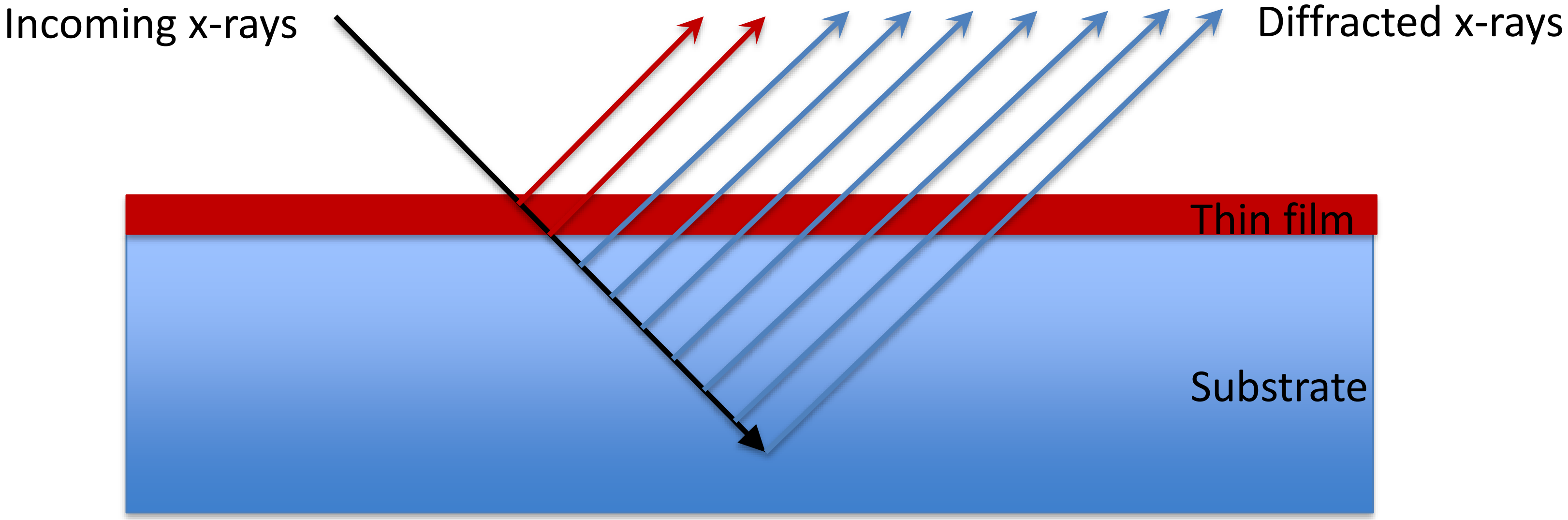
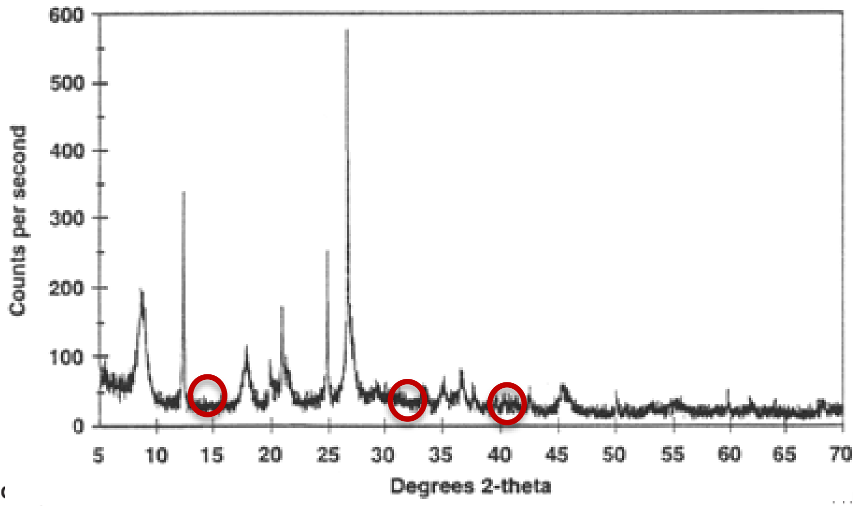
Grazing incidence
X-Ray Diffraction and Scattering

(for thin film structural characterization)

beatriz.moreno@lightsource.ca

Using x-rays to investigate thin films





TOPICS

1. Motivation
2. Is the film thin?
3. X-ray Attenuation

Techniques:

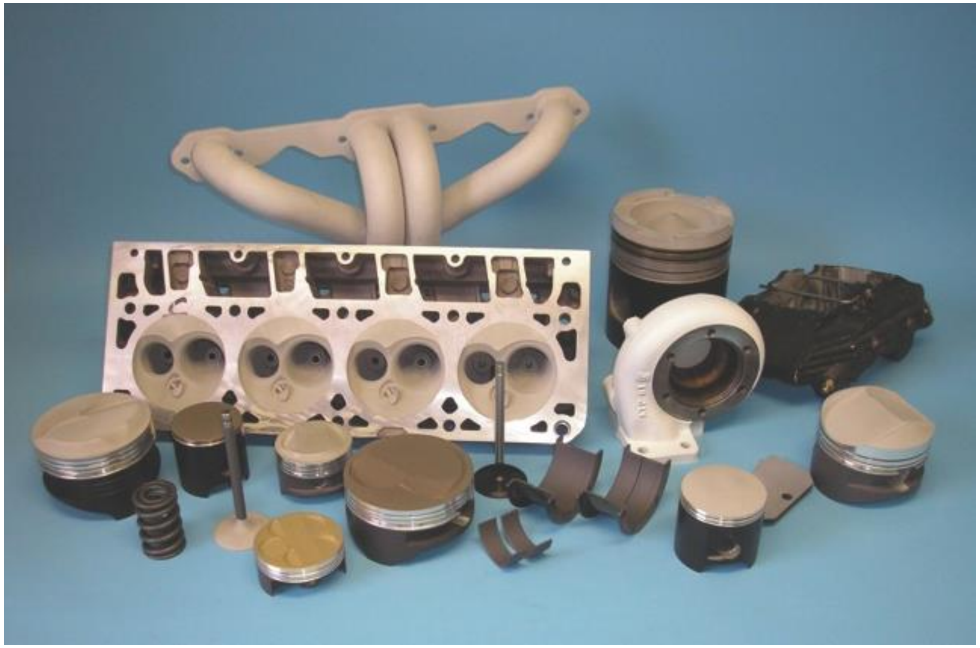
a) GI-powder XRD

b) GI-single crystal XRD

c) Reflectivity

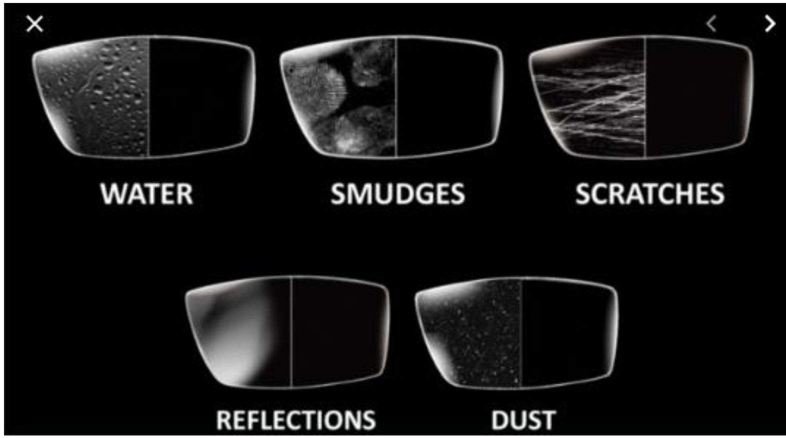
d) GISAXS

Motivation

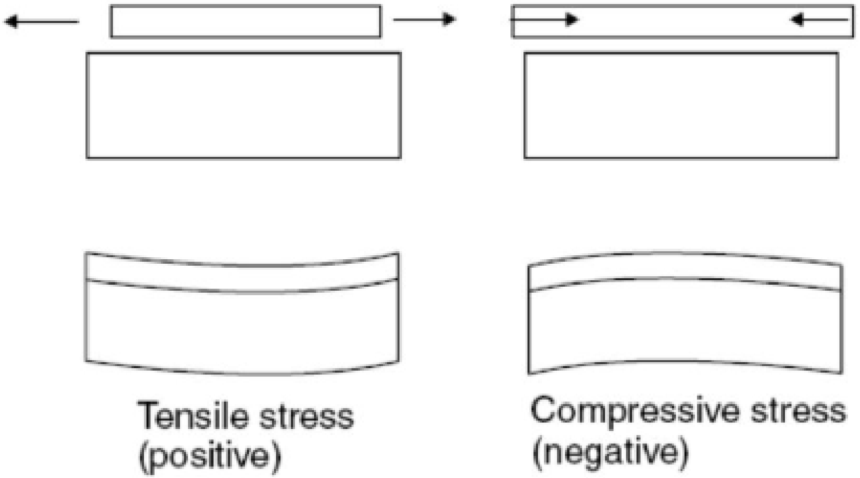


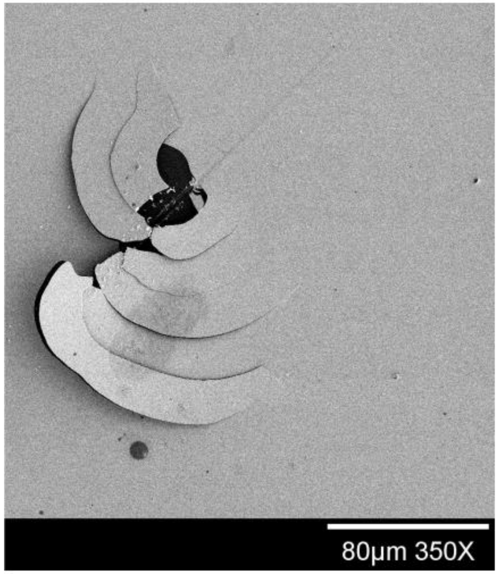
Three Most Common Issues Coatings Address:

1. Friction
2. Heat
3. Corrosion



Structure ⟷ Performance





Stress fracture patterns in ALD W/Si

What can we measure?

Small angle x-ray reflectivity

GI-SAXS

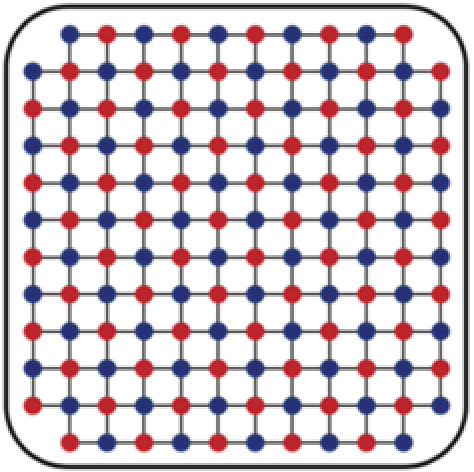
GI-WAXS -- GI – PXRD
-- GI -- RSM

Reflectivity
XRD
Pole figures

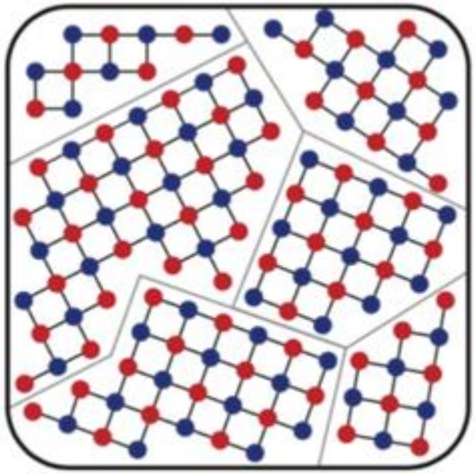
They yield information about:
- ✓Film thickness, roughness, porosity
- ✓Structure, stress, texture, defects
- ✓Composition, interdiffusion, gradients
- ✓Buried nanostructures, size, shape, ordering

What kind of films can we measure?

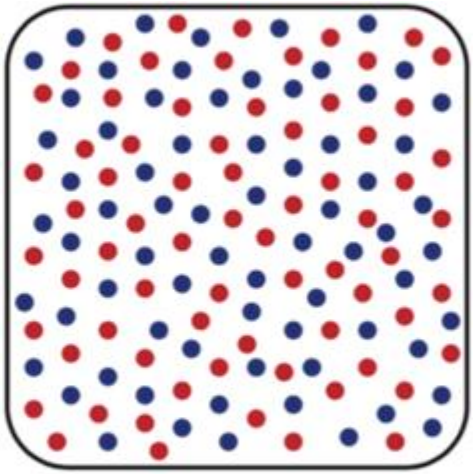
Single-crystal



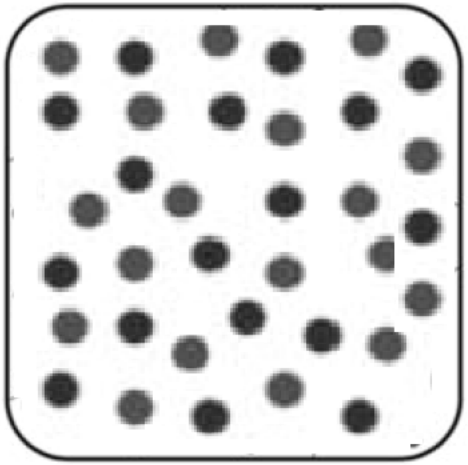
Poly-crystalline



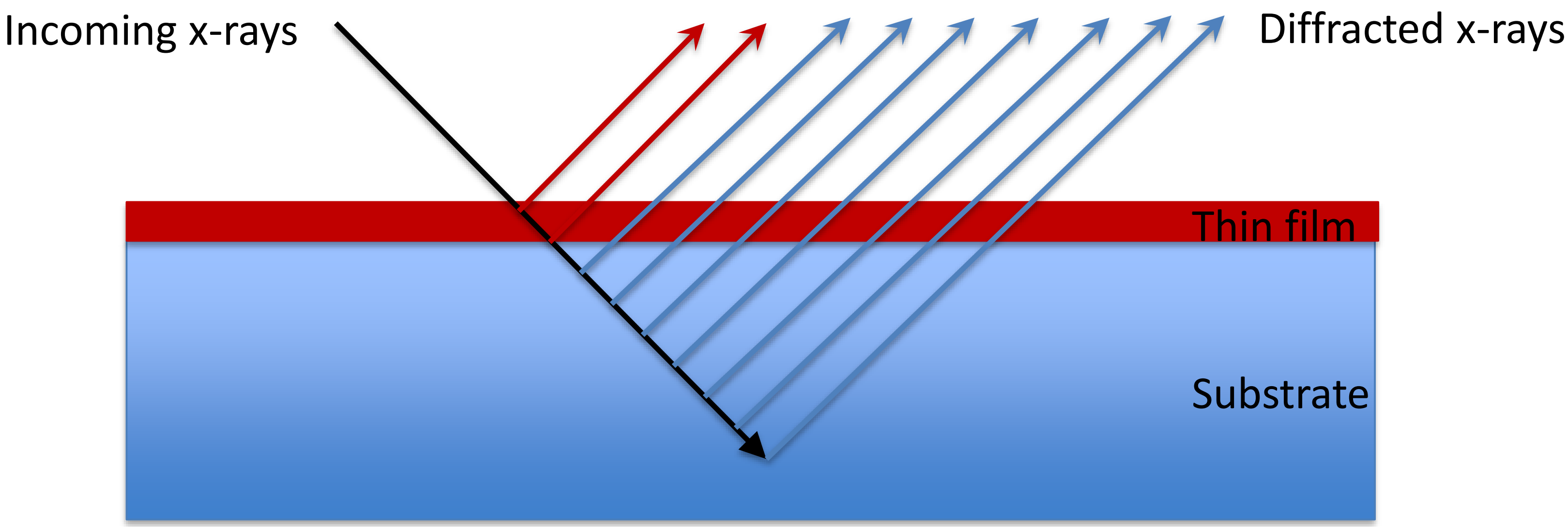
Amorphous

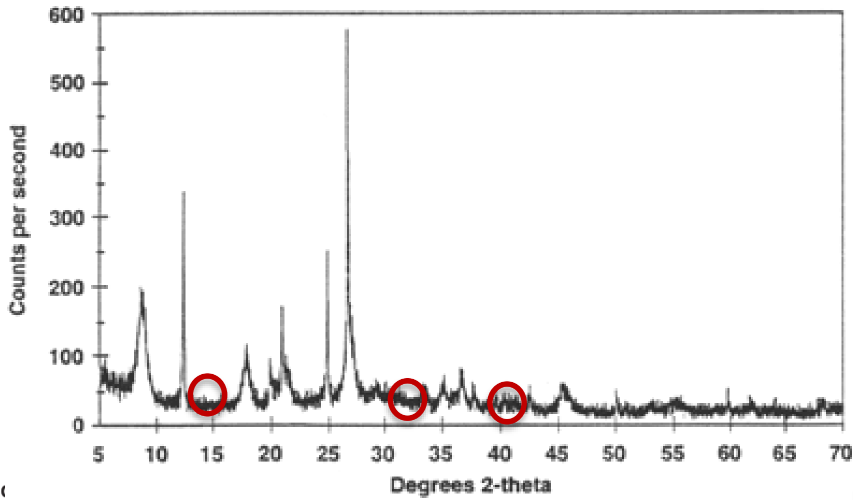


Nanostructures

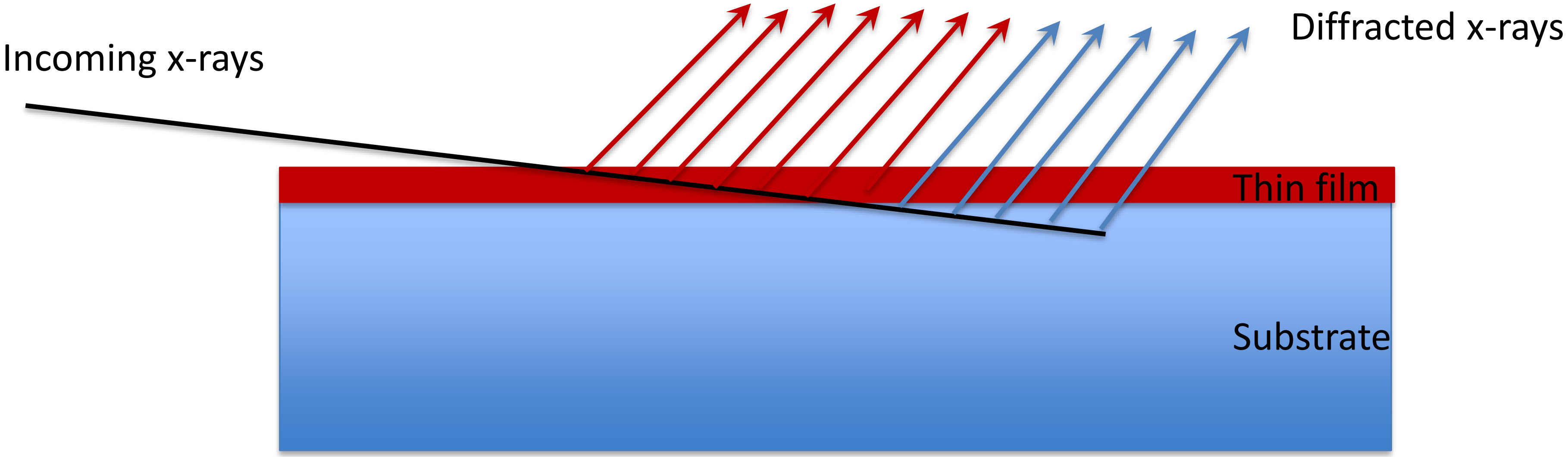


Using X-Rays to investigate thin films





The grazing incidence geometry enhances the film signal relative to the substrate signal



X-Rays attenuation length

The **attenuation length** ε is the distance over which the x-ray beam intensity has dropped to 1/*e* of its incident intensity.

Denser materials will have shorter attenuation lengths.

Higher energies will have longer attenuation lengths

The **attenuation coefficient** μ is simply the inverse of the attenuation length

e = 2.718281828459045

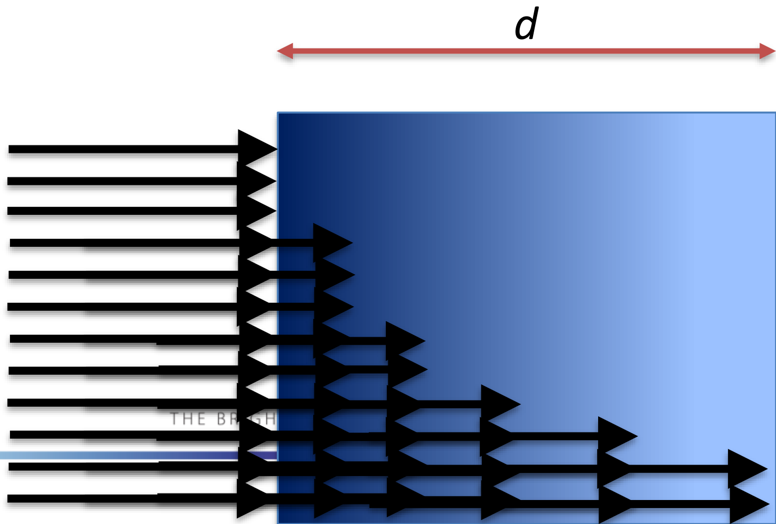
1/e = 0.367879441171

$$I = I_o\ e^{-\frac{d}{\varepsilon}}$$

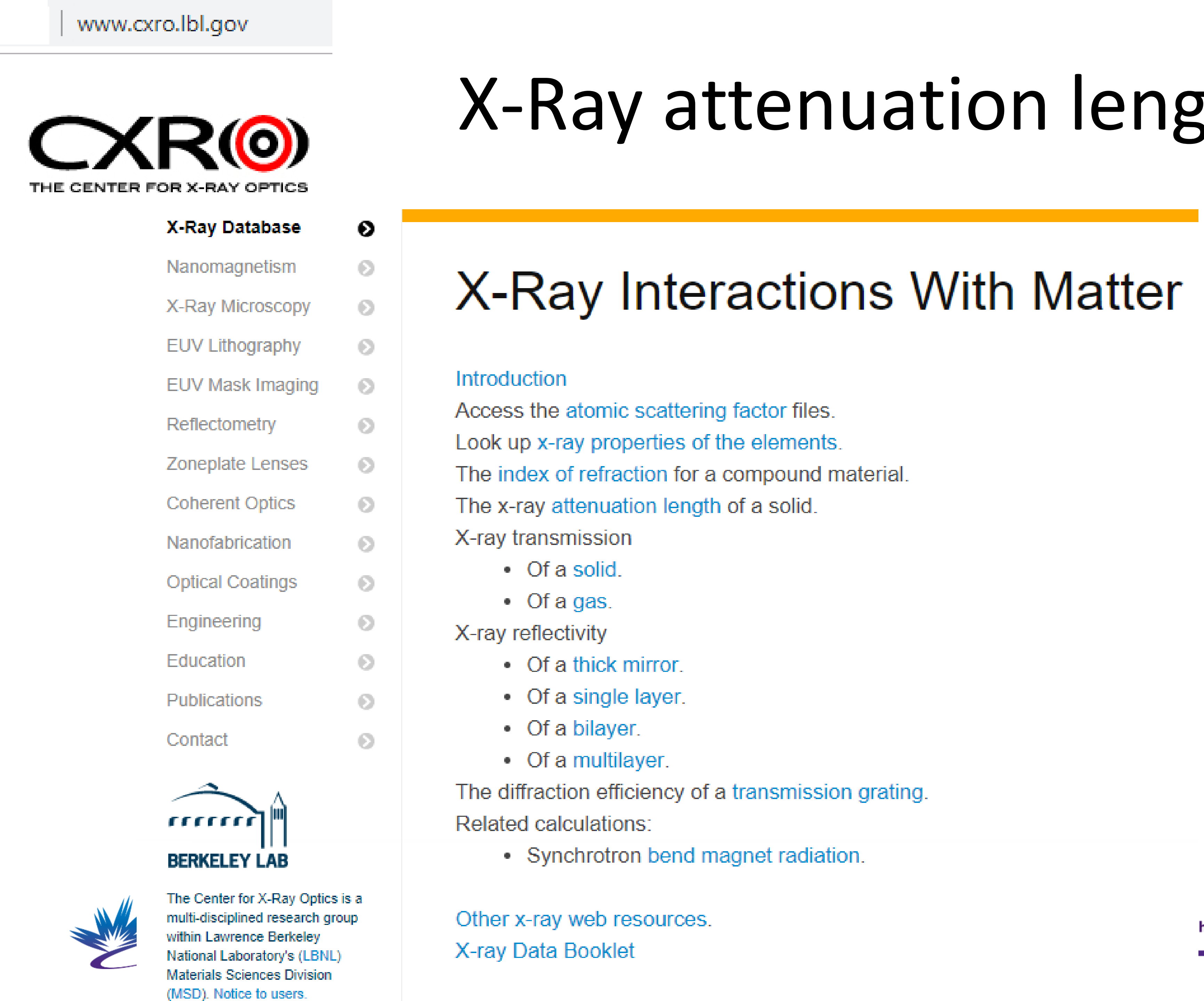
$$I = I_o\ e^{-\mu . d}$$

Where to find attenuation lengths of materials:

- CXRO
- XOP/XPOWER
- …



X-Ray attenuation length



The Center for X-Ray Optics is a multi-disciplined research group within Lawrence Berkeley National Laboratory's (LBNL) Materials Sciences Division (MSD). Notice to users.

