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SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY:
"John Fuggle Memorial"

3 November - 5 December 1997

Miramare - Trieste, Italy

The application of multilayer coatings in synchrotron radiation research

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School on the use of Synchrotron Radiation
in Science and Technology: "John Fuggle Memorial"
ICTP, November 14th, 1997

The application of multilayer coatings in synchrotron radiation research

Werner Jark

Multilayer Technology Laboratory

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34012 Basovizza (TS), Italy

I will try to give answers to the following questions:

a) Why do we need them?

b) How do we make them?

c) Can we simulate their performance?

d) How do we test them?

e) Do experiment and simulation really agree?

f) Where do we finally use them?

We all know that using visible light

(red = λ = 800 nm = 1.5 eV;
violet = λ = 400 nm = 3 eV)

- we can take an image with a camera by use of lenses or mirror optics!

- we can make an enlarged image in a microscope once more using either lenses or less often mirror systems!

- we can make simple polarizers or phase retarders by use of birefringent material!

What happens if we want to use these devices in the soft x-ray range (10 eV - 2000 eV)?

With increasing photon energy the light starts

a) to be absorbed in lenses

b) to not be dispersed anymore in lenses

c) to find little anisotropy in lenses/filters

d) to not be reflected anymore in normal incidence

Why this:

let's take some examples:
n = index of refraction

a) focal length of lens: $(1/f) = (n-1)((1/r_1) + (1/r_2))$ r_1, r_2 = radii

b) normal incidence reflectivity: $R = ((n-1)/(n+1))^2$

The index of refraction varies as follows for glass (SiO_2):

photon energy:	3 eV	30 eV	100 eV	1000 eV
n =	1.5	0.9	0.985	0.9987
a) f =	e.g. 0.2 m	- 1 m	- 6.6 m	-80 m
b) R =	0.04	0.0028	$6\ 10^{-5}$	$4\ 10^{-7}$
R = (Au)	0.37	0.08	0.0014	$1\ 10^{-6}$

So what can we do?

a) Not much as far as classical lenses are concerned!

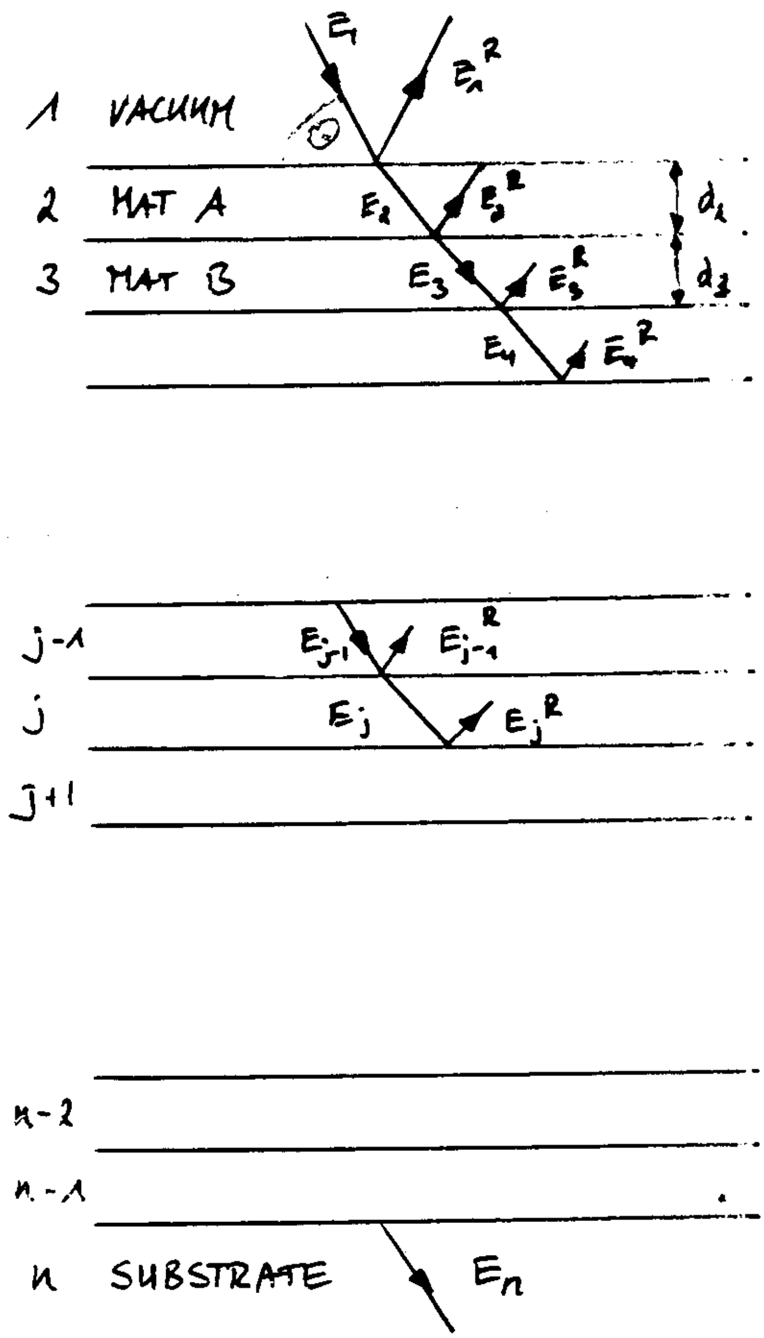
b) However, for m interfaces in a sufficiently transparent structure we can get R_{total} = m R_{int}, which becomes interesting for heavier materials with better R_{int} than glass.

