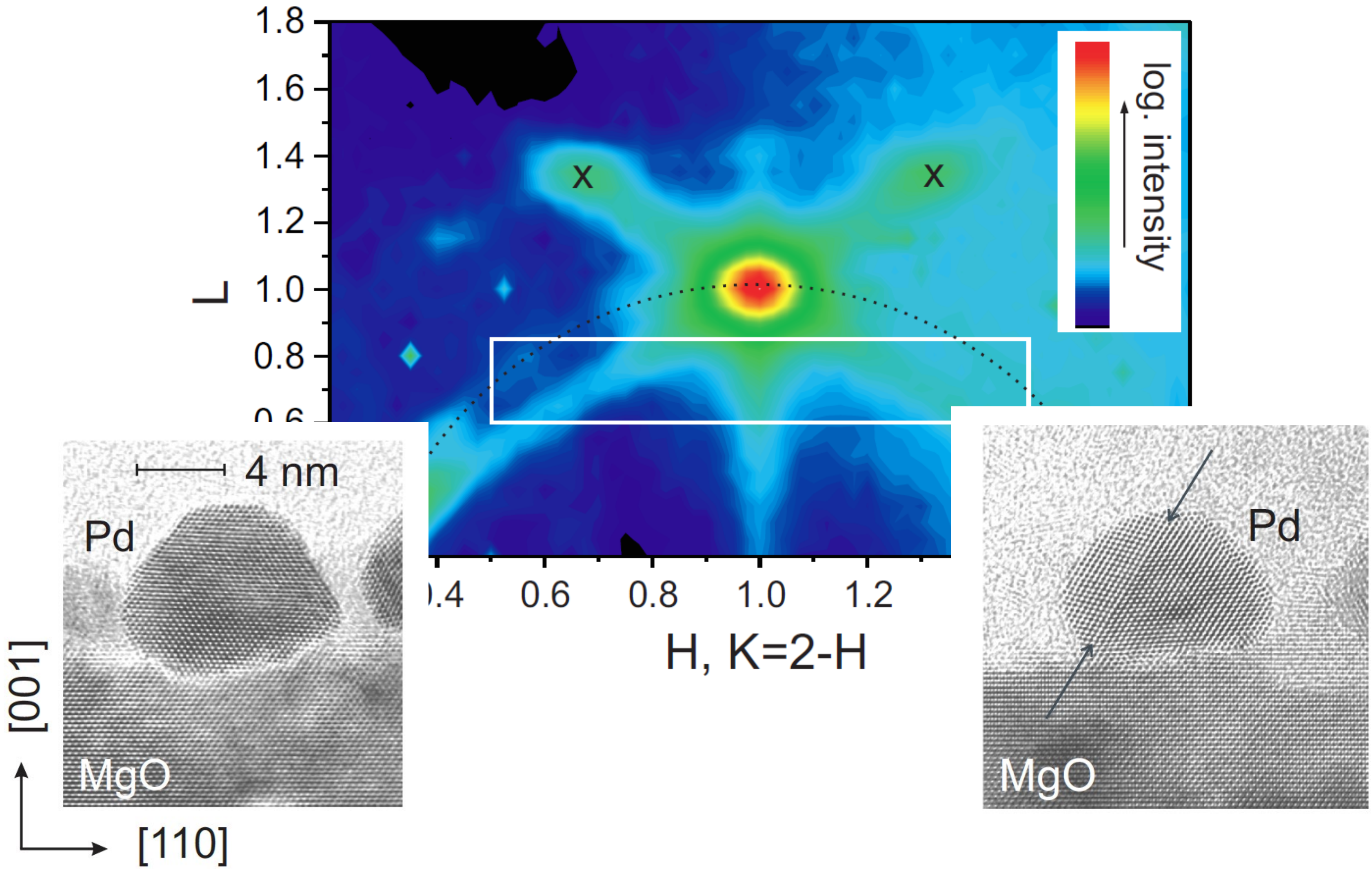


[redacted]

HR-TEM MPI IS (MPI-MF) Stuttgart

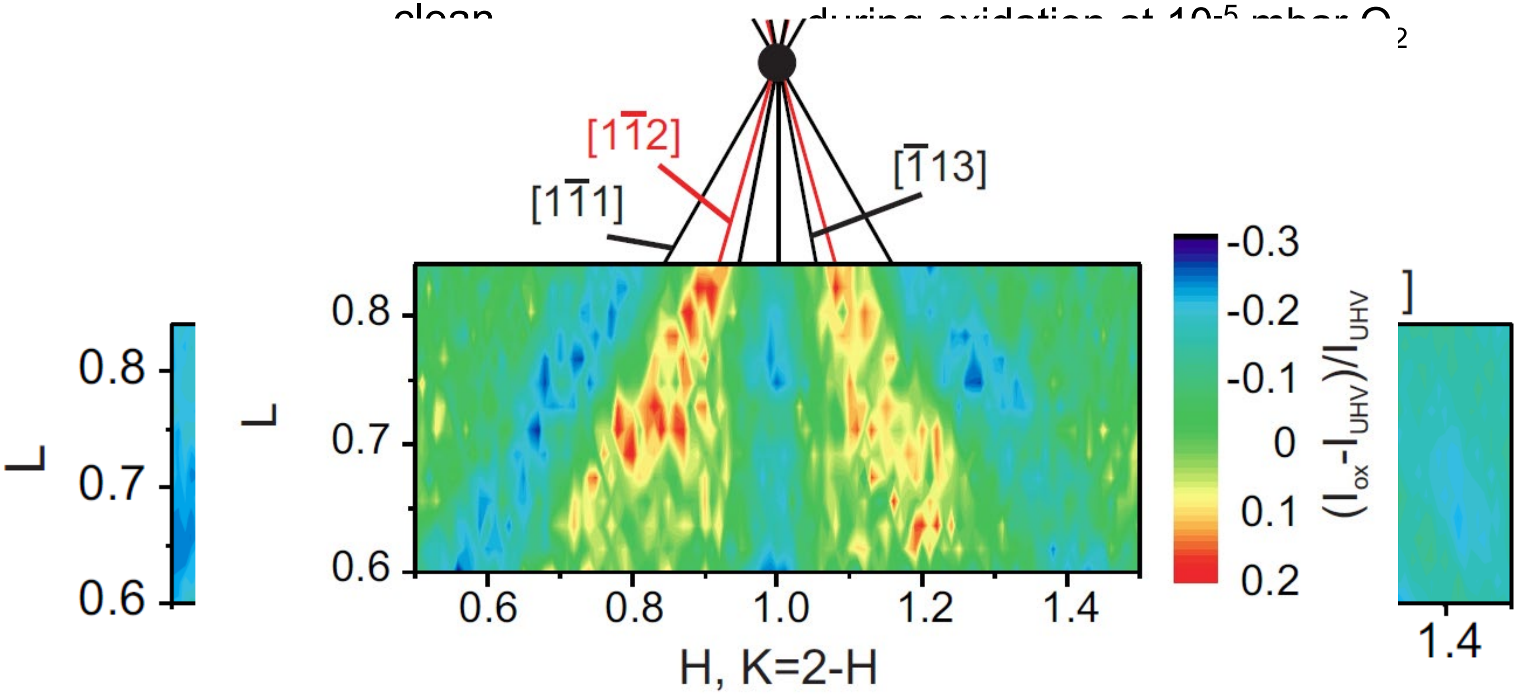
N.Y. Jin-Phillipp, et al., Surf. Sci. 603, 2551 (2009)

Pd on MgO(100): Overview Mesh Scan



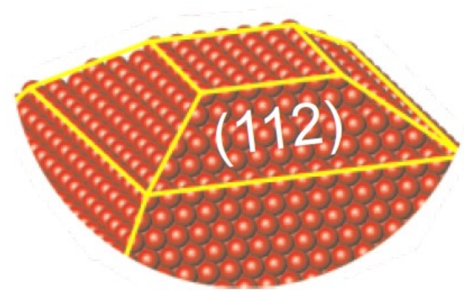
P. Nolte, et al., Nano Letters 11, 4505 (2011)