X-Ray Interactions With Matter

Introduction

Access the atomic scattering factor files.

Look up x-ray properties of the elements.

The index of refraction for a compound material.

The x-ray attenuation length of a solid.

X-ray transmission

- Of a solid.
- Of a gas.

X-ray reflectivity

- Of a thick mirror.
- Of a single layer.
- Of a bilayer.
- Of a multilayer.

The diffraction efficiency of a transmission grating.

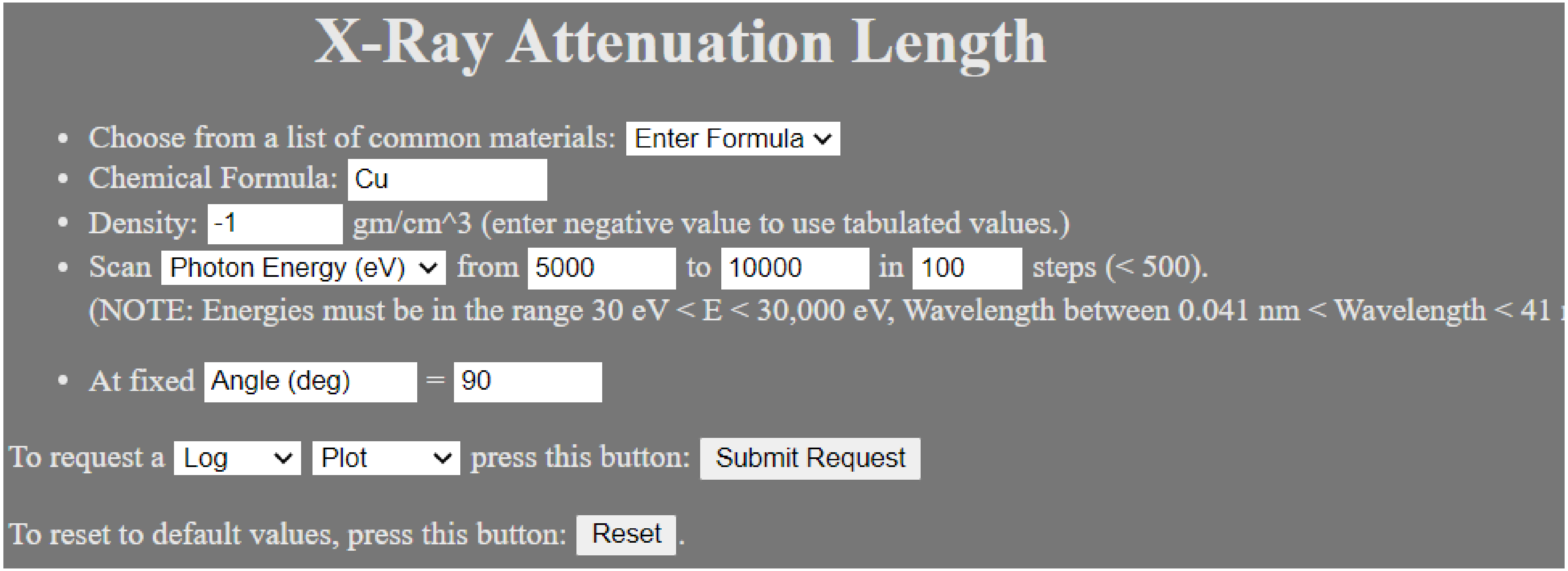
Related calculations:

- Synchrotron bend magnet radiation.

Other x-ray web resources.

X-ray Data Booklet

X-Ray attenuation length



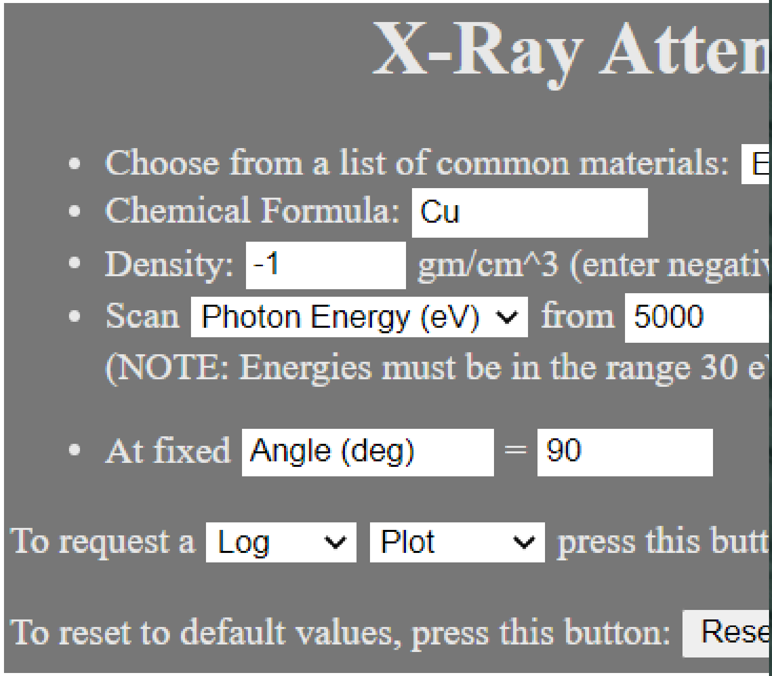
X-Ray Attenuation Length

- Choose from a list of common materials: Enter Formula
- Chemical Formula: Cu
- Density: -1 gm/cm^3 (enter negative value to use tabulated values.)
- Scan Photon Energy (eV) from 5000 to 10000 in 100 steps (< 500).
  (NOTE: Energies must be in the range 30 eV < E < 30,000 eV, Wavelength between 0.041 nm < Wavelength < 41
- At fixed Angle (deg) = 90

To request a Log Plot press this button: Submit Request

To reset to default values, press this button: Reset.

X-Ray attenuation length



X-Ray Atten

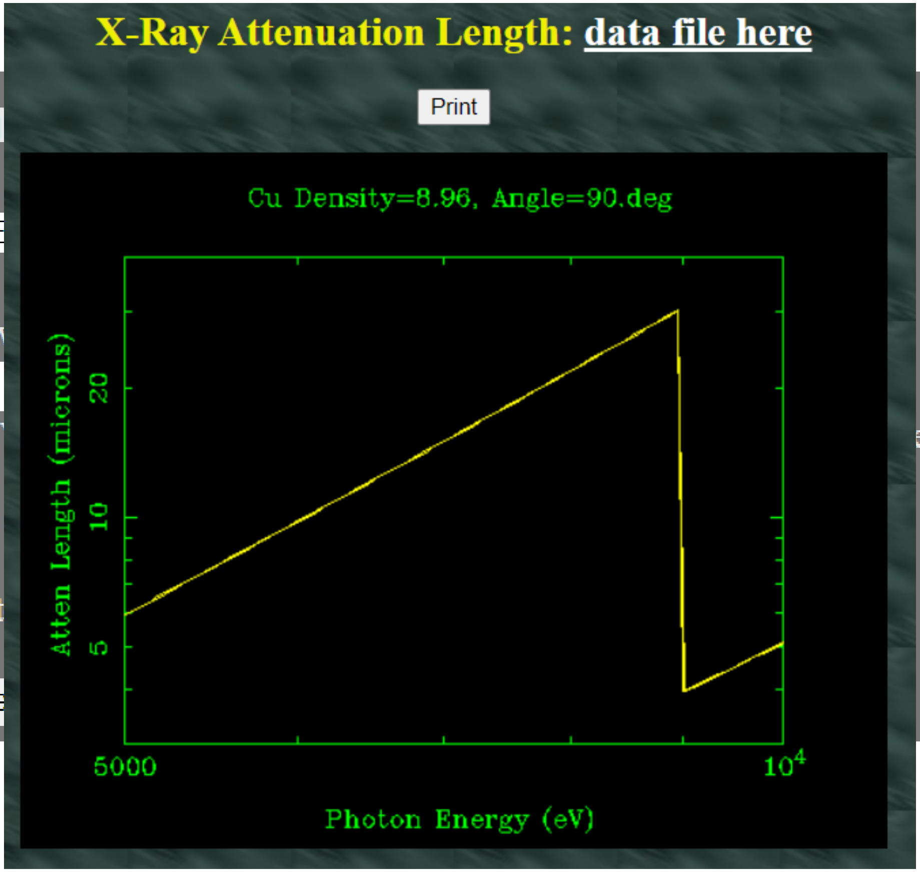
- Choose from a list of common materials: E
- Chemical Formula: Cu
- Density: -1 gm/cm^3 (enter negativ
- Scan Photon Energy (eV) from 5000

  (NOTE: Energies must be in the range 30 e
- At fixed Angle (deg) = 90

To request a Log Plot press this butt

To reset to default values, press this button: Rese

ength < 41



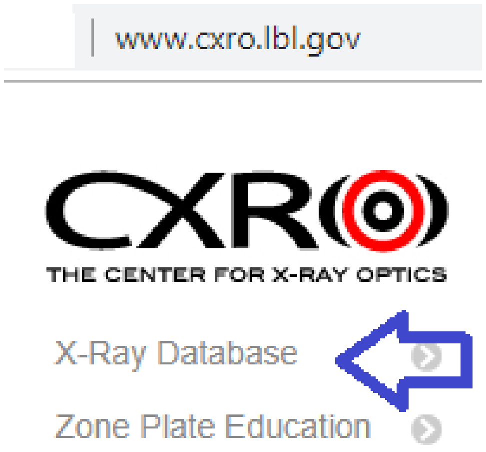
X-Ray Attenuation Length: data file here

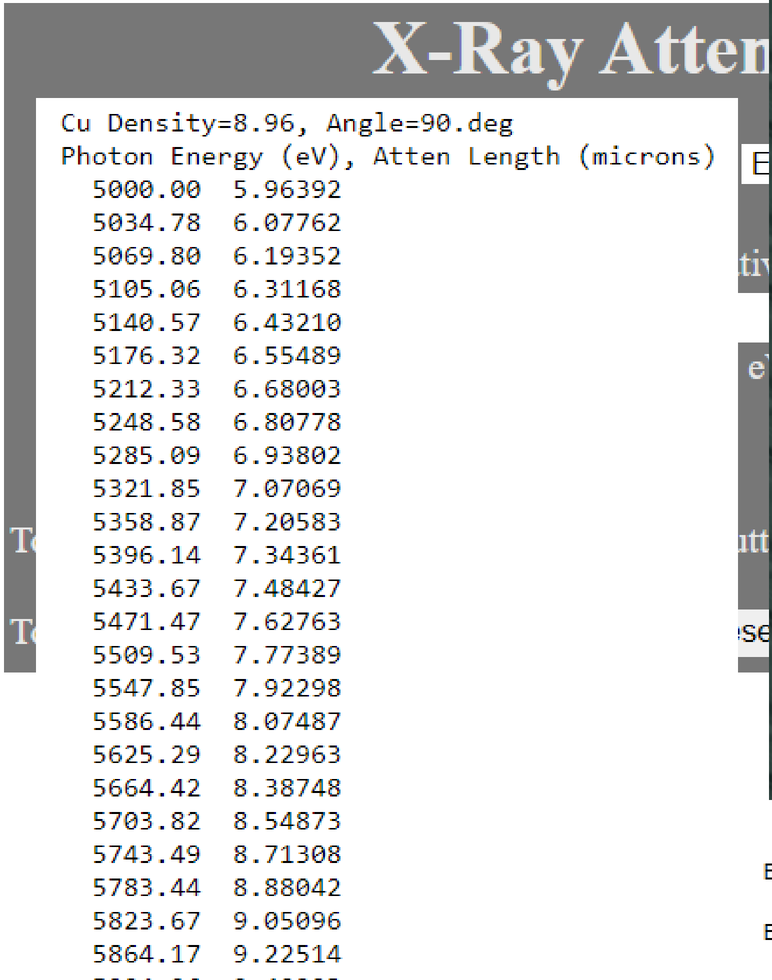
Print

Element 29: Cu

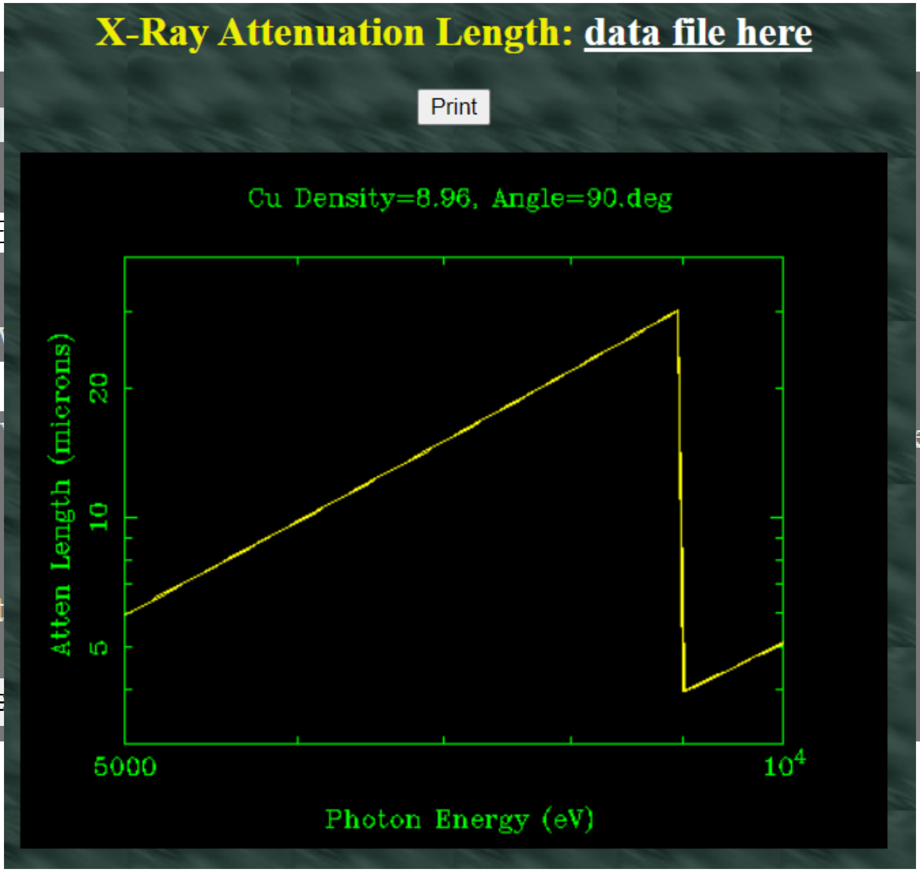
Edge keV
K 8.9789

X-Ray attenuation length





```
Cu Density=8.96, Angle=90.deg
Photon Energy (eV), Atten Length (microns)
  5000.00  5.96392
  5034.78  6.07762
  5069.80  6.19352
  5105.06  6.31168
  5140.57  6.43210
  5176.32  6.55489
  5212.33  6.68003
  5248.58  6.80778
  5285.09  6.93802
  5321.85  7.07069
  5358.87  7.20583
  5396.14  7.34361
  5433.67  7.48427
  5471.47  7.62763
  5509.53  7.77389
  5547.85  7.92298
  5586.44  8.07487
  5625.29  8.22963
  5664.42  8.38748
  5703.82  8.54873
  5743.49  8.71308
  5783.44  8.88042
  5823.67  9.05096
  5864.17  9.22514
```



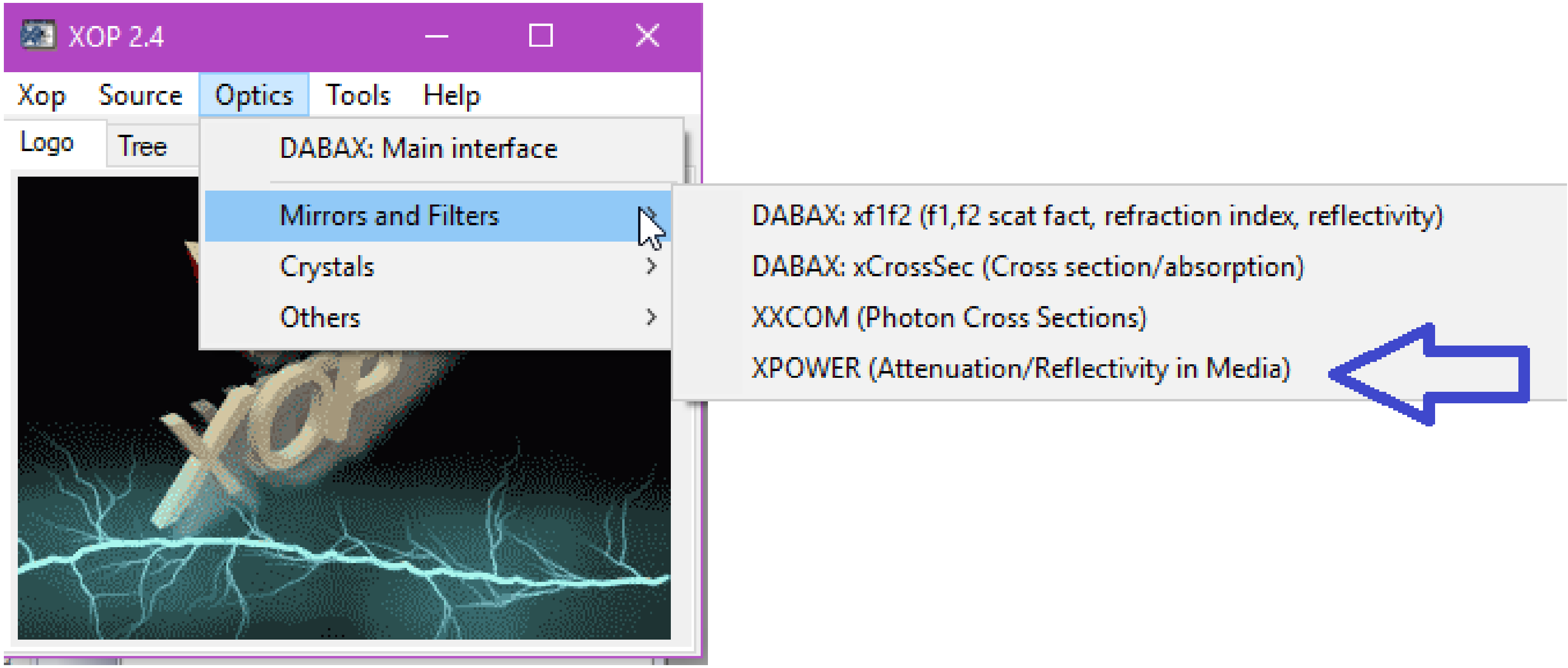
```
Element 29: Cu

Edge          keV
 K         8.9789
```

