Grazing incidence
X-Ray Fluorescence Analysis
and
X-Ray Reflectivity

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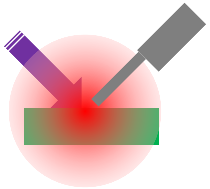
Caen, France

XRF configurations

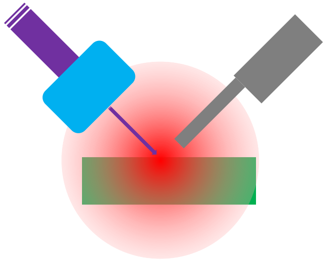
XRF



bulk
analysis

↓

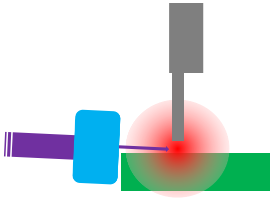
micro-XRF



2D - 3D
micrometre spot

→

grazing incidence



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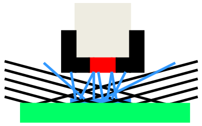
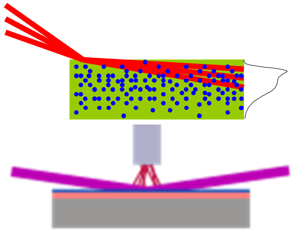
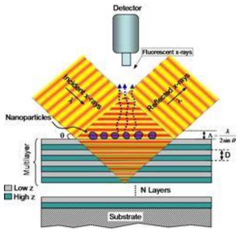


TXRF

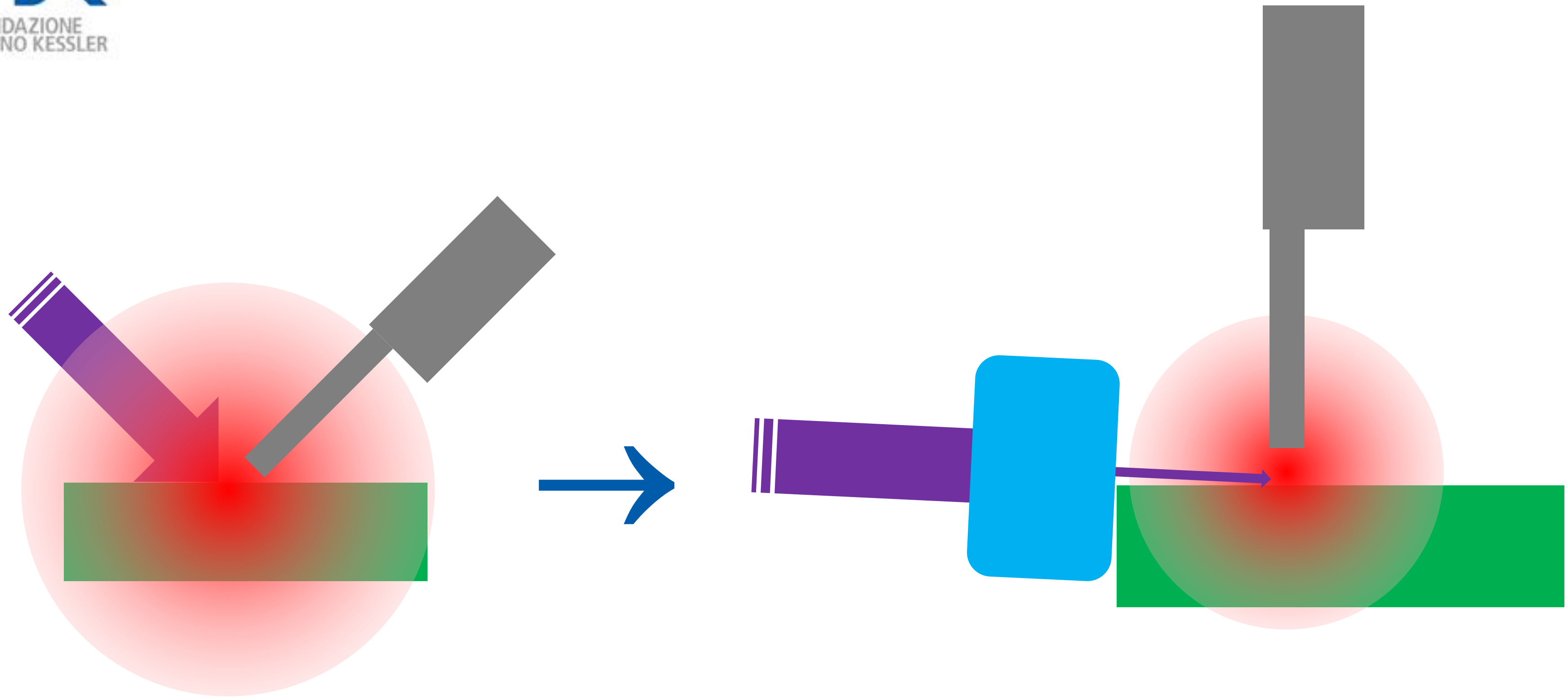


GI-XRF



XSW

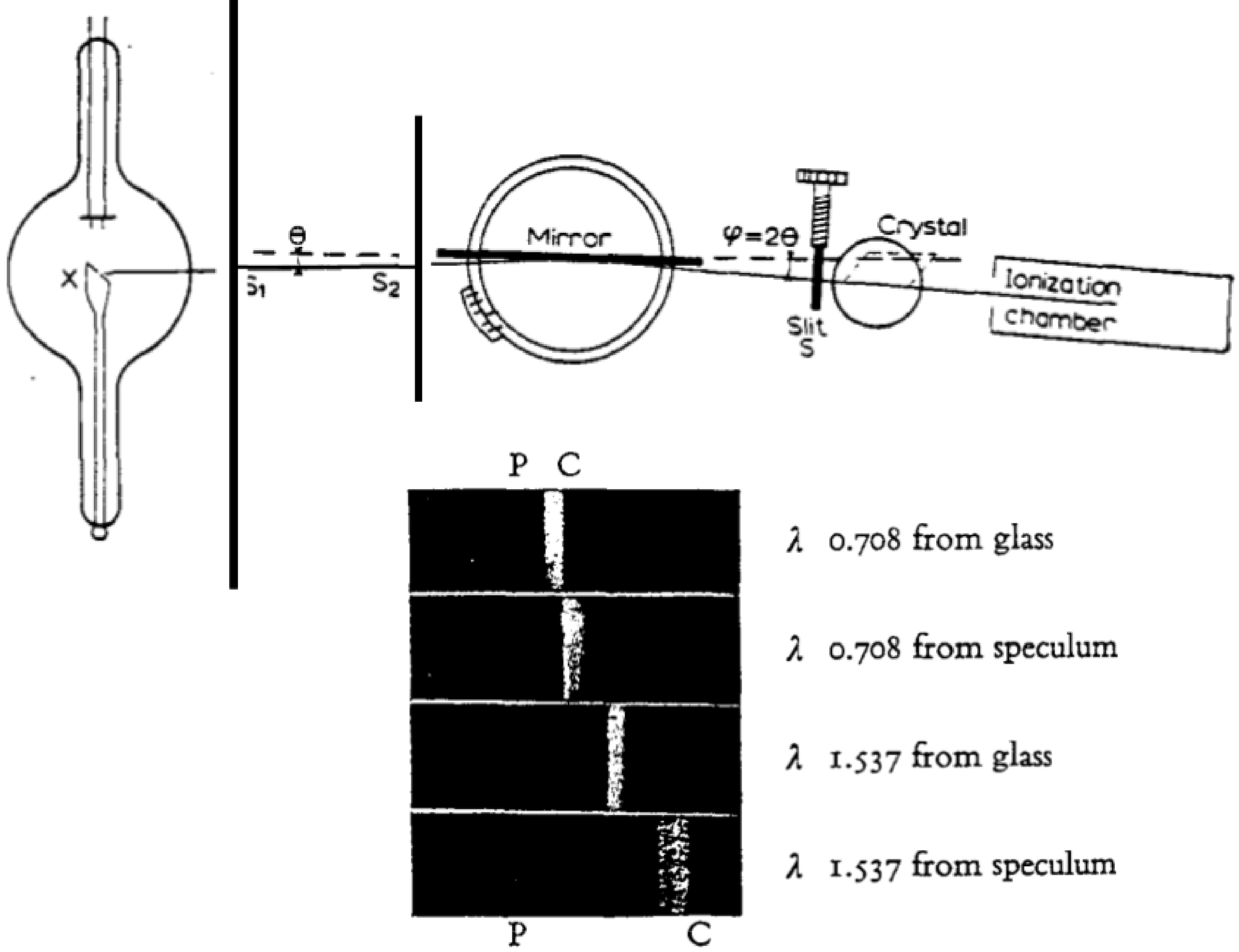
XRF → GIXRF



Why?

XRF → GIXRF

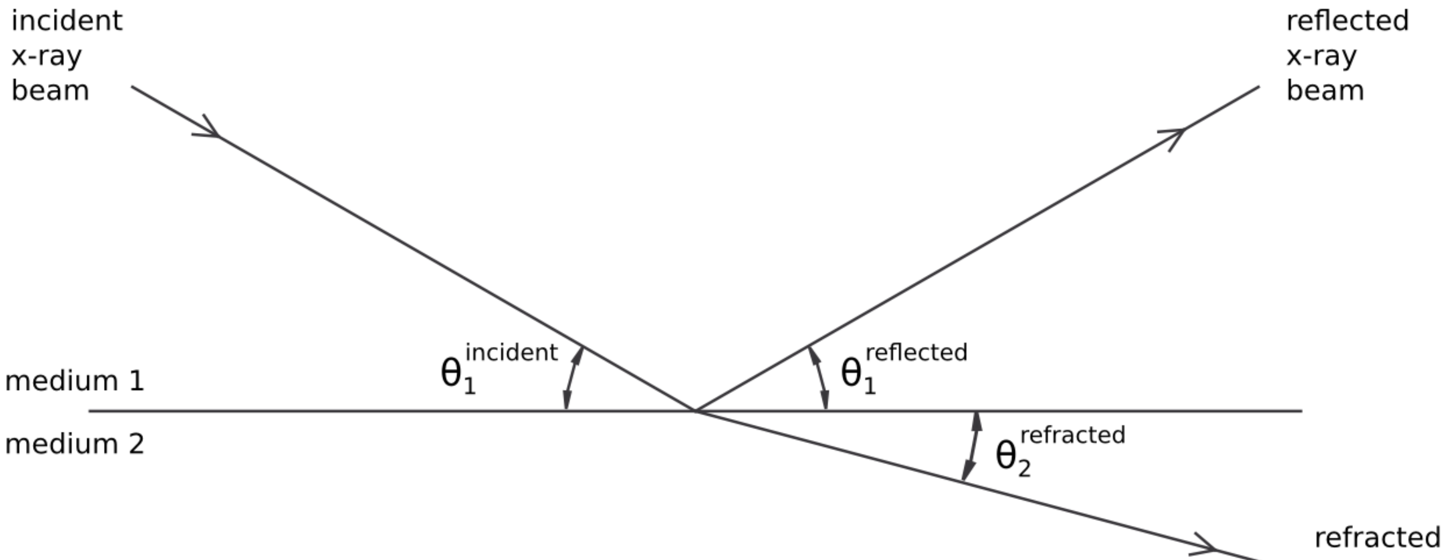
A. H. Compton,
The total Reflection of X-Rays,
Phil. Mag., 45, 1121; 1923

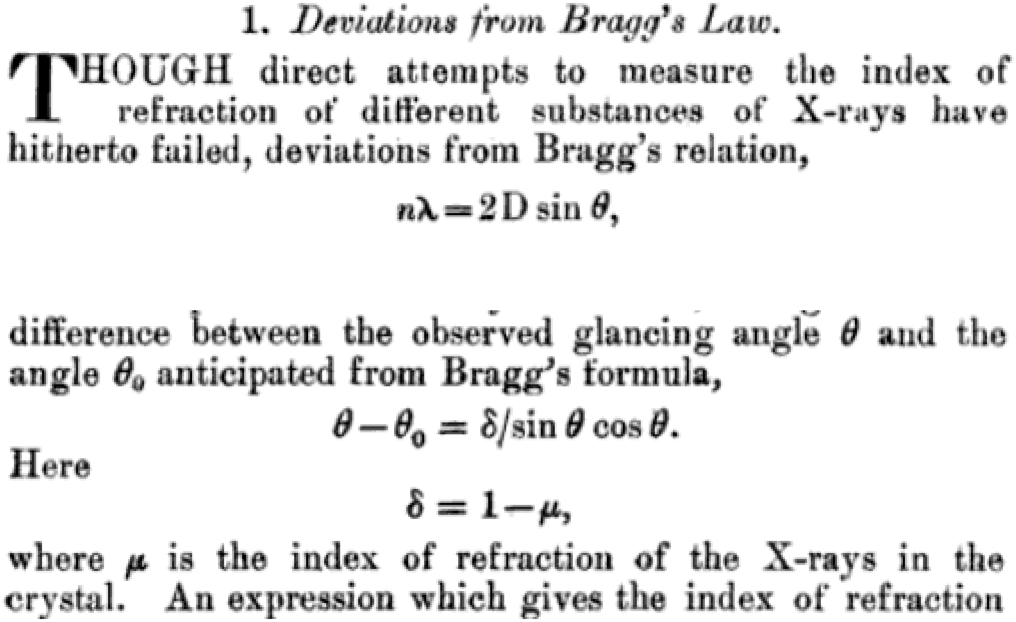


Pictures from the

Nobel Lecture,
December 12, 1927

Snell’s law – x-ray region





1. *Deviations from Bragg’s Law.*

THOUGH direct attempts to measure the index of refraction of different substances of X-rays have hitherto failed, deviations from Bragg’s relation,

$$n\lambda = 2D\sin\theta,$$

difference between the observed glancing angle θ and the angle θ_0 anticipated from Bragg’s formula,

$$\theta - \theta_0 = \delta/\sin\theta\cos\theta.$$

Here

$$\delta = 1 - \mu,$$

where μ is the index of refraction of the X-rays in the crystal. An expression which gives the index of refraction