Pd Nanoparticles on MgO(100)
SXRD Reciprocal Space Maps at T=570 K



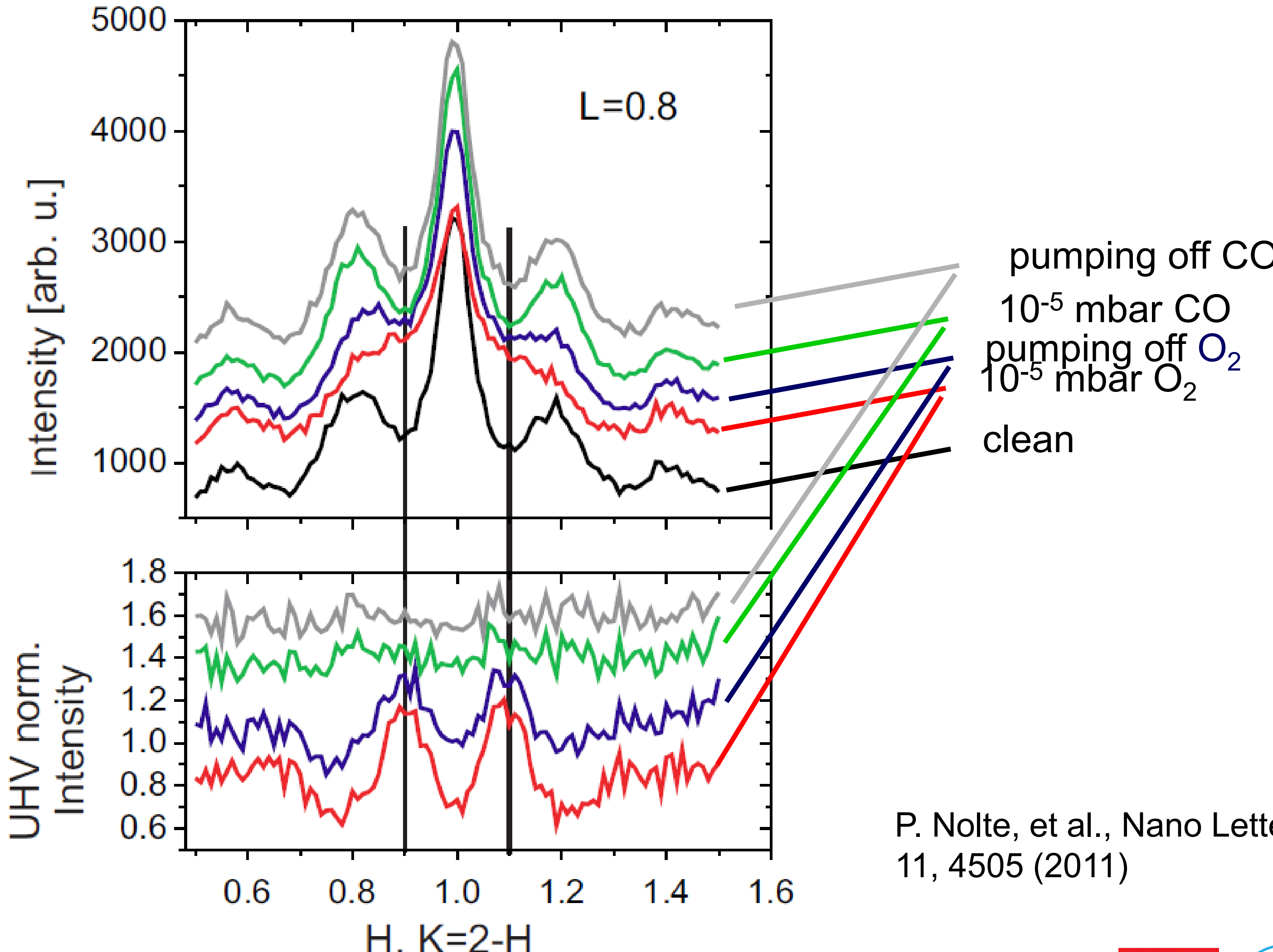
difference map

Particle model with (112) facets



Pd Nanoparticles on MgO(100)
Reversibility of Shape Change at 570 K

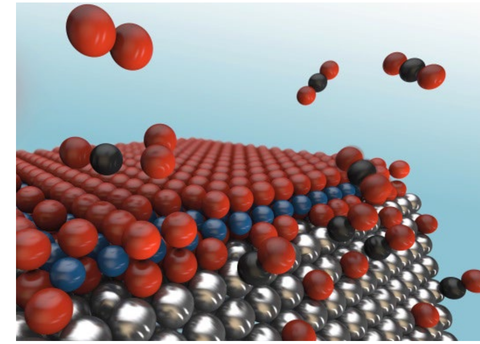
Linescans at L=0.8



P. Nolte, et al., Nano Letters 11, 4505 (2011)

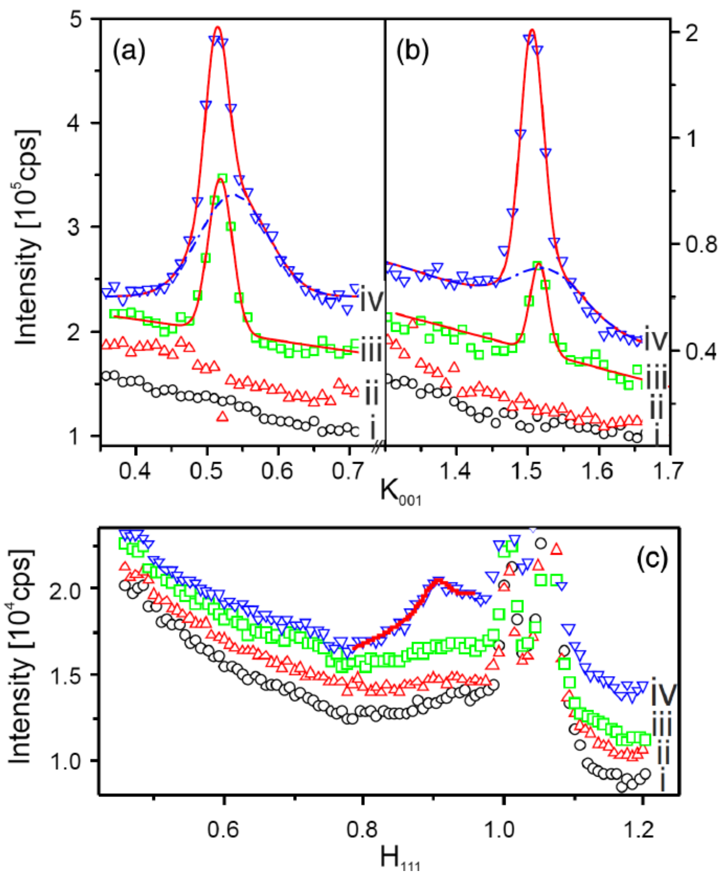
PtRh Nanoparticles under Operando CO Oxidation

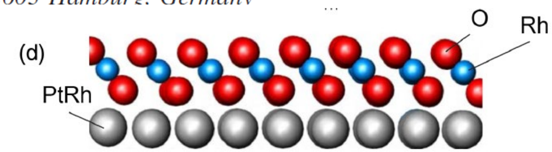
PHYSICAL REVIEW LETTERS **120**, 126101 (2018)

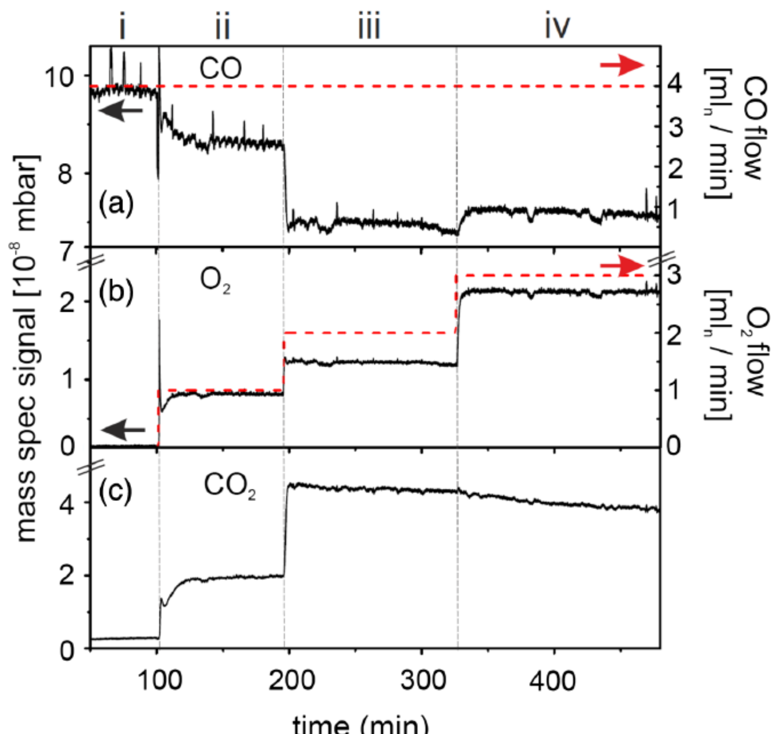


Identification of a Catalytically Highly Active Surface Phase for CO Oxidation over PtRh Nanoparticles under Operando Reaction Conditions