But is it really so simple?

Not really, the different waves need to collaborate in phase, which is affected by the index of refraction n of a layer and which can undergo additional changes at any reflexion at and any transmission through an interface.

<u>So let us write a program!</u>

Multilayer simulation:



Reflectivity and transmittance can be calculated for this stack in principle for up to $(n-2)$ different materials with $(n-2)$ different thicknesses

most common are stacks of just 2 different materials with a total of 10 to >200 periods of equal spacing.

Solution of Parratt (Phys. Rev. 95, 359 (1954))

E_{tang} = const at interfaces

a_j = amplitude factor $= \exp(-i\pi \frac{g_j d_j}{\lambda})$

d = thickness

λ = wavelength

$g_j = \tilde{n}_j \cdot \sin\Theta_j$

$$a_j E_j + a_j^{-1} E_j^R = a_{j+1}^{-1} E_{j+1} + a_{j+1} \cdot E_{j+1}^R$$

$$g_j (a_j E_j - a_j^{-1} E_j^R) = g_{j+1} (a_{j+1} E_{j+1} - a_{j+1} E_{j+1}^R)$$

solution is a recursion equation

$$R_{j,j+1} = a_j^4 \left[\frac{R_{j+1,j+2} + F_{j,j+1}}{R_{j+1,j+2} \cdot F_{j,j+1} + 1} \right]$$

$$R_{j,j+1} = a_j^2 \cdot \frac{E_j^R}{E_j}$$

$$F_{j,j+1} = \frac{E_j^R}{E_j} = \frac{g_j - g_{j+1}}{g_j + g_{j+1}} \quad \text{for s-pol } (\sigma)$$

$$= \frac{g_j/\tilde{n}_j^2 - g_{j+1}/\tilde{n}_{j+1}^2}{g_j/\tilde{n}_j^2 + g_{j+1}/\tilde{n}_{j+1}^2} \quad \text{for p-pol } (\pi)$$

finally $R = \frac{I}{I_0} = |R_{12}|^2$

more elegant to write: $(\tilde{\varepsilon}_j = \tilde{n}_j^2)$

with wavevector in a medium: $\tilde{k}_j = \frac{2\pi}{\lambda} \cdot \sqrt{\tilde{\varepsilon}_j - \varepsilon_0 \cdot \cos^2\Theta}$

$$R_{0,1,m} = \frac{R_{0,1,m} + R_{1,2,m} \cdot \exp(2id\tilde{k}_1)}{1 + R_{0,1,m} \cdot R_{1,2,m} \cdot \exp(2id\tilde{k}_1)}$$

$m = s, p$

0 = vacuum

$$R_{j,j+1,s} = \frac{\tilde{k}_j - \tilde{k}_{j+1}}{\tilde{k}_j + \tilde{k}_{j+1}}$$

$$R_{j,j+1,s} = \frac{\tilde{\varepsilon}_{j+1} \cdot \tilde{k}_j - \tilde{\varepsilon}_j \cdot \tilde{k}_{j+1}}{\tilde{\varepsilon}_{j+1} \cdot \tilde{k}_j + \tilde{\varepsilon}_j \cdot \tilde{k}_{j+1}}$$

finally $R = |R_{0,1,m}|^2$

RECURSION starts always at the last interface to the substrate $\Rightarrow$ proceeds upwards.

A recursion equation can also easily be transferred to a matrix multiplication.