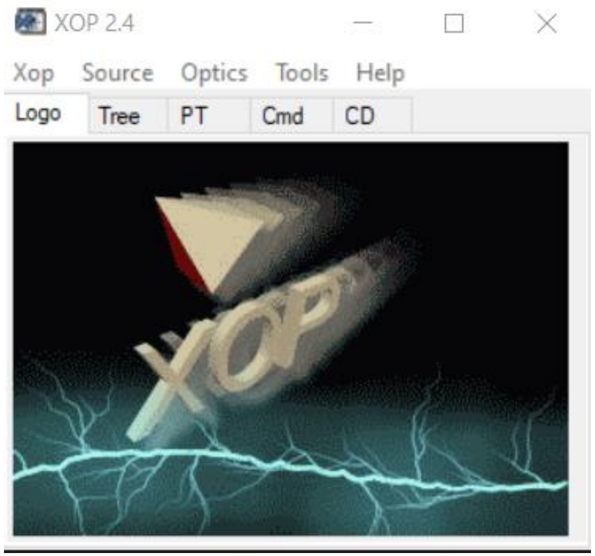
X-Ray attenuation length

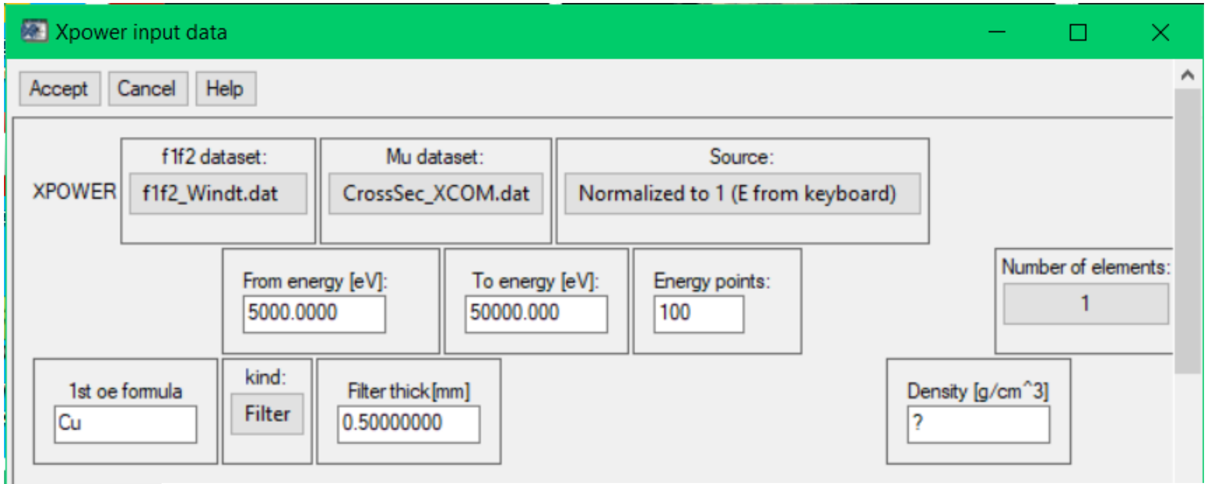
XOP/XPOWER

https://www.aps.anl.gov/Science/Scientific-Software/XOP



X-Ray attenuation length





XPOWER

f1f2 dataset: f1f2_Windt.dat

Mu dataset: CrossSec_XCOM.dat

Source: Normalized to 1 (E from keyboard)

From energy [eV]: 5000.0000

To energy [eV]: 50000.000

Energy points: 100

Number of elements: 1

1st oe formula: Cu

kind: Filter

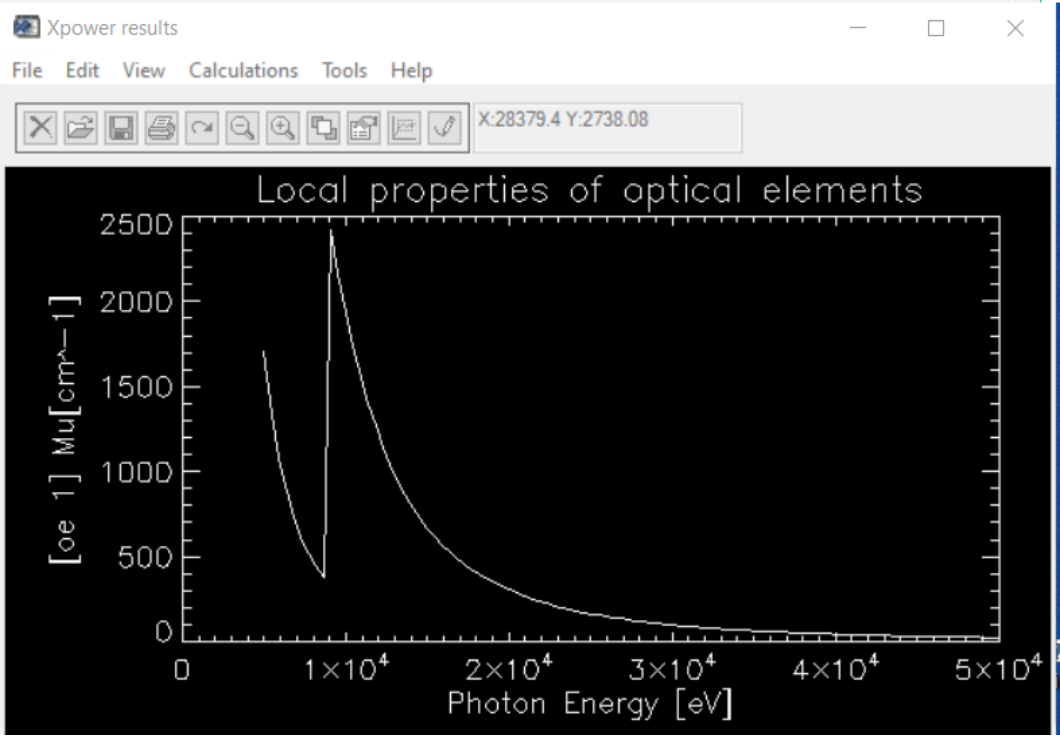
Filter thick[mm]: 0.50000000

Density [g/cm^3]: ?

Xpower

Attenuation & reflectivity in media

Effect on source spectrum



X:28379.4 Y:2738.08

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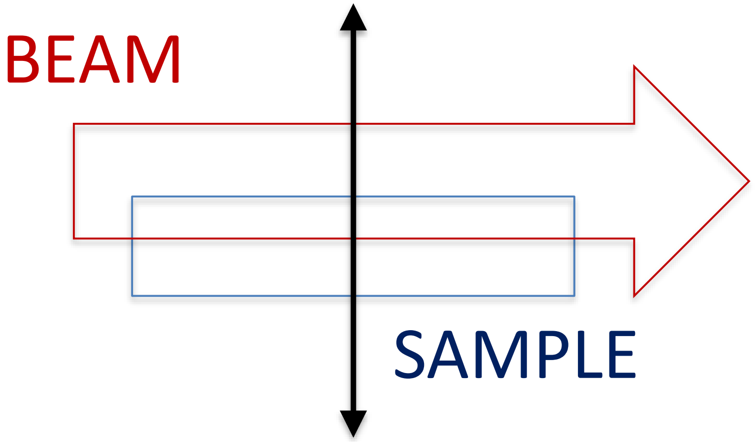
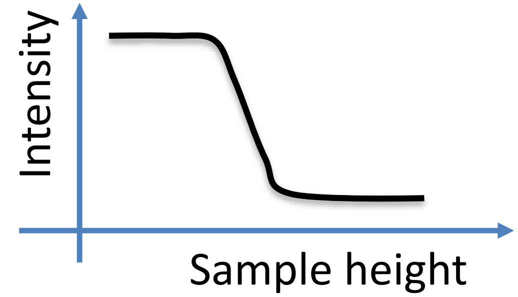
How do we measure?

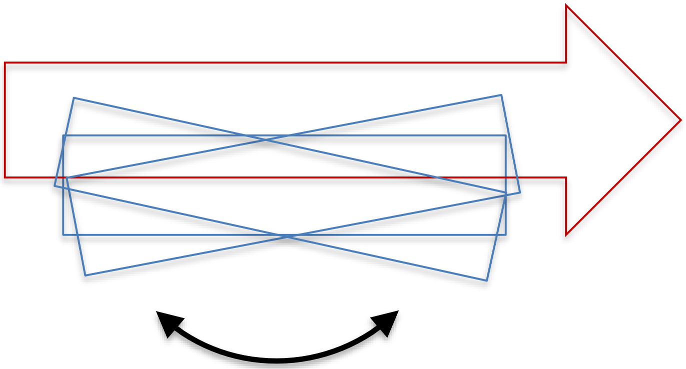
Sample alignment

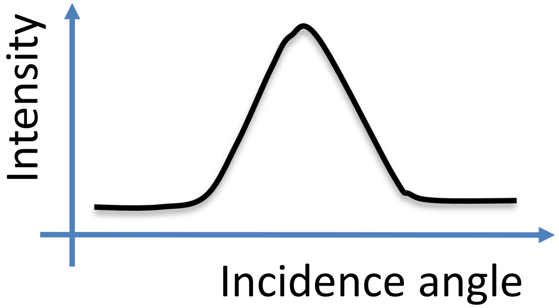

BEAM

SAMPLE

DETECTOR





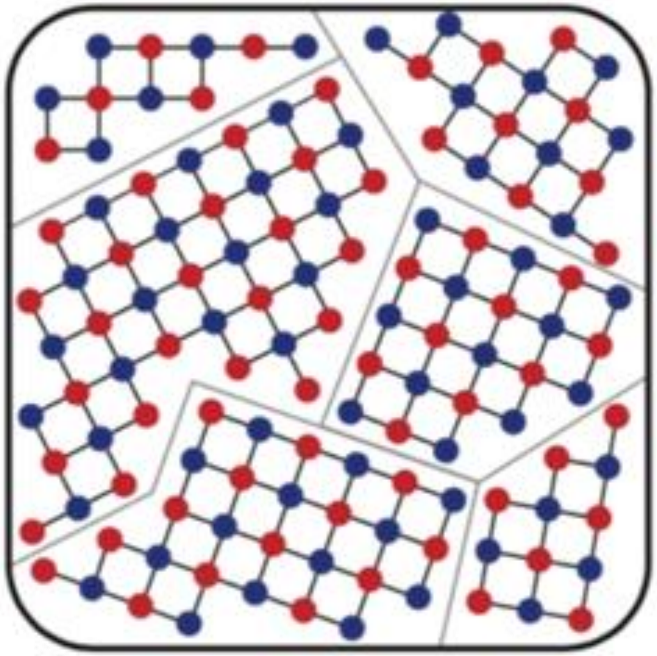


Iterate!

Grazing incidence diffraction

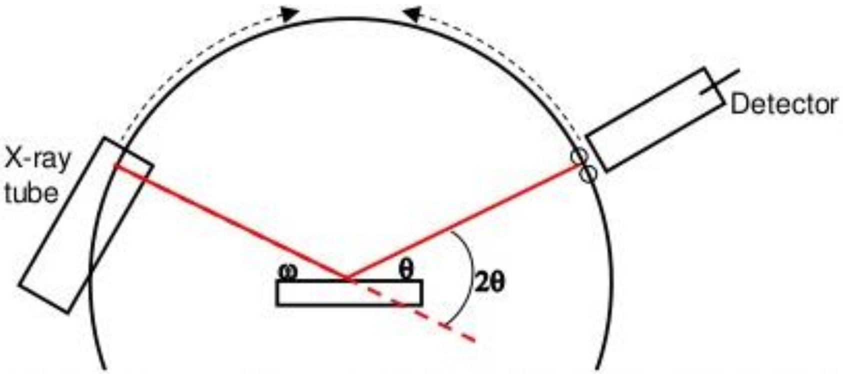
applied to

polycrystalline films

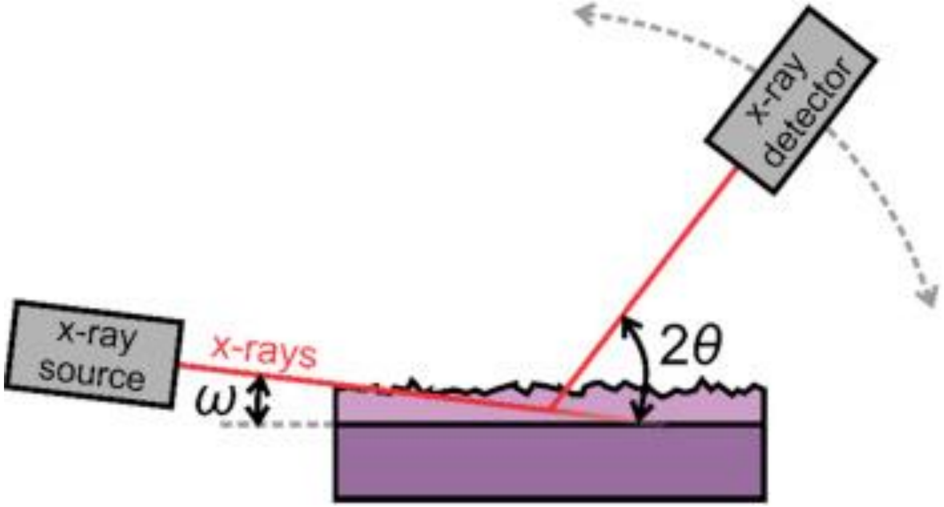


Grazing incidence diffraction

Regular specular geometry, ω = θ



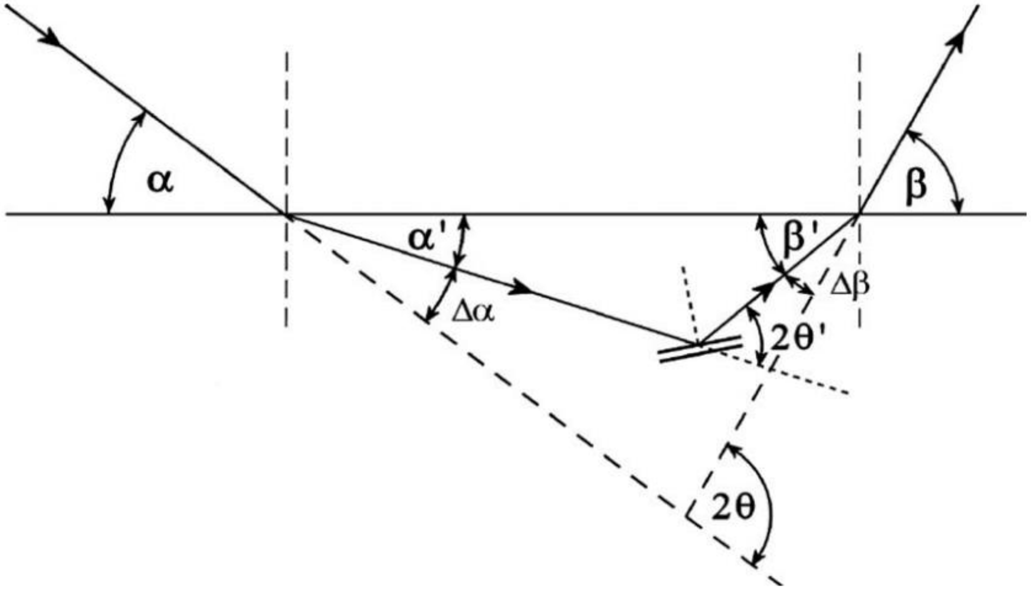
Grazing incidence geometry



https://www.sciencedirect.com/science/article/pii/S0022311517313946

Grazing incidence diffraction

Refraction correction

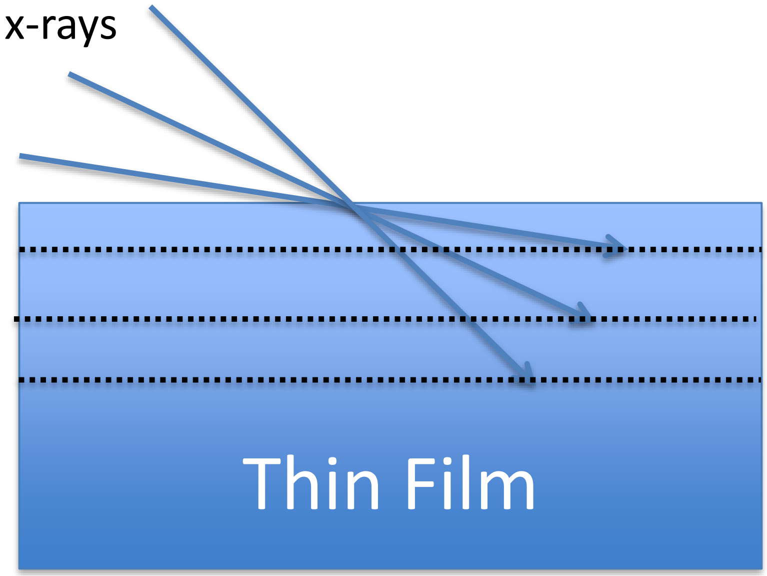


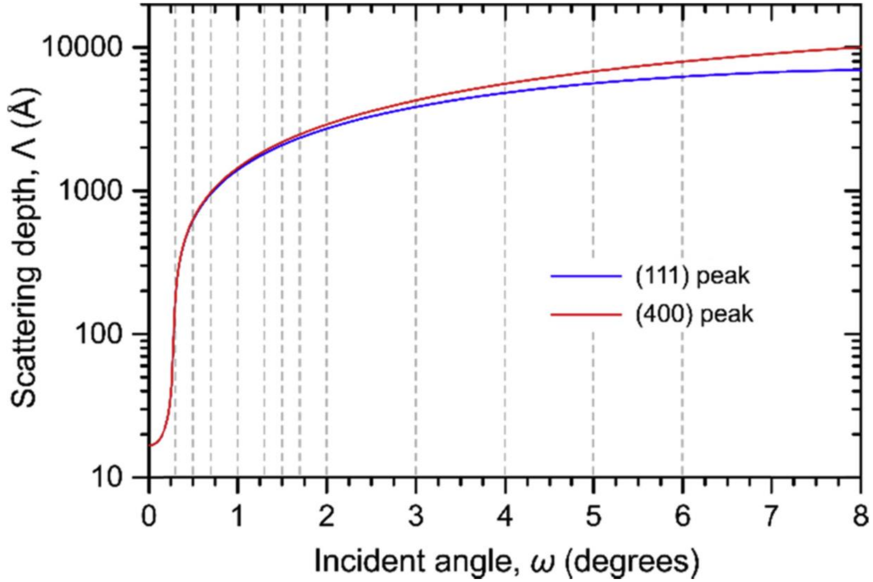
$$\Delta 2\theta = \delta[\cot\alpha + \cot(2\theta - \alpha) + 2\tan\theta]$$

Powder Diffraction **24**(S1): S11-S15, 2012

Grazing incidence diffraction

Depth sensitivity

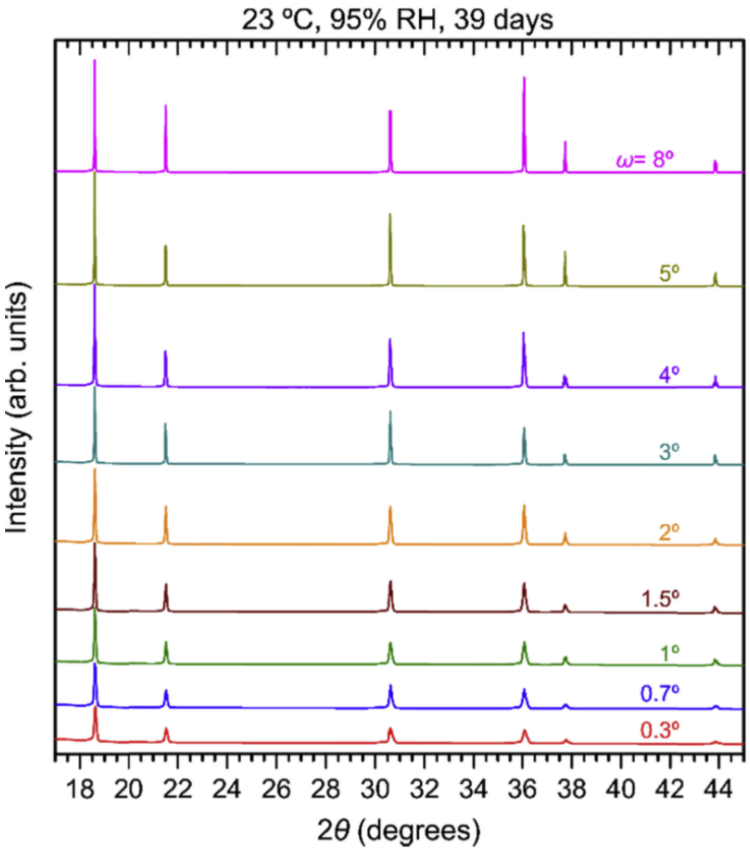


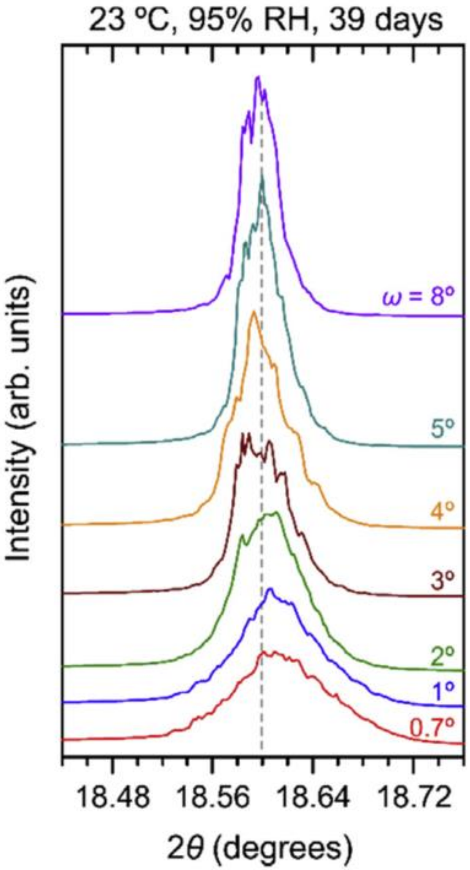


Journal of Nuclear Materials **502**: 68-75, 2018.

Grazing incidence diffraction

Uranium Oxide (UO_2) exposed to air





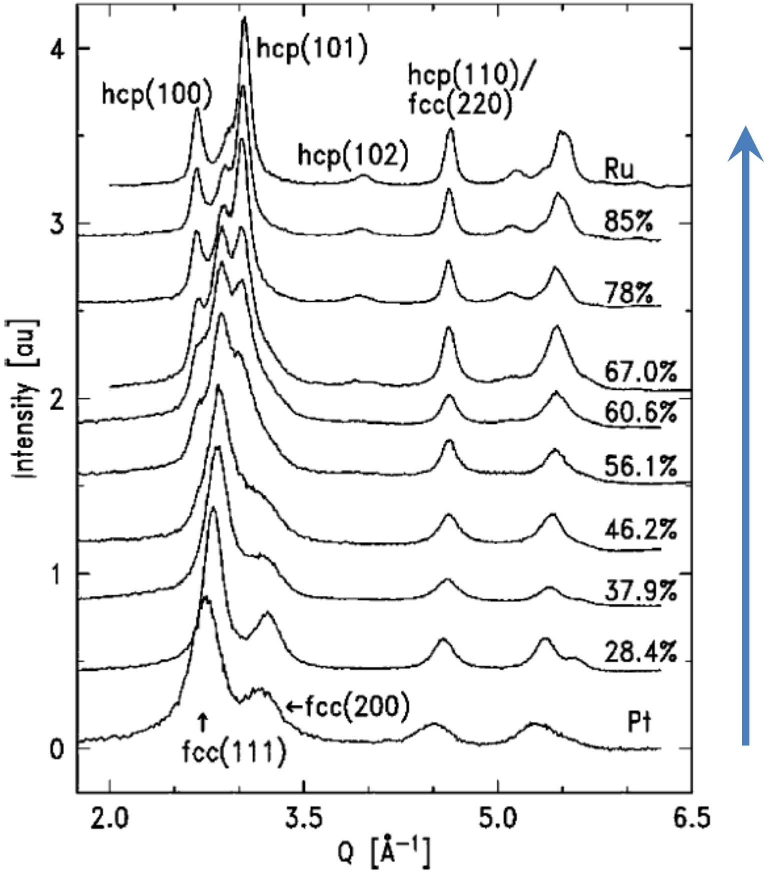
Journal of Nuclear Materials **502**: 68-75, 2018.