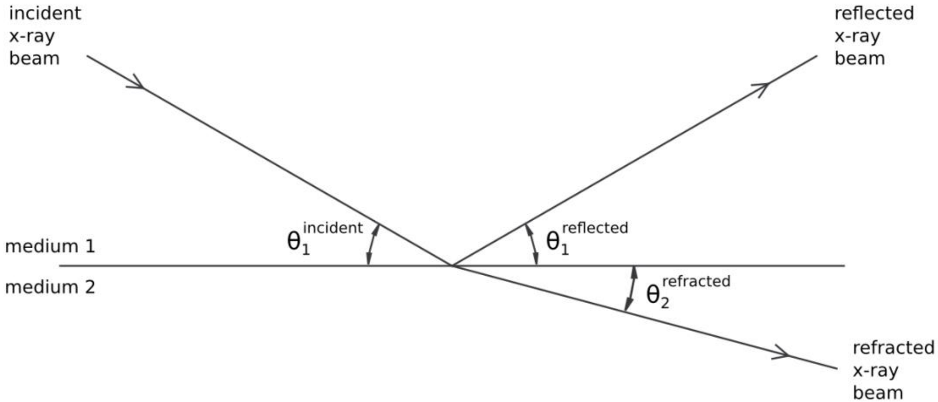
$$n < 1$$

$$n = 1 - \delta$$

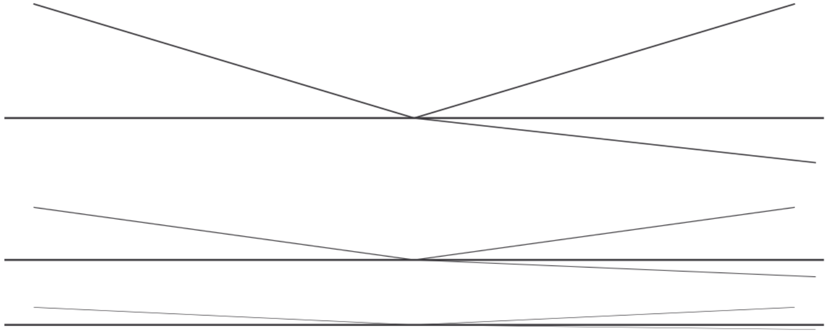
$$n_1 \cos\theta_1 = n_2 \cos\theta_2$$

$$n_1 = 1 \qquad \frac{\cos\theta_1}{\cos\theta_2} = 1 - \delta$$

Snell's law – x-ray region



$$\frac{\cos\theta_1}{\cos\theta_2} = 1 - \delta$$



$$\theta_2 = 0\ ;\quad \theta_1 = \theta_c$$

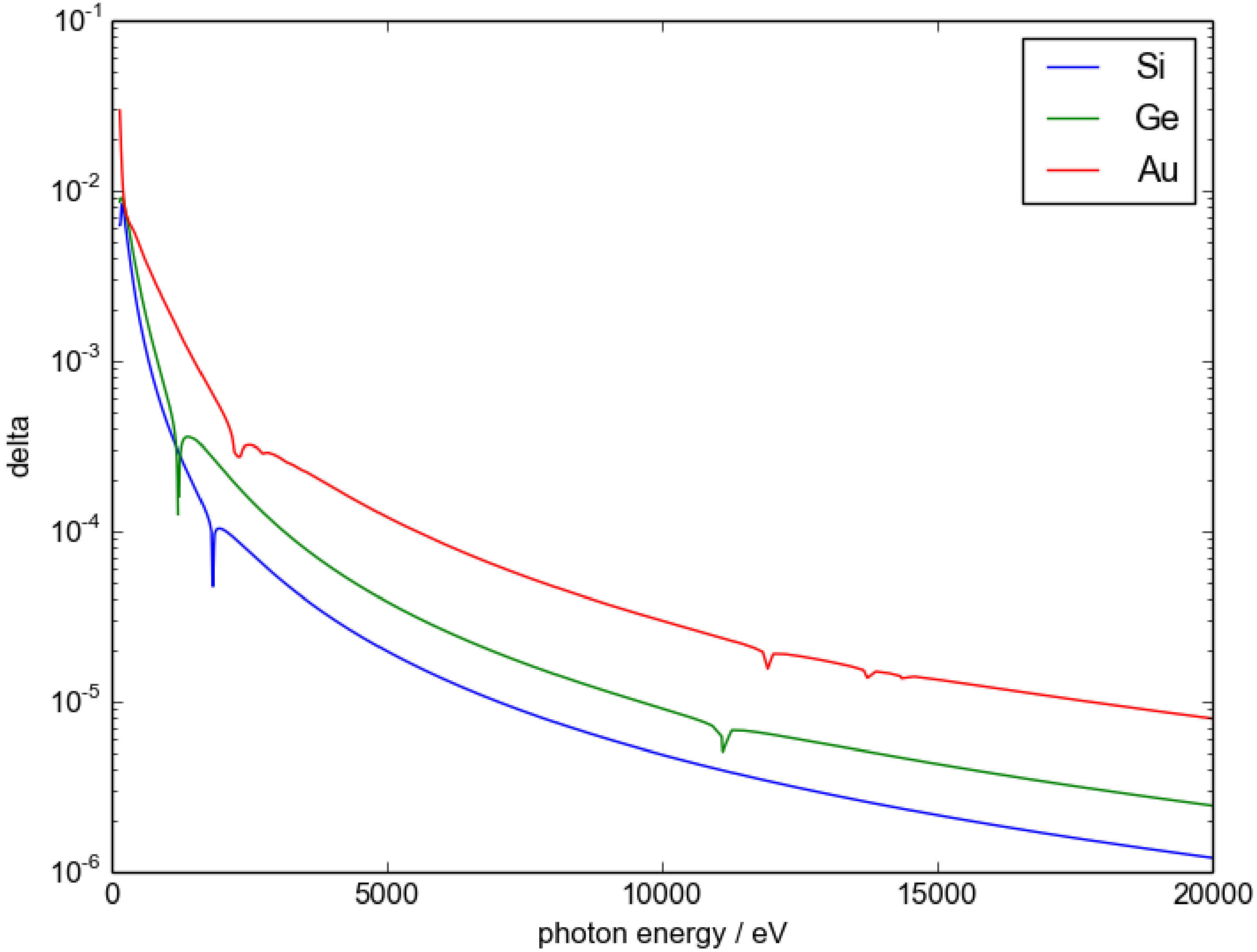
$$\cos\theta_c = 1 - \delta$$

$$\cos x_{(x_0=0)} = 1 - \frac{x^2}{2} + o(x^4)$$

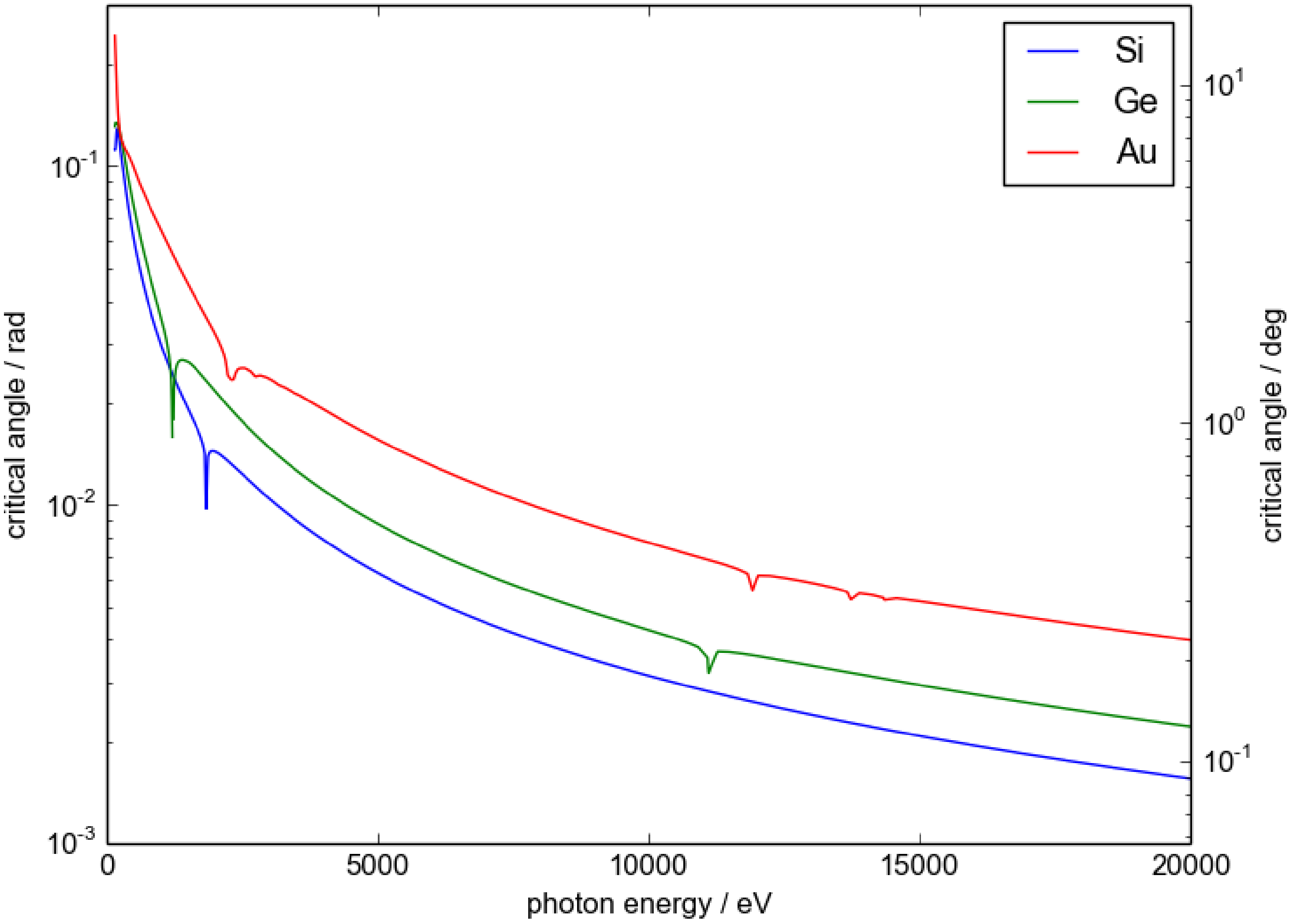
$$1 - \frac{\theta_c^2}{2} \approx 1 - \delta$$

$$\theta_c \approx \sqrt{2\delta}$$

Index of refraction – decrement - delta

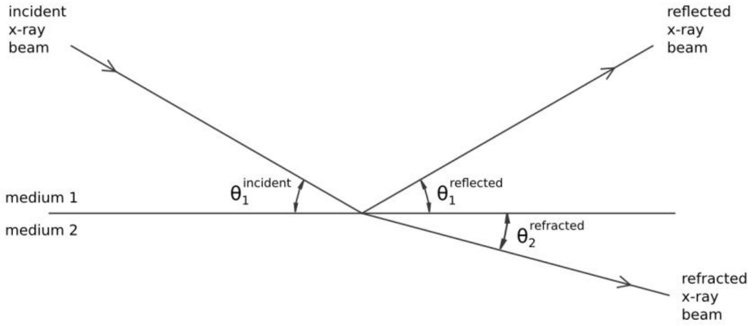


Critical angle for total reflection



Snell’s law – absorption

Beer-Lambert‘s Law:



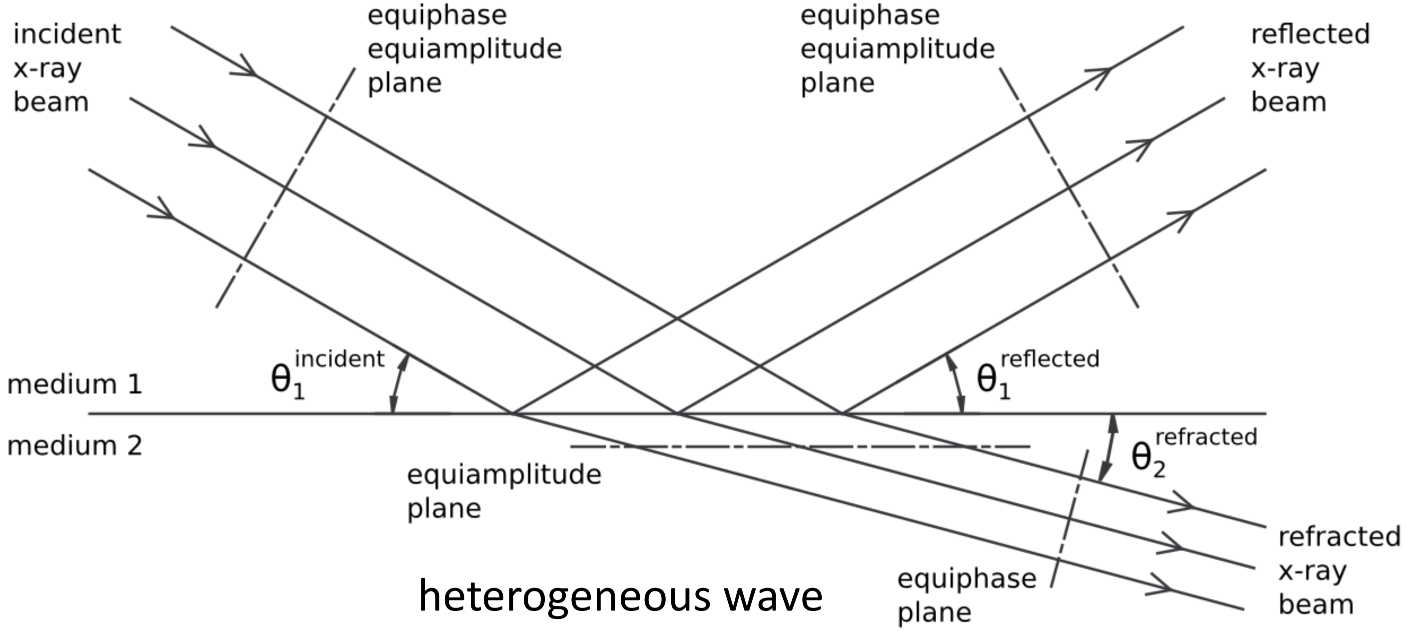
$$\hat{n} = \frac{\cos\phi_1}{\cos\phi_2} = 1 - \delta_2 - i\beta_2$$

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

Linear absorption coefficient:

$$\mu = \tau_{photoelectric} + \sigma_{elastic} + \sigma_{inelastic}$$

Snell's law – x-ray region – with absorption



heterogeneous wave

$$\hat{n} = 1 - \delta - i\beta \qquad \beta = \frac{\lambda\mu}{4\pi}$$

medium 1 is vacuum

$$\hat{n} = \frac{\cos\phi_1}{\cos\phi_2} = 1 - \delta_2 - i\beta_2$$

β is typically 2 orders of magnitude smaller than δ

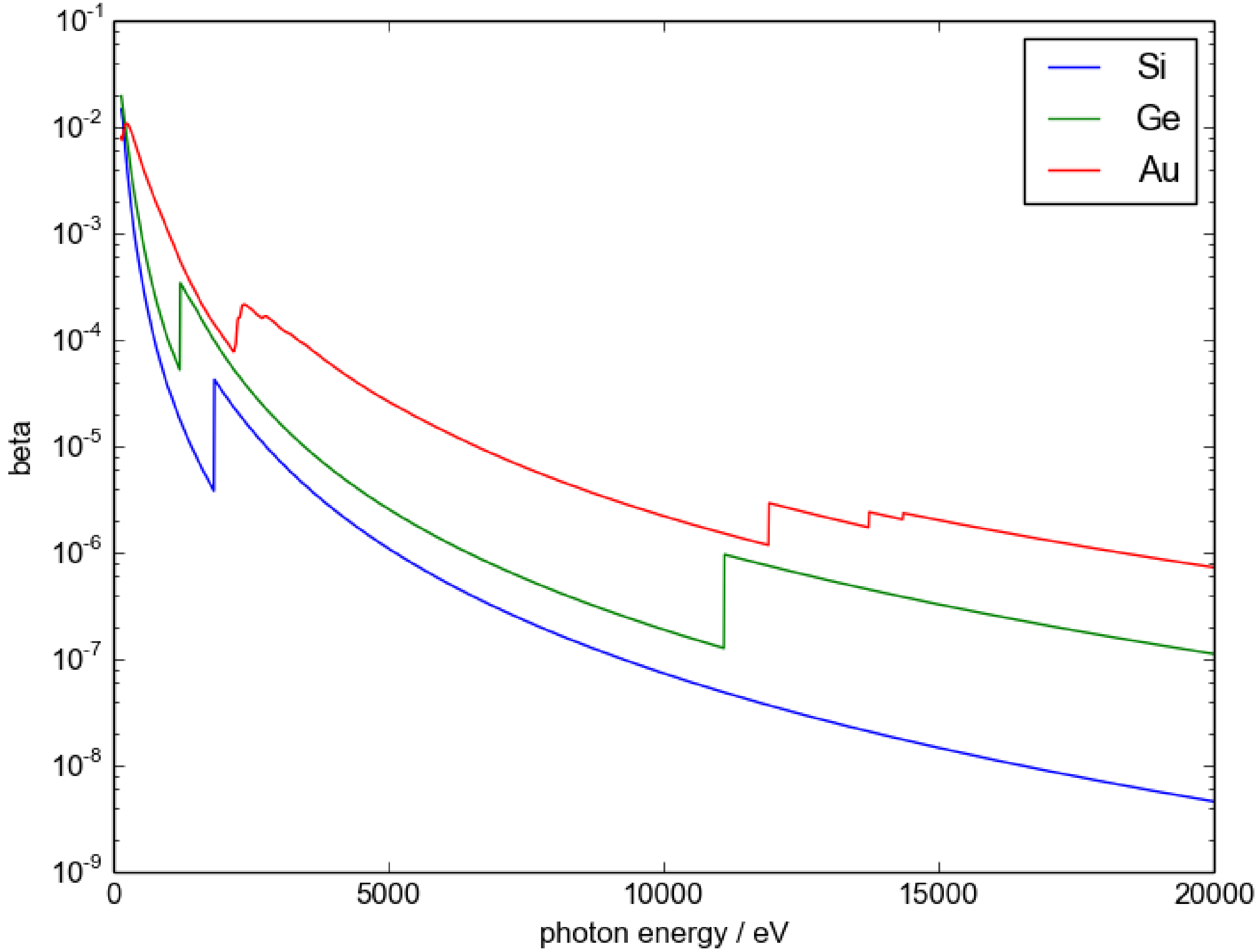
Total external reflection

$$\cos\phi_c = 1 - \delta$$

$$\phi_c \approx \sqrt{2\delta}$$

$$\cos x_{(x_0=0)} = 1 - \frac{x^2}{2} + o(x^4)$$

Beta – absorption



Atomic form factor

$$\frac{d\sigma_{el}}{d\Omega} = \frac{d\sigma_T}{d\Omega}\left|F(x,Z)\right|^2 \qquad x = \frac{\sin\frac{\theta}{2}}{\lambda}$$

$$f = f^0(x,Z) + f'(E,Z) + if''(E,Z)$$

$$\uparrow$$

$$\boxed{F(x,Z) = 4\pi\int_0^{\infty} r^2\rho(r,Z)\frac{\sin(4\pi xr)}{4\pi xr}\,dr}$$

‘anomalous’ energy dependent terms

f'' photoelectric absorption

f' corrections for photoabsorption (Kramers-Kronig dispersion)
relativistic effects, nuclear scattering

Atomic form factor (forward direction)

forward scattering factors (x = theta = q = 0)

$$f = f(0, Z, E) = f_1 + i f_2$$

$$f_2 \equiv f''$$

photoabsorption

$$\mu_a = 2 r_0 \lambda f_2$$

$$f_1 \equiv f^0(x = 0) + f'$$

f1 and f2 are directly related to the index of refraction (reflection, refraction, XRR)

$$n = 1 - \frac{1}{2\pi} N r_0 \lambda^2 (f_1 + i f_2)$$

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

$$\delta = \frac{1}{2\pi} N r_0 \lambda^2 f_1$$

$$\beta = \frac{1}{2\pi} N r_0 \lambda^2 f_2$$

Fresnel – reflected intensity

Propagating electromagnetic field

$$\nabla^2 \mathbf{E} - \frac{\epsilon\mu}{c^2}\ddot{\mathbf{E}} = 0 \qquad \nabla^2 \mathbf{H} - \frac{\epsilon\mu}{c^2}\ddot{\mathbf{H}} = 0$$

$$\mathbf{E} = \mathbf{E}_0 e^{-i(\mathbf{k}\cdot\mathbf{r}-\omega t)}$$

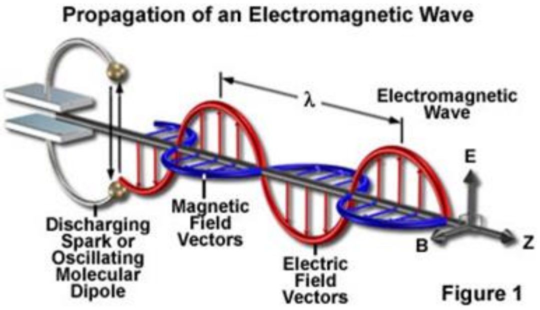


Figure 1

Photon Energy

$$E = h\nu \qquad \omega = 2\pi\nu$$

$$\mathbf{E}_1(\mathbf{r},t) = \mathbf{E}_0\, e^{i(\omega t - \mathbf{k}_1\cdot\mathbf{r})}$$

$$\mathbf{E}_1^R(\mathbf{r},t) = \mathbf{R}\, e^{i\left(\omega t - \mathbf{k}_1^R\cdot\mathbf{r}\right)}$$

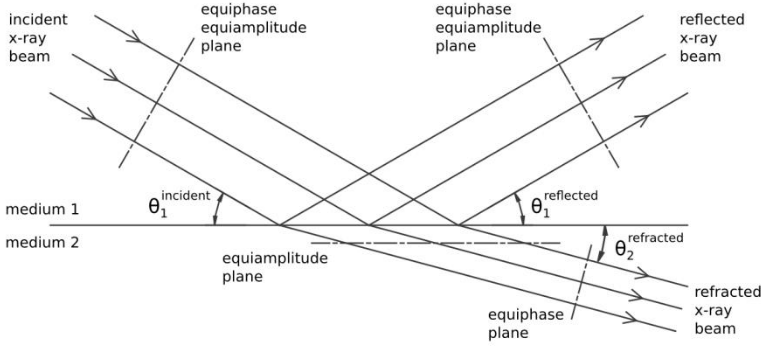
$$\mathbf{E}_2(\mathbf{r},t) = \mathbf{T}\, e^{i(\omega t - \mathbf{k}_2\cdot\mathbf{r})}$$

Energy of the electromagnetic field, number of photons

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$

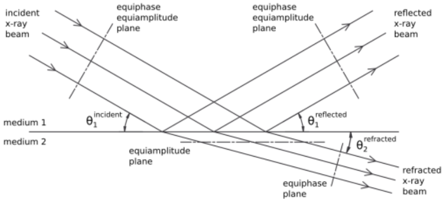
$$I_0 \doteq <\mathbf{S}> \propto |\mathbf{E}_0|^2$$

$$\mathcal{R} = \frac{|\mathbf{R}|^2}{|\mathbf{E}_0|^2}$$



Fresnel – 2 media

$\mathcal{R}^{\perp}$ Electric vector perpendicular to the plane of incidence (s, TE, polarisation)
In German senkrecht = perpendicular



$$\mathcal{R}^{\perp} = \frac{\left|R^{\perp}\right|^2}{\left|E_0^{\perp}\right|^2} = \frac{a_0^2\left(\sin\phi_1 - a_0\right)^2 + \beta^2}{a_0^2\left(\sin\phi_1 + a_0\right)^2 + \beta^2}$$

$$\hat{n} = 1 - \delta - i\beta$$

Approximations
(ignore quadratic terms):

$$\hat{n}^2 \simeq 1 - 2\delta - 2\beta$$

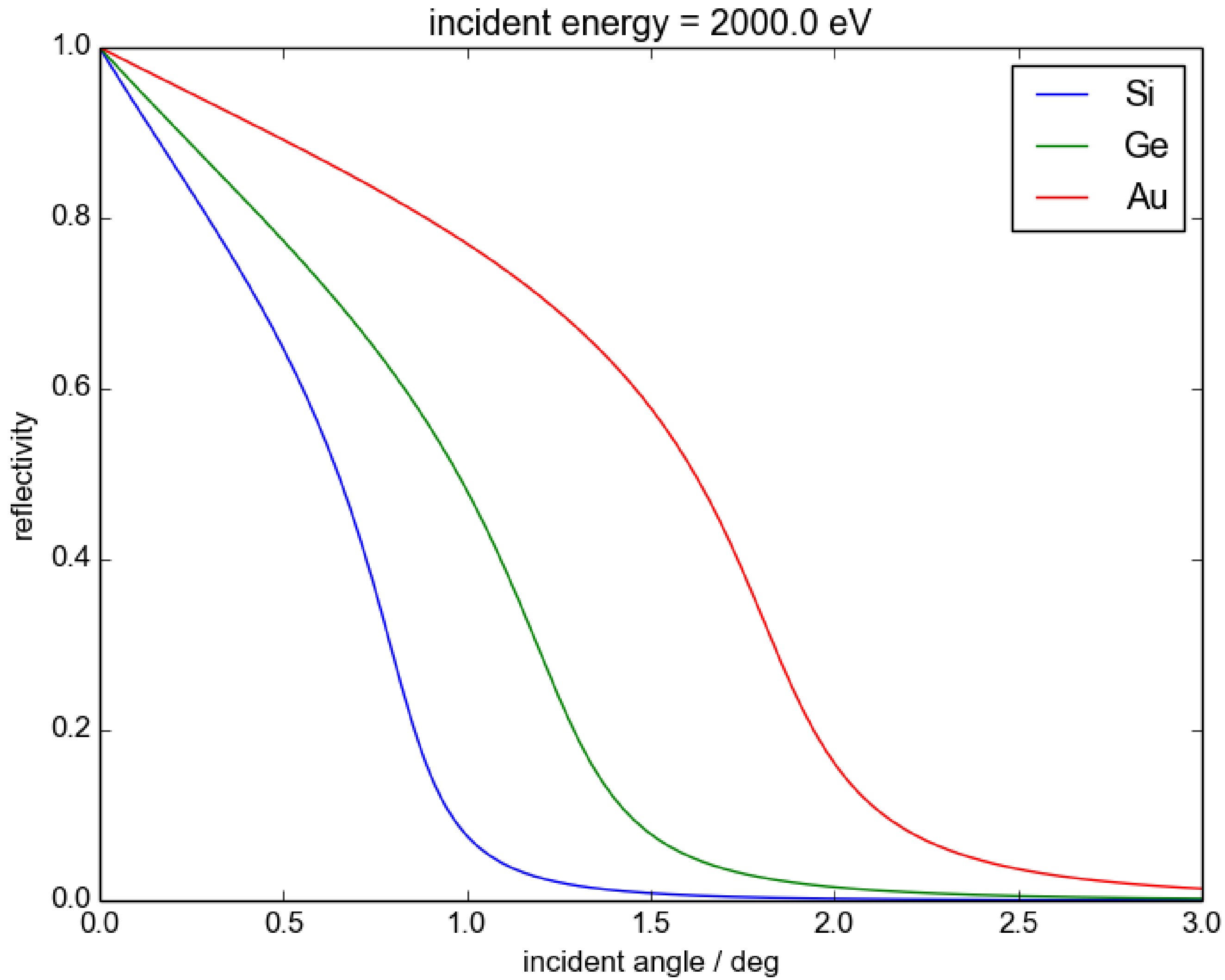
$$\phi_2 = \arctan(a_0)$$

$$a_0 = \sqrt{\frac{1}{2}\sqrt{\left(\phi_1^2 - 2\delta\right)^2 + 4\beta^2} - \left(\phi_1^2 - 2\delta\right)}$$