U. Hejral,[1,2,3,†] D. Franz,[1,2] S. Volkov,[1,2] S. Francoual,[1] J. Strempfer,[1] and A. Stierle[1,2,*]
[1]Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany

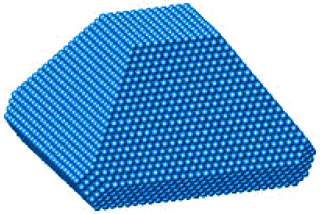




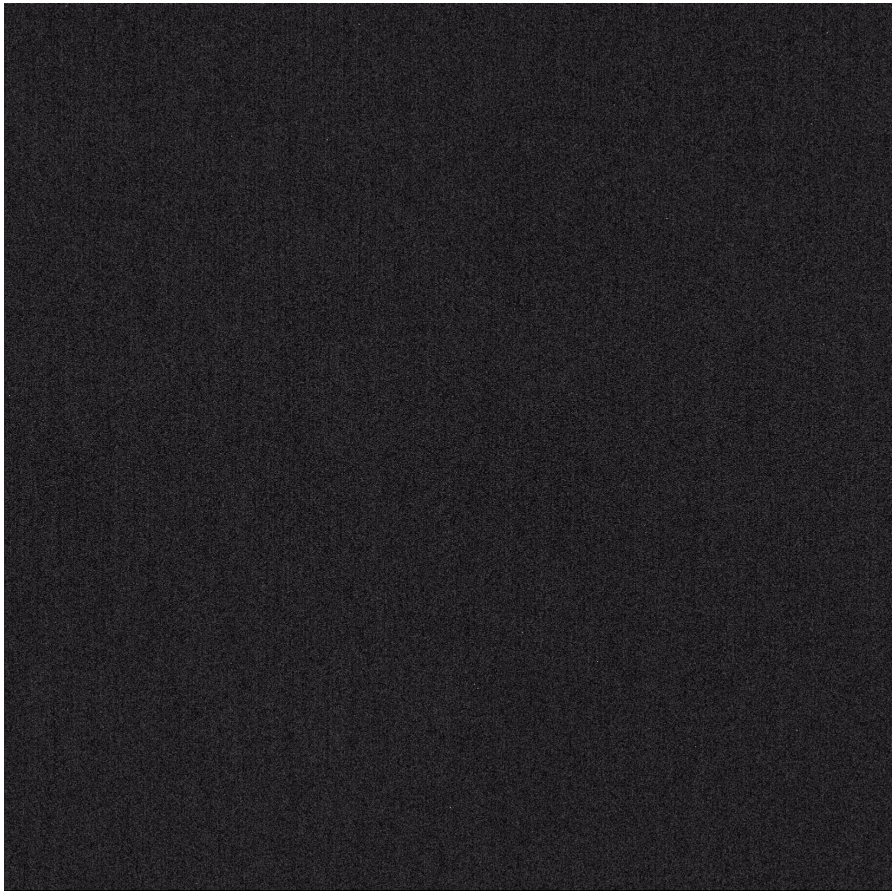


l State Phys

Time Resolved High Energy X-ray Diffraction (80 keV)

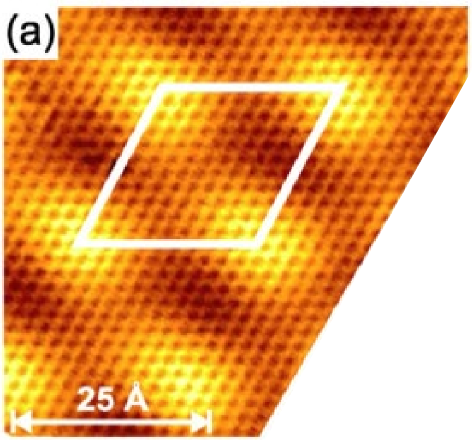


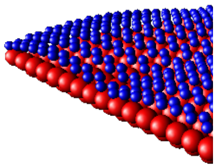
Rh nanoparticle oxidation

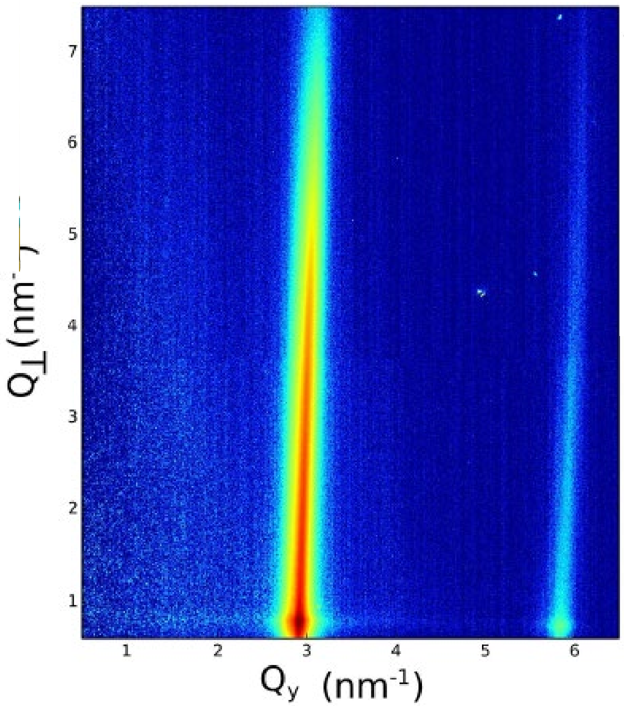


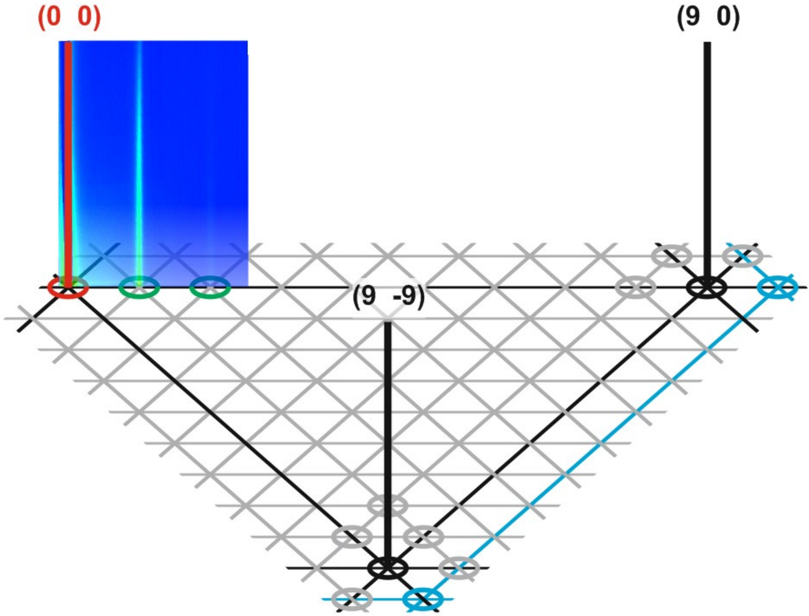
Atomic Structure of Ultra-small Nanoparticles (< 2 nm)