Matrix approach:

e.g. P. Lee (Opt. Commun. **43**, 237 (1982))

attention: applicable only close to 45^0

N = number of periods — for layer pairs

d = period thickness — 2 components: γd, $(1-\gamma)d$

n_i = refractive index — $(n = 1-\delta+i\beta)$

Θ = angle of grazing incidence

average unit decrement of refractive index:

$$\bar{\delta} = \gamma\cdot\delta_1 + (1-\gamma)\cdot\delta_2 \qquad \bar{\beta} = \gamma\beta_1 + (1-\gamma)\cdot\beta_2$$

phase shift Ψ per period

$$\Psi = \frac{2\pi\cdot d}{\lambda}\cdot\sin\Theta\cdot\left(1-\frac{\bar{\delta}+i\bar{\beta}}{\sin^2\Theta}\right)$$

instead per layer Ψ_1, Ψ_2

reflection coefficient for large angles:

$$r = \frac{(\Delta\delta + i\Delta\beta)\cdot P(\Theta)}{2\sin^2\Theta} \qquad P(\Theta) = \begin{cases} 1 & \text{s-pol} \\ \cos 2\Theta & \text{p-pol}\end{cases}$$

$$\Delta\delta = \delta_1 - \delta_2 \qquad \Delta\beta = \beta_1 - \beta_2$$

E_{tang} in one period with respect to the others:

$$[A] = (1-r^2)^{-1}\cdot\begin{pmatrix} e^{i\Psi}(1-r^2e^{-2i\Psi_1}) & 2ir\,e^{i\Psi_2}\cdot\sin\Psi_1 \\ -2ir\,e^{i\Psi_2}\cdot\sin\Psi_1 & e^{-i\Psi}(1-r^2e^{2i\Psi_1}) \end{pmatrix}$$

after extension to N periods the reflection coefficient is:

$$R(\Theta) = \frac{-2ir\,e^{i\Psi_2}\cdot\sin\Psi_1\cdot S_{N-1}(x)}{e^{i\Psi}(1-r^2e^{-2i\Psi_1})\cdot S_{N-1}(x) - \sqrt{\Delta}\cdot S_{N-2}(x)}$$

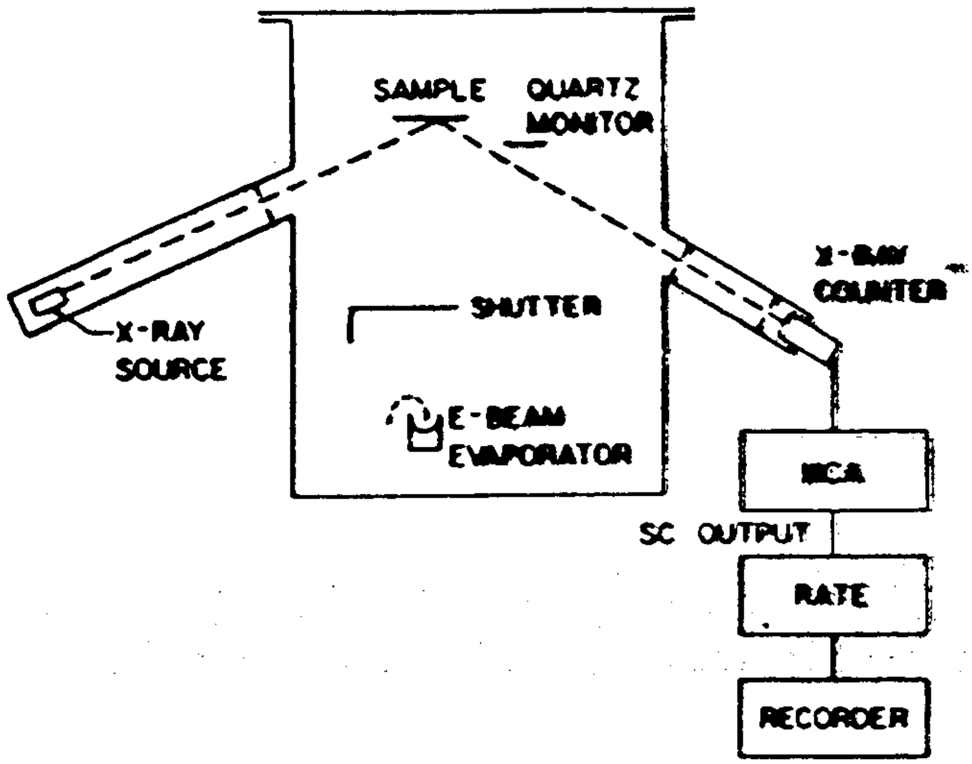
$$S_N(x) = \sin\left[(N+1)\cos^{-1}(x)\right] / \sin\left(\cos^{-1}(x)\right)$$