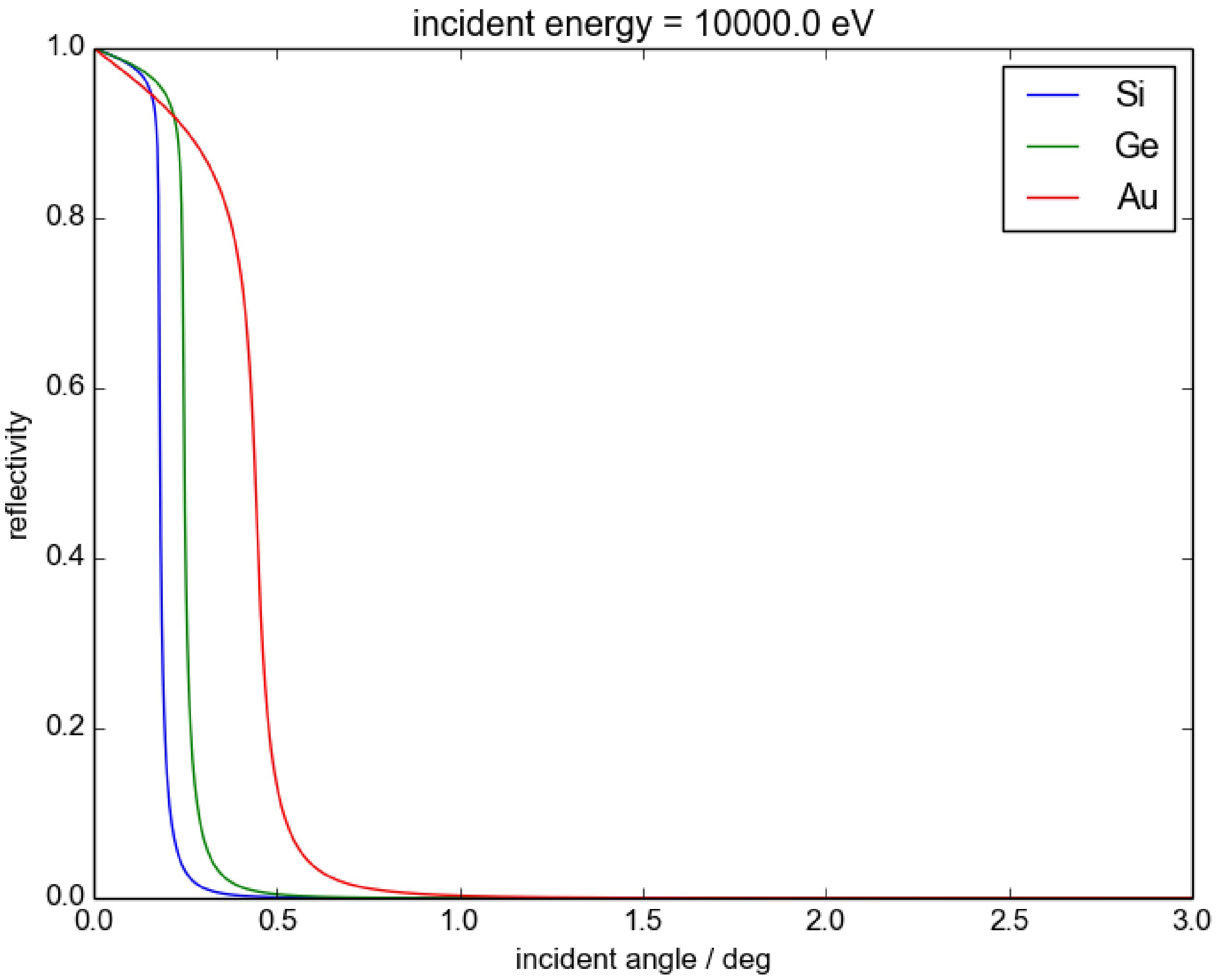
Same formalism as
for XRR
X-Ray Reflectivity

$$\mathcal{R}^{\parallel} = \frac{\left|R^{\parallel}\right|^2}{\left|E_0^{\parallel}\right|^2} = \frac{\left(\sin\phi_1 - 2\delta\sin\phi_1 - a_0\right)^2 + \left(2\beta\sin\phi_1 - b_0\right)^2}{\left(\sin\phi_1 - 2\delta\sin\phi_1 + a_0\right)^2 + \left(2\beta\sin\phi_1 + b_0\right)^2}$$

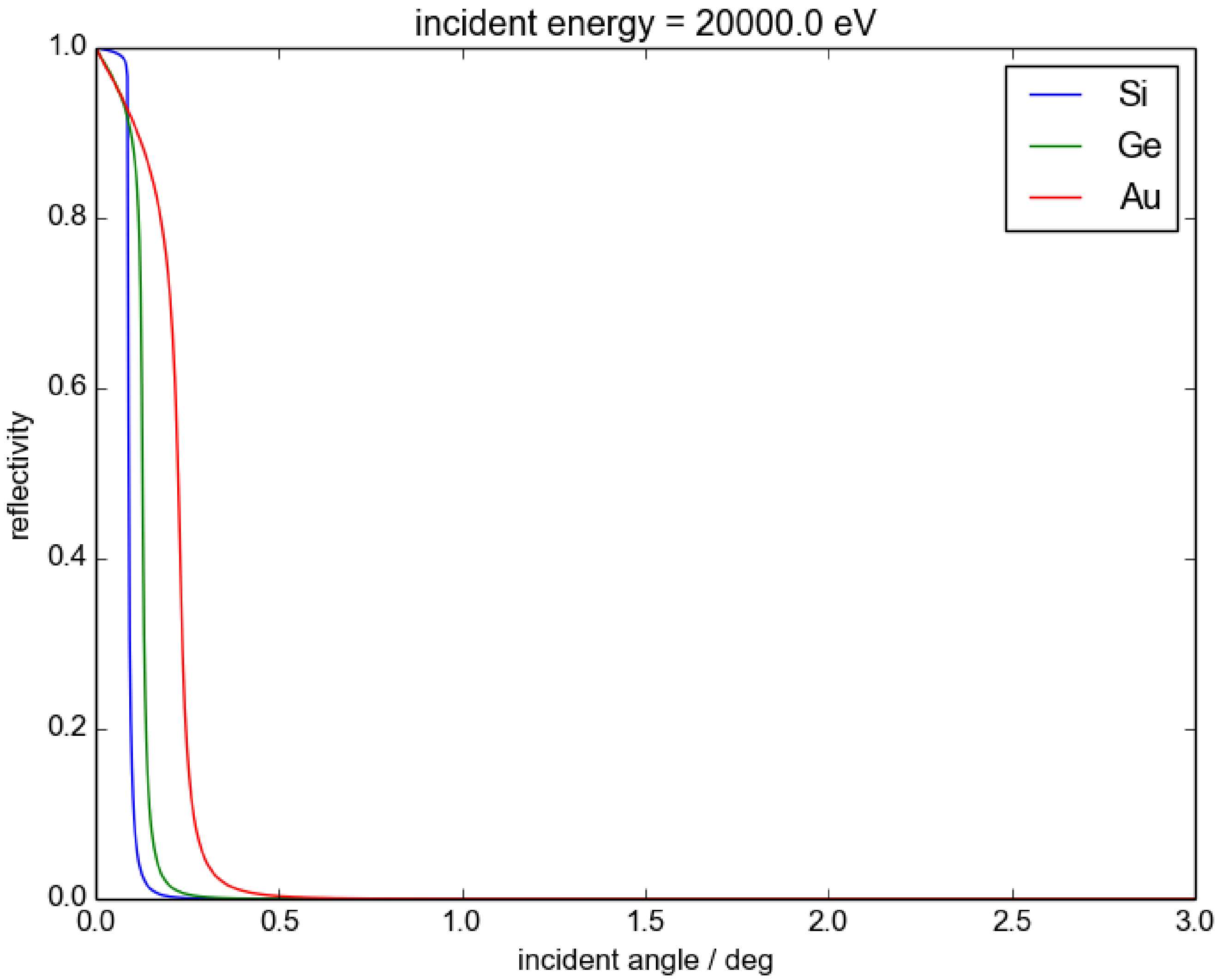
Reflectivity



Reflectivity



Reflectivity



Fresnel – x-ray region – exact

$\hat{\epsilon} = 1 - \alpha - i\gamma$ Complex dielectric constant

$$n = \sqrt{\epsilon} \;\Rightarrow\; 1 - \alpha - i\gamma = \left(1 - \delta - i\beta\right)^2$$

$$\alpha = 2\delta - \delta^2 + \beta^2$$

$$\gamma = 2\left(1 - \delta\right)\beta$$

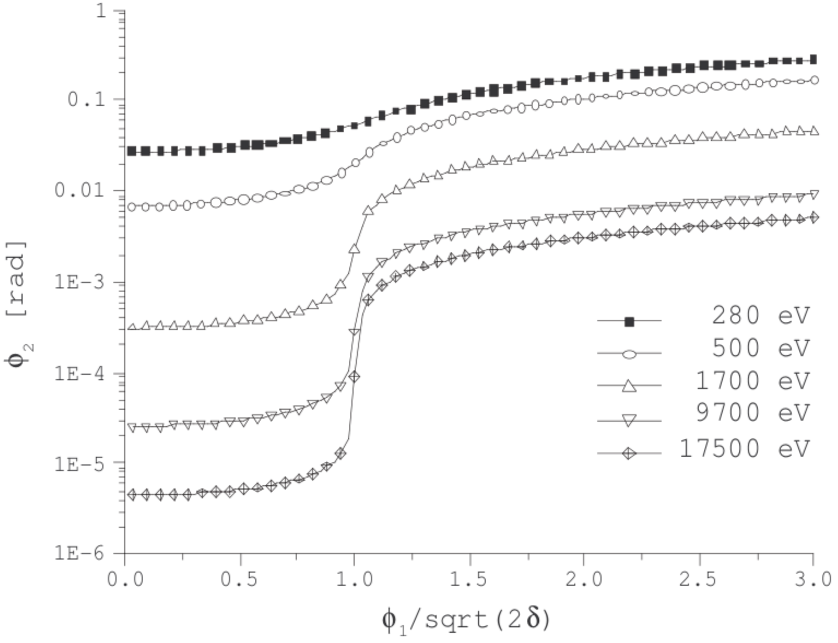
$$\mathcal{R}^{\perp} = \frac{4a^2\left(\sin\phi - a\right)^2 + \gamma^2}{4a^2\left(\sin\phi + a\right)^2 + \gamma^2} \qquad \phi_2^{\perp} = \arcsin\frac{a}{\sqrt{\cos^2\phi + a^2}}$$

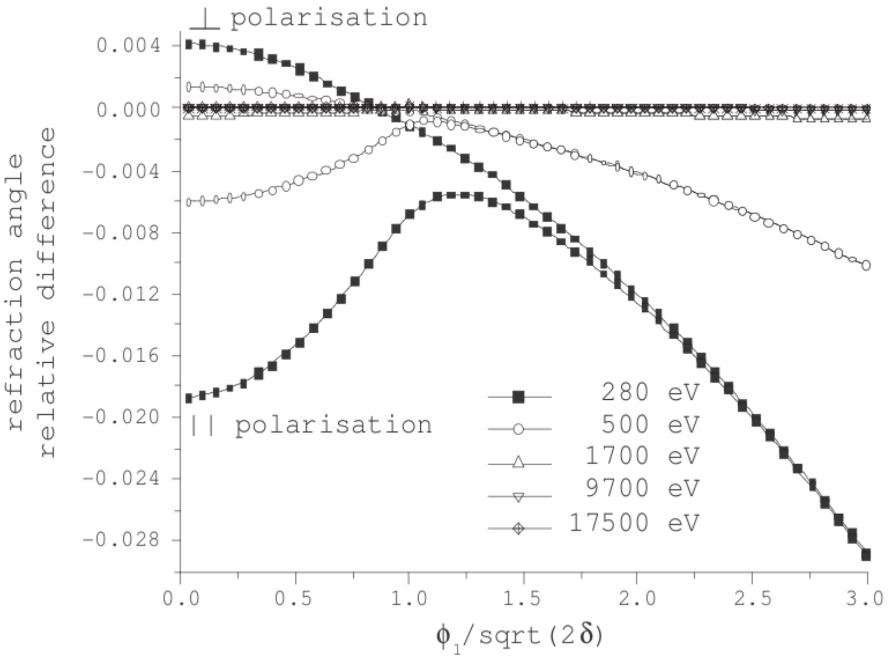
$$a = \sqrt{\frac{1}{2}\left\{\sin^2\phi_1 - \alpha + \sqrt{\left(\sin^2\phi_1 - \alpha\right)^2 + \gamma^2}\right\}}$$

B.L. Henke, Phys. Rev. A, 6, 1, (1972)
M.-R. Lefévère, M. Montel, Opt. Acta 20, 97 (1973)

Fresnel – approximated vs exact - angle of refraction

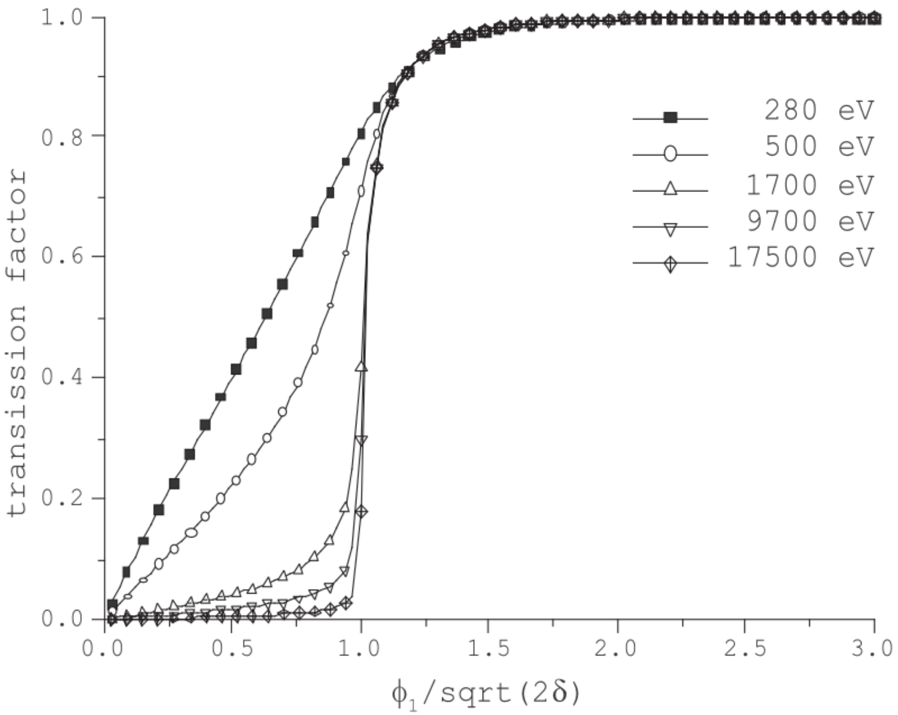
$$\mathcal{A}^{relative}_{difference} = \frac{\mathcal{A}^{approximated} - \mathcal{A}^{exact}}{\mathcal{A}^{approximated}}$$

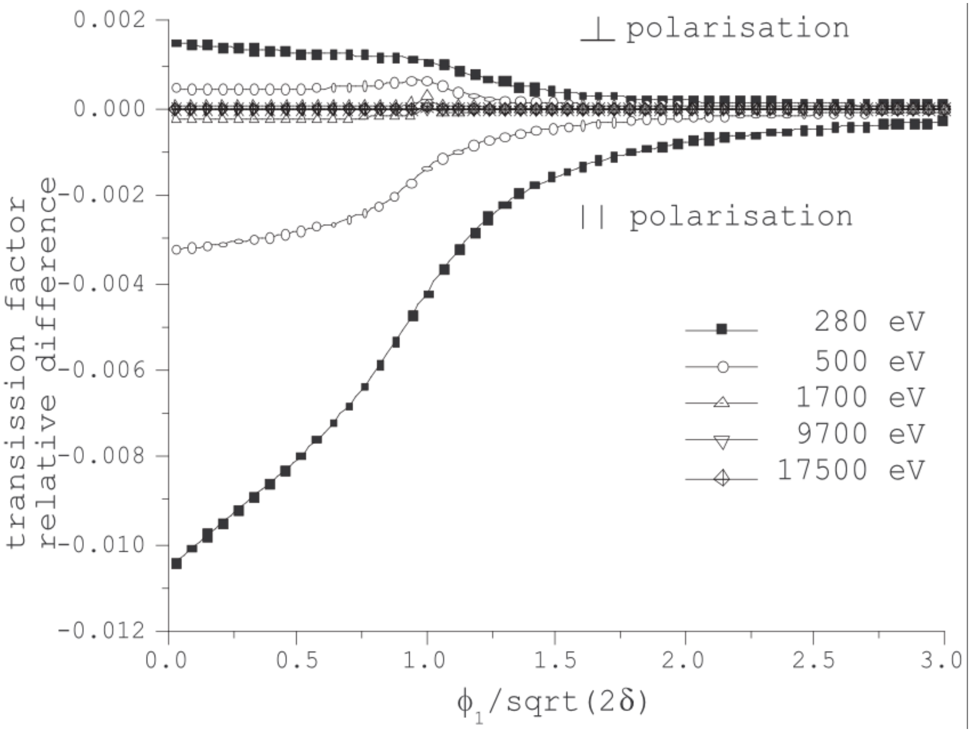




Fresnel – approximated vs exact - transmission

$$\mathcal{A}^{\substack{relative\\difference}} = \frac{\mathcal{A}^{approximated} - \mathcal{A}^{exact}}{\mathcal{A}^{approximated}}$$