Nanoparticles: Pt, Ir, Pd(Ir), Fe(Ir), Au(Ir), Rh
Support: graphene









Reciprocal space

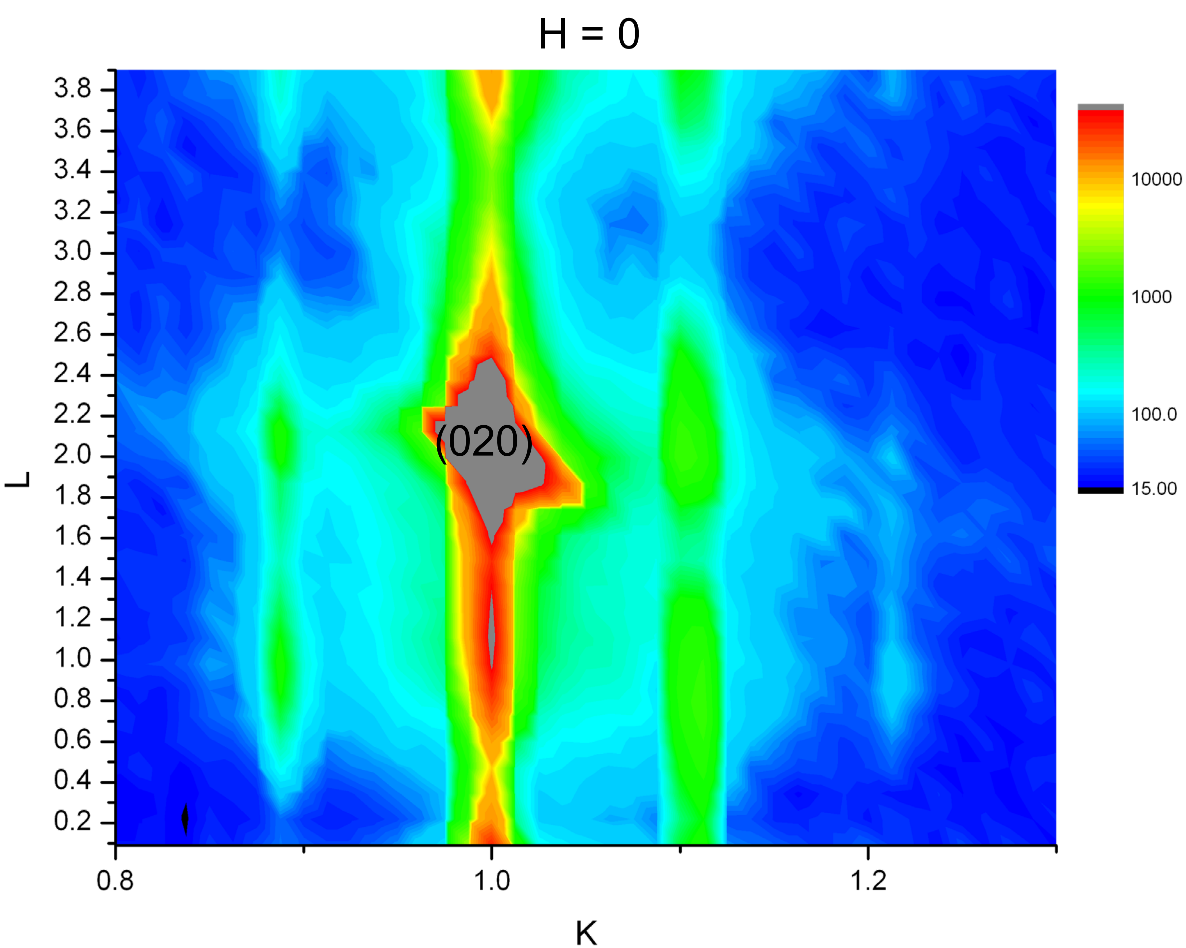
T. Michely, Uni Köln

GISAXS 0.1 ML Pt

A. T. N'Diaye, S. Bleikamp, P. J. Feibelman, T. Michely, Phys. Rev. Lett. 97, 215501, (2006)

Ultrasmall Particles Supported by Graphene

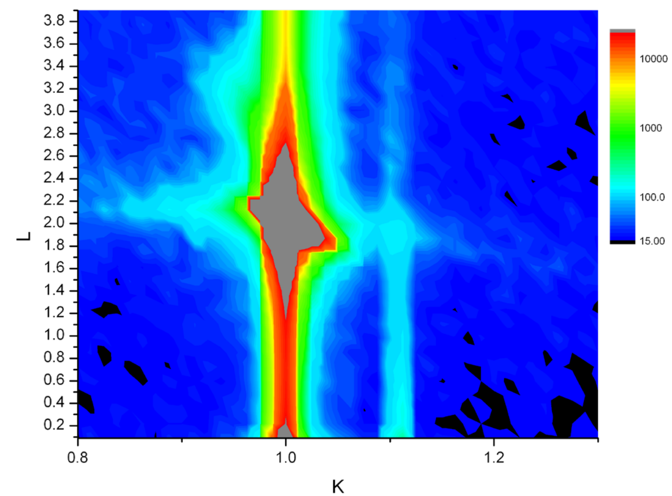
Ir nanoparticle superlattice enhanced x-ray diffraction



(0KL) map – sample with NP (~1ML)

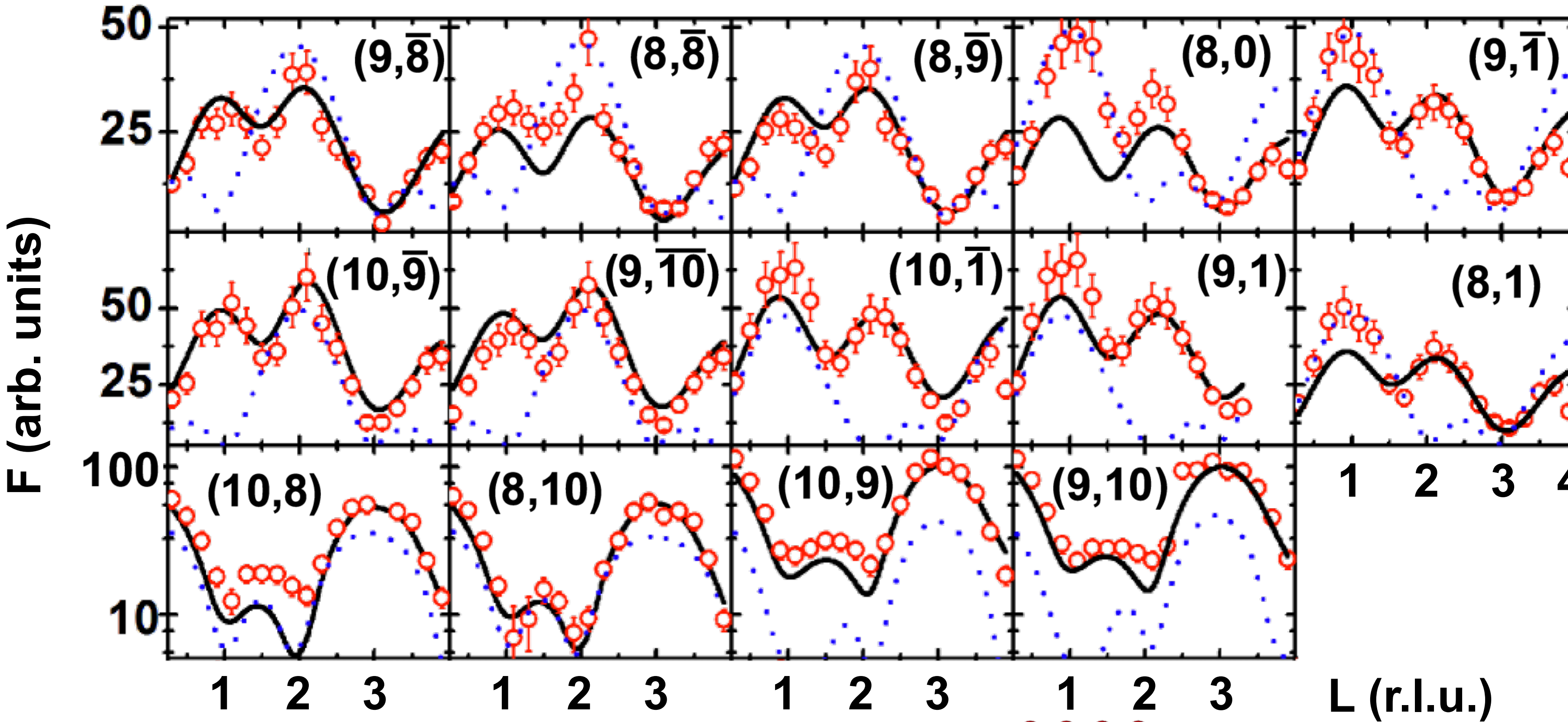
Features of map:

- (0 1) CTR,(0 1) SR
- (0 2 0) Bragg-Peak
- superstructure rods
- oscillation of rods (crystalline NP, well defined height)



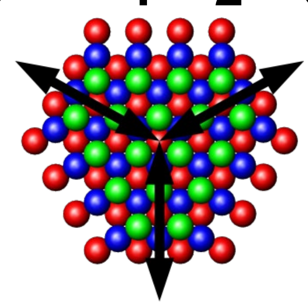
(0KL) map – clean sample

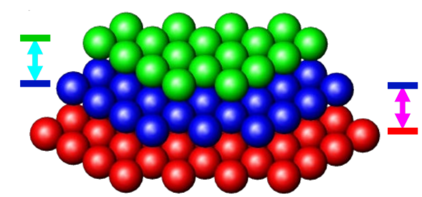
Ultrasmall Particles Supported by Graphene



Fit-Results:

- three/four layered cluster with ABC and ACB stacking
- occupancies (b, 2nd , t-layer): 53 % , 49 %, 45 %
- strain (b, 2nd, t -layer): 2.5 %, 2.3 %, 3.6 %
- z - displacement: **-4.8 %** (2nd-layer), **+3.9 %** (3rd-layer)





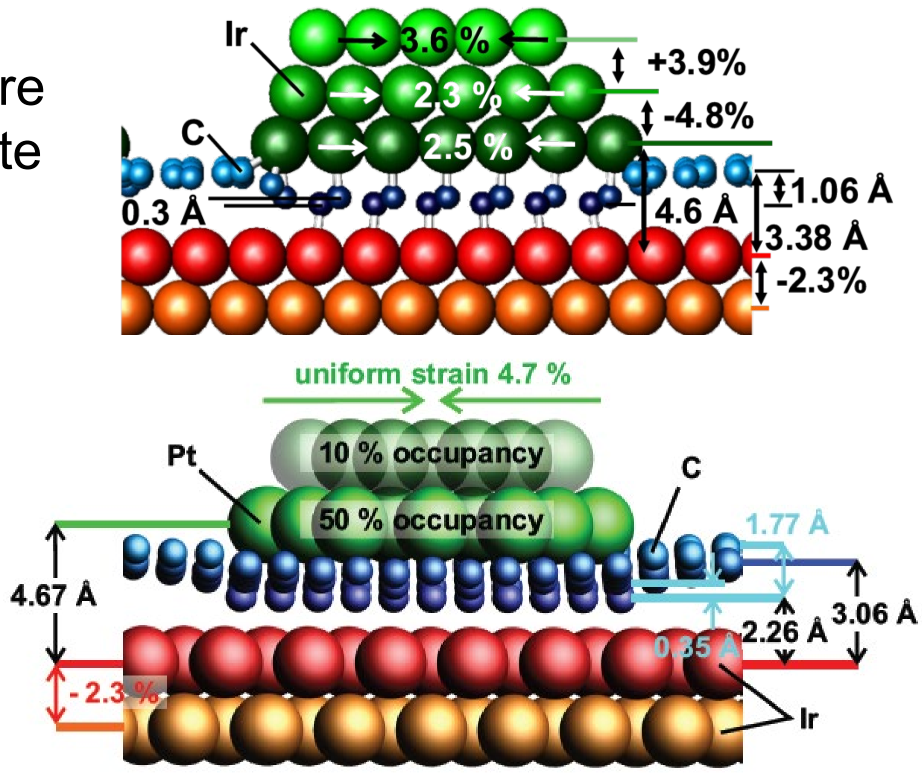
Ultrasmall Particles Supported by Graphene

- SXRD together with graphene moire templated growth is a possible route of metal cluster structure analysis

➢ Gas adsorption experiments (suitable metals, reactions)

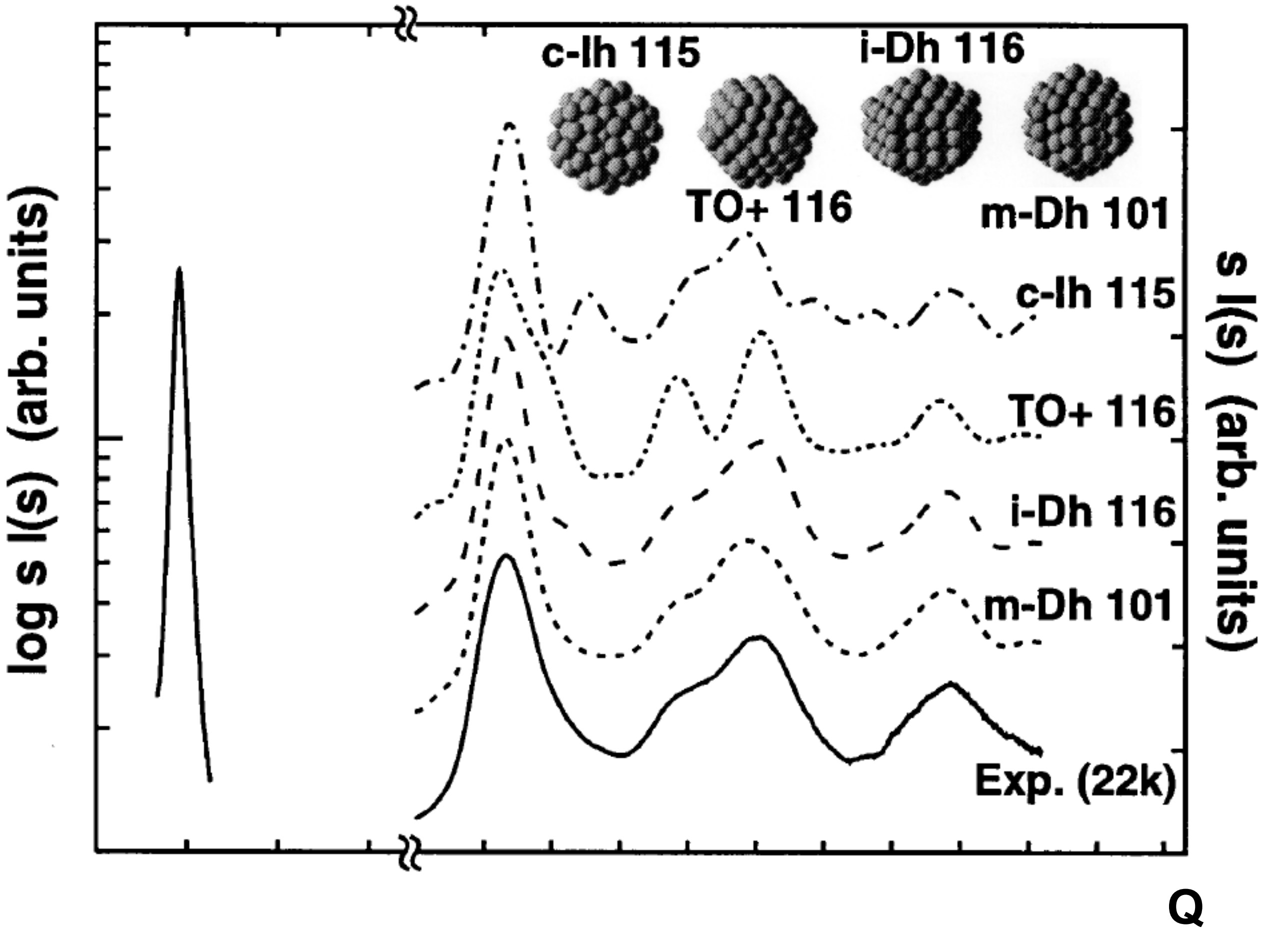
➢ Alloy nanoparticles in confinement

➢ Magnetism



D. Franz, S. Runte, C. Busse, S. Schumacher, T. Gerber, T. Michely, M. Mantilla, V. Kilic, J. Zegenhagen, A. Stierle, Phys. Rev. Lett. 110, 065503 (2013).
S. Billinge, Nature 495, 453 (2013)
PhD work Dirk Franz