Chebyshev polynominal of 2. kind

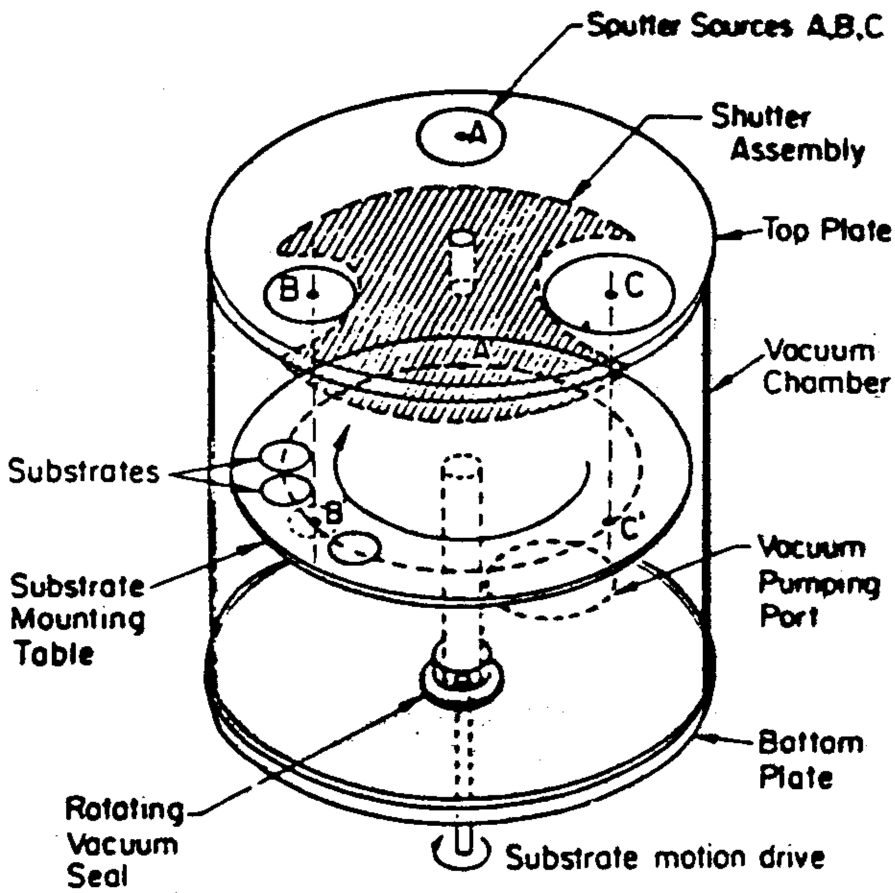
$$\Delta = (1-r^2)^2 \qquad x = \frac{\cos\Psi - r^2\cos(\Psi_1-\Psi_2)}{\sqrt{\Delta}}$$