Grazing incidence diffraction

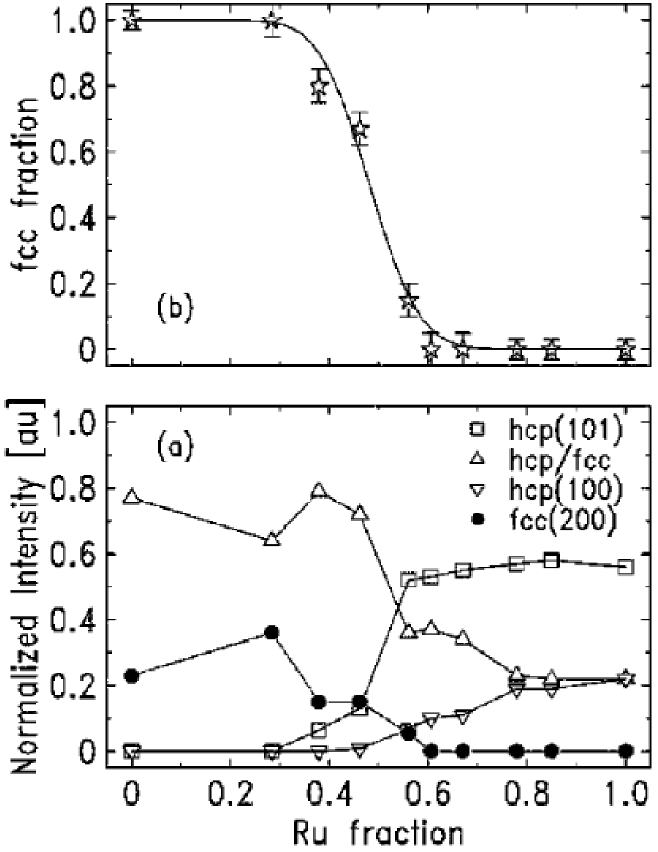
Structure and electrocatalysis of sputtered RuPt thin-film electrodes