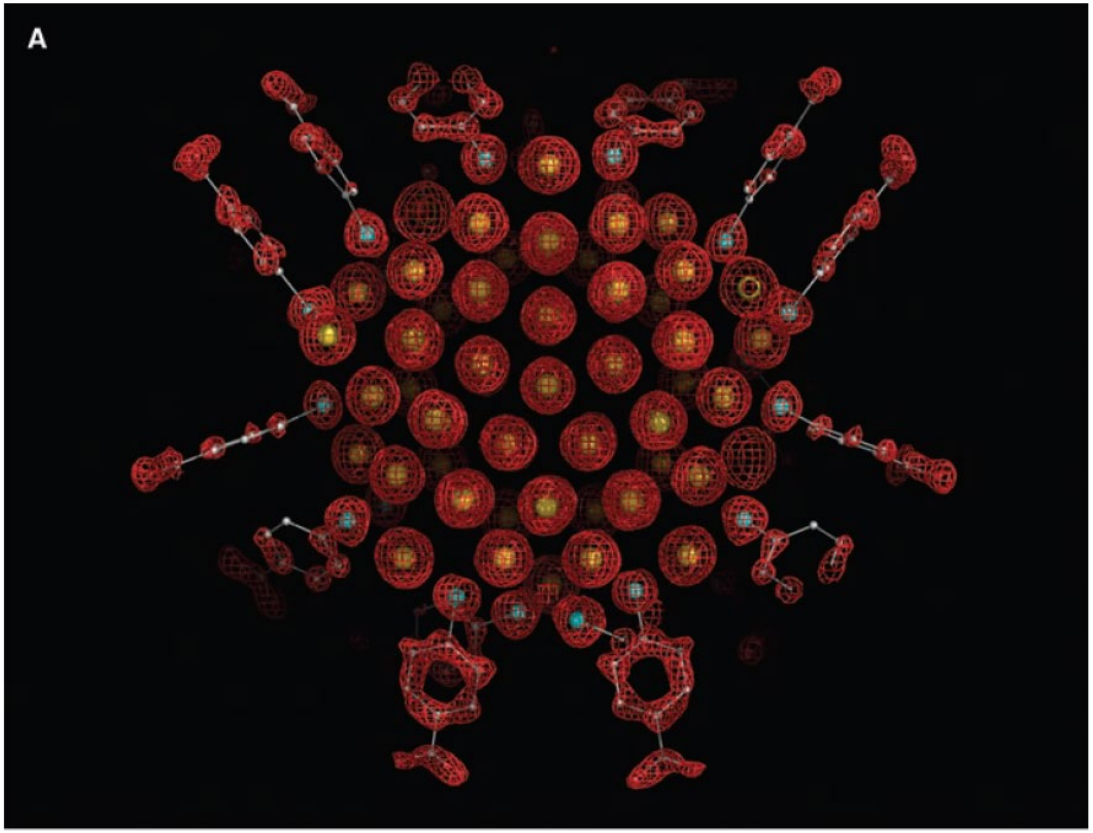
Pair Distribution Function Analysis



Au nanoparticles with different shape

Cleveland, et al. Phys. Rev. Lett. 79, 1873 (1997)

Single crystal XRD from 3D nanoparticle lattices



Thiol stabilized Au nanoparticles grown into a single crystal

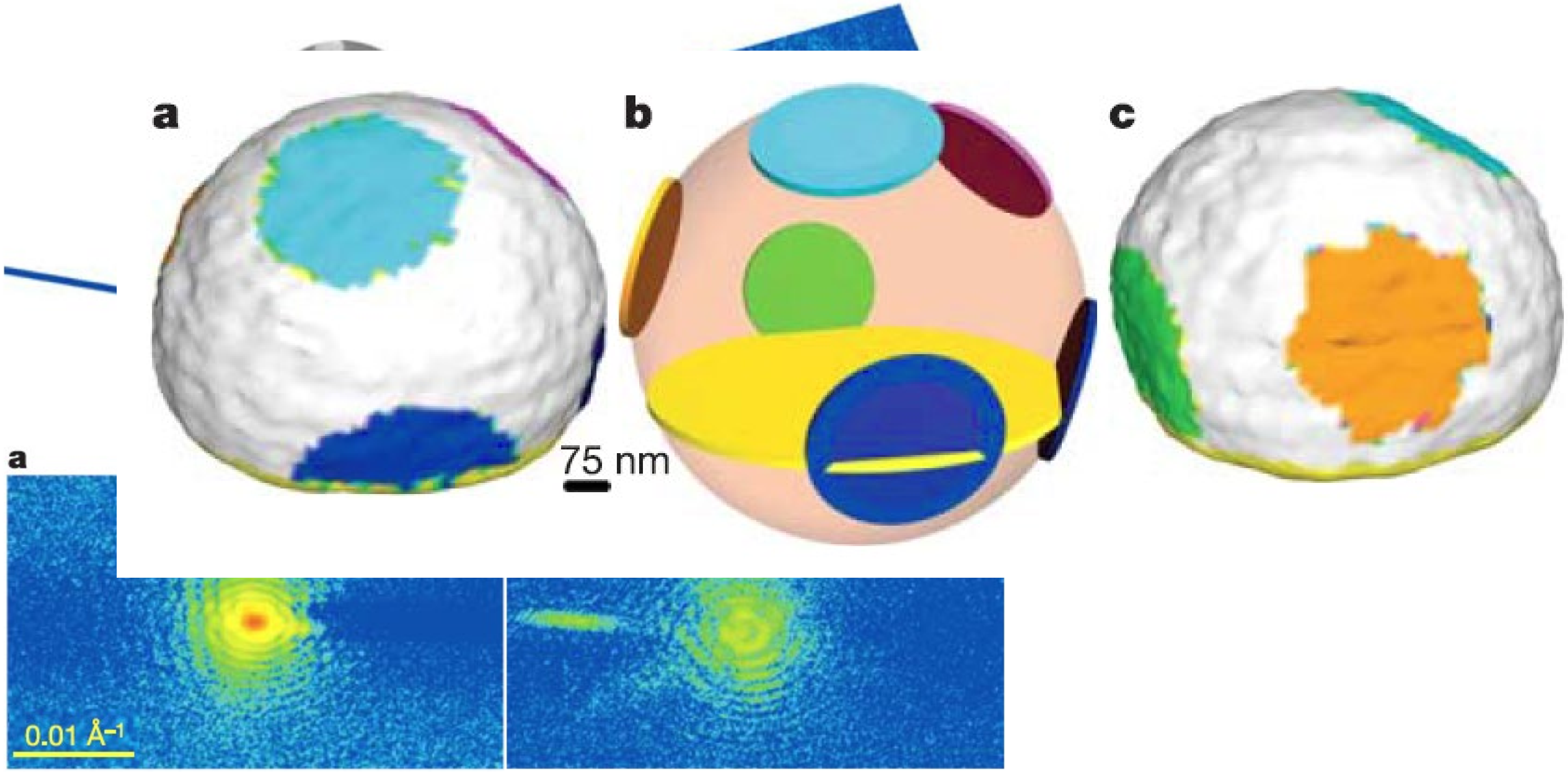
Jadzinsky, et al. Science 318, 430 (2007)

Nanoparticle Structural Analysis

Summary nanoparticle structural analysis

- **Atomic structure of nanoparticles: size, shape**
- **Model systems needed to address nanoparticle surface**
- **Analysis complicated by broad Bragg reflections, random particle orientation and size distribution**
- **Protein crystallography approach allows to get atomic scale information**
- **EXAFS: local structure, chemically sensitive**