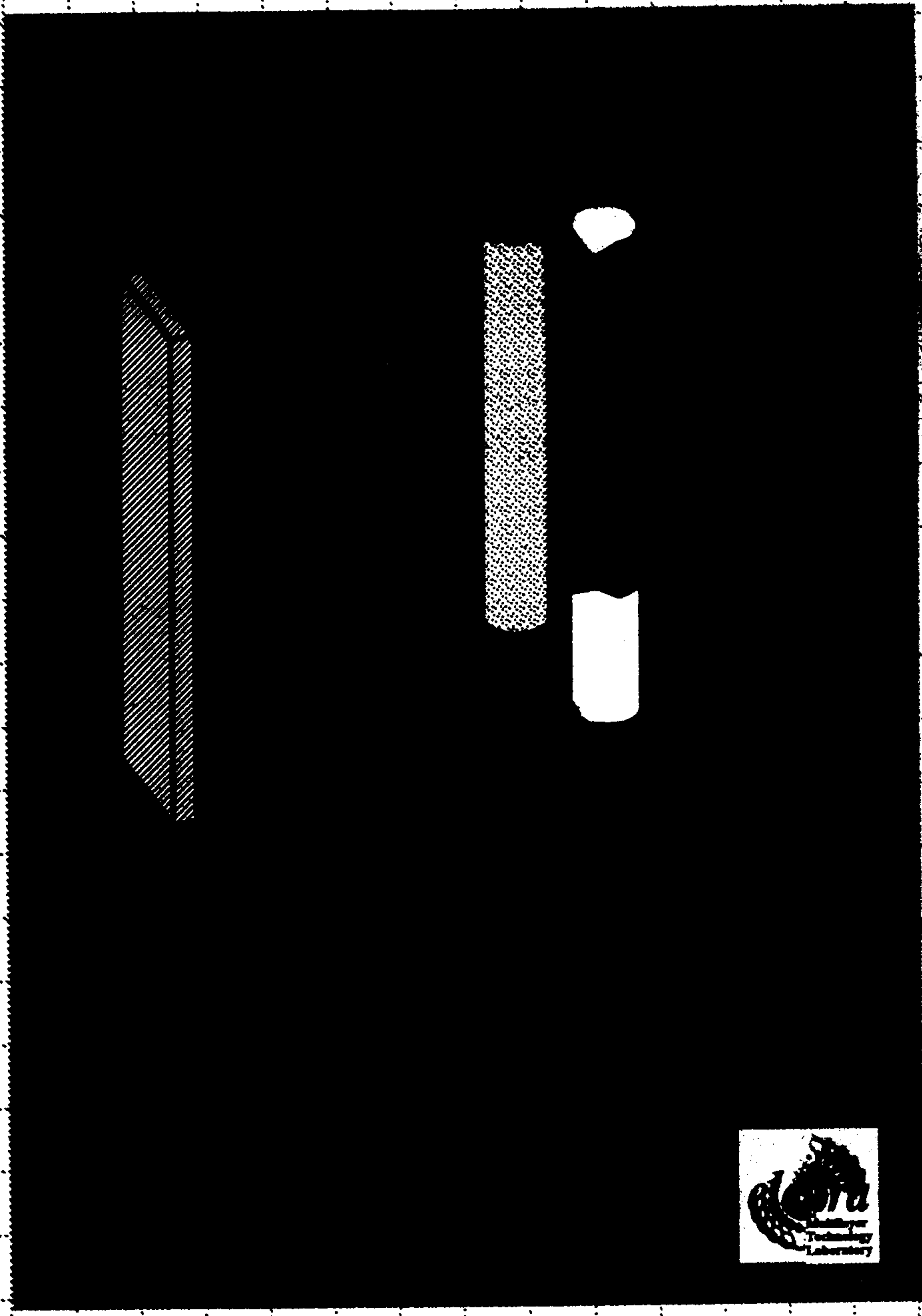
equation is not plausible anymore!

BUT, it is an analytical equation, which works and can be programmed in about $\frac{1}{2}$ hour.



Multilayer production





Is it really this simple? Are there no problems?

NO!!

Evaporation:

- repeatability
- cluster evaporation
- sublimation
- monitoring of thickness
- homogeneity over large sample sizes

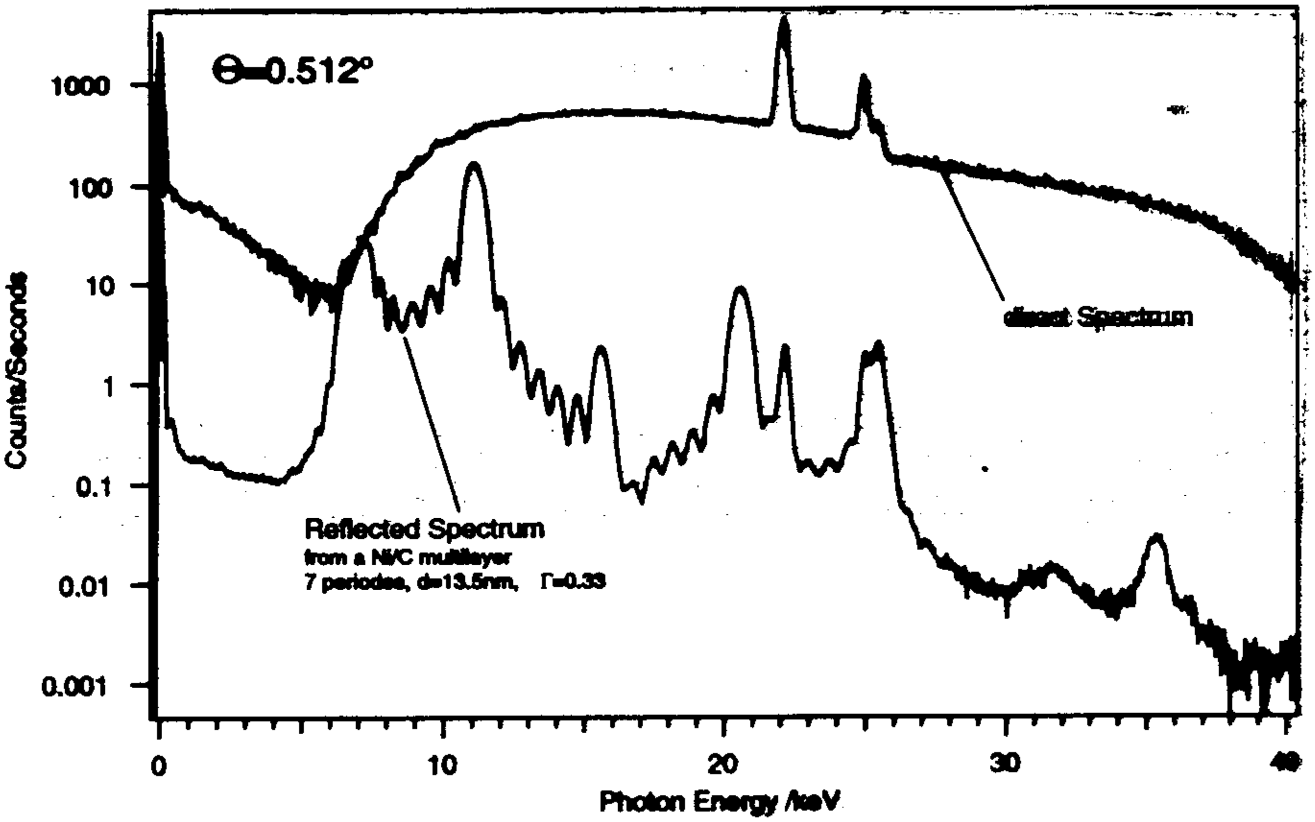
Sputtering:

- homogeneity over large sample sizes
- simultaneous bombardement of sample with plasma electrons
- plasma gas inclusions ($p \approx 1 \ldots 100$ mbar)
- reactions with restgas of vacuum

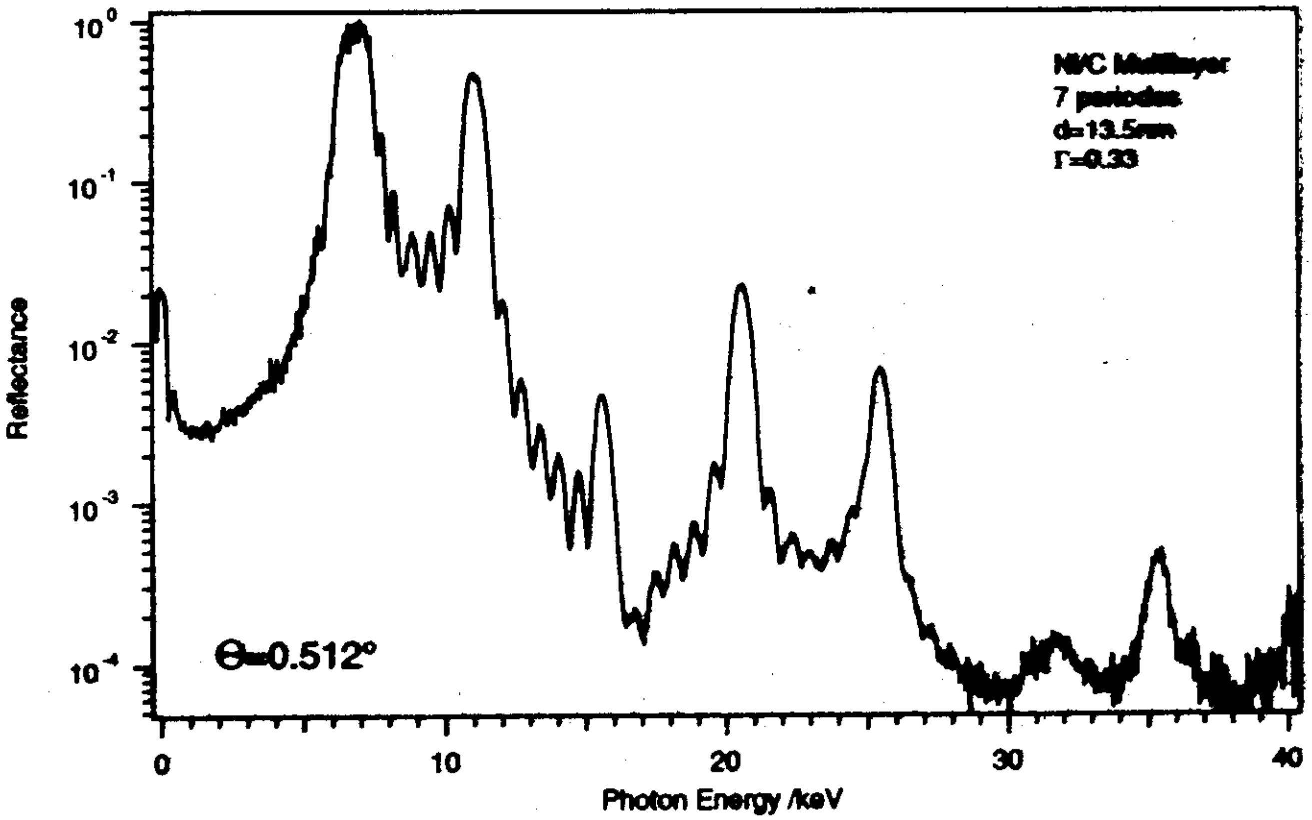
but: easy monitoring and very repeatable due to plasma stability and reproducibility
$\Rightarrow$ monitoring by timing
(or charge transfer)