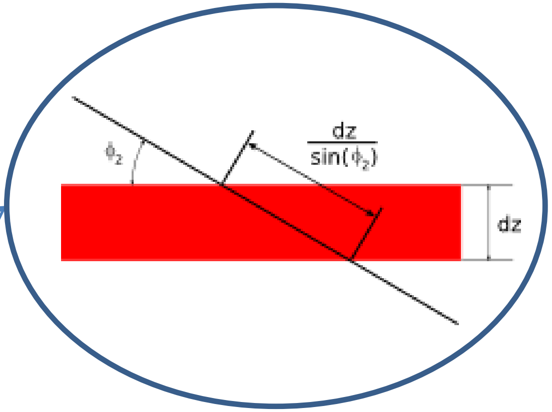


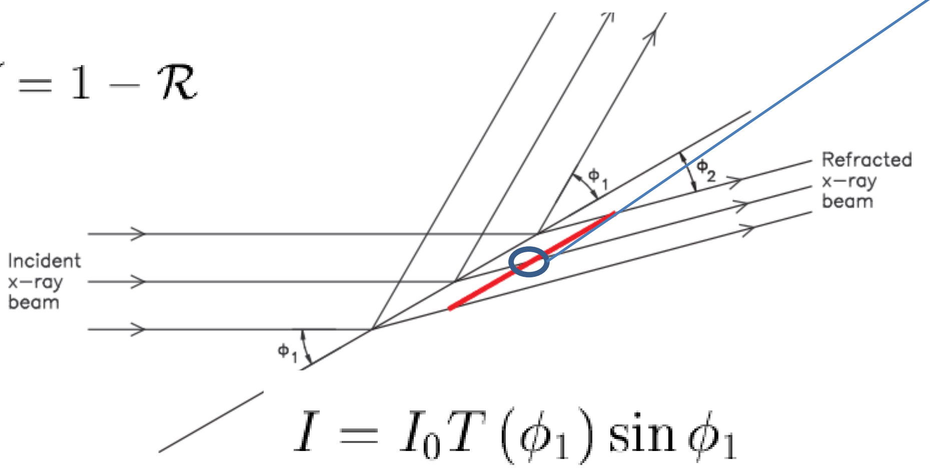


GIXRF - intensity calculation – 1 interface – thin layer

$$\mathcal{R}^{\perp} = \frac{\left|R^{\perp}\right|^2}{\left|E_0^{\perp}\right|^2} = \frac{a_0^2\left(\sin\phi_1 - a_0\right)^2 + \beta^2}{a_0^2\left(\sin\phi_1 + a_0\right)^2 + \beta^2}$$

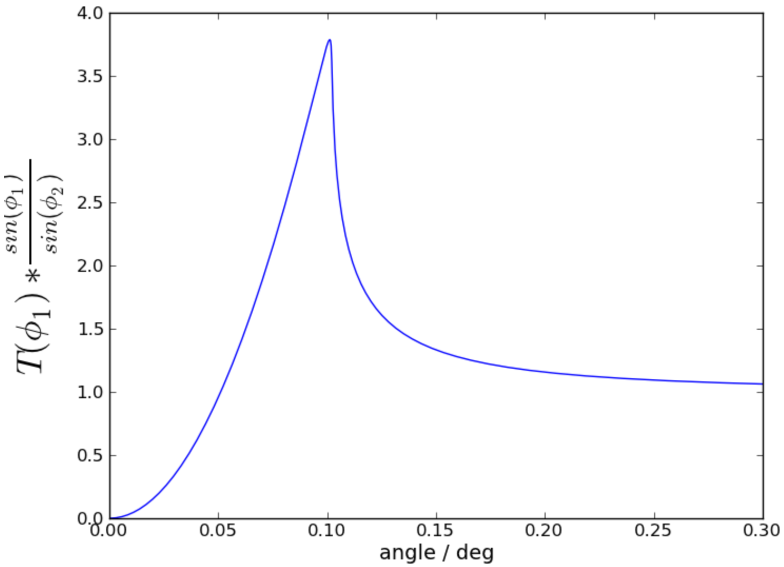
$$\mathcal{T} = 1 - \mathcal{R}$$





$$I_{abs} = I\left(z\right)T\left(\phi_1\right)\sin\phi_1 \frac{\mathcal{T}_s}{\sin\phi_2}dz$$

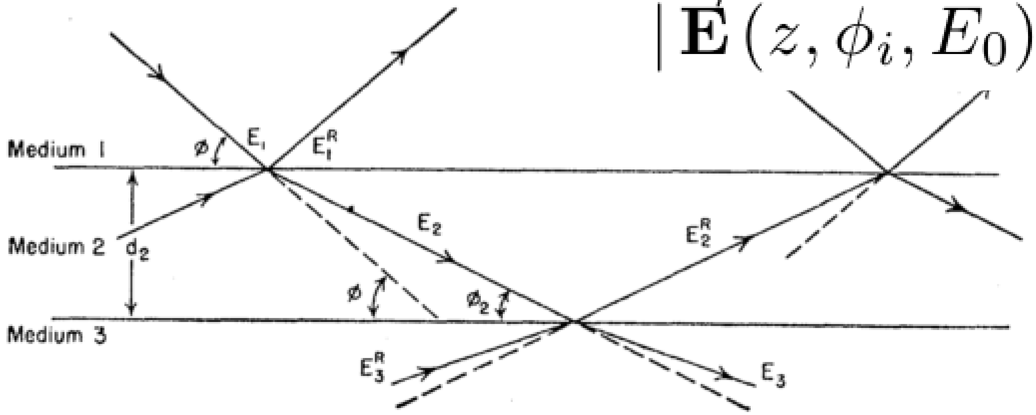
$$I = I_0 T\left(\phi_1\right)\sin\phi_1$$



P. Kregsamer, (1991), Spectrochimica Acta Part B, 46(10), 1332–1340. (1991)

Multiple layers

$$|\overrightarrow{\mathbf{E}}(z,\phi_i,E_0)|^2$$



L. Parratt, Physical Review, 95(2), 359–369, 1954

$$a_{n-1}E_{n-1}+a_{n-1}^{-1}E_{n-1}^{R}=a_n^{-1}E_n+a_nE_n^{R}, \qquad (5)$$

$$(a_{n-1}E_{n-1}-a_{n-1}^{-1}E_{n-1}^{R})f_{n-1}k_1 = (a_n^{-1}E_n-a_nE_n^{R})f_nk_1, \qquad (6)$$

where the amplitude factor a_n for *half* the perpendicular depth d_n is, from Eq. (2),

$$a_n=\exp\left(-ik_1f_n\frac{d_n}{2}\right)=\exp\left(-i\frac{\pi}{\lambda}f_nd_n\right). \qquad (7)$$

$$R_{n-1,\,n}=a_{n-1}^{4}\left[\frac{R_{n,\,n+1}+F_{n-1,\,n}}{R_{n,\,n+1}F_{n-1,\,n}+1}\right],$$

where

$$R_{n,\,n+1}=a_n^{2}(E_n^{R}/E_n)$$

and

$$F_{n-1,\,n}=\frac{f_{n-1}-f_n}{f_{n-1}+f_n}.$$

X-Ray Reflectivity
(but GIXRF also “given”)

In the optical range:
F. Abeles, Le Journal de Physique et le Radium, "La théorie générale des couches minces", 11, 307–310 (1950)
Recursive transfer matrix method, used also for XRR

Multiple layers

PHYSICAL REVIEW B VOLUME 44, NUMBER 2 1 JULY 1991-II

Glancing-incidence x-ray fluorescence of layered materials

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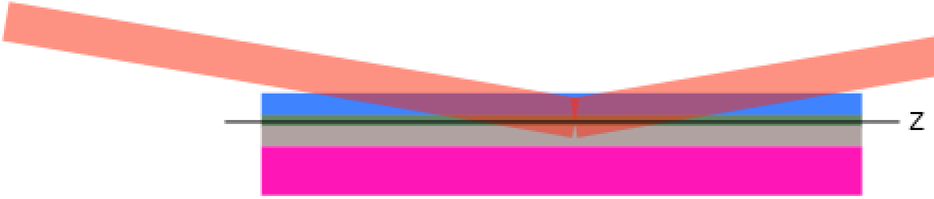
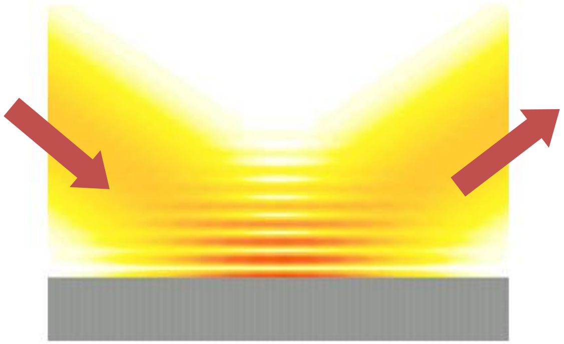
(Received 2 January 1991)



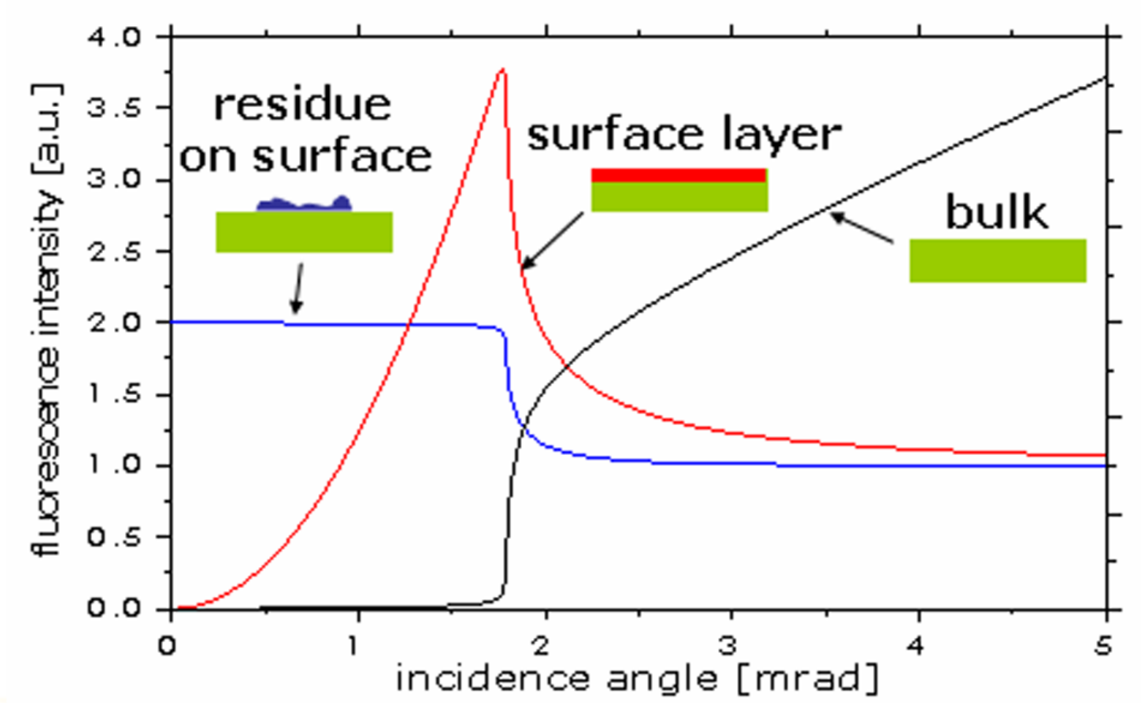
$$-\frac{\partial P_{jz}}{\partial z}=\frac{1}{2Z_0}\frac{4\pi}{\lambda}N'_{jz}N''_{jz}\left\{|E_j^t|^2\exp\left[-\frac{4\pi N''_{jz}z}{\lambda}\right]+|E_j^r|^2\exp\left[\frac{4\pi N''_{jz}z}{\lambda}\right]+\left[E_j^{t*}E_j^r\exp\left[\frac{4\pi i N'_{jz}z}{\lambda}\right]+\text{c.c.}\right]\right\}. \qquad (24)$$

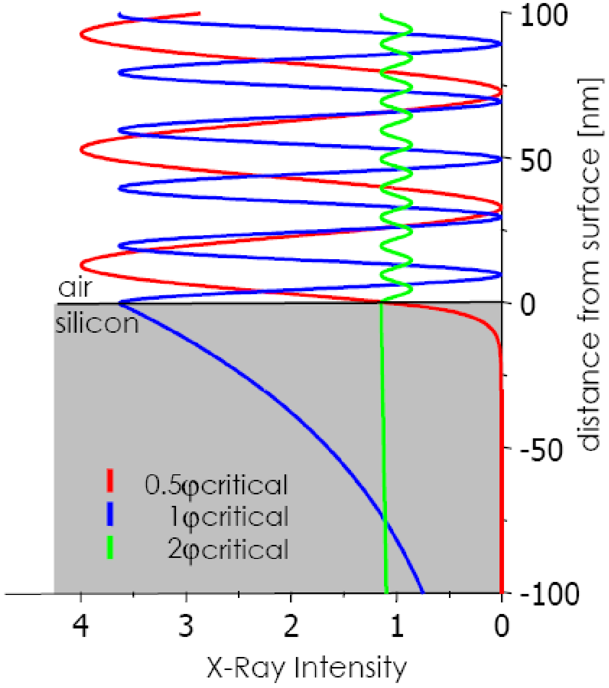
$$I_{aj}=\frac{\lambda}{hc}C_{aj}\frac{\tau_{a\lambda}}{\mu_{j\lambda}/\rho_j}J_{a\lambda}w_a g_a\exp\left[-\sum_{n=1}^{j-1}\frac{\mu_{na}d_n}{\sin\psi_d}\right]\times\int_0^{d_j}dz\left[-\frac{\partial P_{jz}}{\partial z}\right]\exp\left[-\frac{\mu_{ja}z}{\sin\psi_d}\right],$$

Total reflection, OK, but practically?



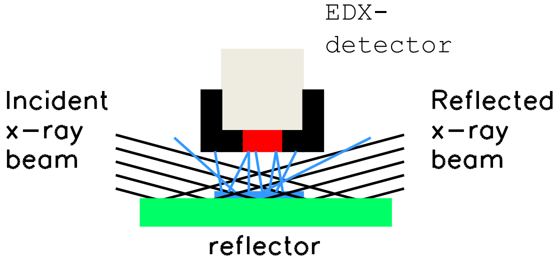
The interference of incident and reflected beam causes a standing wave field above the reflectors surface.





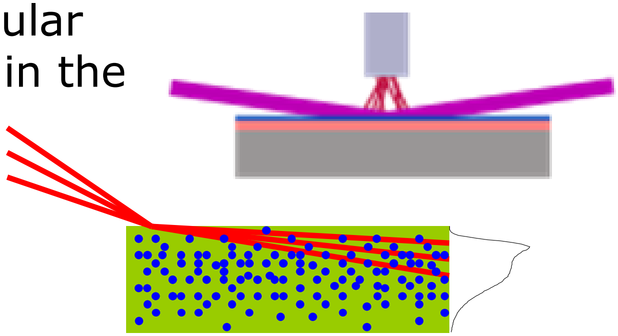
Intensity distribution as a function of incident angle and depth

Total reflection, OK, but practically?

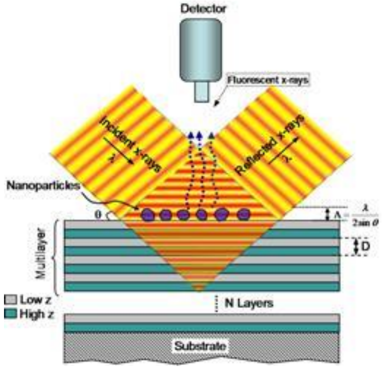


TXRF – analysis of surface contamination
analysis of materials deposited on flat reflecting surface

GIXRF – get “positional-structural” (as well as chemical) information through the angular dependence of fluorescence in the grazing incidence region:
above-below surface
film-like, particle-like
particle size
layered samples



XSW – standing wave field created by interference of incident and Bragg reflected field
but also the study of crystalline like “super-structures” (e.g. Langmuir-Blodgett films)



Quantitative analysis

Empirical
methods

PROS
No physical model needed

CONS
Need of SPECIFIC standard samples
One calibration per experimental condition

APPLICATION
Good for monitoring very similar samples

First principles /
fundamental parameters
- deterministic
- Monte Carlo

PROS
NON SPECIFIC standard samples
used to evaluate model parameters
One calibration per experimental condition

CONS
Need a physical model to simulate results

APPLICATION
Good if samples keep changing

Quantitative analysis

First principles /
fundamental parameters
- deterministic
- Monte Carlo

PROS
NON SPECIFIC standard samples
used to evaluate model parameters
One calibration per experimental condition

CONS
Need a physical model to simulate results

APPLICATION
Good if samples keep changing

Describe/model

- source
- detector (efficiency)
- sample

Interactions:
- scattering
- photoelectric absorption
- fluorescence/auger

Fundamental Parameters

Quantitative analysis

First principles /
fundamental parameters
- deterministic
- Monte Carlo

PROS
NON SPECIFIC standard samples
used to evaluate model parameters
One calibration per experimental condition

CONS
Need a physical model to simulate results

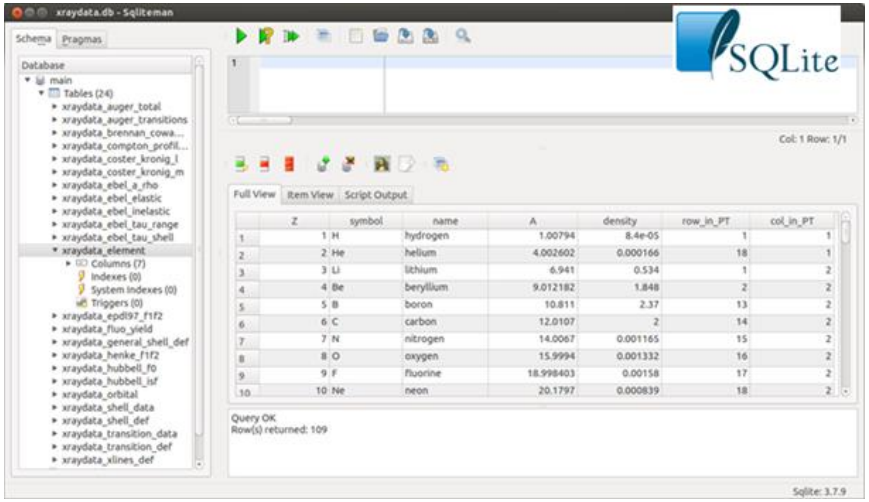
APPLICATION
Good if samples keep changing