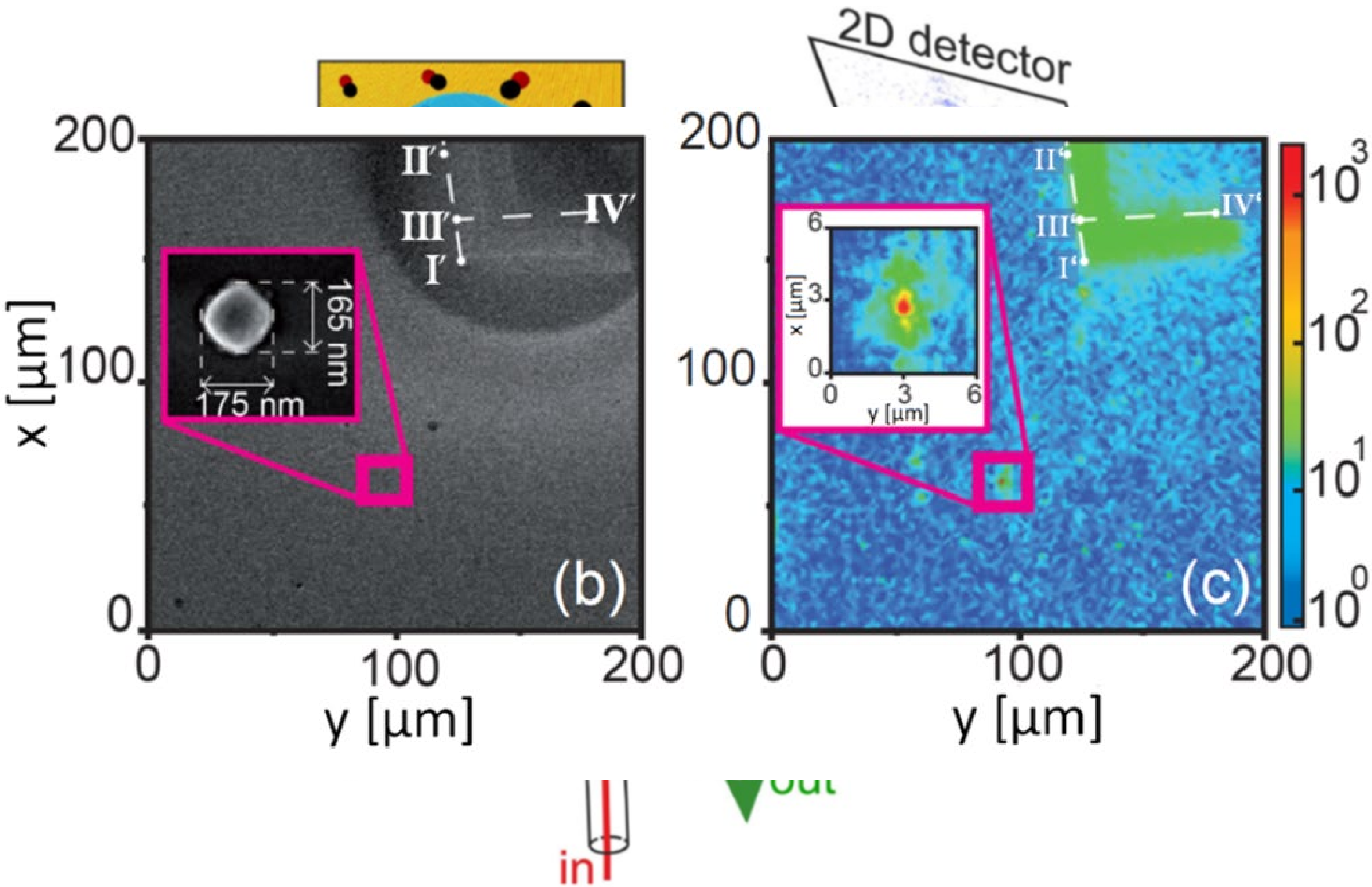
Coherent Diffraction X-Ray Imaging



Single particle diffraction with coherent x-ray beam

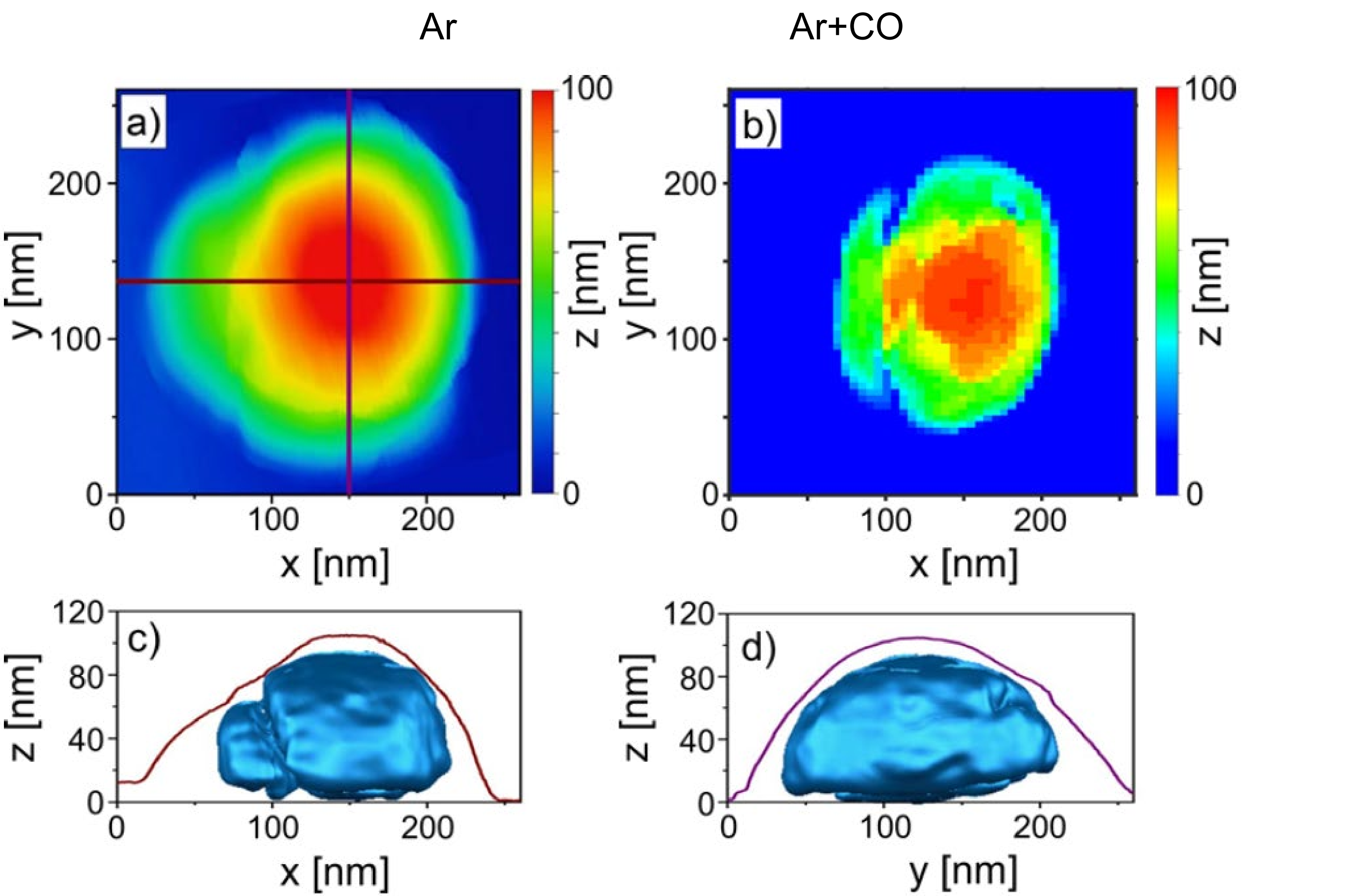
M. A. Pfeifer, et al., Nature 442, 63 (2006).