130 Å thick

Grazing incidence x-ray diffraction



Phase diagram determination

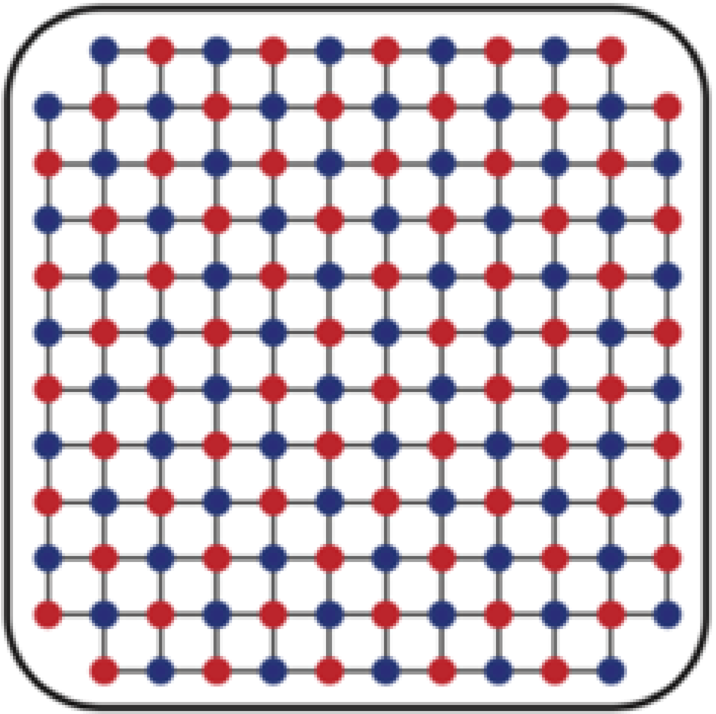


J. Phys. Chem. B **109**, 12845, 2005. Kim et al.

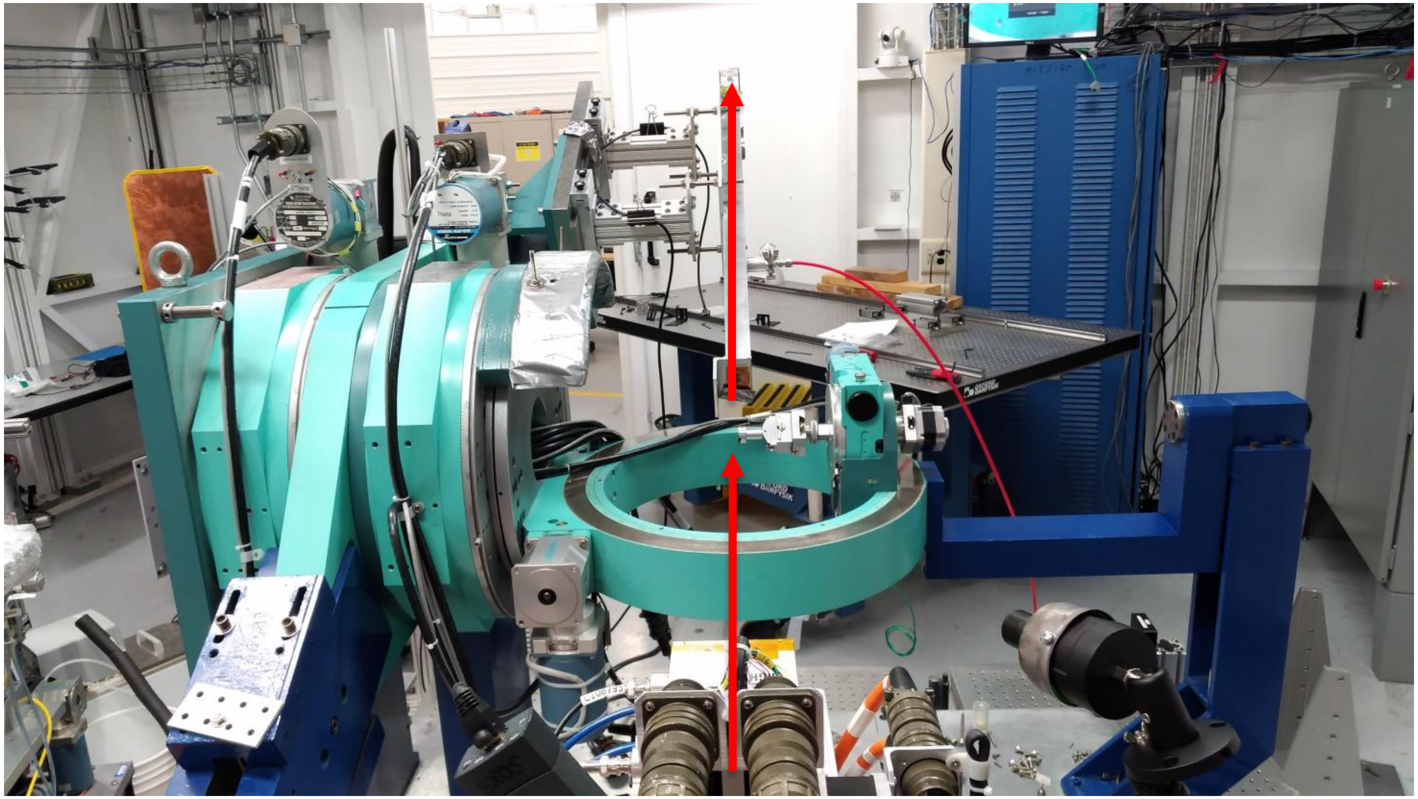
Grazing incidence diffraction

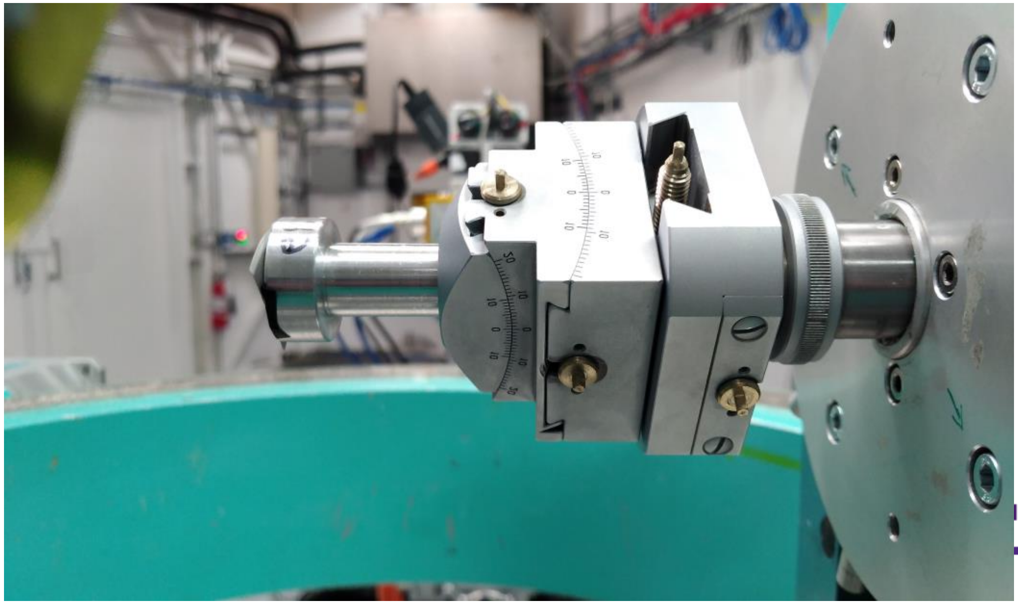
applied to

single crystal films

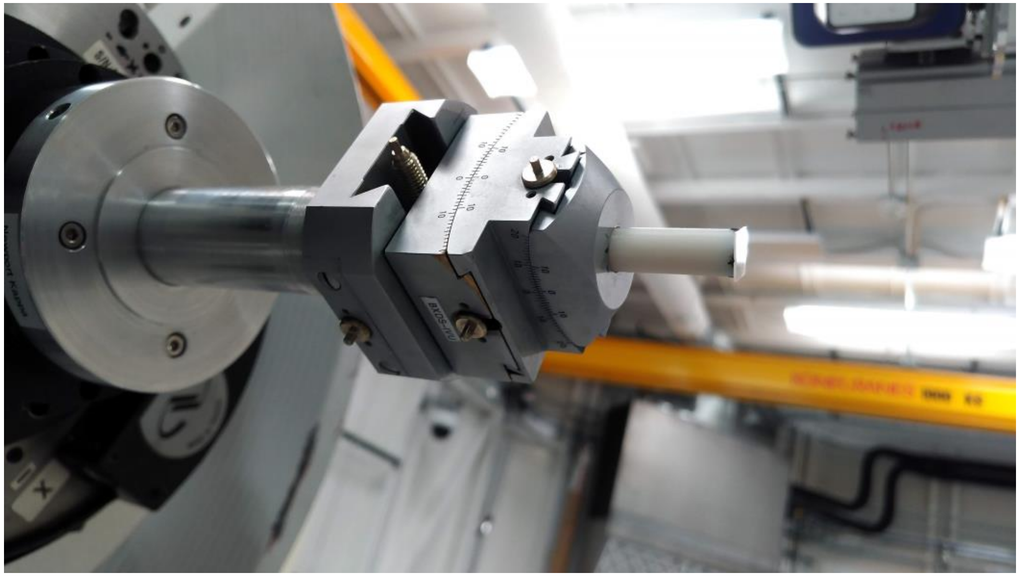


GID setup

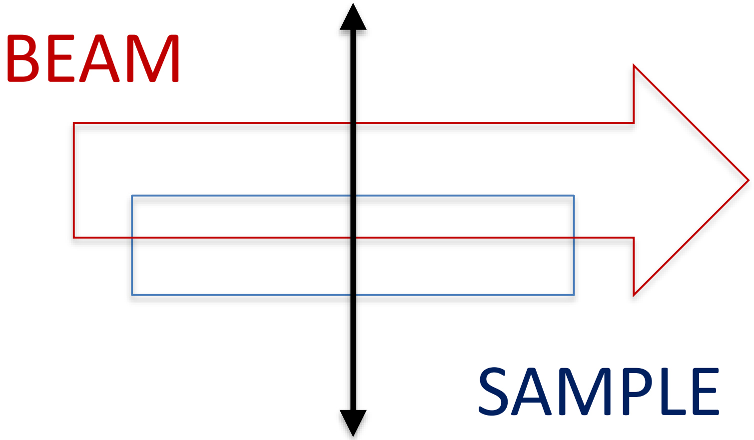


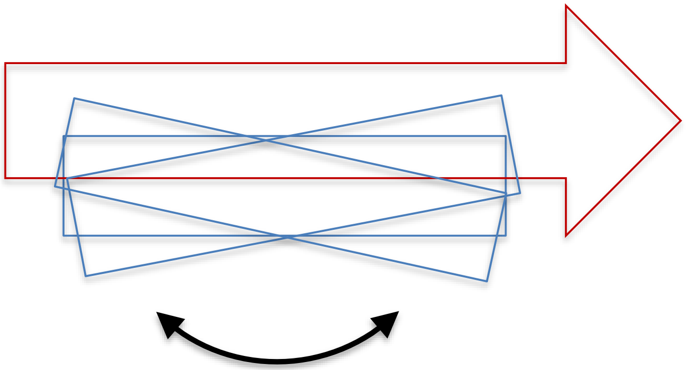


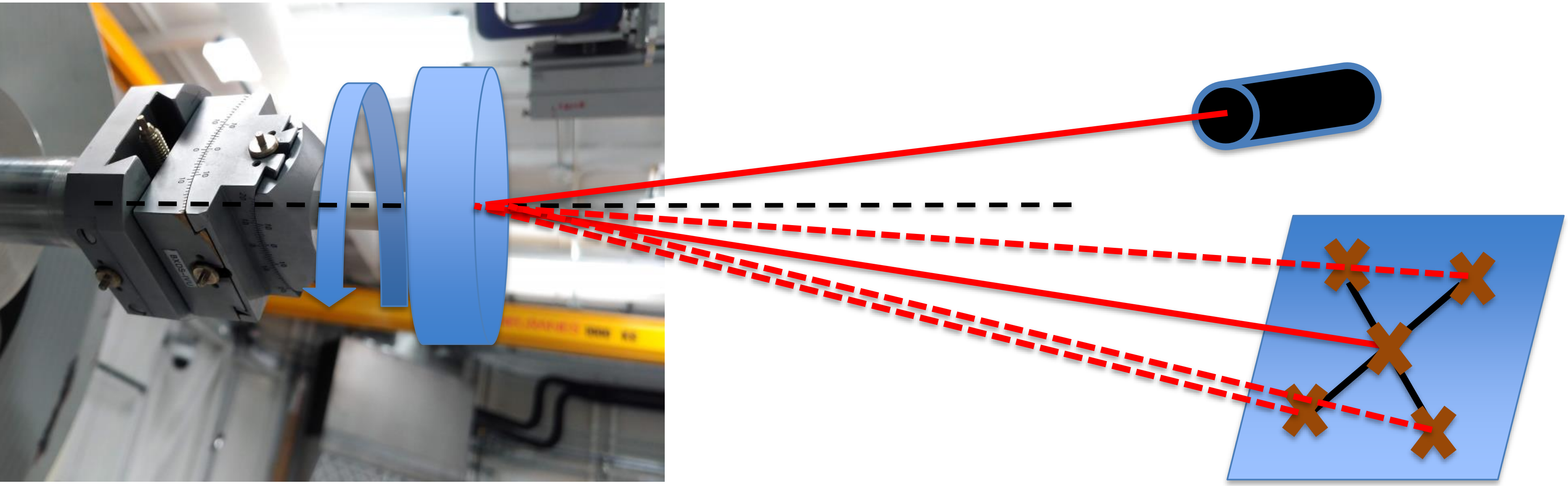
GID setup



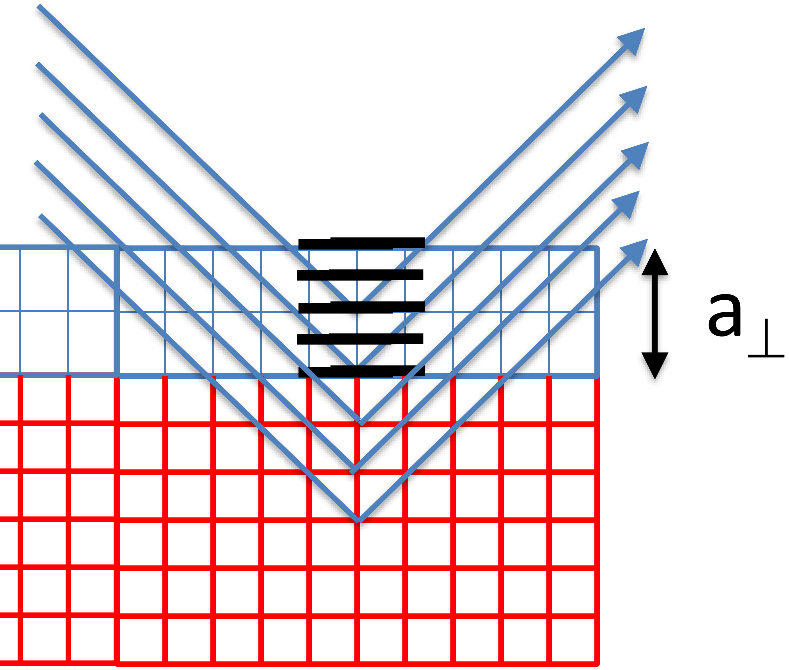
Sample alignment

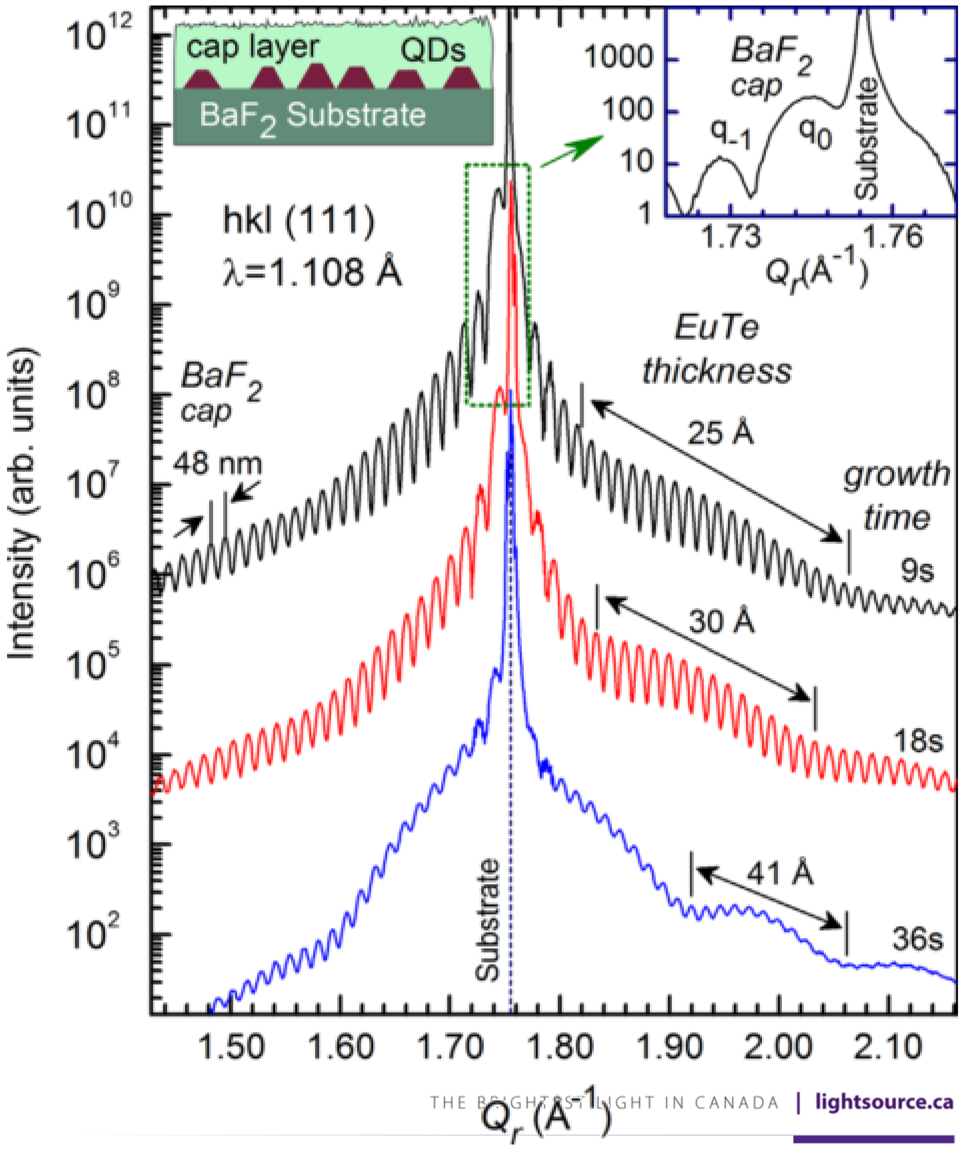






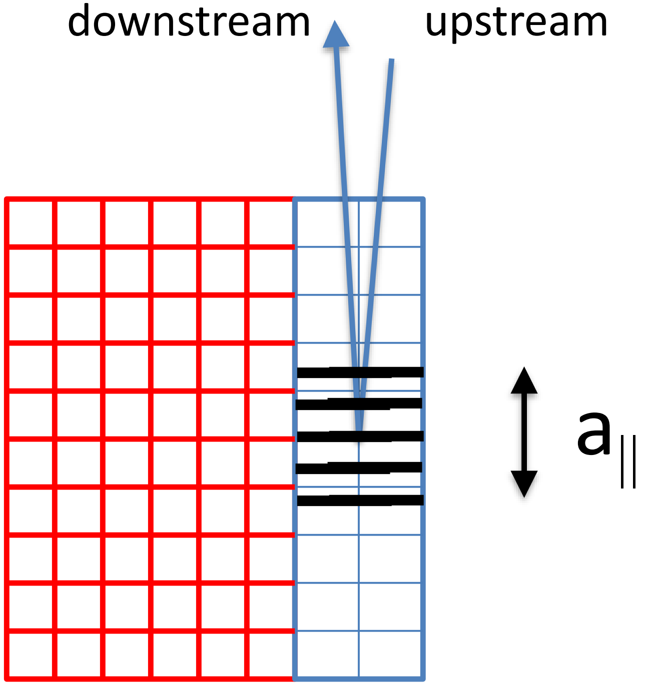
Not-Grazing incidence diffraction

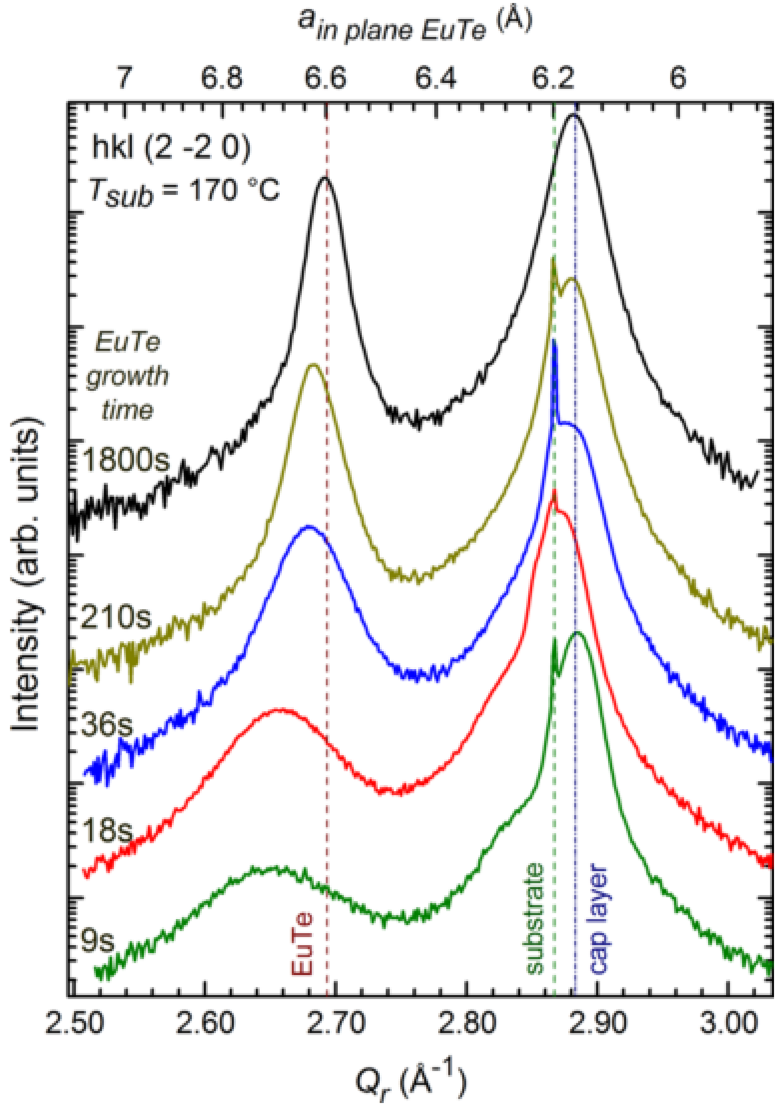




Journal of Crystal Growth **386**(0): 139-145, 2014

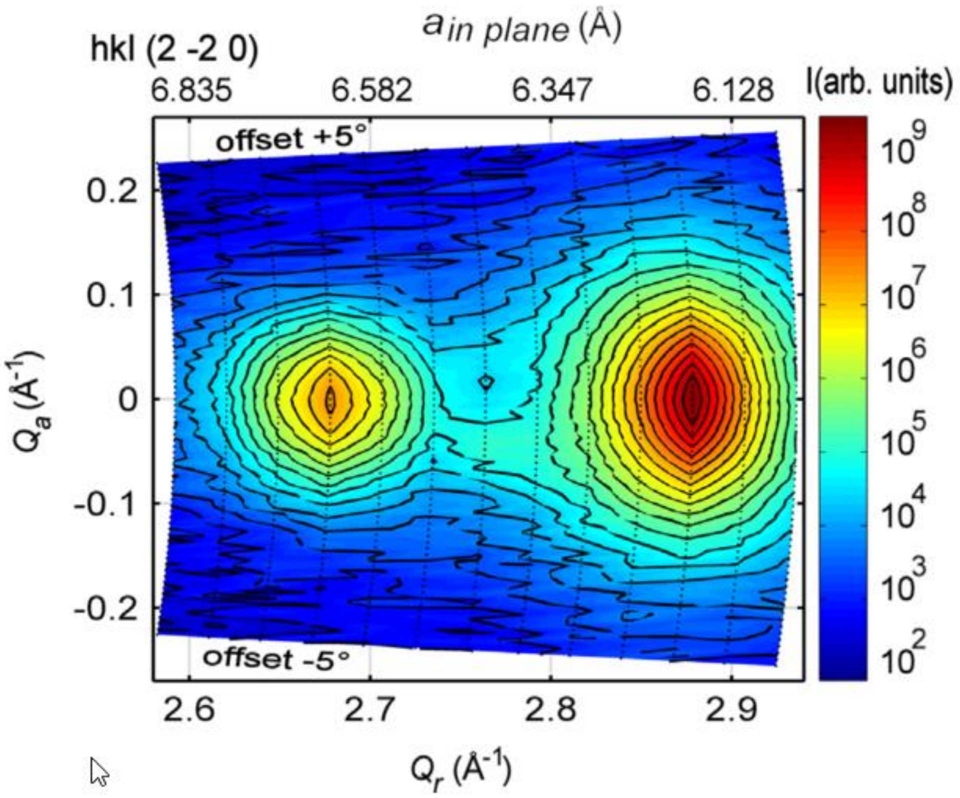
Grazing incidence diffraction

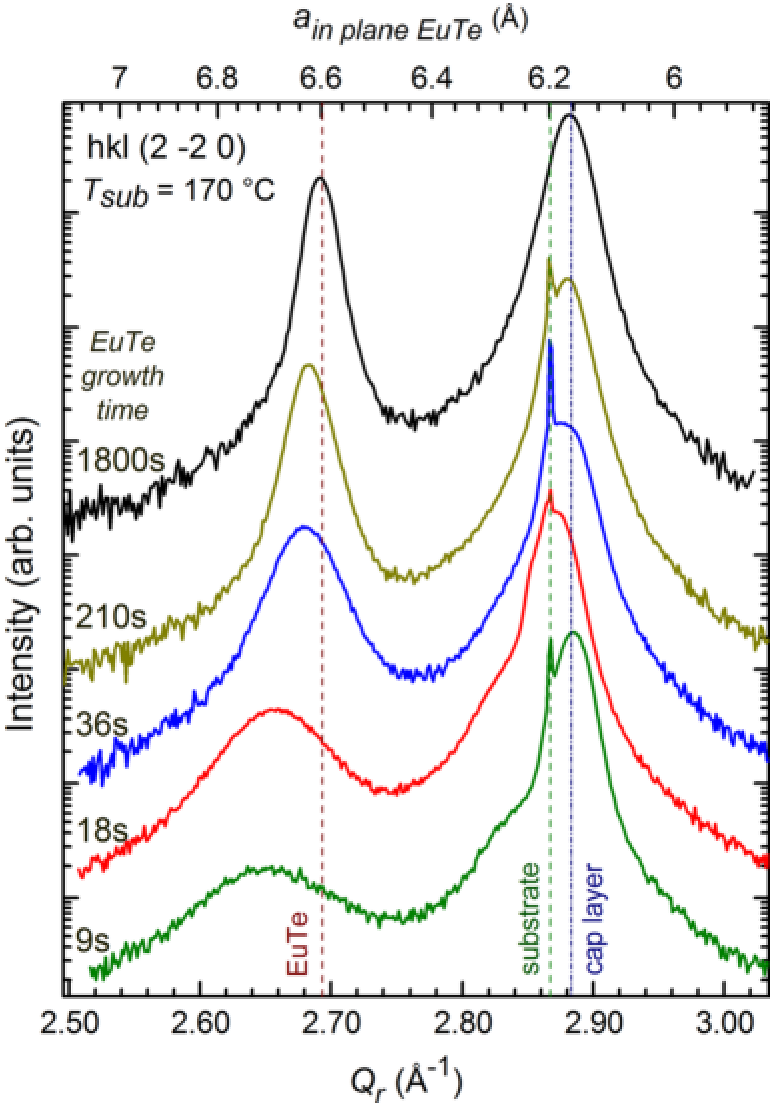




Journal of Crystal Growth **386**(0): 139-145, 2014

Grazing incidence diffraction





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Journal of Crystal Growth **386**(0): 139-145, 2014

Small angle x-ray reflectivity

Single crystal films

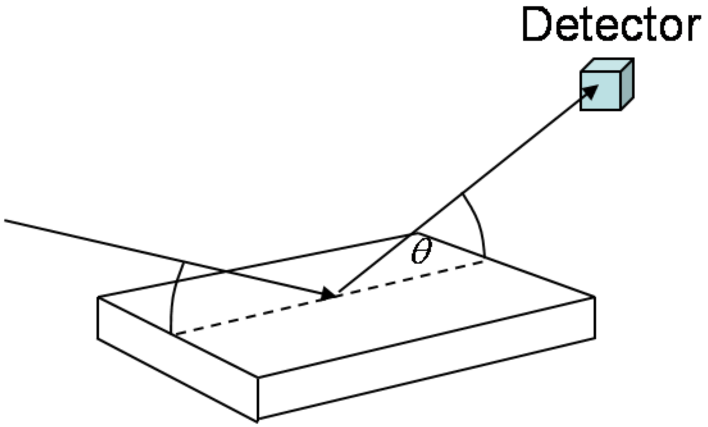
Polycrystalline films

Amorphous films

Small angle X-Ray reflectivity

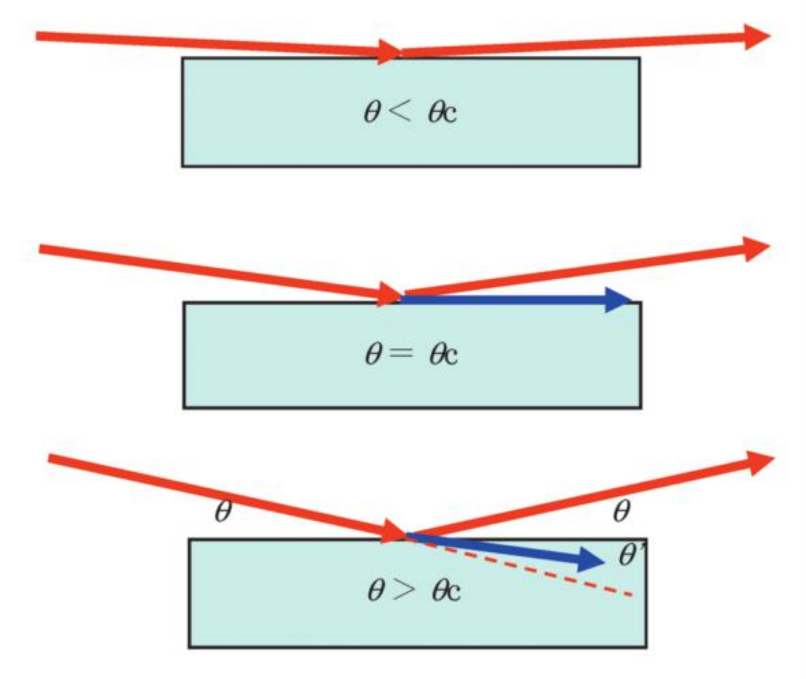
- Reflectivity yields information about the
  - Thicknesses
  - Density / porosity
  - Roughness of the interfaces

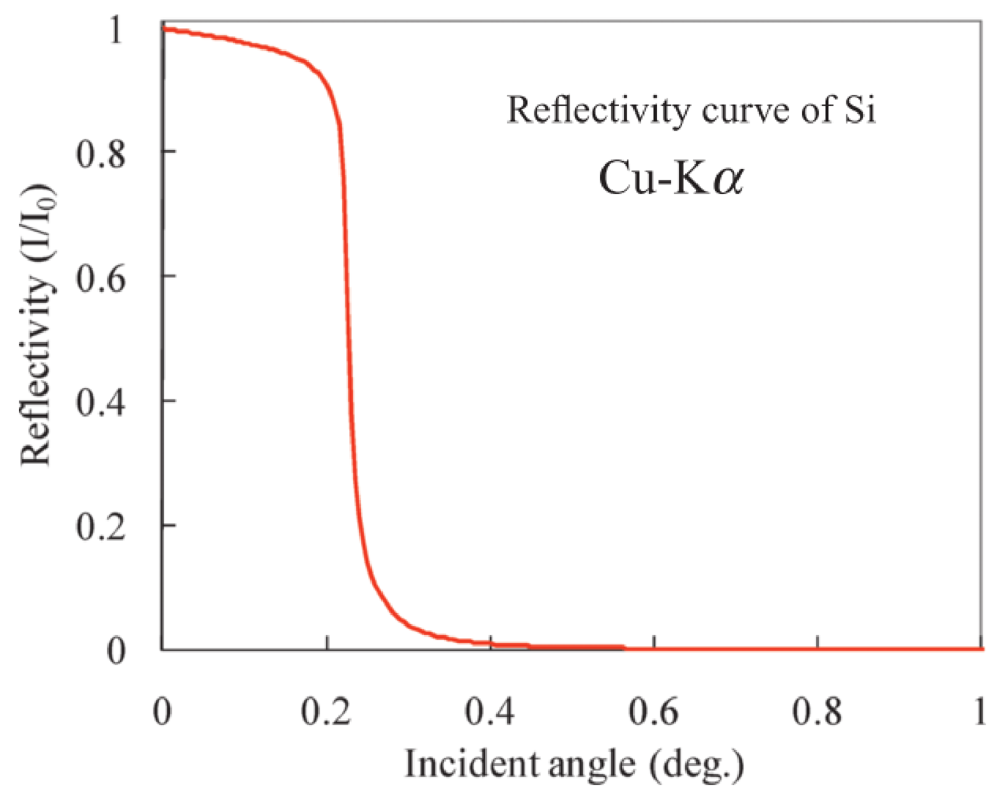
- Other names:
  - X-ray specular reflectivity
  - X-ray reflectometry
  - XRR



No diffraction!

Small angle X-Ray reflectivity

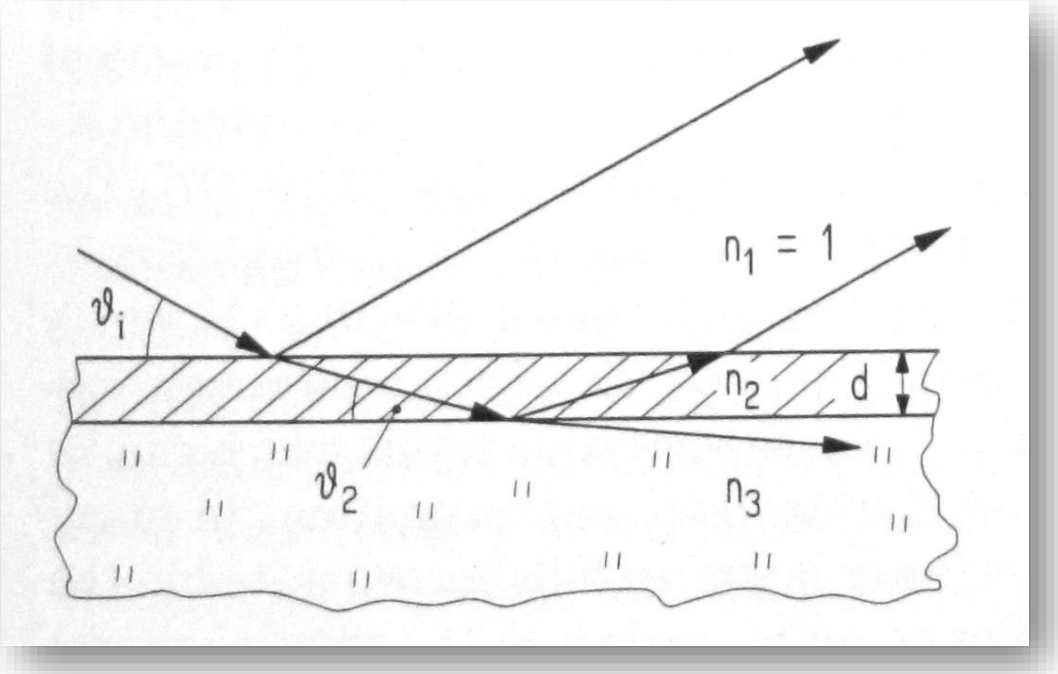




$$\theta_c \sim \lambda\sqrt{\rho}$$

The Rigaku Journal, **26**(2), 2010

Small angle X-Ray reflectivity



Snell's law

$n_1 \cos \vartheta_1 = n_2 \cos \vartheta_2$

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

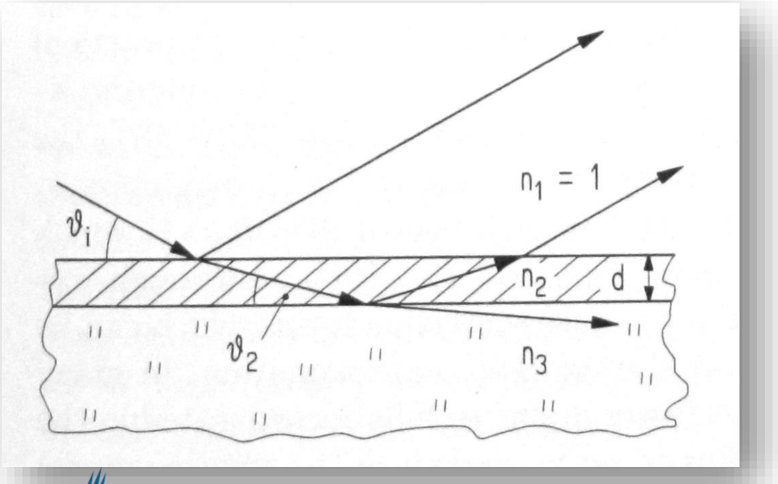
Gibaud 2013 – X-ray reflectivity chapter

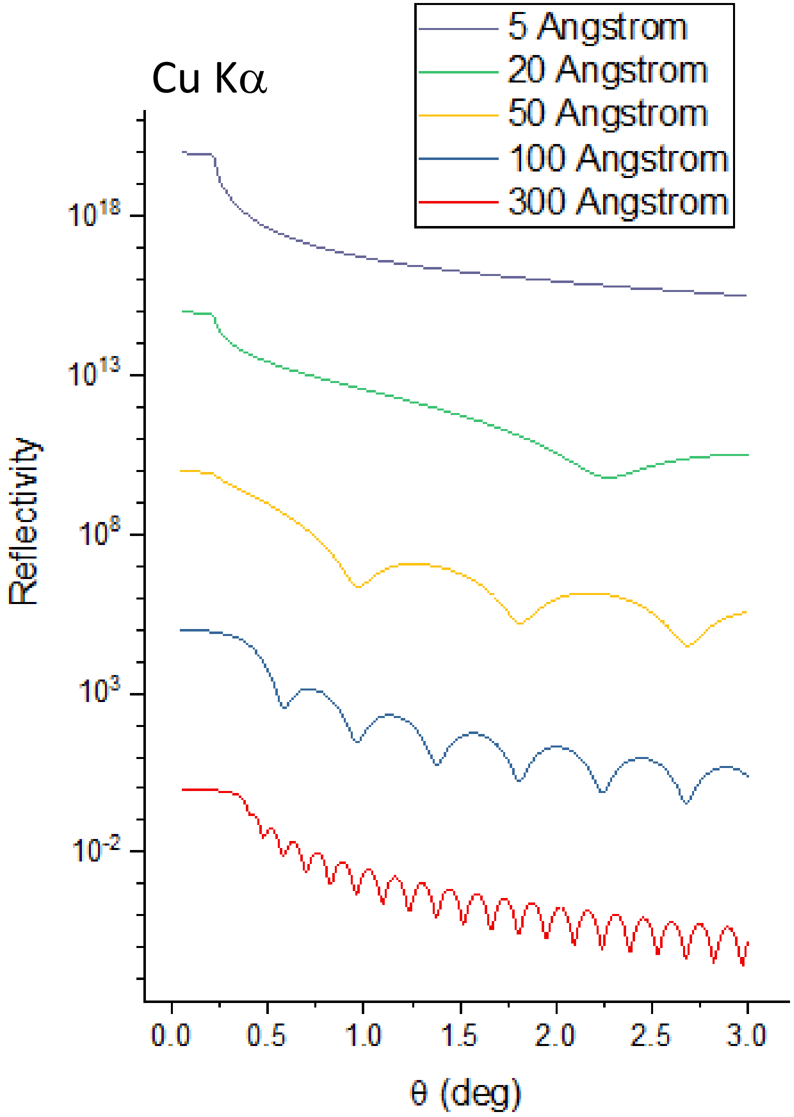
Small angle X-Ray reflectivity

Reflectivity of a chromium film on
top of silicon substrate, Cr/Si,
for different thicknesses
between 5 and 300 Å.