Multilayer Technology Laboratory

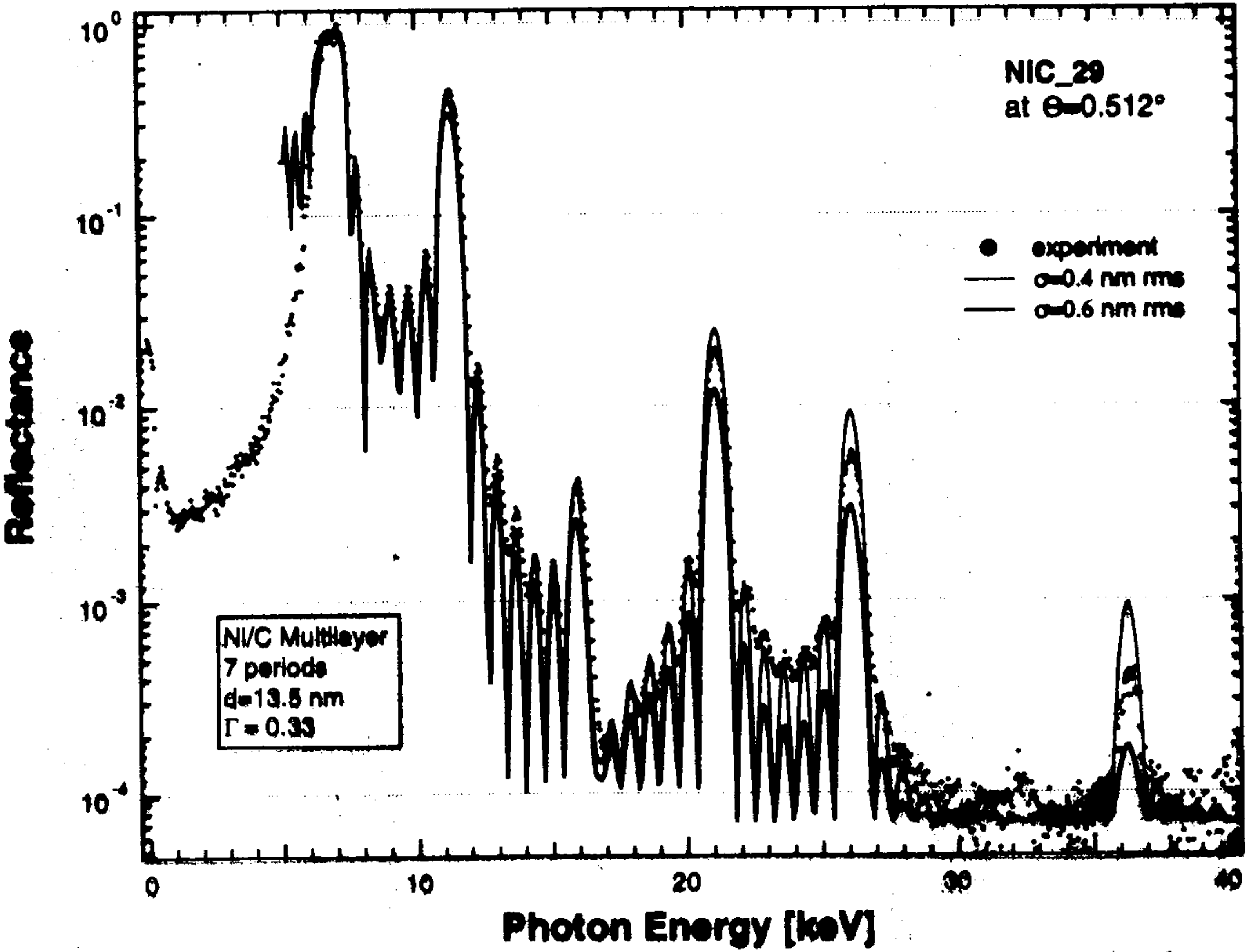
WHITE X RA



Θ=0.512°
Counts/Seconds
1000
100
10
1
0.1
0.01
0.001
direct Spectrum
Reflected Spectrum
from a Ni/C multilayer
7 periodes, d=13.5nm, Γ=0.33
0
10
20
30
40
Photon Energy /keV