Peak intensity
Extraction
Intensity
simulation/comparison/fitting

Spectrum (spectra)
simulation/comparison/fitting

Fundamental parameters

https://data-minalab.fbk.eu/txrf/xraydata/



	Z	symbol	name	A	density	row_in_PT	col_in_PT
1	1	H	hydrogen	1.00794	8.4e-05	1	1
2	2	He	helium	4.002602	0.000166	18	1
3	3	Li	lithium	6.941	0.534	1	2
4	4	Be	beryllium	9.012182	1.848	2	2
5	5	B	boron	10.811	2.37	13	2
6	6	C	carbon	12.0107	2	14	2
7	7	N	nitrogen	14.0067	0.001165	15	2
8	8	O	oxygen	15.9994	0.001332	16	2
9	9	F	fluorine	18.998403	0.00158	17	2
10	10	Ne	neon	20.1797	0.000839	18	2

```
Query OK
Row(s) returned: 109
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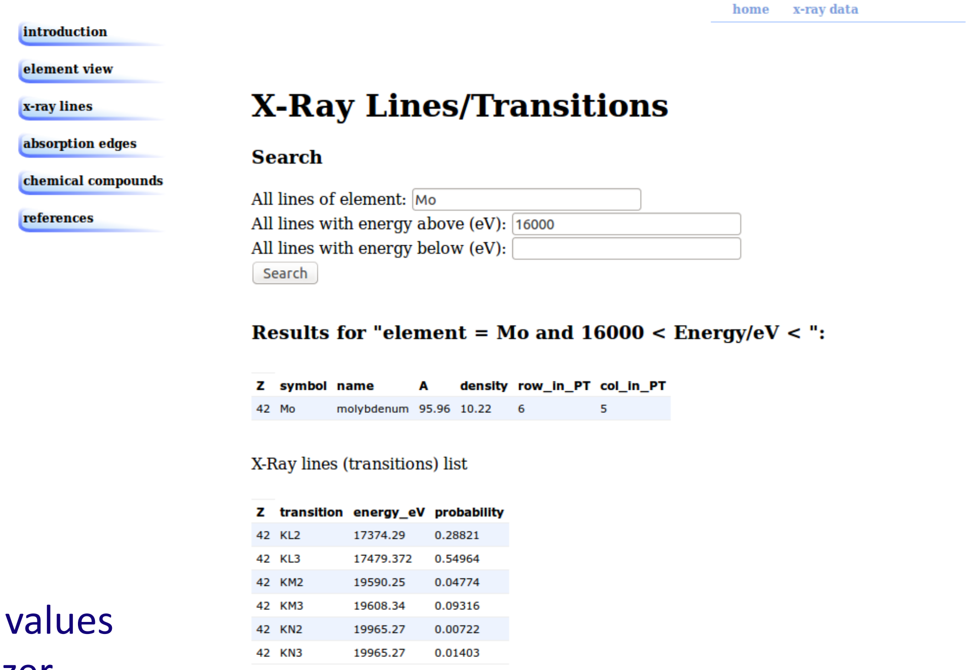


X-Ray Lines/Transitions

Search

All lines of element: Mo
All lines with energy above (eV): 16000
All lines with energy below (eV):

Results for "element = Mo and 16000 < Energy/eV < ":

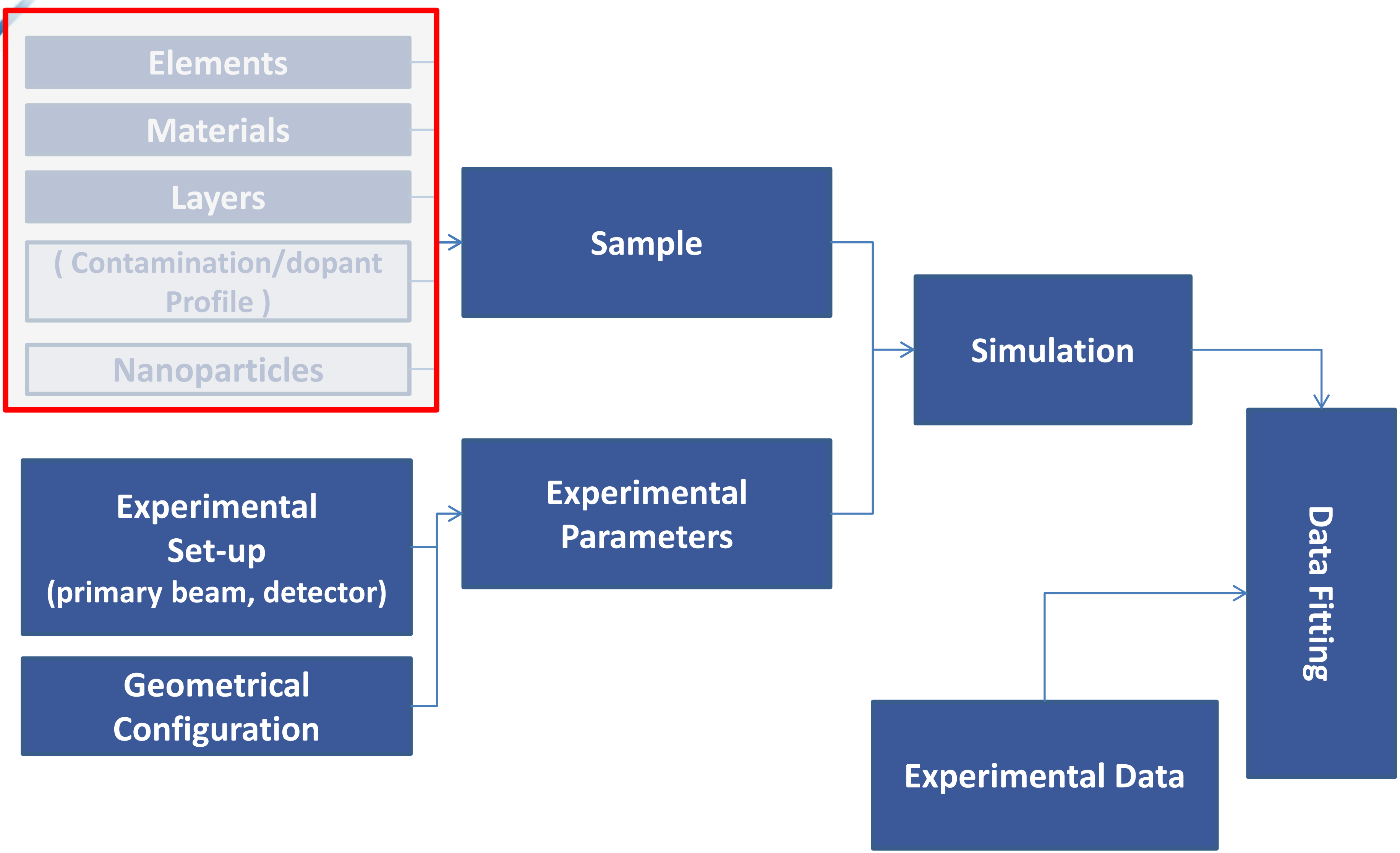
Z	symbol	name	A	density	row_in_PT	col_in_PT
42	Mo	molybdenum	95.96	10.22	6	5

X-Ray lines (transitions) list

Z	transition	energy_eV	probability
42	KL2	17374.29	0.28821
42	KL3	17479.372	0.54964
42	KM2	19590.25	0.04774
42	KM3	19608.34	0.09316
42	KN2	19965.27	0.00722
42	KN3	19965.27	0.01403

- **Standard Atomic Weight:** IUPAC recommended values
- **Elemental densities:** J. H. Hubbell and S. M. Seltzer
- **Electron binding energies, Edge Jump, X-Ray lines, Transition probabilities, Fluorescence yield, Cascade effect**: xraylib, T. Schoonjans et al.
- **Atomic energy level widths:** J. L. Campbell, T. Papp
- **Fluorescence yield, Coster-Kronig probabilities:** M. O. Krause
- **Atomic scattering factors (150eV-30000eV):** B. L. Henke et al.
- **Atomic scattering factors (30000eV - 300000 eV)**: S. Brennan et al.
- **Phoelectric (shell-specific and total), elastic and inelastic scattering cross sections:** H.Ebel et al.

Fundamental parameters



Elements

Materials

Layers

(Contamination/dopant Profile)

Nanoparticles

Sample

Simulation

Experimental Set-up (primary beam, detector)

Geometrical Configuration

Experimental Parameters

Data Fitting

Experimental Data

Fundamental parameters

Elements

Materials

Layers

(Contamination/dopant Profile)

Nanoparticles

In XRF:
Cross sections are tabulated in cm^2/g
For single elements

$$\left(\frac{\tau}{\rho}\right)_{sample} = \sum_{\varsigma} W_{\varsigma} \left(\frac{\tau}{\rho}\right)_{\varsigma}$$

$$(\tau)_{\varsigma} = \left(\frac{\tau}{\rho}\right)_{\varsigma} W_{\varsigma}\, \rho_s$$

To define a material in XRF you must provide:
Weight fractions and density

In XRD:
you just need the phase parameters

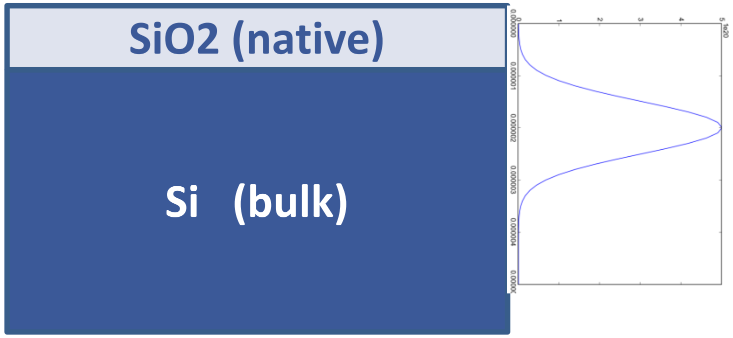
Phases

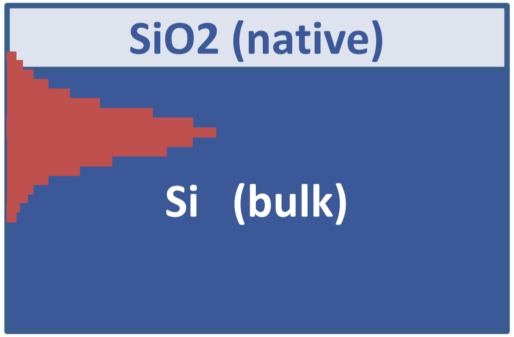
Layers