Kiessig fringes

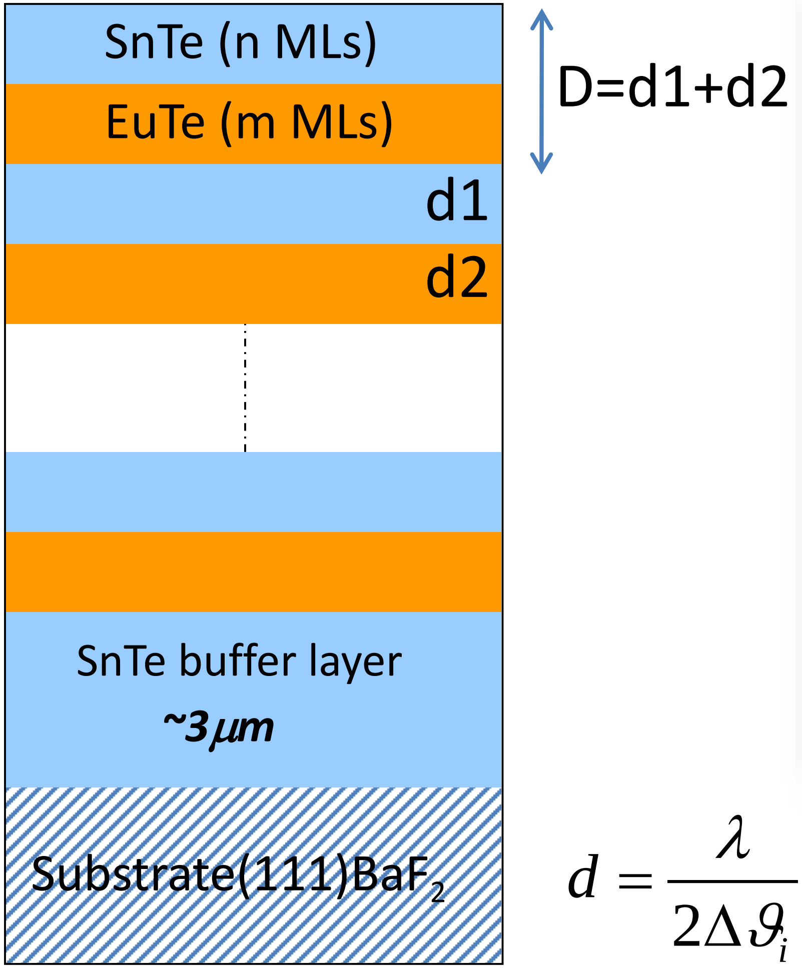
$$d = \frac{\lambda}{2\Delta\theta_r}$$





$$\frac{1.54\cdot \text{Angstrom}}{2\cdot 0.01\cdot \text{deg}} = 0.4\ \mu\text{m}$$

Small angle X-Ray reflectivity



SnTe (n MLs)

EuTe (m MLs)

d1

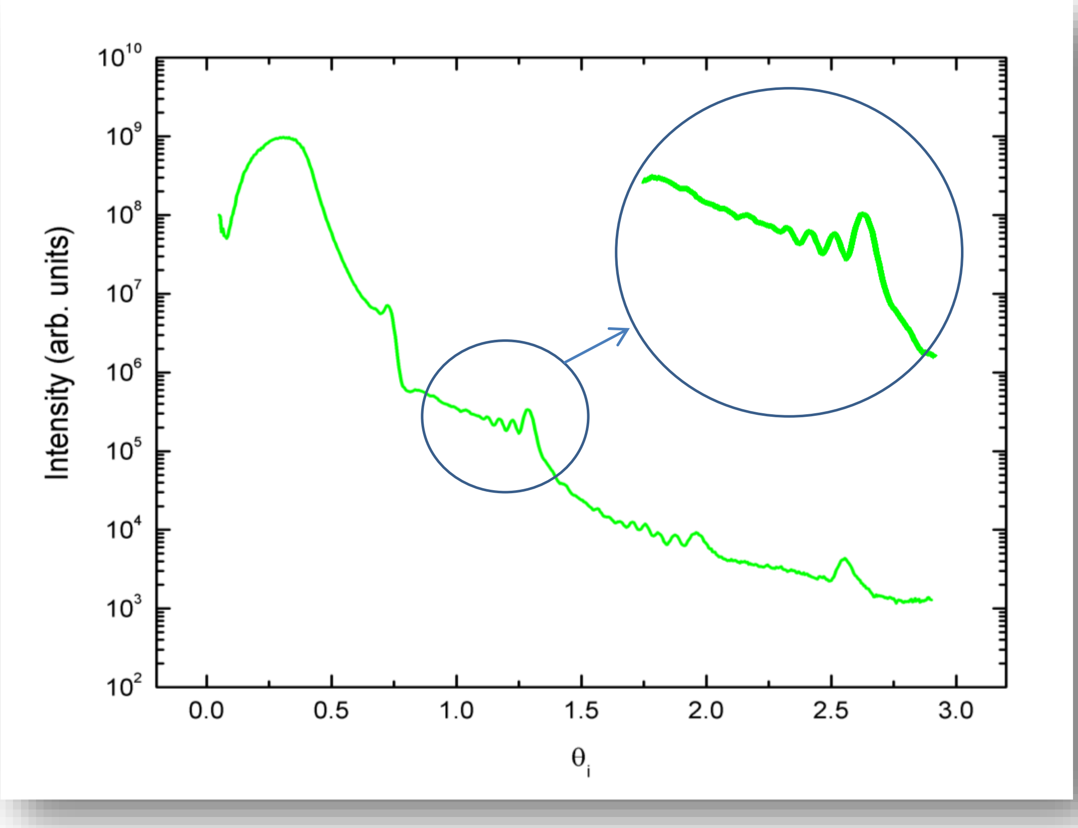
d2

D=d1+d2

SnTe buffer layer

~3 μm

Substrate(111)BaF_2



$$d = \frac{\lambda}{2\Delta\vartheta_i}$$

Kiessig fringes spacing:

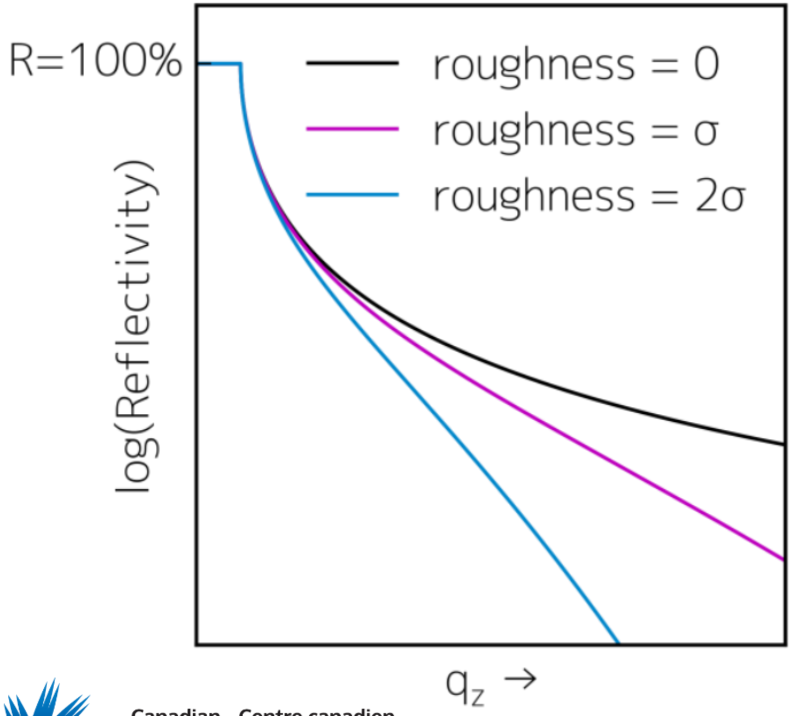
0.61 deg ~ 83 Å (SL period)

0.05 deg ~ 994.9 Å (Stack thickness)

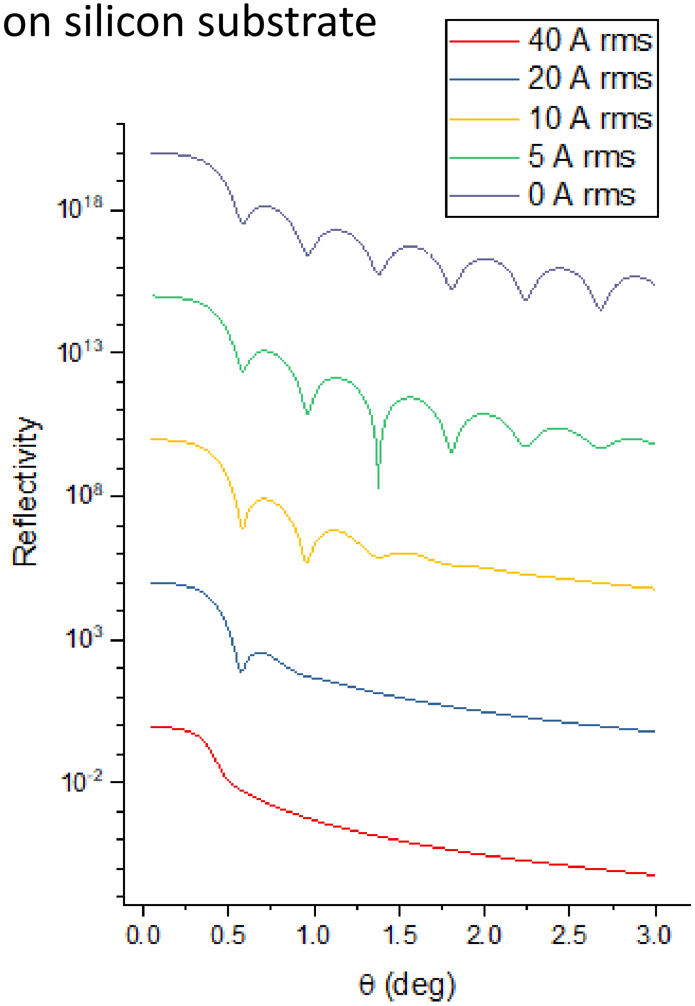
Small angle X-Ray reflectivity

Surface roughness

$$R_{rough} = R \cdot e^{-\frac{q_z^2 \sigma^2}{2}}$$



100 Angstrom chromium layer on silicon substrate



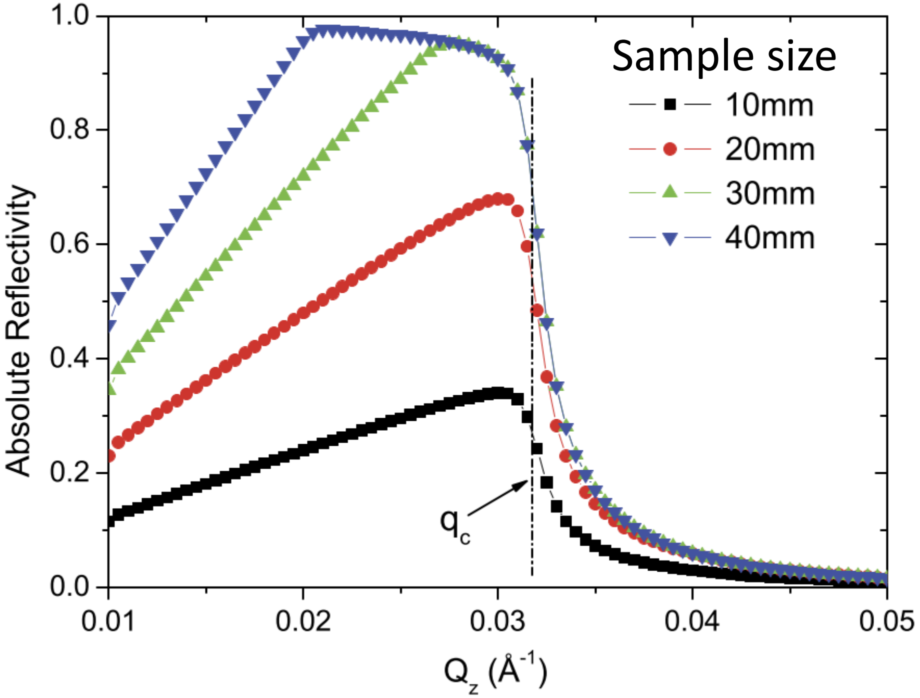
Small angle X-Ray reflectivity

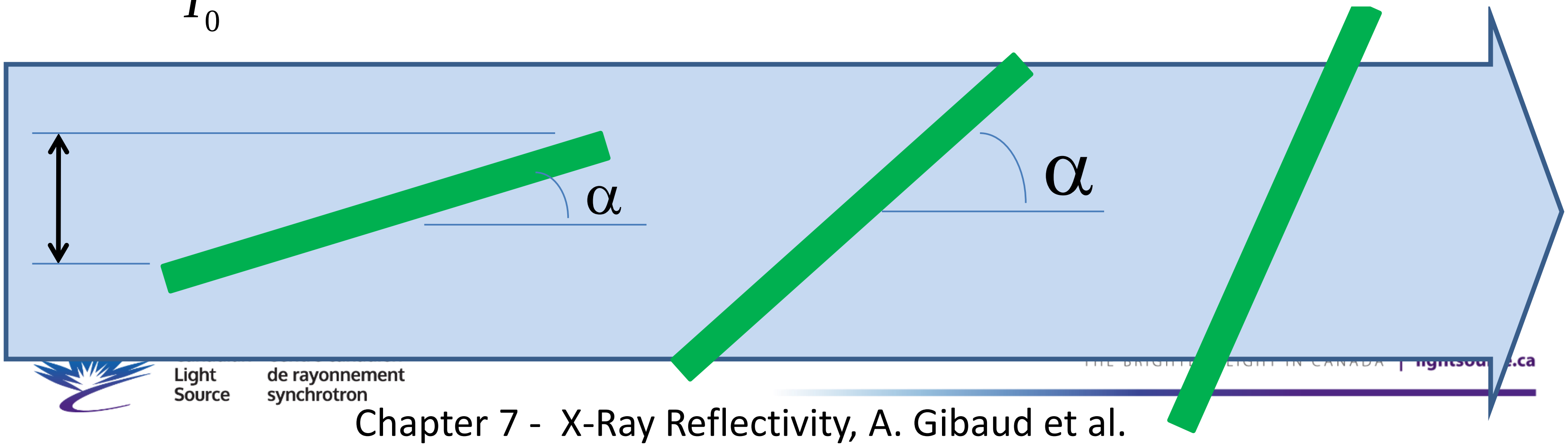
Footprint correction

Beam footprint length:

$$F = \frac{t}{\sin(\alpha)}$$

$$R = \frac{I}{I_0}$$

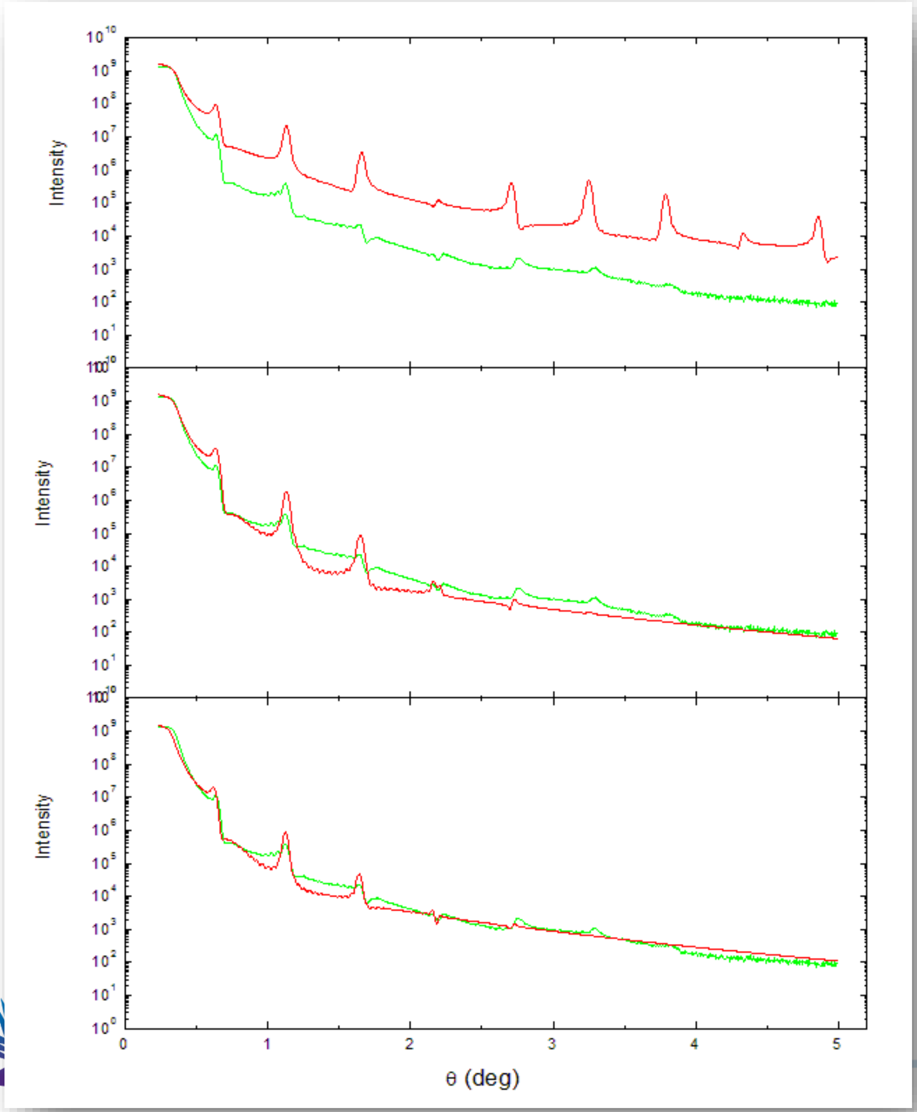




Chapter 7 - X-Ray Reflectivity, A. Gibaud et al.

Small angle X-Ray reflectivity

Fits to the measurement



Smooth interfaces

Rough interfaces

Lower densities
(porous sample?)

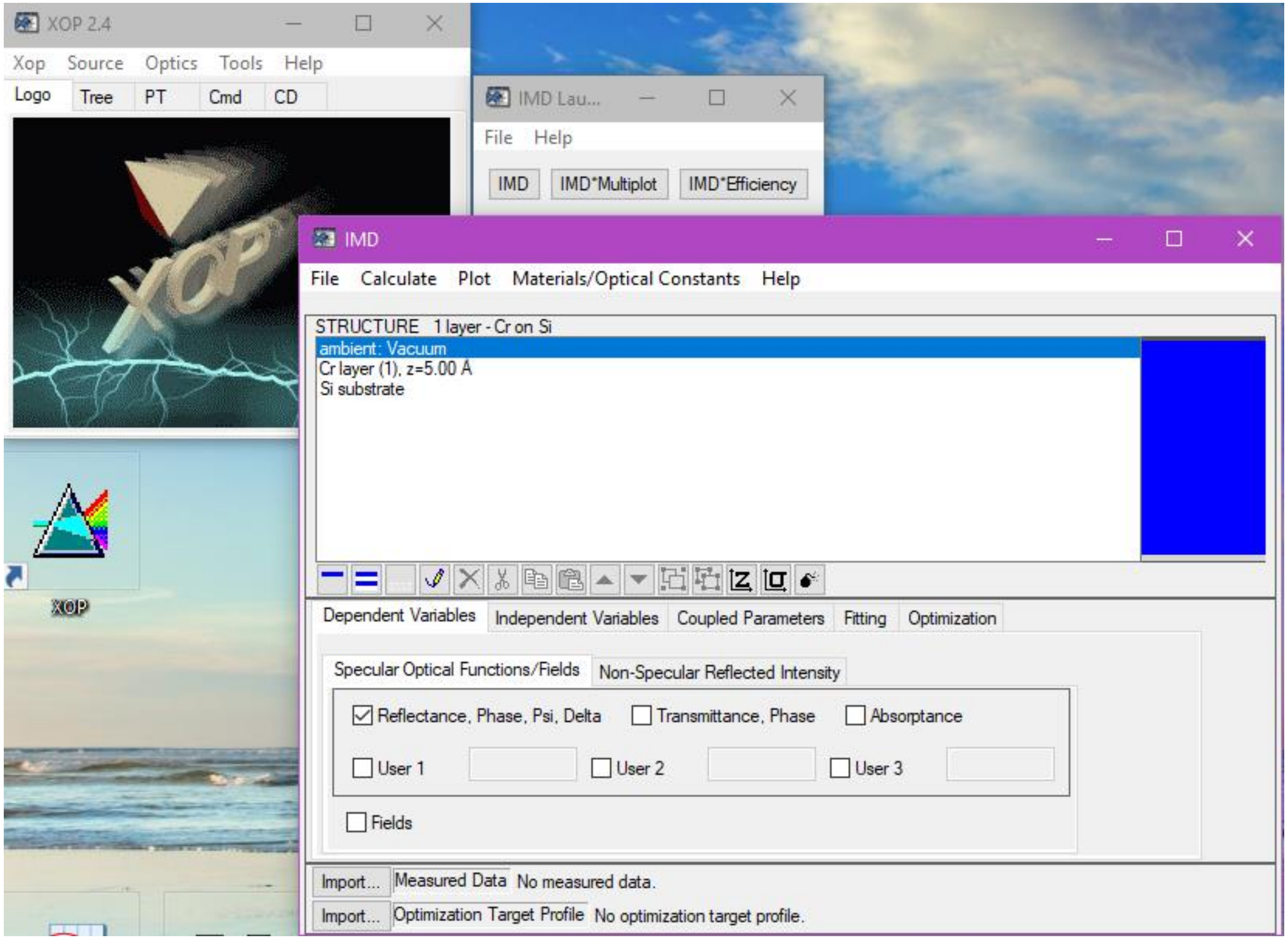
Oxide layer cap!

Programs for simulating and fitting reflectivity

- GSAS II !
- Parratt 32
- RFit2000
- WinGixa (Panalytical)
- XOP / IMD

For more x-ray related softwares, consult website: http://gisaxs.com/index.php/Software#Crystallography

IMD/XOP to simulate x-ray reflectivity



STRUCTURE 1 layer - Cr on Si
ambient: Vacuum
Cr layer (1), z=5.00 Å
Si substrate

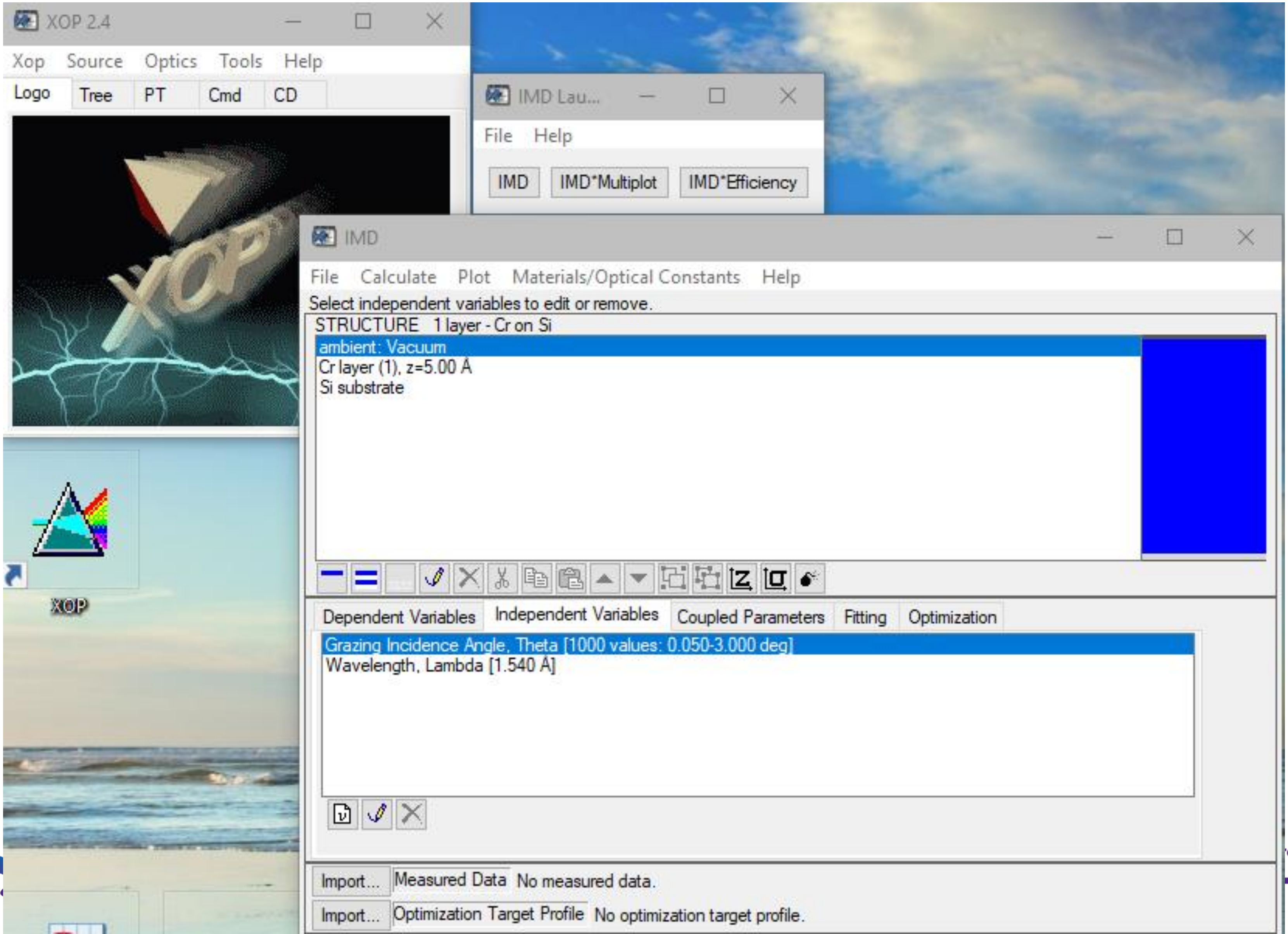
☑ Reflectance, Phase, Psi, Delta ☐ Transmittance, Phase ☐ Absorptance
☐ User 1 ☐ User 2 ☐ User 3
☐ Fields

Measured Data No measured data.
Optimization Target Profile No optimization target profile.

https://www.aps.anl.gov/Science/Scientific-Software/XOP

http://www.rxollc.com/idl/IMD.pdf

IMD/XOP to simulate x-ray reflectivity



Select independent variables to edit or remove.