Coherent Diffraction X-Ray Imaging

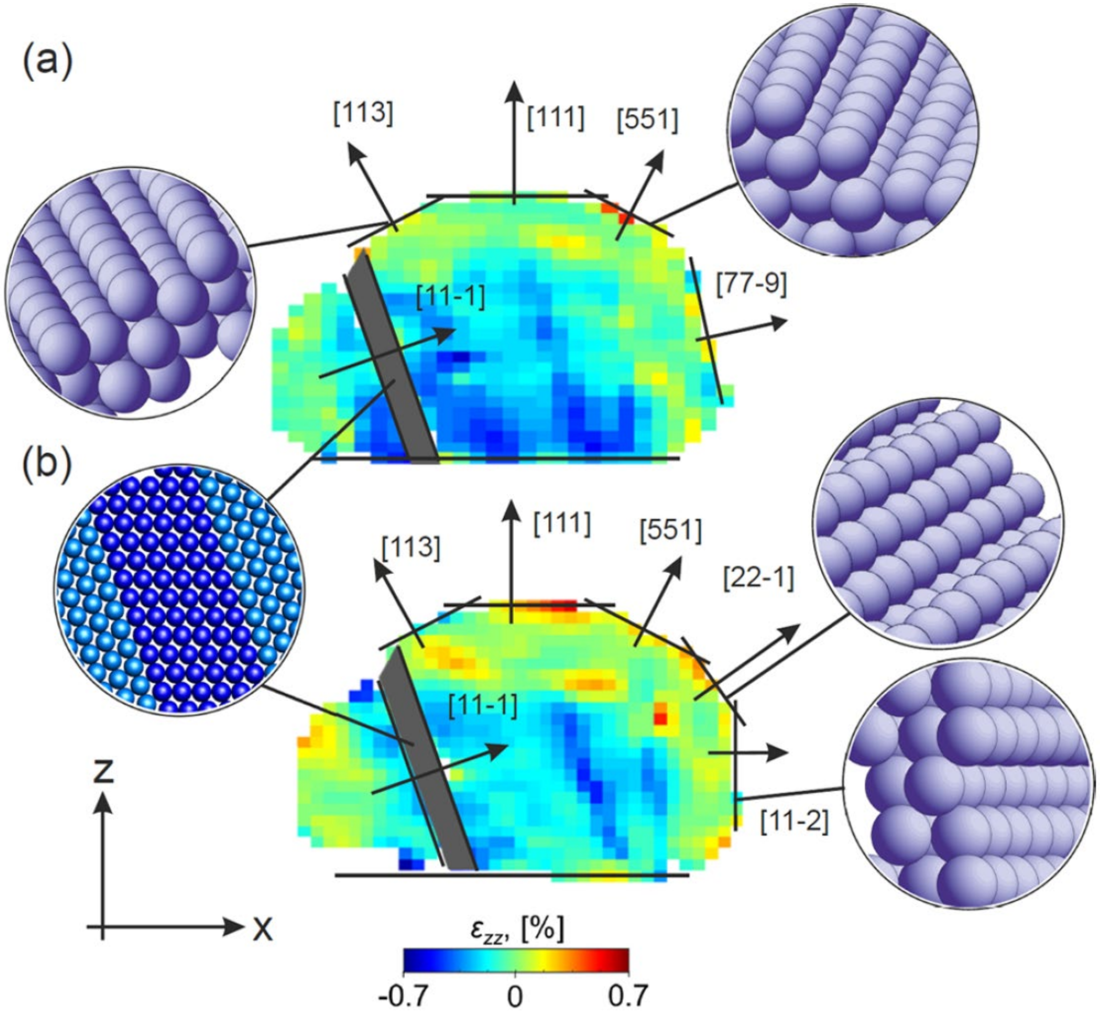


M. Abuin, et al., ACS Applied Nanomaterials 2,8, 4818 (2019)

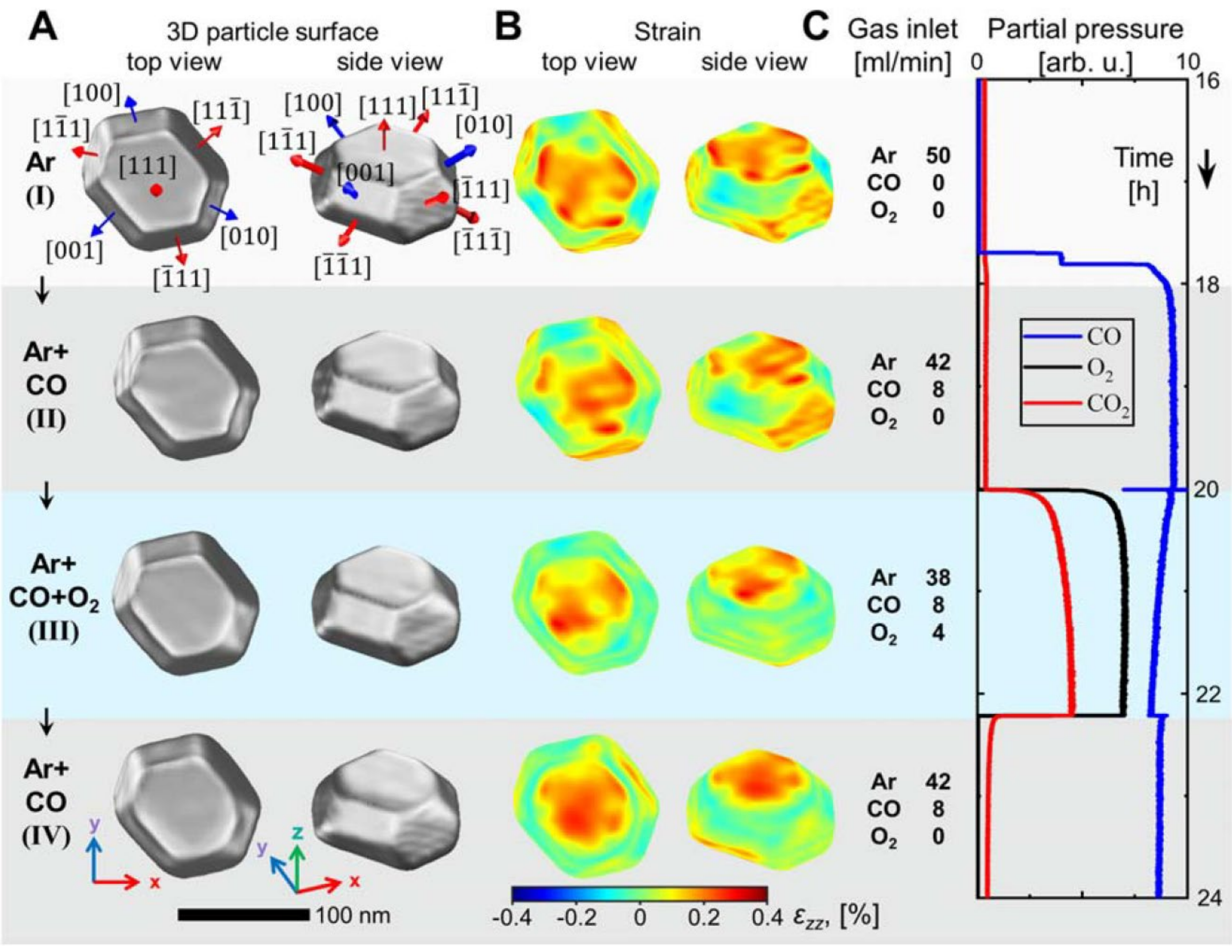
Coherent Diffraction X-Ray Imaging

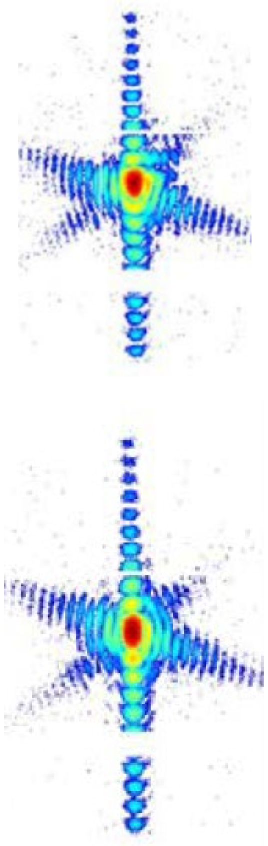


Structure and strain



Coherent Diffraction X-Ray Imaging under Reaction Conditions





Y. Y. Kim, T. F. Keller, T. J. Gonvalves, M. Abuin, H, Runge, L. Gelisio, J. Carnis, V. Vonk, P. N. Plessow, I. A. Vartaniants, A. Stierle, Science Advances, Vol 7, 40 (2021)

Coherent Diffraction X-Ray Imaging under Reaction Conditions