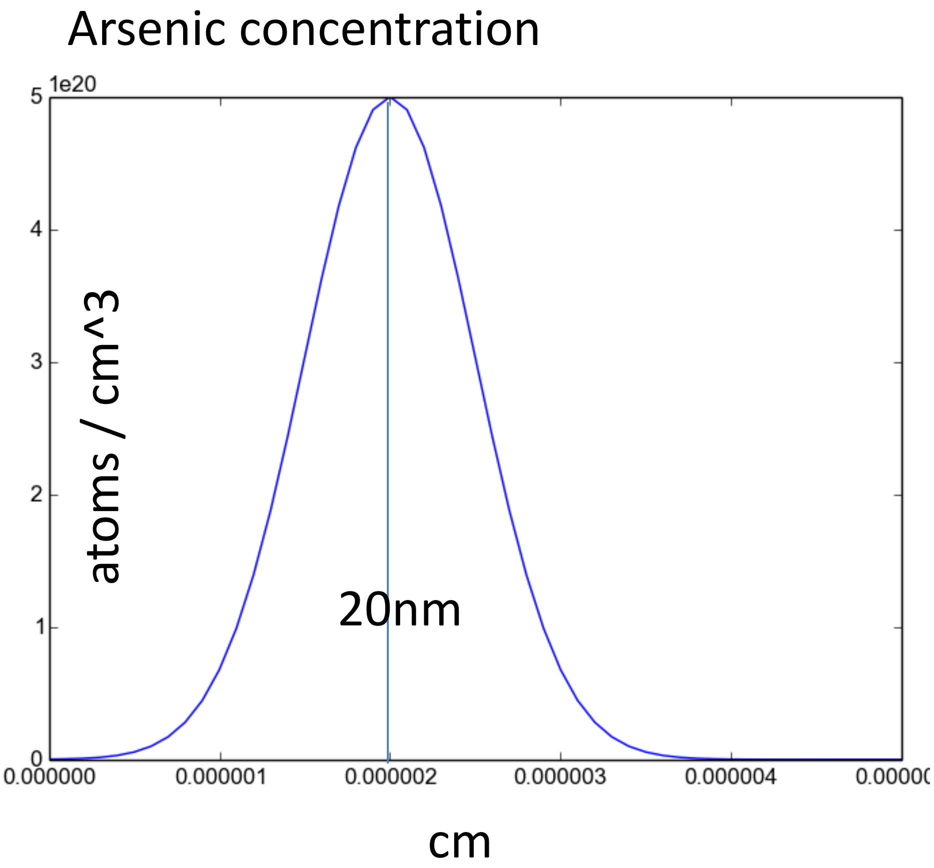
(Contamination/dopant Profile)

Nanoparticles

Example : doped silicon surface







GIXRF quantitative analysis

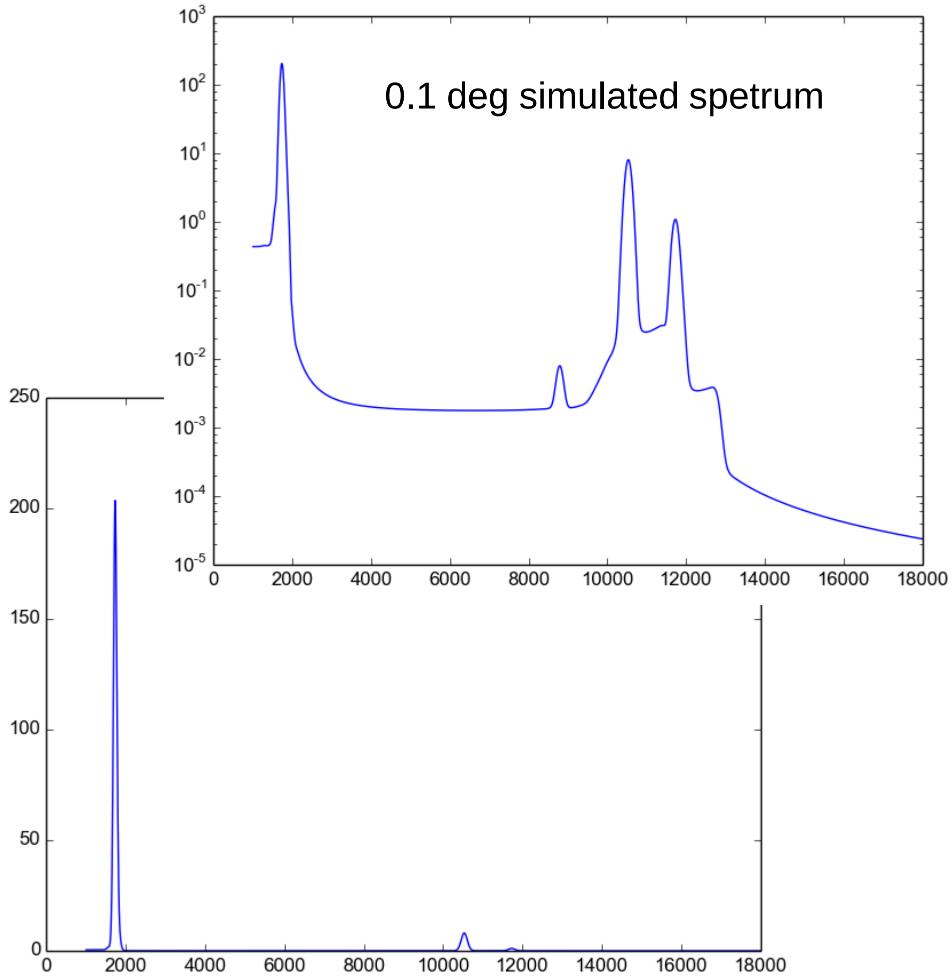
$$dI_{\zeta jk} \propto \overbrace{e^{-\mu_{s,E_0}\frac{z}{\sin\phi_i}}}^{1.}\ \overbrace{W_\zeta\left(\frac{\tau_j}{\rho}\right)_{\zeta_{E_0}} \rho_s dz}^{2.}\ \cdot$$

$$\cdot\ \underbrace{\omega_{\zeta j}}_{3.}\ \underbrace{p_{\zeta jk}}_{4.}\ \underbrace{e^{-\mu_{s,E_{\zeta jk}}\frac{z}{\sin\phi_f}}}_{5.}\ \underbrace{\epsilon_{E_{\zeta jk}}}_{6.}$$

$$\int dI(z)dz = \sum_{all\,layers} I_l$$

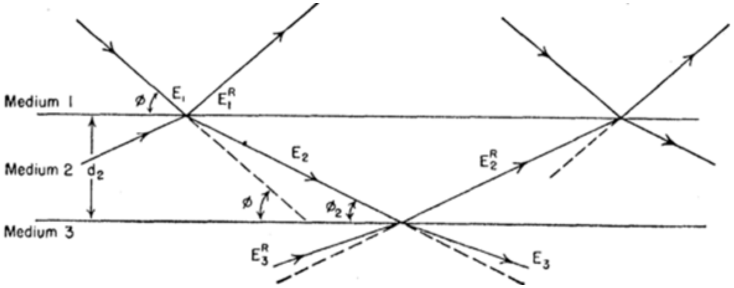
$$I_{\zeta jk\,layer} \propto W_\zeta\left(\frac{\tau_j}{\rho}\right)_{\zeta_E} \rho_s\ \omega_{\zeta j} p_{\zeta jk}\ \cdot$$

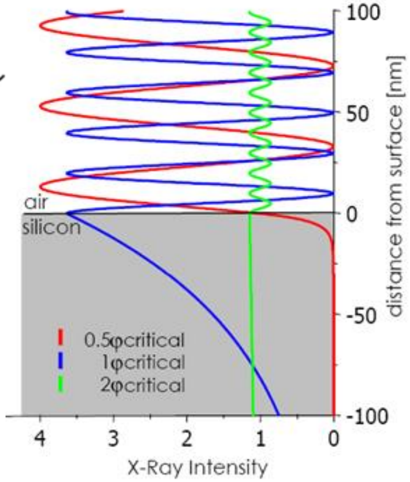
$$\cdot\ \frac{1-e^{-\left(\frac{\mu_{s,E_{\zeta jk}}}{\sin\phi_f}+\frac{\mu_{s,E}}{\sin\phi_i}\right)T}}{\frac{\mu_{s,E_{\zeta jk}}}{\sin\phi_f}+\frac{\mu_{s,E}}{\sin\phi_i}}$$

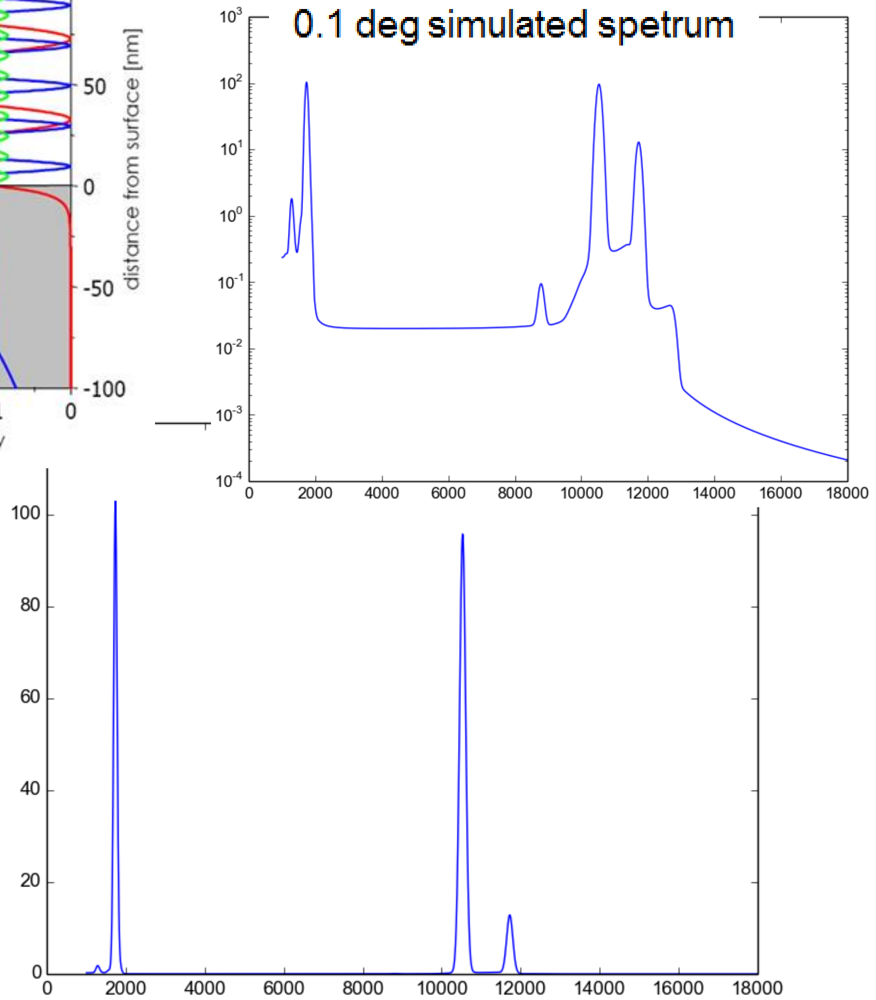


0.1 deg simulated spetrum

GIXRF quantitative analysis

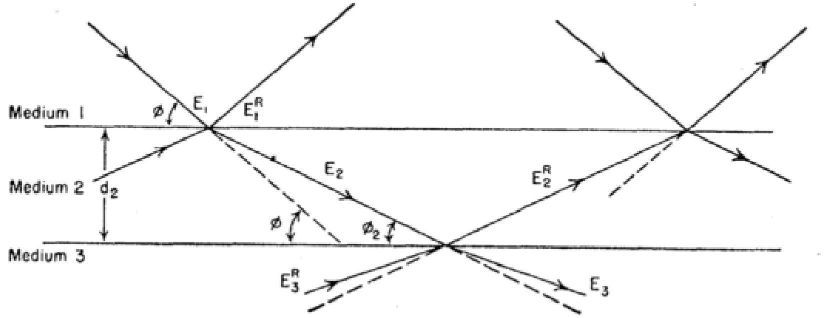


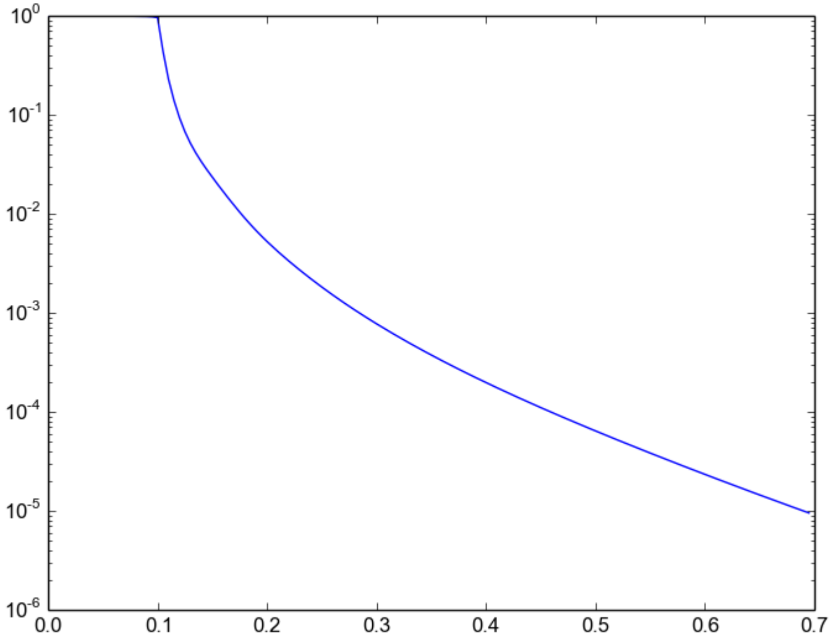




$$dI_{\zeta jk} \propto \boxed{|\overrightarrow{\mathbf{E}}(z,\phi_i,E_0)|^2}\,\overbrace{e^{-\mu_{s,E_0}\frac{z}{\sin\phi_i}}}^{1.} \cdot \overbrace{\boxed{W_\zeta(layer_z)}\left(\frac{\tau_j}{\rho}\right)_{\zeta_{E_0}}\rho_s dz}^{2.} \cdot \underbrace{\omega_{\zeta j}}_{3.}\,\underbrace{p_{\zeta jk}}_{4.}\,\underbrace{e^{-\mu_{s,E_{\zeta jk}}\frac{z}{\sin\phi_f}}}_{5.}\,\underbrace{\epsilon_{E_{\zeta jk}}}_{6.}$$

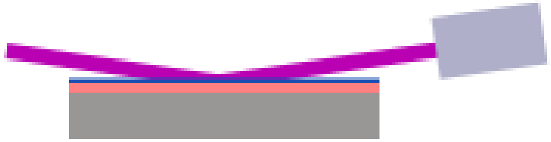
XRR





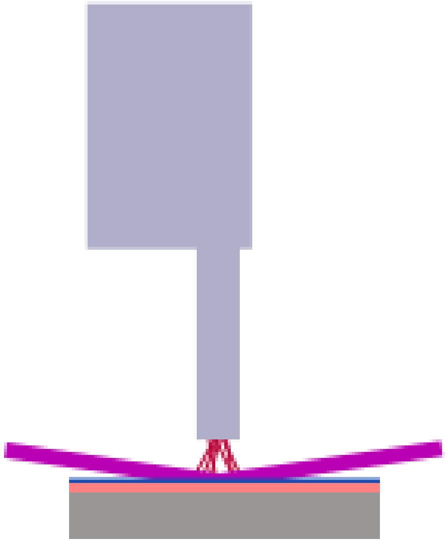
GIXRF vs XRR ?

GIXRF - intensity calculation – 1 interface



XRR

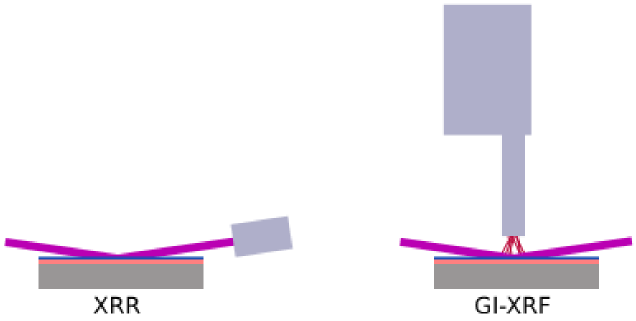
sensitive to electron density and its changes:
- material density
  - film thickness
  - optical constants
  - roughness

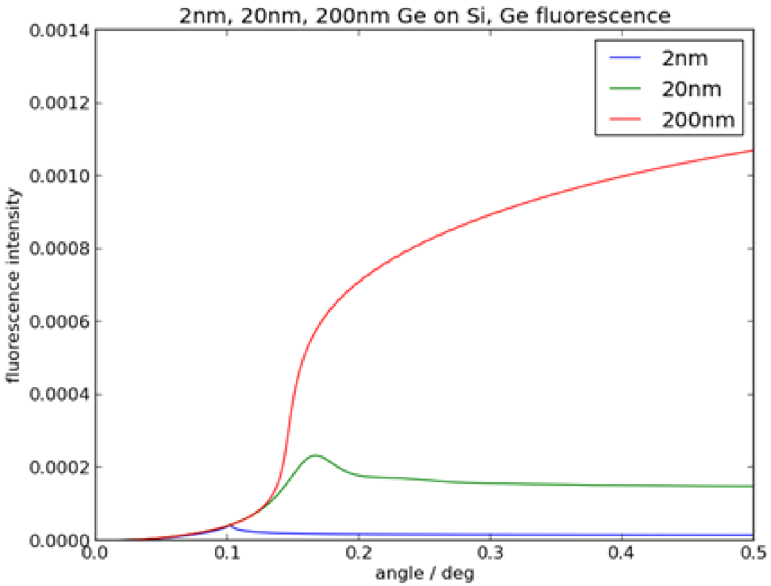


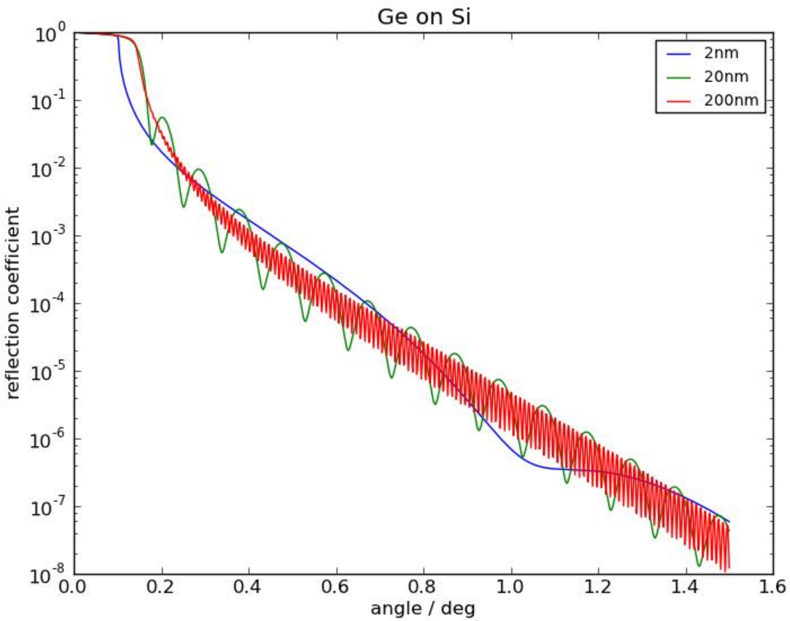
GI-XRF

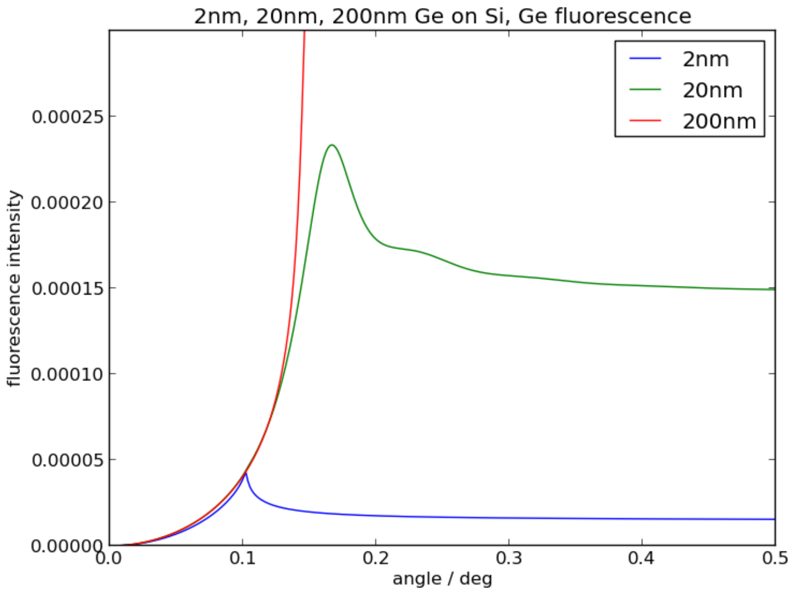
reveals elemental surface concentrations:
- material composition
  - in depth elemental information

GIXRF vs XRR

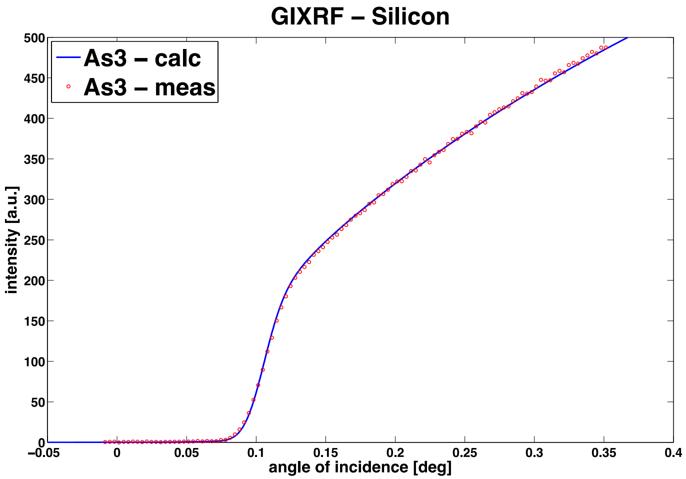

XRR
GI-XRF

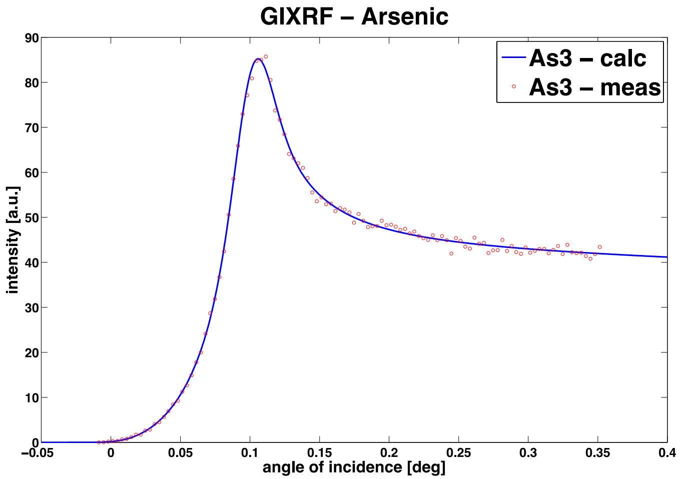

2nm, 20nm, 200nm Ge on Si, Ge fluorescence
2nm
20nm
200nm
fluorescence intensity
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0.0
0.1
0.2
0.3
0.4
0.5
angle / deg

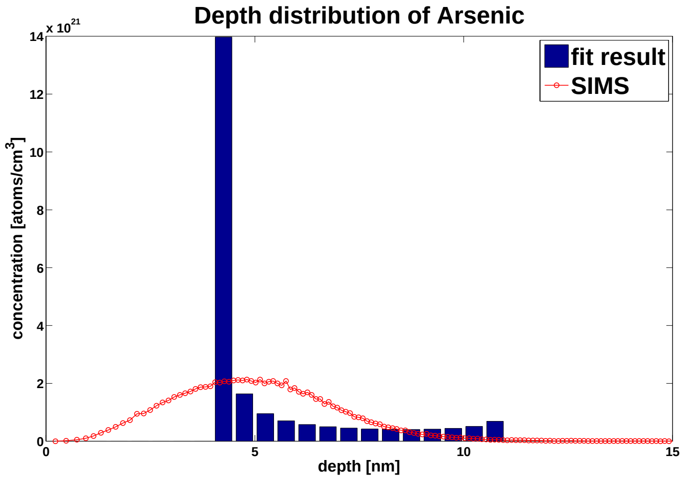

Ge on Si
2nm
20nm
200nm
reflection coefficient
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
angle / deg


2nm, 20nm, 200nm Ge on Si, Ge fluorescence
2nm
20nm
200nm
fluorescence intensity
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