STRUCTURE 1 layer - Cr on Si

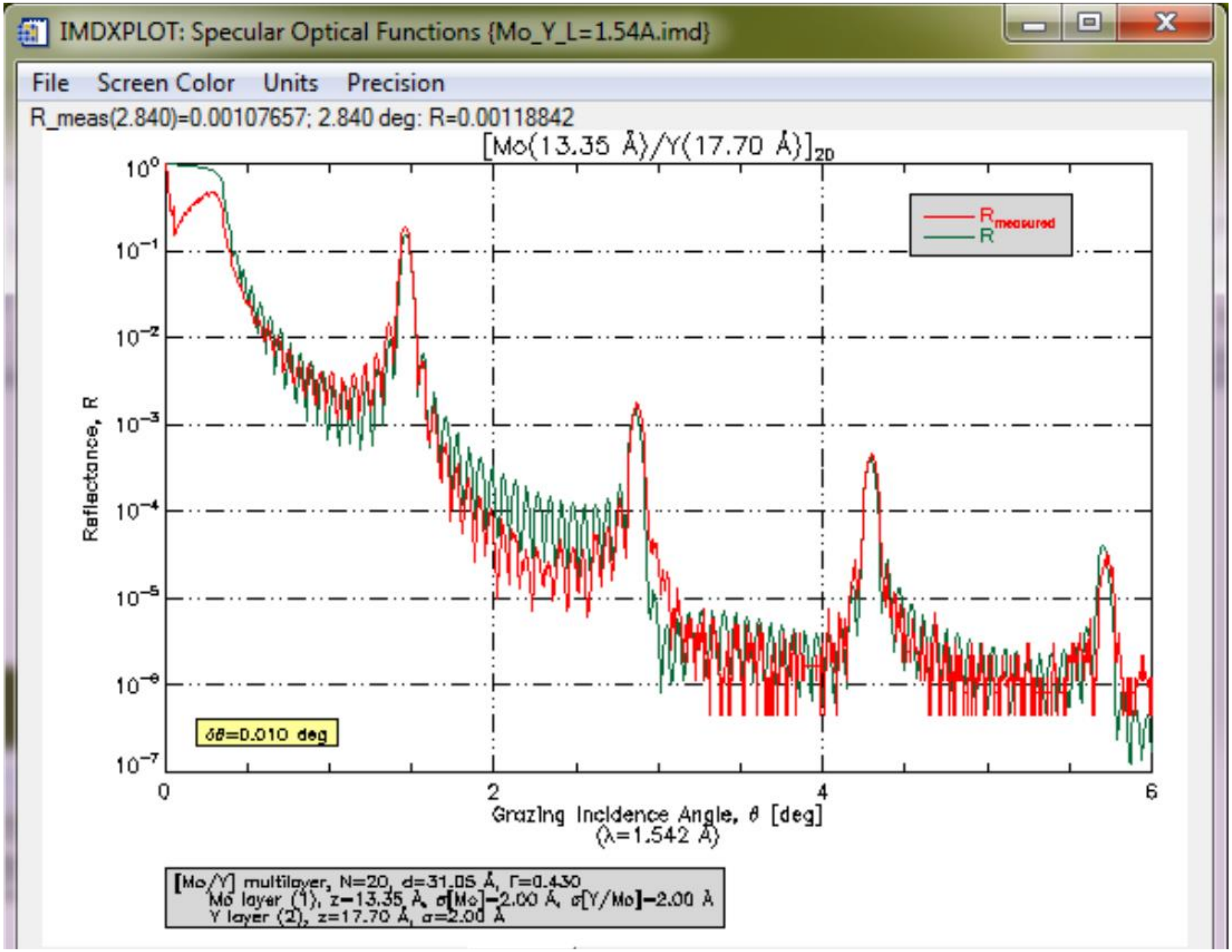
ambient: Vacuum
Cr layer (1), z=5.00 Å
Si substrate

Grazing Incidence Angle, Theta [1000 values: 0.050-3.000 deg]
Wavelength, Lambda [1.540 Å]

Measured Data: No measured data.

Optimization Target Profile: No optimization target profile.

IMD/XOP to simulate x-ray reflectivity



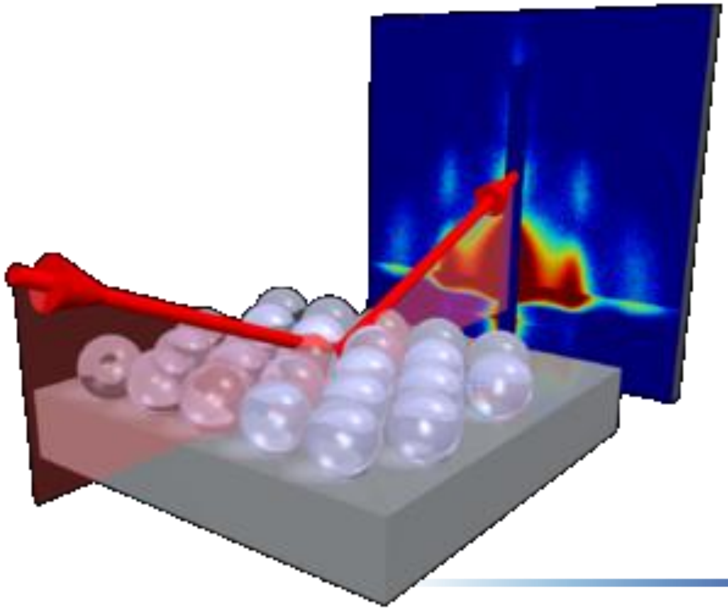
R_meas(2.840)=0.00107657; 2.840 deg: R=0.00118842

[Mo/Y] multilayer, N=20, d=31.05 Å, Γ=0.430
Mo layer (1), z=13.35 Å, σ[Mo]=2.00 Å, σ[Y/Mo]=2.00 Å
Y layer (2), z=17.70 Å, σ=2.00 Å

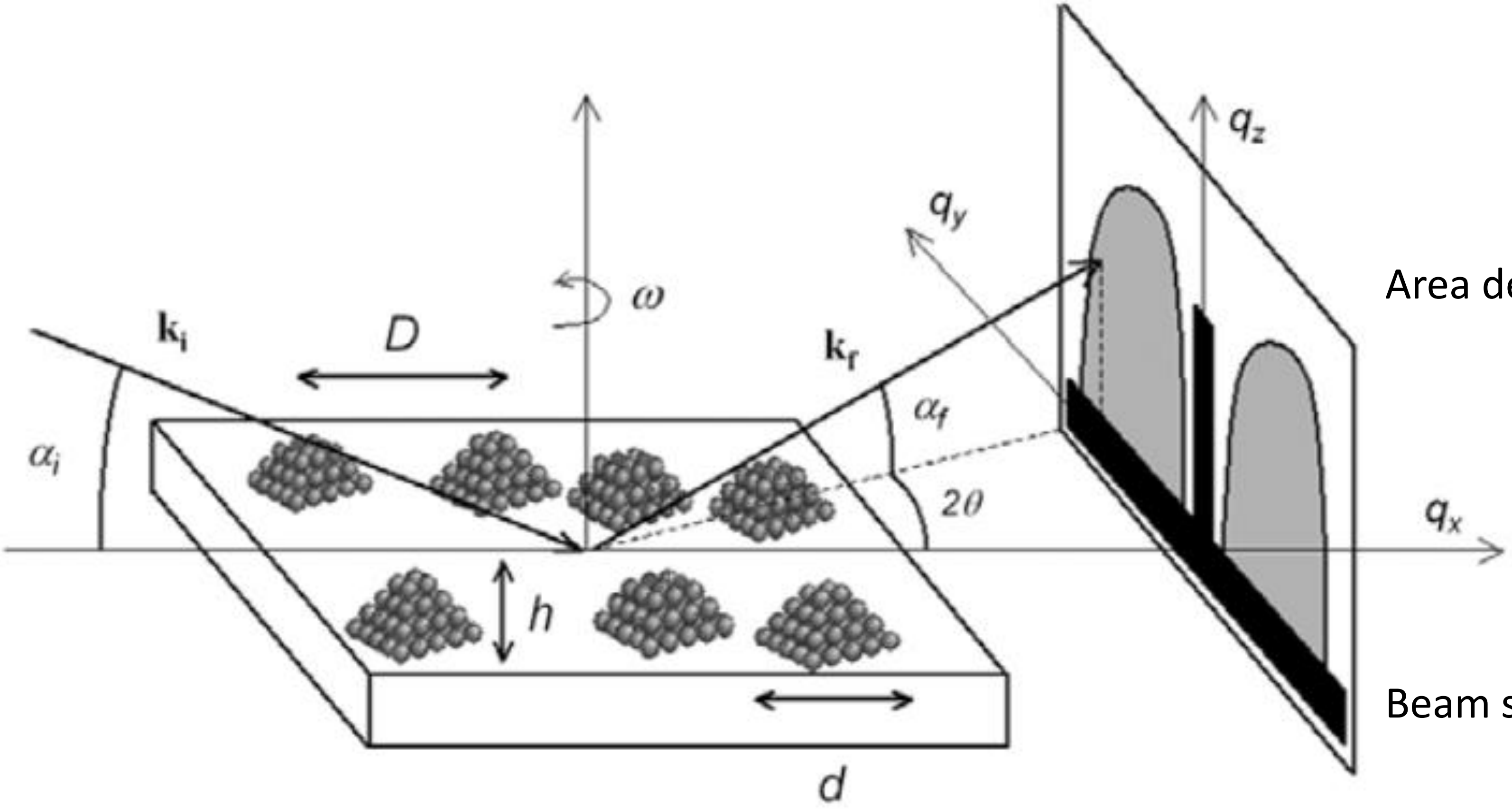
Grazing **I**ncidence

Small **A**ngle **X**-ray **S**cattering

GISAXS



GISAXS measurements



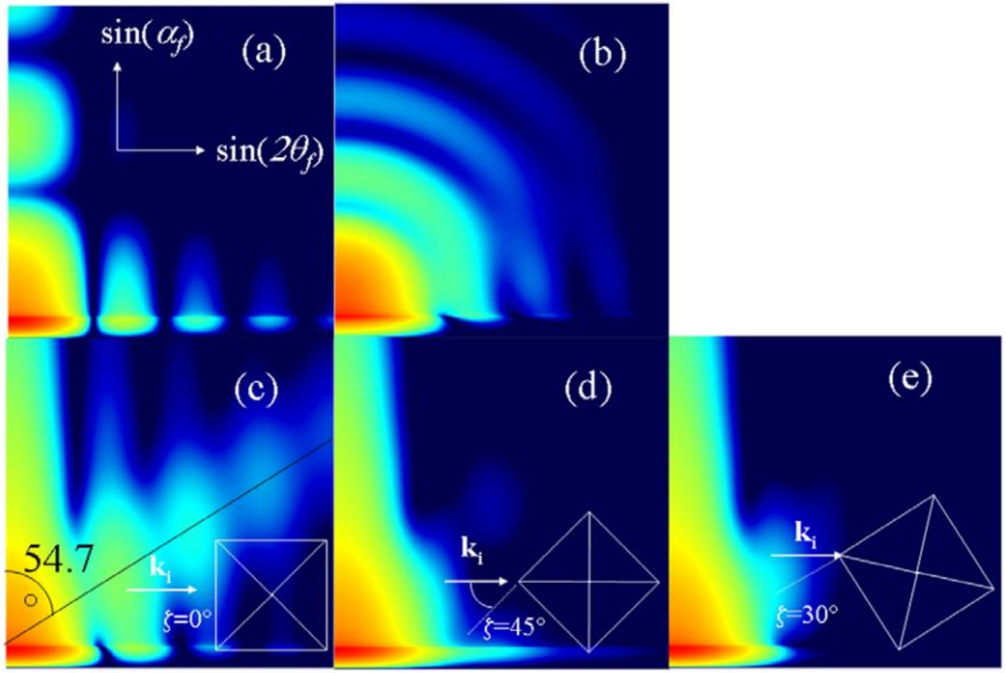
Area detector

Beam stop

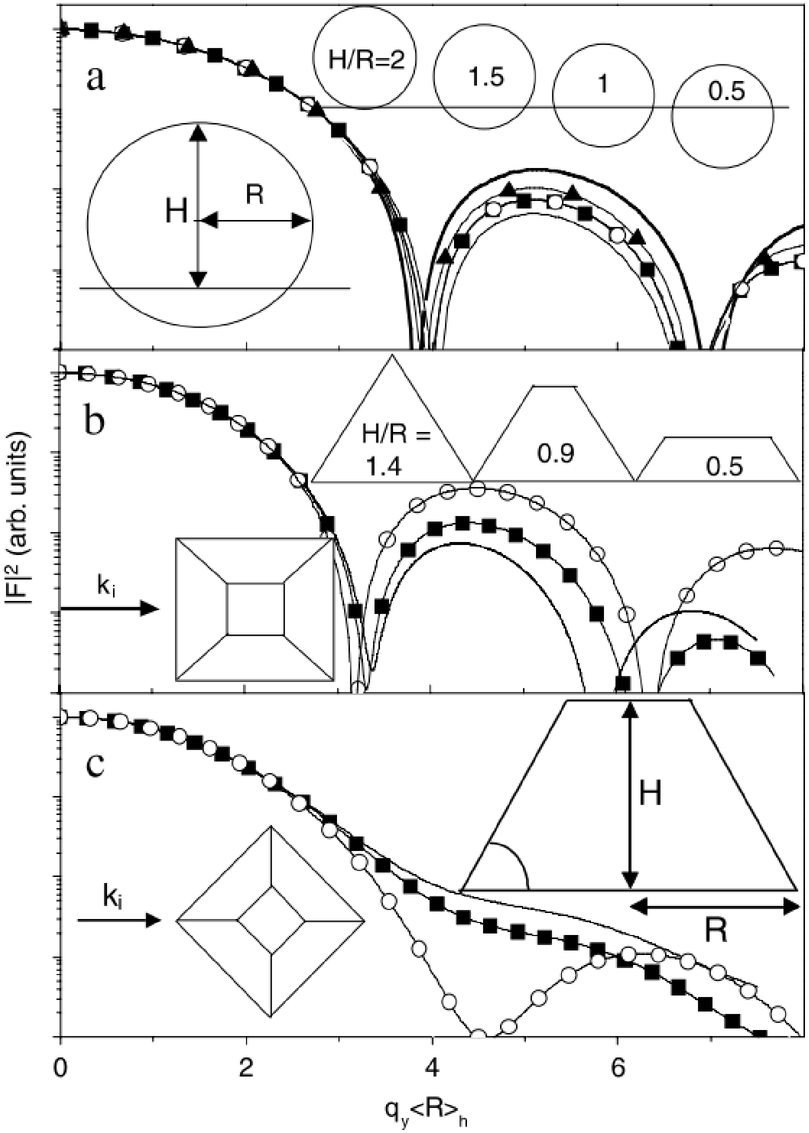
Surface Science Reports **64**(8): 255-380, 2009.

GISAXS:

Form factors of particles of different shapes



q_y



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Surface Science Reports **64**(8): 255-380.

Modelling software

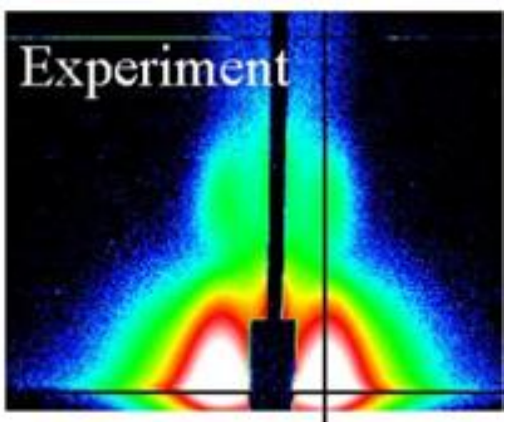
- R. Lazzari, IsGISAXS: A program for grazing-incidence small-angle X-ray scattering analysis of supported islands, J. Appl. Crystallogr. 35 (2002) 406–421.
- http://www.insp.jussieu.fr/oxydes/IsGISAXS/isgisaxs.htm

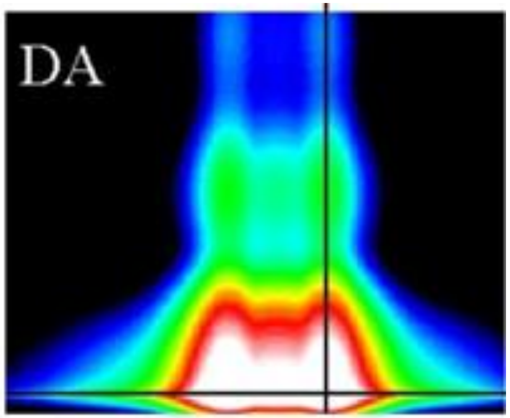
- Jiang, Z. (2015). "GIXSGUI: a MATLAB toolbox for grazing-incidence X-ray scattering data visualization and reduction, and indexing of buried three-dimensional periodic nanostructured films." Journal of Applied Crystallography **48**(3): 917-926.
- https://www.aps.anl.gov/Science/Scientific-Software/GIXSGUI

- FitGISAXS, BornAgain, HipGISAXS, NANOCELL, SimDiffraction,…

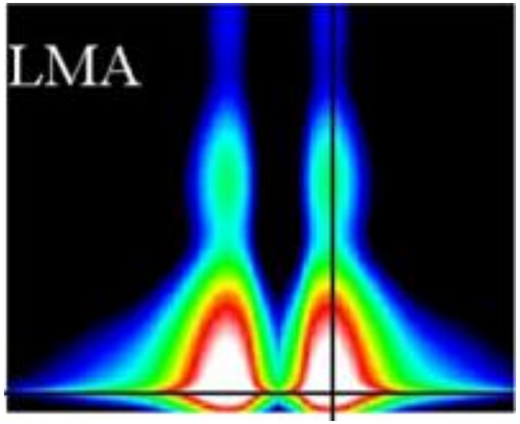
IsGISAXS

Pd islands on MgO(100)

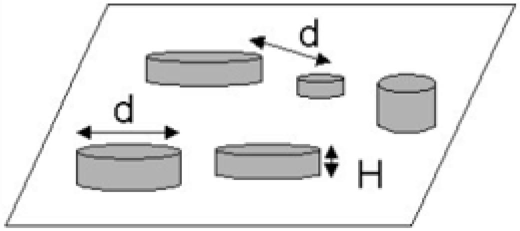




Decoupling Approximation (DA)



Local Monodisperse
Approximation (LMA)



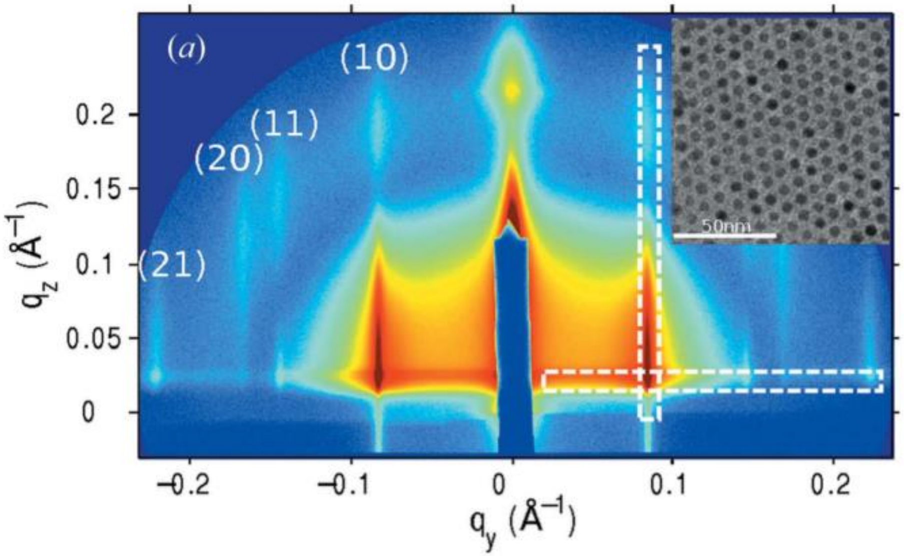
PARAMETERS :
cylinder
D = 20.7 nm
d = 10.2 nm
H = 6.6 nm
$\sigma_R = 1.3$
$\sigma_H = 1.1$

- ✓ Shape
- ✓ Average size
- ✓ Size spread
- ✓ Distance among them

http://www.insp.jussieu.fr/oxydes/IsGISAXS/isgisaxs.htm#Introduction

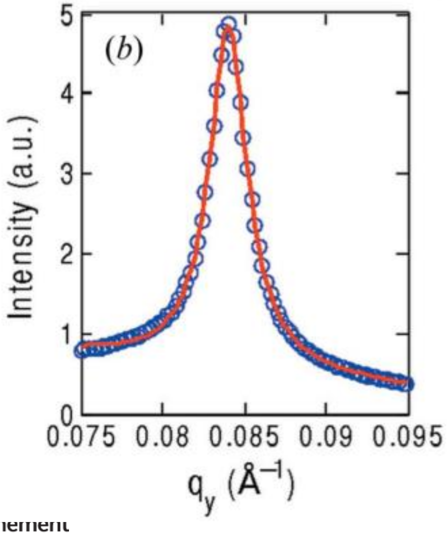
GISAXS

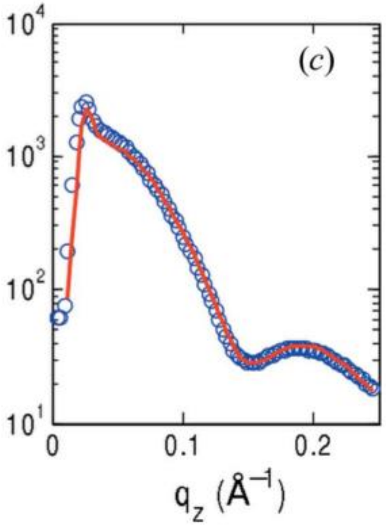
Spherical gold nanoparticles in silicon



Horizontal line profile:

- ✓ Lattice parameter
- ✓ Coherent domain size





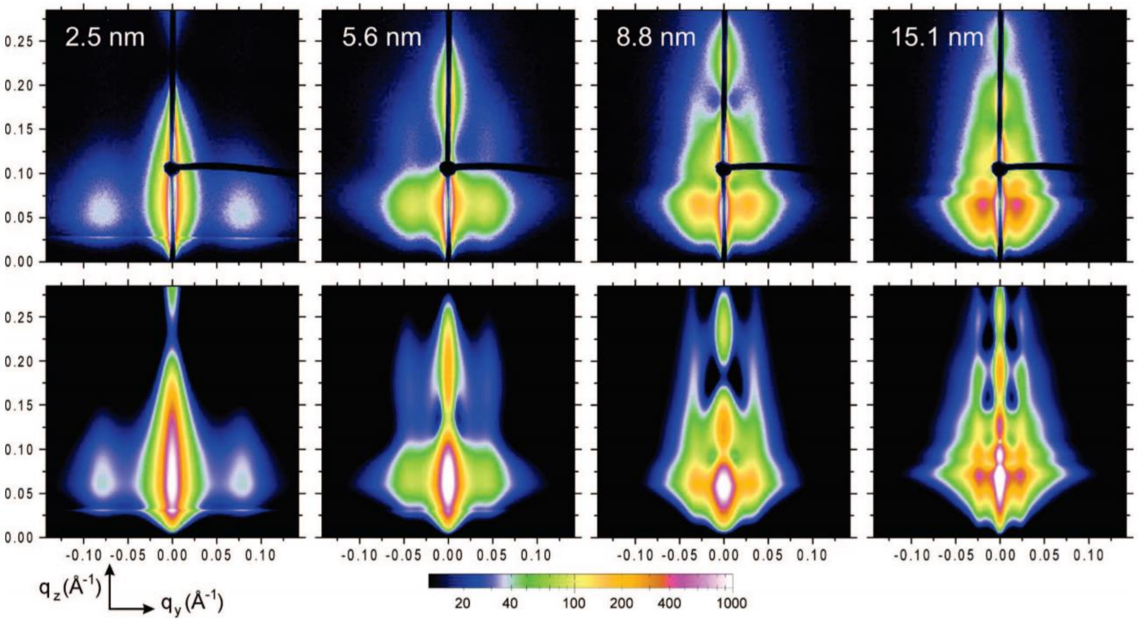
Vertical line profile:

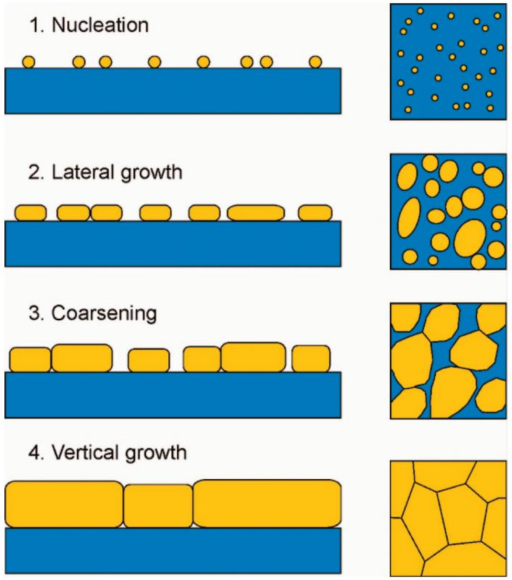
- ✓ Nanoparticle size
- ✓ Polydispersity

Journal of Applied Crystallography **48**(3): 917-926, 2015

In situ GISAXS

Gold film growth on conducting polymer





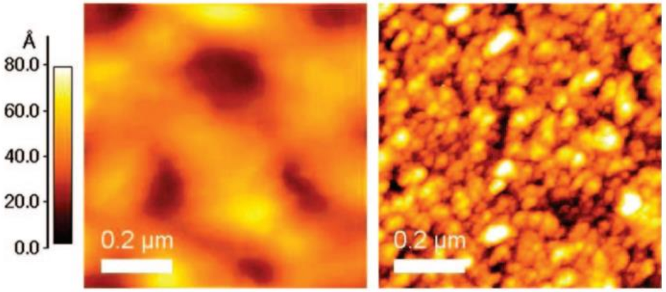
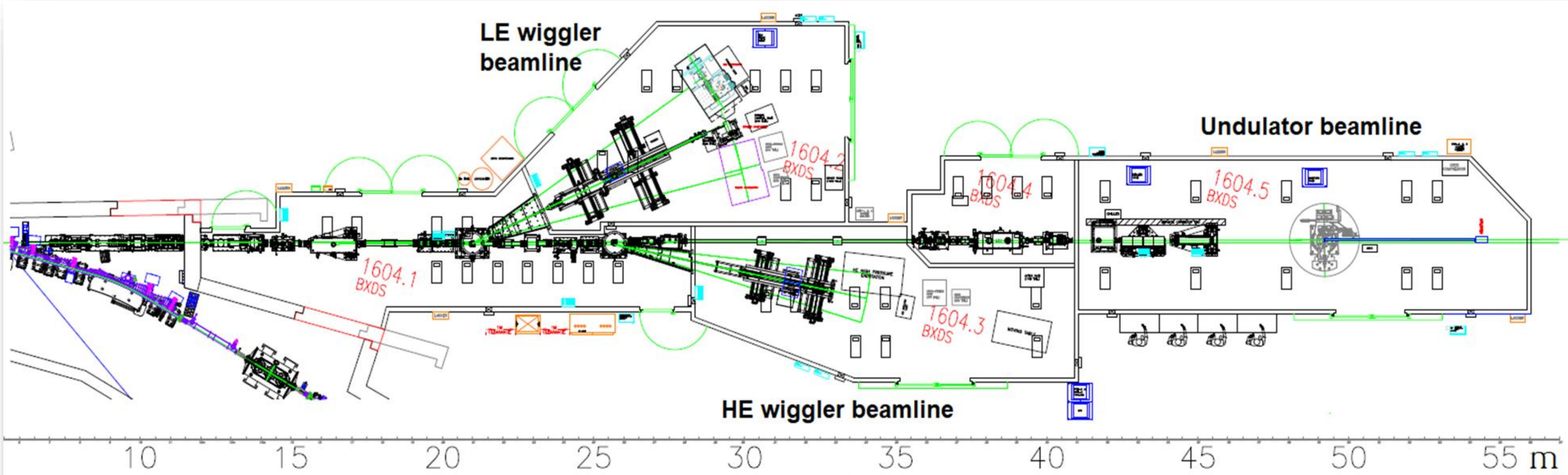


Table 1. Morphological Parameters Extracted from Simulation of the Data by Use of a Model Consisting of Parallelepiped and Spheroid Particle Geometries To Describe the Cluster Shape[a]

t (min)	d_0 (nm)	d (nm)	r_p (nm)	σ_p (nm)	h_p (nm)	r_s (nm)	σ_s (nm)	h_s (nm)	D (nm)	ω (nm)
9	3.9	2.5	4.8	20.0	3.6	4.8	11.0	4.3	11.8	3.8
19	8.2	5.6	9.1	22.5	6.1	9.1	5.3	6.8	19.0	7.2
29	12.5	8.8	13.5	17.6	8.8	13.5	14.9	9.9	27.0	10.2
49	21.1	15.1	20.0	36.0	15.2	20.0	18.0	16.4	40.0	15.2

ACS Applied Materials & Interfaces **1**(2): 353-360, 2009

Thin film characterization at the Brockhouse sector



Brockhouse beamlines layout

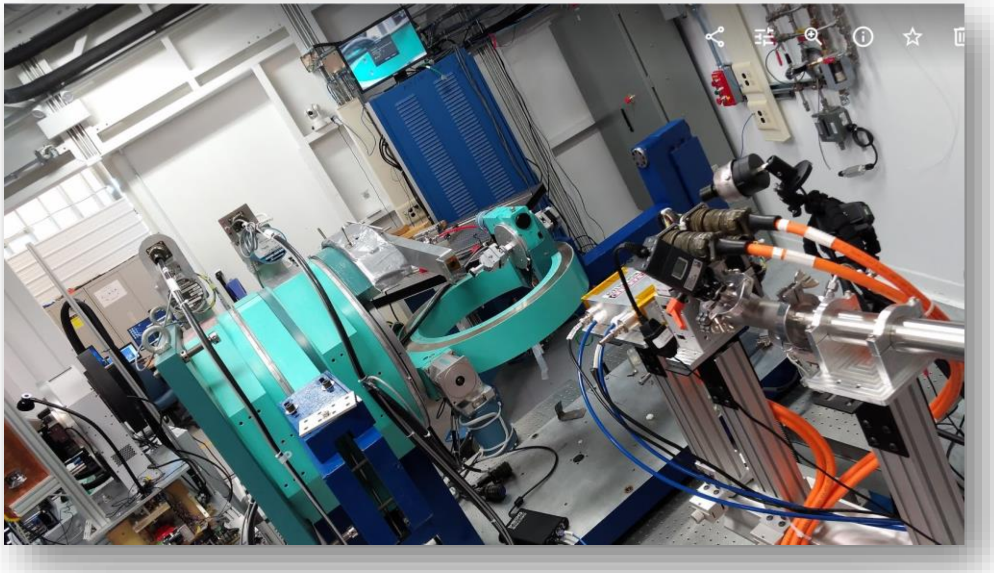
Beamlines energy range

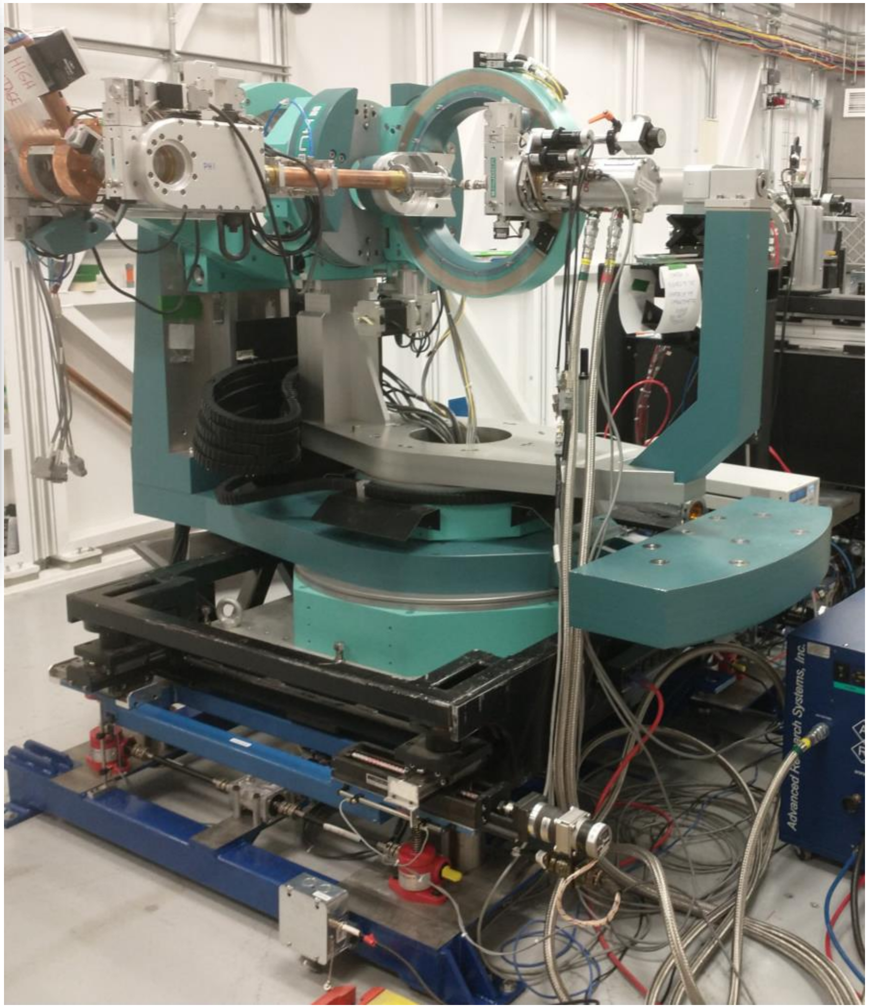
Lower energy wiggler beamline: 7 – 22 keV

Undulator beamline: 5 – 24 keV

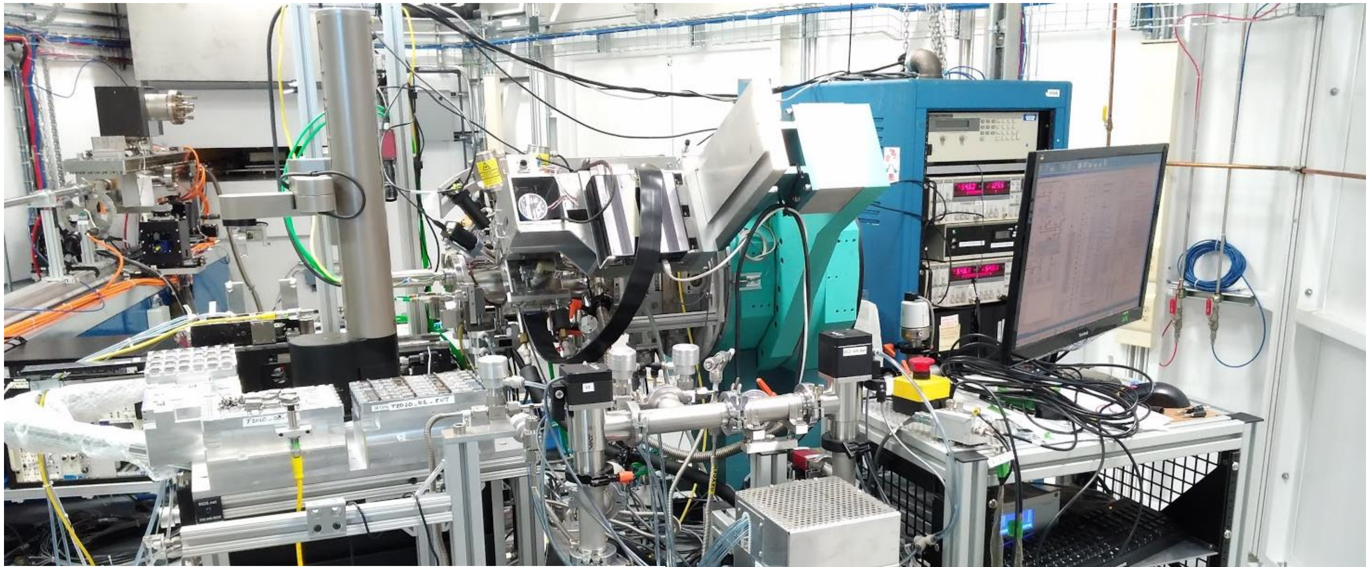
Higher Energy wiggler beamline: 20 – 95 keV

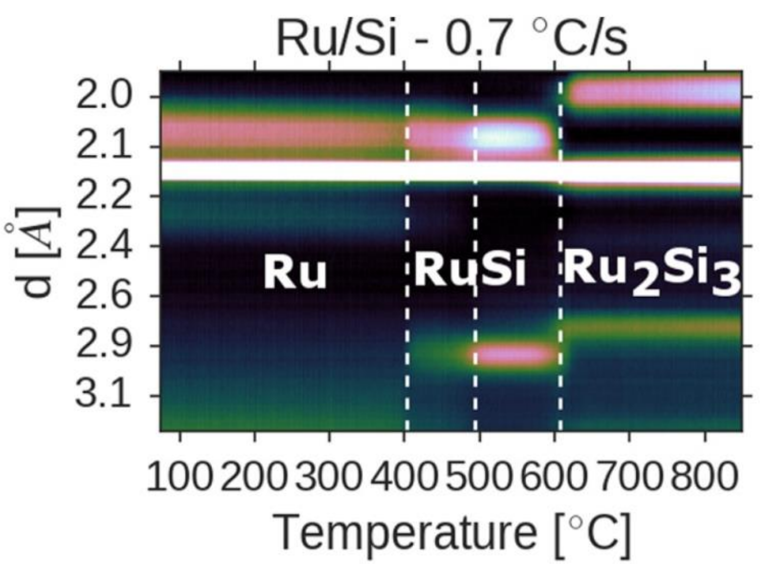
Thin film characterization at the Brockhouse sector





Thin film characterization at the Brockhouse sector





IBM in-situ station

XRD

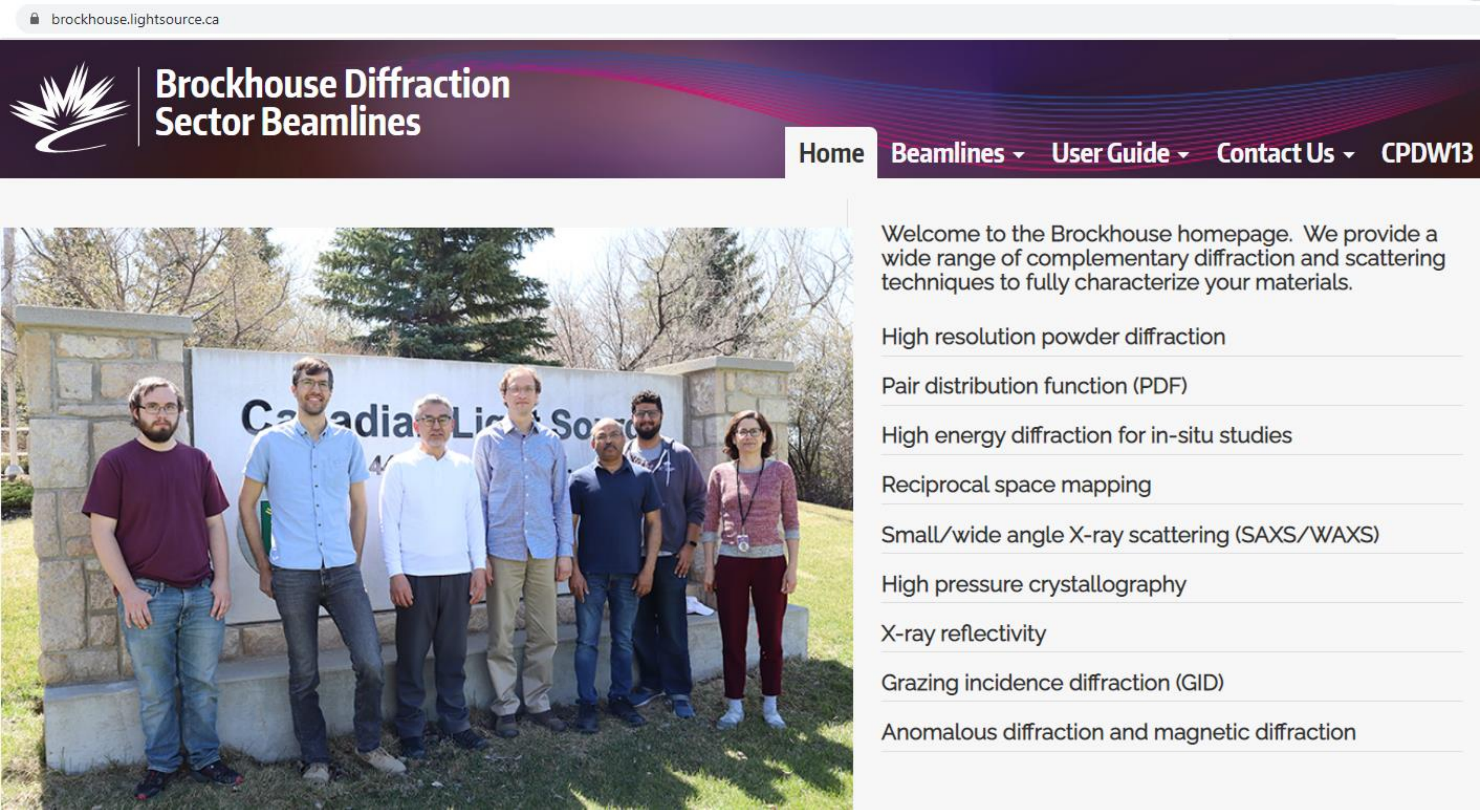
RTA up to 1000 °C

H_2 or N_2 ultrahigh purity atmosphere

Resistance probe

Roughness probe

BXDS – Brockhouse X-ray Diffraction and Scattering for materials science



Welcome to the Brockhouse homepage. We provide a wide range of complementary diffraction and scattering techniques to fully characterize your materials.

- High resolution powder diffraction
- Pair distribution function (PDF)
- High energy diffraction for in-situ studies
- Reciprocal space mapping
- Small/wide angle X-ray scattering (SAXS/WAXS)
- High pressure crystallography
- X-ray reflectivity
- Grazing incidence diffraction (GID)
- Anomalous diffraction and magnetic diffraction

Conclusions

If you have a sample… → measure XRD!

If it is a very thin film… → try one of the techniques with grazing incidence geometry

They can yield information about:

- ✓ Structure / texture / stress
- ✓ Defects
- ✓ Thickness
- ✓ Roughness
- ✓ Composition, interdiffusion, gradients
- ✓ Size, morphology, ordering
- ✓ How does it perform under real working conditions?

→Come to a synchrotron and perform in-situ experiments!

Further reading

- Thin Film Analysis by X-Ray Scattering, by Mario Birkholz, 2006

- Surface Science Techniques
  - Chapter 6: Grazing incidence X-Ray diffraction by Osami Sakata and Masashi Nakamura
  - Chapter 7: X-Ray Reflectivity by Gibaud, Chebil and Beuvier

- Renaud, G., et al. (2009). "Probing surface and interface morphology with Grazing Incidence Small Angle X-Ray Scattering." Surface Science Reports **64**(8): 255-380

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