0.0
0.1
0.2
0.3
0.4
0.5
angle / deg

GIXRF - ambiguity problem - As doping profile


GIXRF – Silicon


GIXRF – Arsenic


Depth distribution of Arsenic

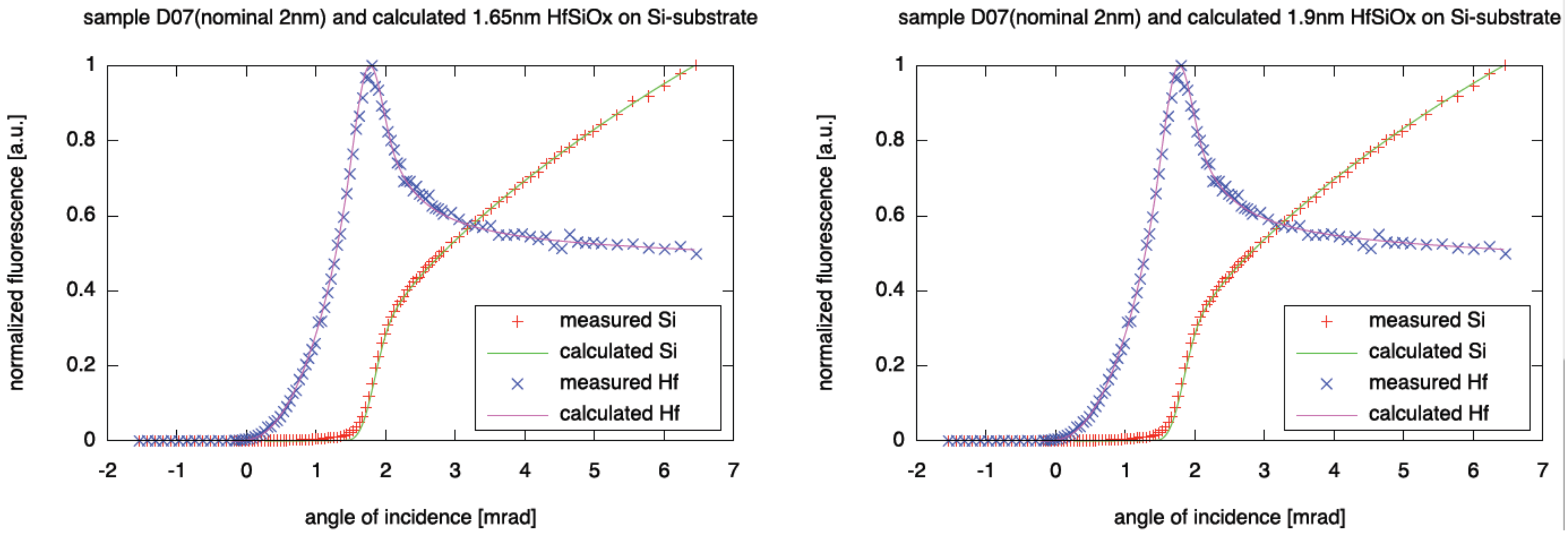
GIXRF fit result looks very good, almost no difference between calculation and measurement

… but the result for the depth distribution is unrealistic

-> GIXRF is ambiguous

courtesy of Dieter Ingerle

GIXRF - ambiguity problem – Hf thin film

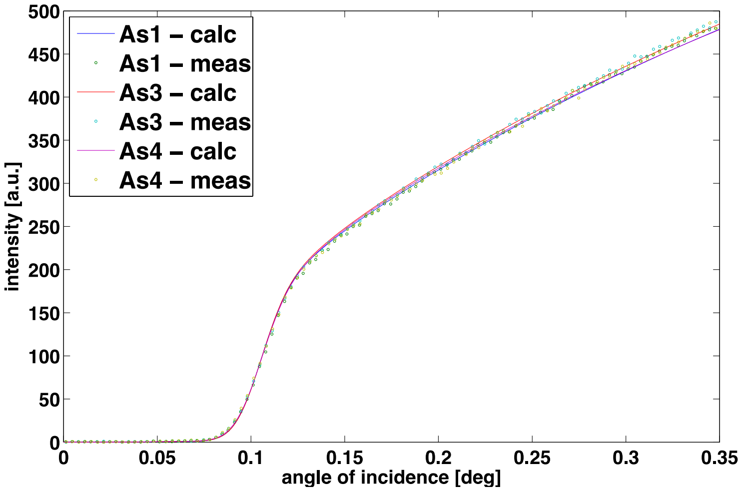


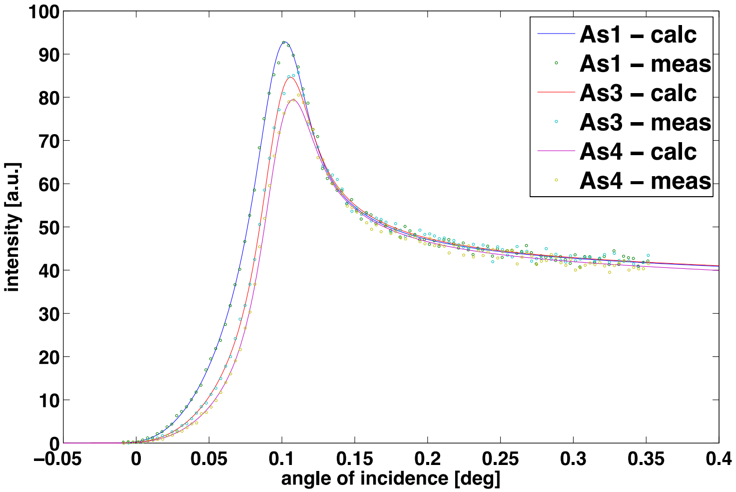
GIXRF measurement data fitted to calculated values. This comparison shows the ambiguity of GIXRF concerning density and thickness. For the left side a layer-density of 6.7 g/m3 was used, while on the right 6.1 g/m3 was used

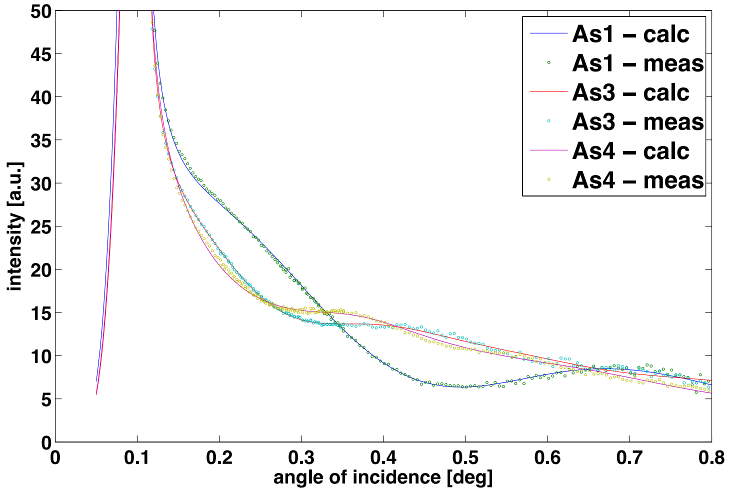
GIXRF can only determine surface mass concentration!
Ambiguity thickness vs. density (XRR probably better)

courtesy of Dieter Ingerle

GIXRF - XRR combined

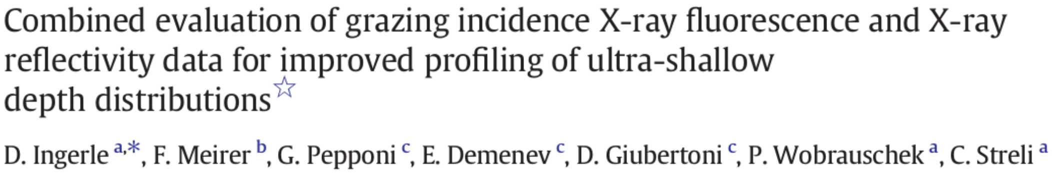






Si wafers implanted with 1E15 atoms/cm^2 of Arsenic by beamline ion implantation with different implantation energies:

- As1 – 0.5keV
- As3 – 2keV
- As4 – 3keV



Combined evaluation of grazing incidence X-ray fluorescence and X-ray reflectivity data for improved profiling of ultra-shallow depth distributions☆

D. Ingerle [a,*], F. Meirer [b], G. Pepponi [c], E. Demenev [c], D. Giubertoni [c], P. Wobrauschek [a], C. Streli [a]

Roughness

Multiply reflectivity and transmission by a damping factor

P. Croce and L. Nevot, Rev. Phys. Appl. 11, 113 (1976)

L. Nevot, P. Croce, Revue de physique appliquée, 15, 761 (1980)

$Q_{j,j+1} = 1$ smooth surface

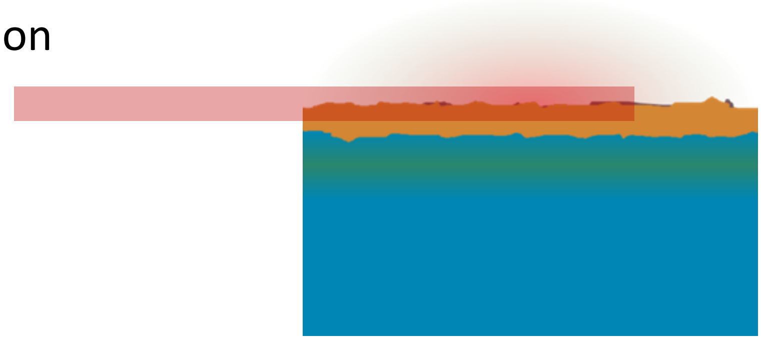
$Q_{j,j+1} = e^{-2\sigma_j^2 k_j^2}$ Debye-Waller factor

$Q_{j,j+1} = e^{-2\sigma_j^2 k_j k_{j+1}}$ Nevot-Croce factor

factors multiplying the Fresnel coefficient

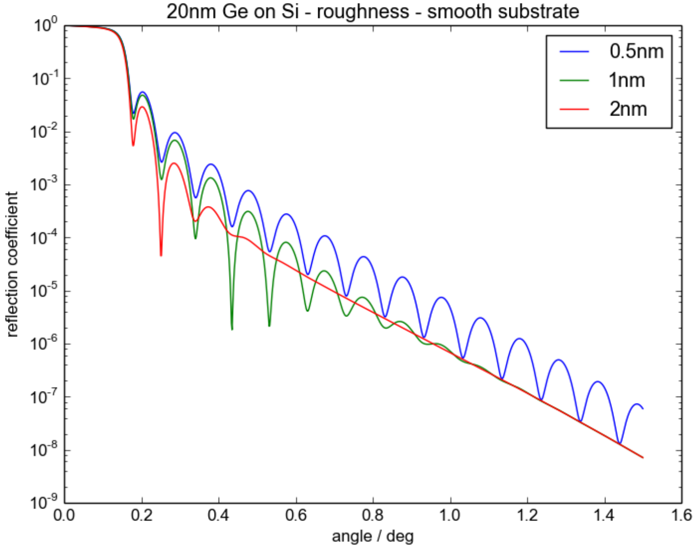
All good for XRR but what about Fluorescence???

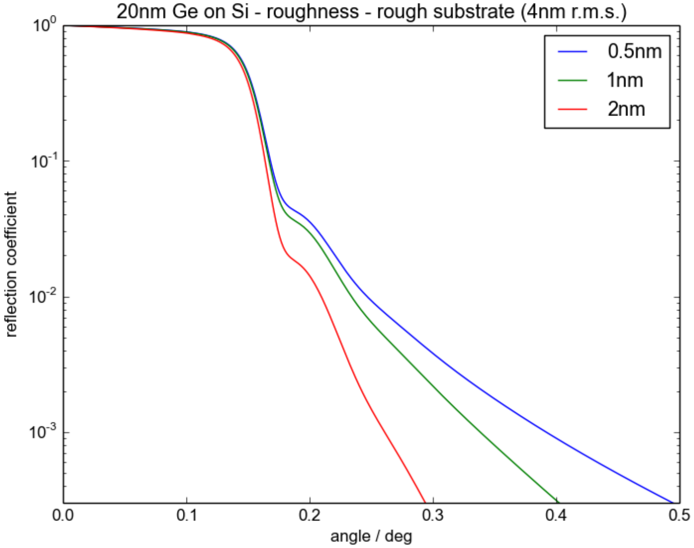
interface layers with changing index of refraction
- error function , linear

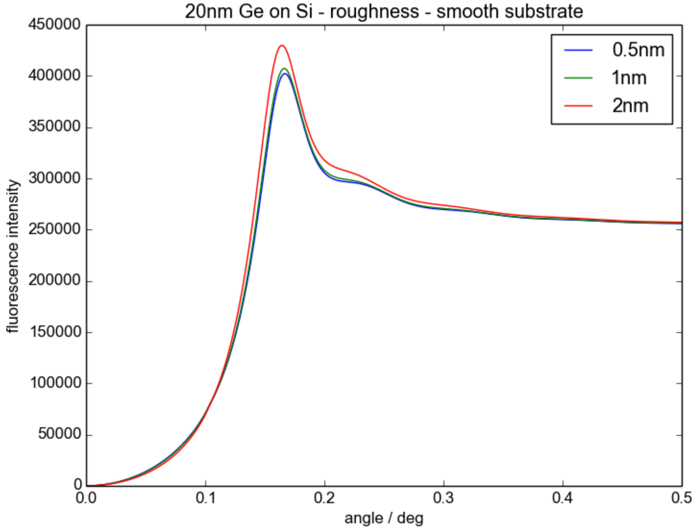


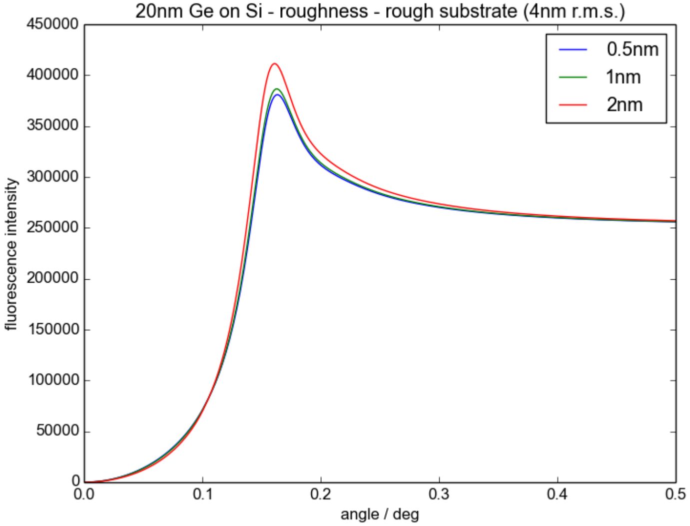
Can we model it as particles?

Roughness


20nm Ge on Si - roughness - smooth substrate
reflection coefficient
angle / deg
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0.5nm
1nm
2nm


20nm Ge on Si - roughness - rough substrate (4nm r.m.s.)
reflection coefficient
angle / deg
10^{0}
10^{-1}
10^{-2}
10^{-3}
0.0
0.1
0.2
0.3
0.4
0.5
0.5nm
1nm
2nm

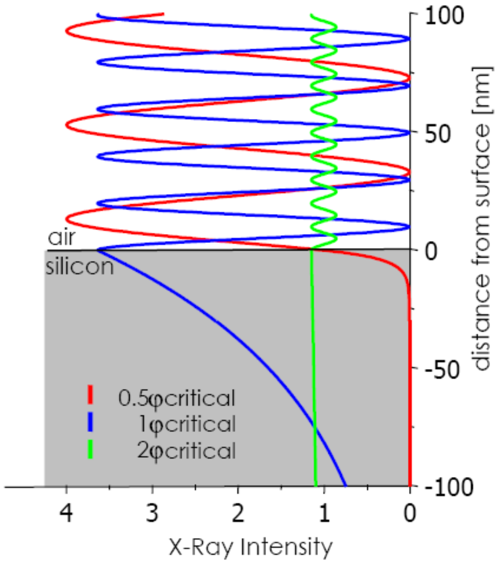

20nm Ge on Si - roughness - smooth substrate
fluorescence intensity
angle / deg
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0.0
0.1
0.2
0.3
0.4
0.5
0.5nm
1nm
2nm

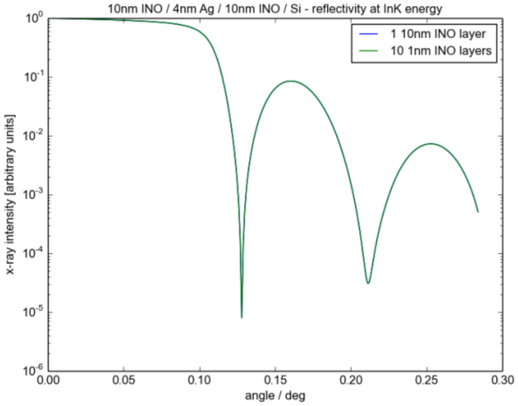

20nm Ge on Si - roughness - rough substrate (4nm r.m.s.)
fluorescence intensity
angle / deg
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0.0
0.1
0.2
0.3
0.4
0.5
0.5nm
1nm
2nm

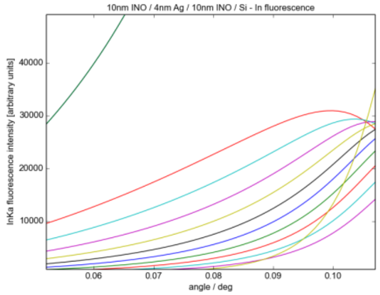
Depth resolution – buried layers and interfaces

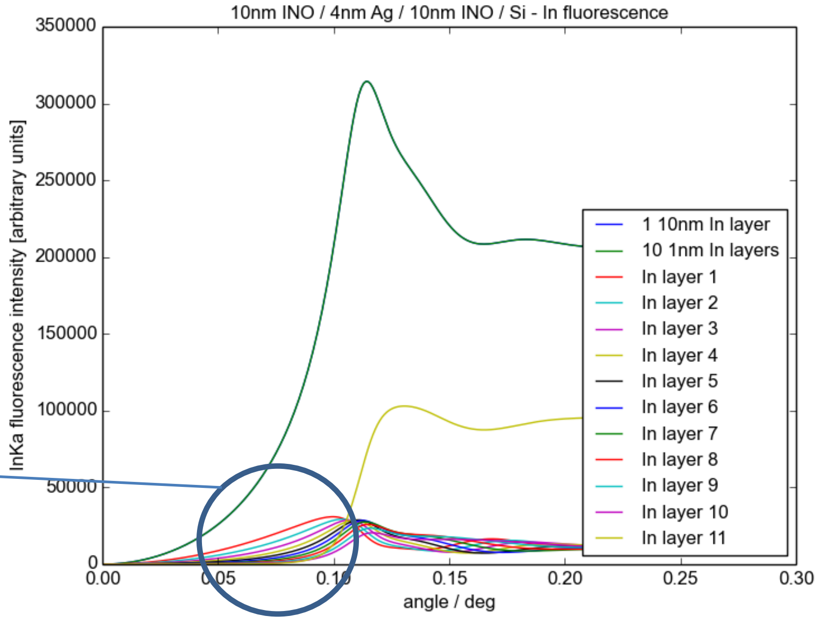
Definition of depth resolution:
- different at different depths

Sample 10nm In2O3 / 4nmAg / 10nm In2O3

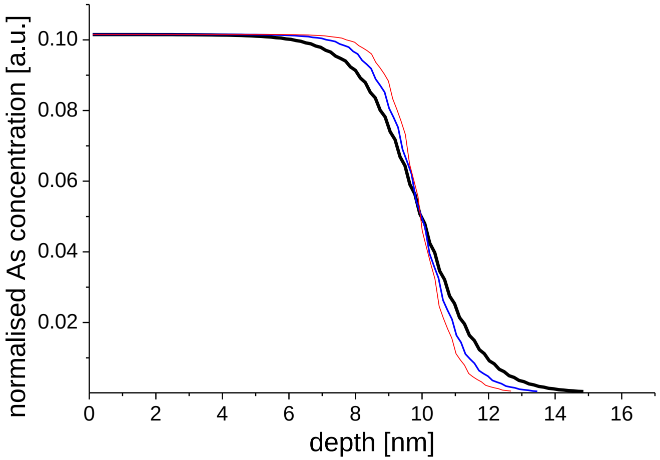


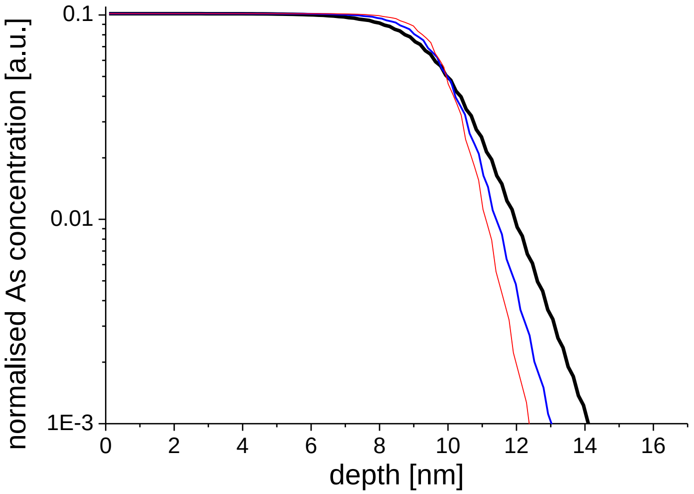


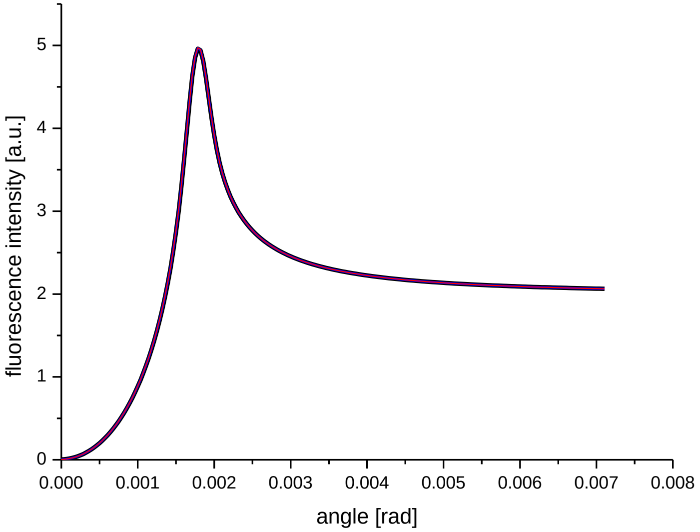


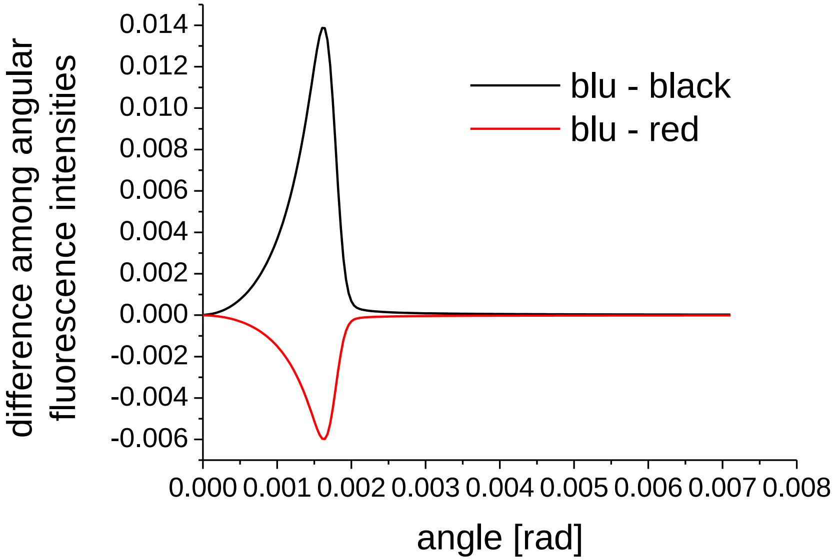


Depth resolution – junction depth

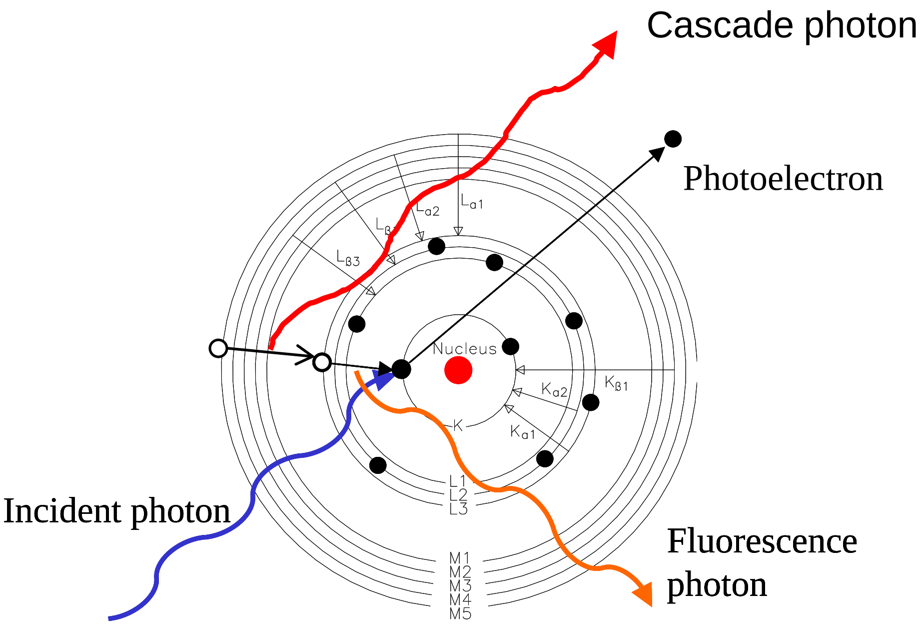








Fluorescence intensity
cascade effect – secondary fluorescence

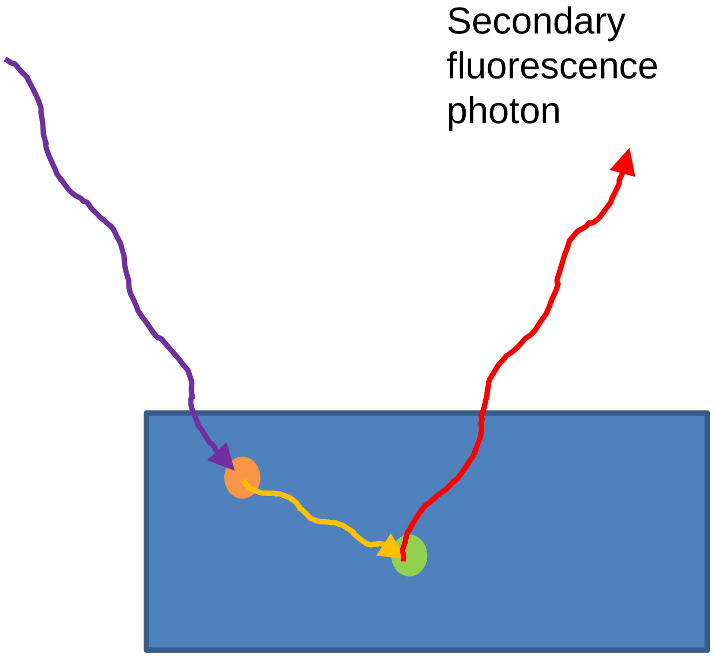


Cascade photon

Photoelectron

Incident photon

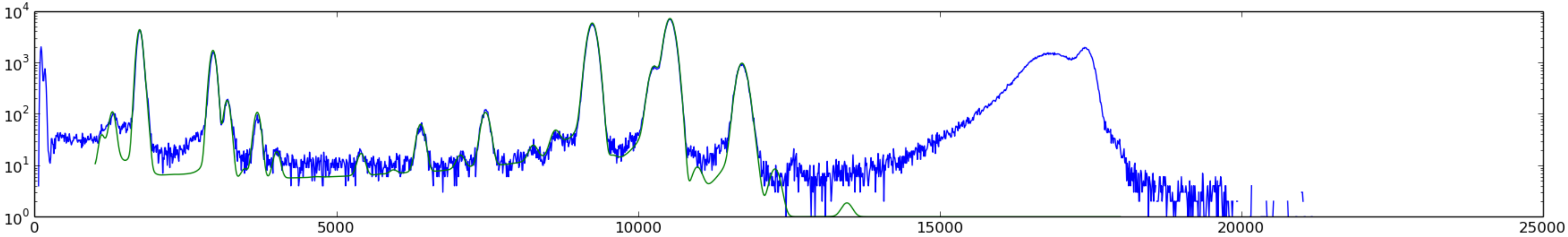
Fluorescence photon



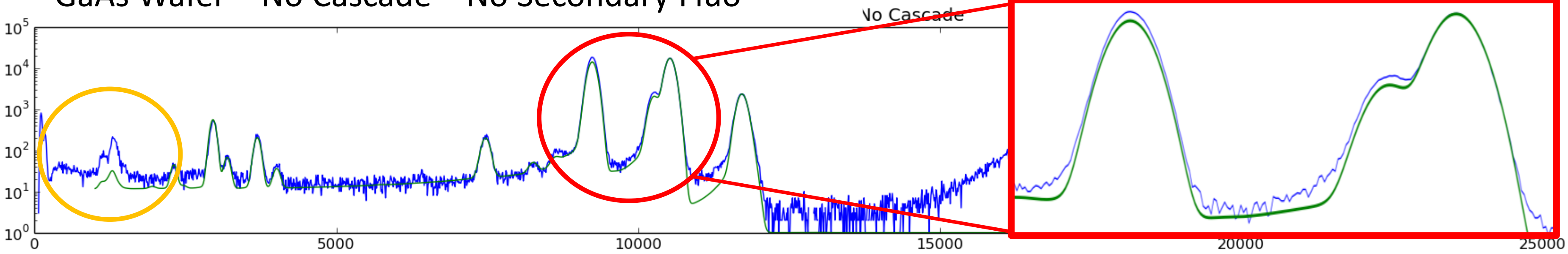
Secondary fluorescence photon

Fluorescence intensity
cascade effect – secondary fluorescence

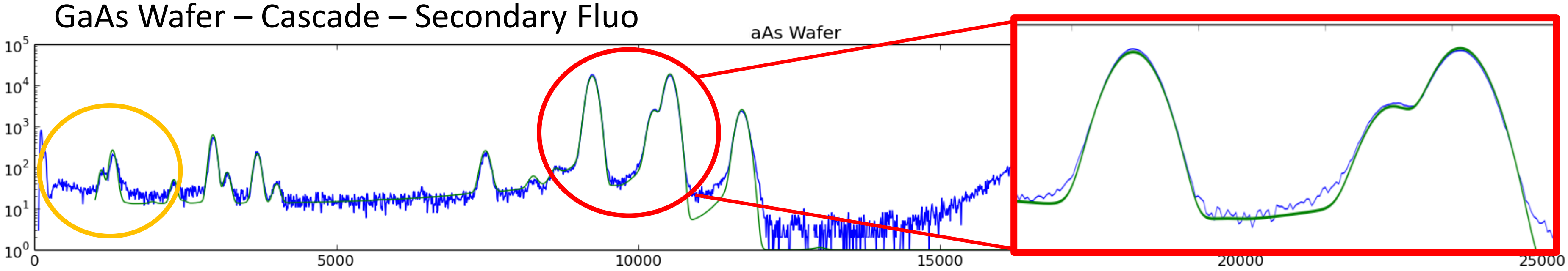
GaAs solution deposited on silicon – Cascade – No Secondary Fluo



GaAs Wafer – No Cascade – No Secondary Fluo



GaAs Wafer – Cascade – Secondary Fluo

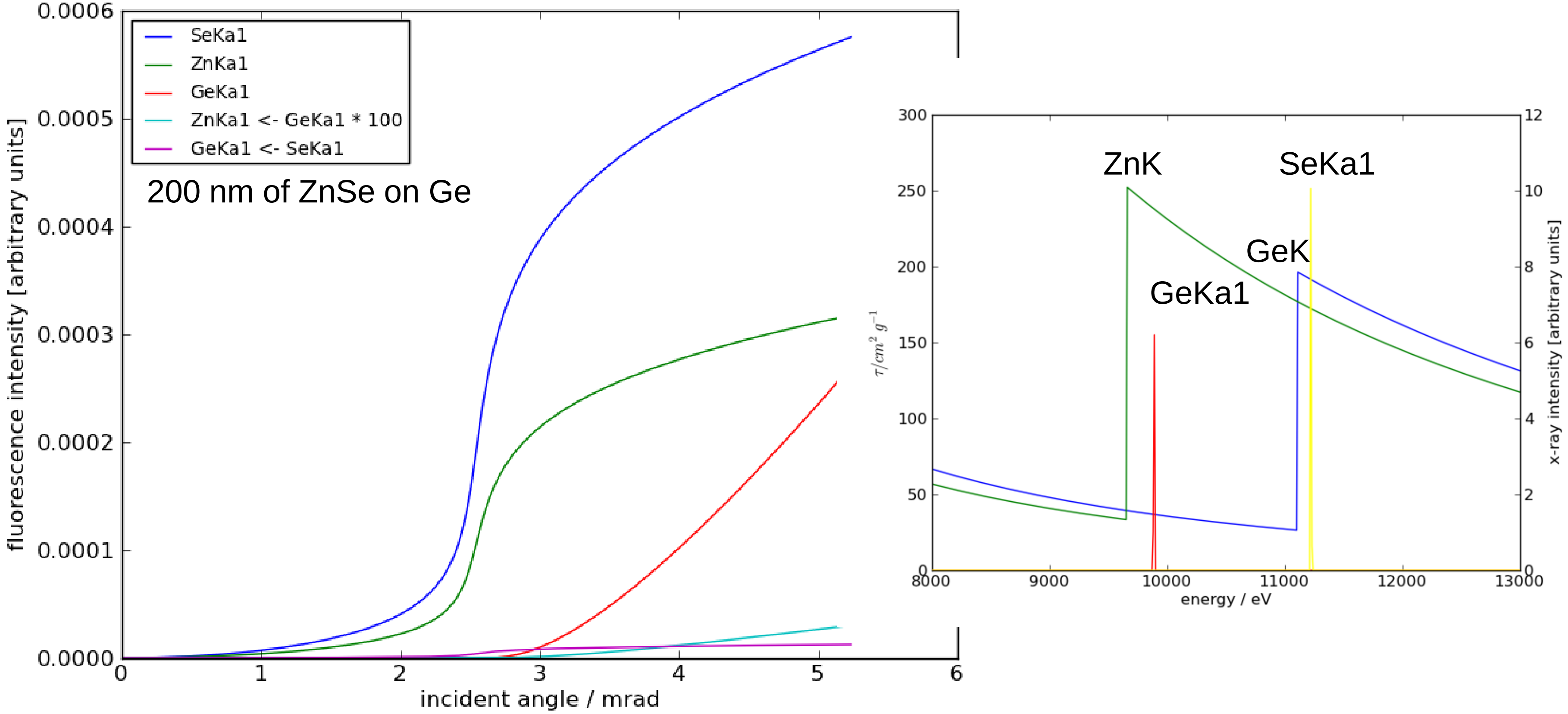


GIXRF - secondary fluorescence

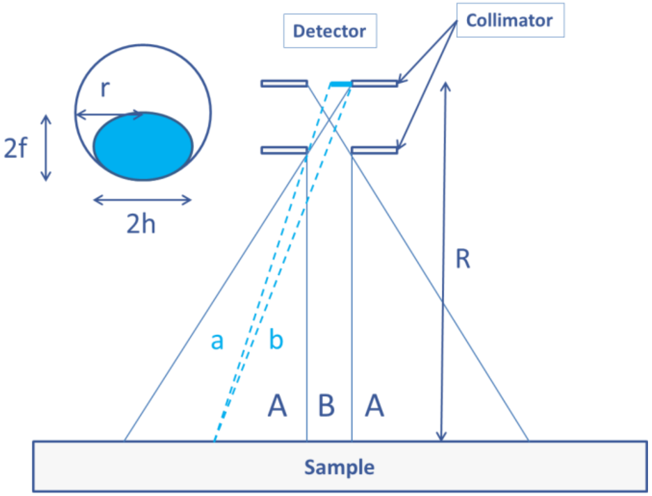
J. Appl. Phys. **75**, 2026 (1994); http://dx.doi.org/10.1063/1.356303 (*3 pages*)

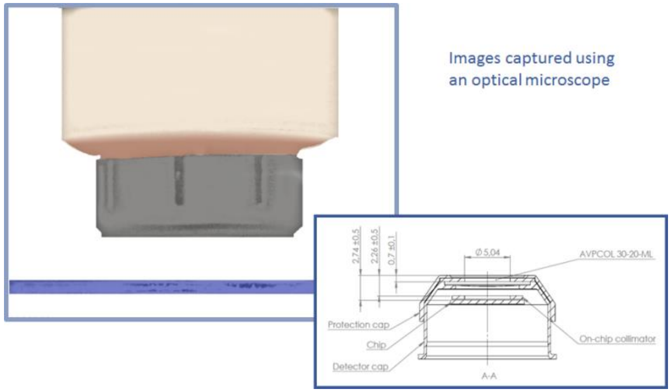
Molecular beam epitaxial growth of single domain ZnSe on Ge

L. K. Li, Y. Wang, M. Jurkovic, and W. I. Wang

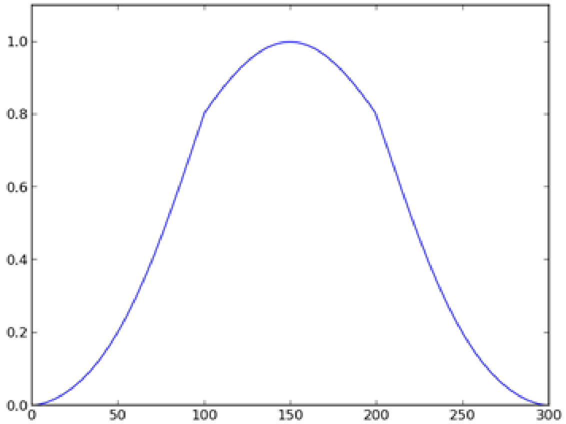


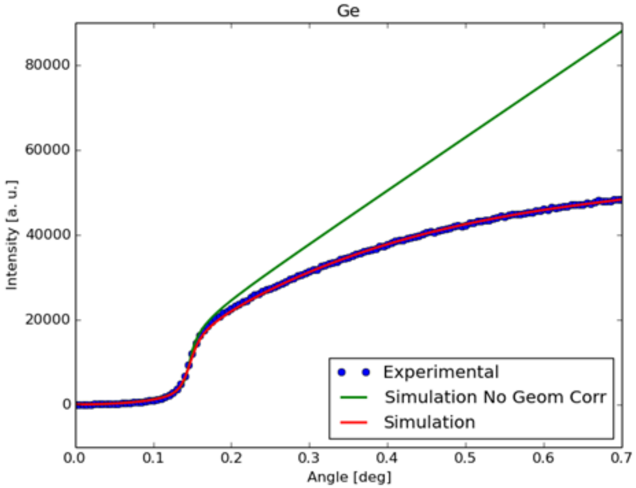
Geometric corrections





Images captured using an optical microscope

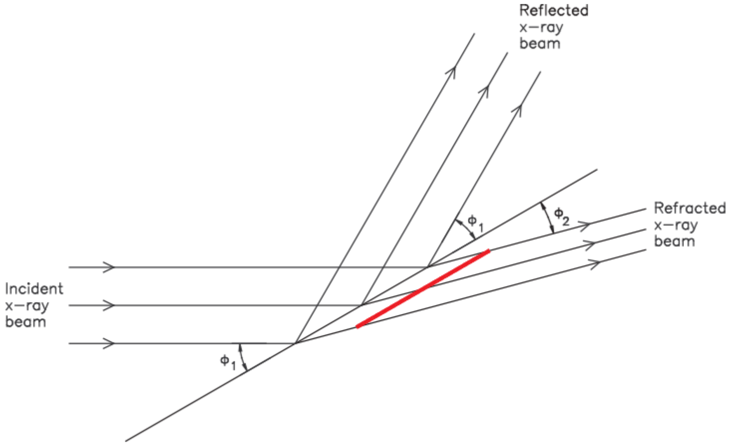


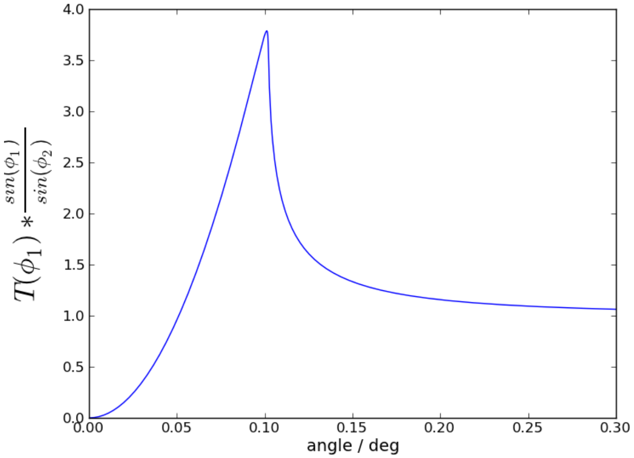


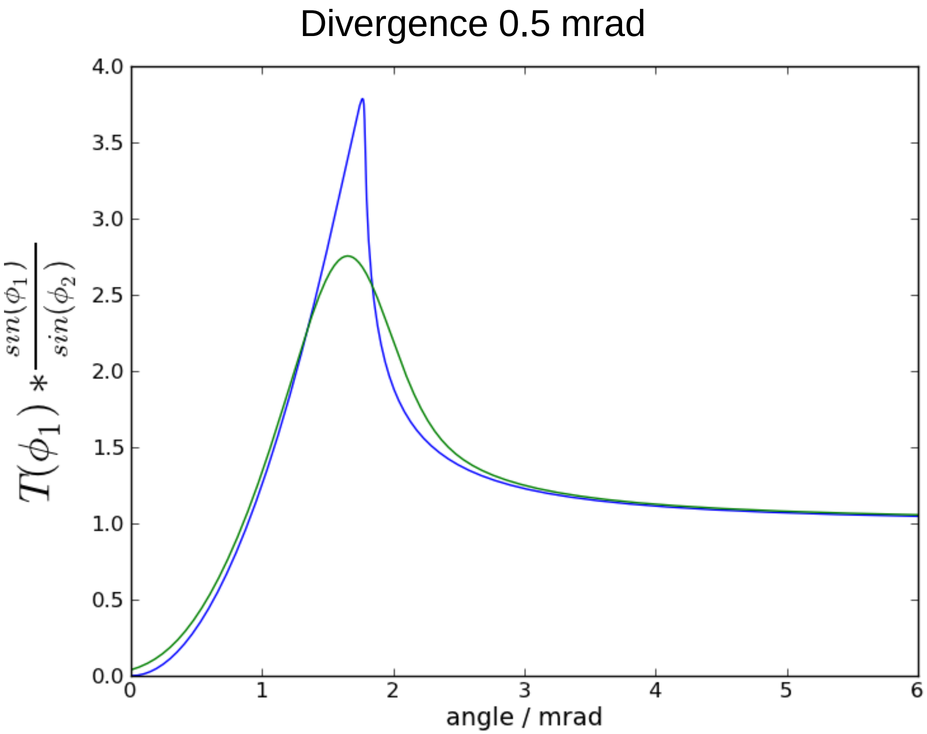
Conway, John T. , Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 614.1 (2010): 17-27.

Divergence

$$I_{abs} = I\left(z\right) T\left(\phi_1\right) \sin\phi_1 \frac{\tau_s}{\sin\phi_2} dz$$

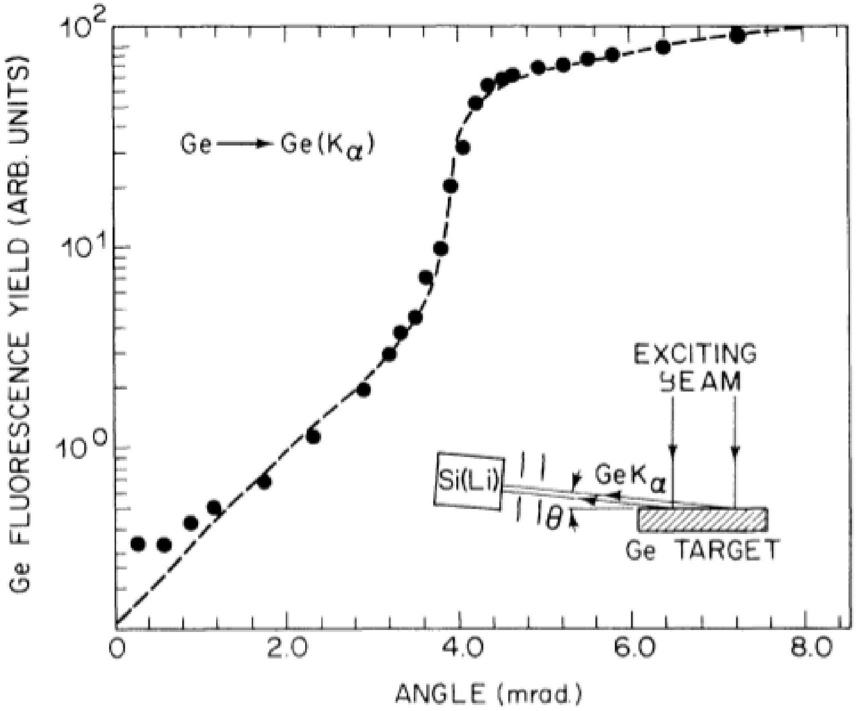





Divergence 0.5 mrad

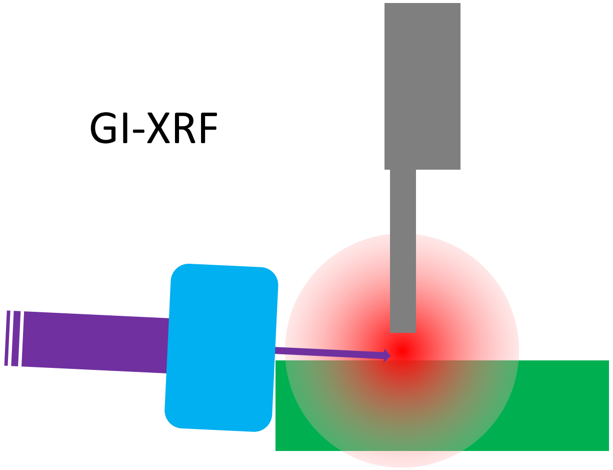
Grazing exit x-ray fluorescence

R. Becker, J. Golovchenko,
J. Patel, PRL 50(3), 153–156

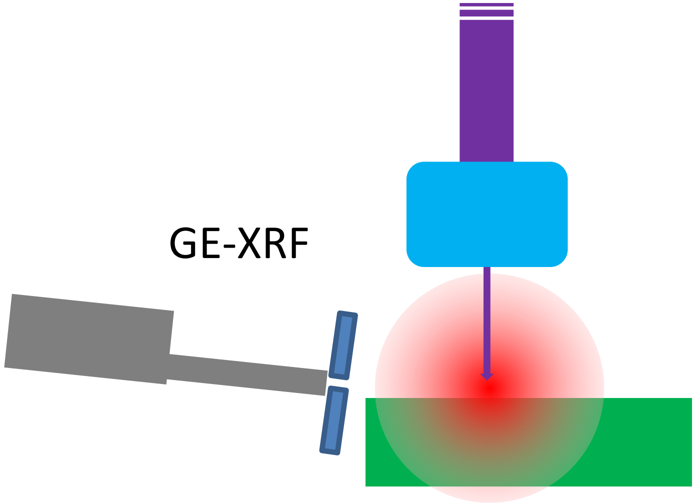


“the principle of microscopic reversibility predicts that the results of absorption- and emission-type experiments should be identical were they performed with the same wavelength radiation.”

GI-XRF



GE-XRF



Advantage:
- higher lateral resolution

Disadvantage:
- reduced sensitivity

Thank you for your attention!

For any further question or doubt:
pepponi@fbk.eu