Ni/C Multilayer
7 periodes
d=13.5nm
Γ=0.33
Reflectance
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Θ=0.512°
0
10
20
30
40
Photon Energy /keV



Inclusion of roughness : $\tilde{r}_n \longrightarrow \tilde{r}_n \cdot \exp\left(-\frac{2\pi}{\lambda} \cdot \sigma \sin\Theta\right)$

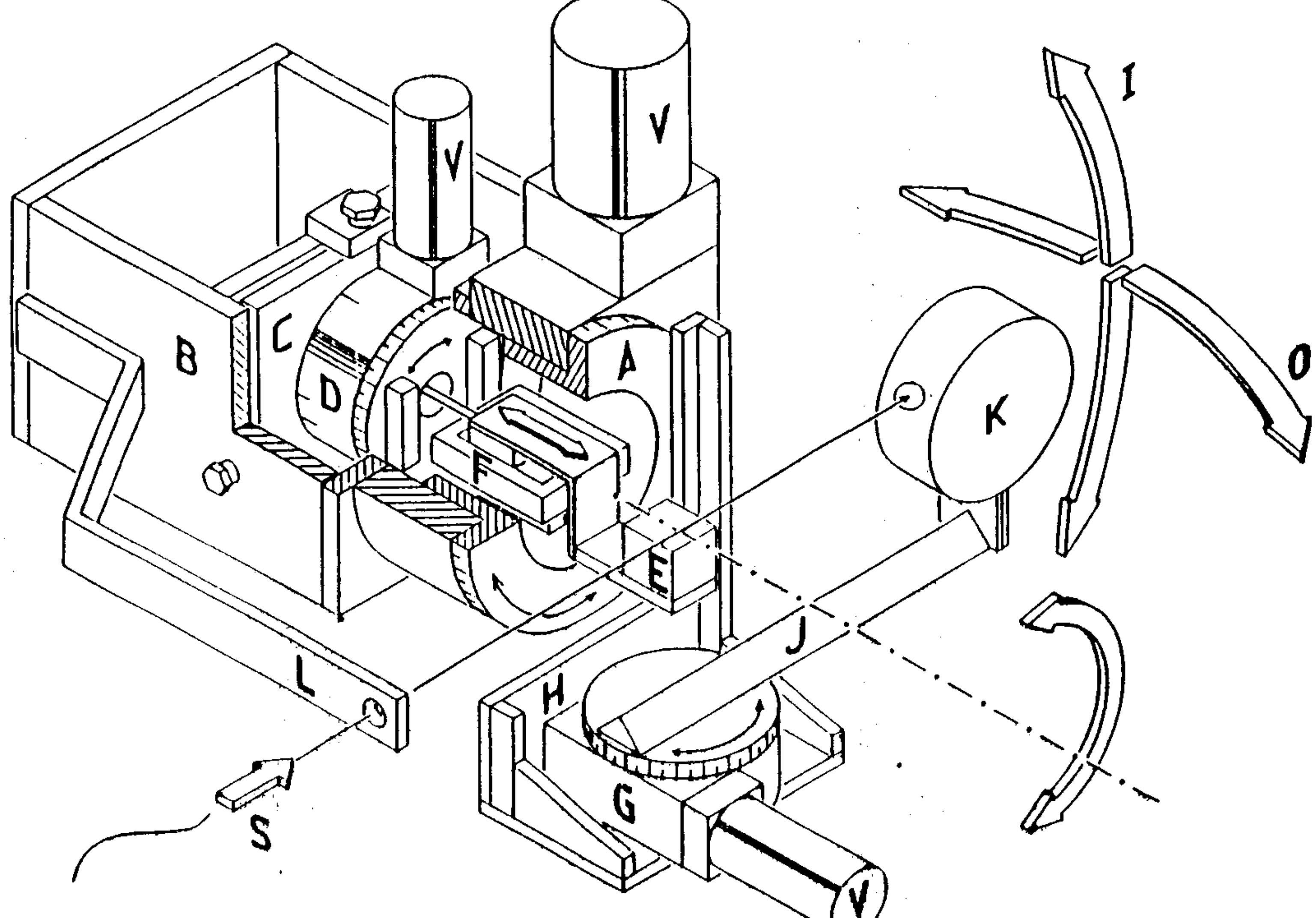
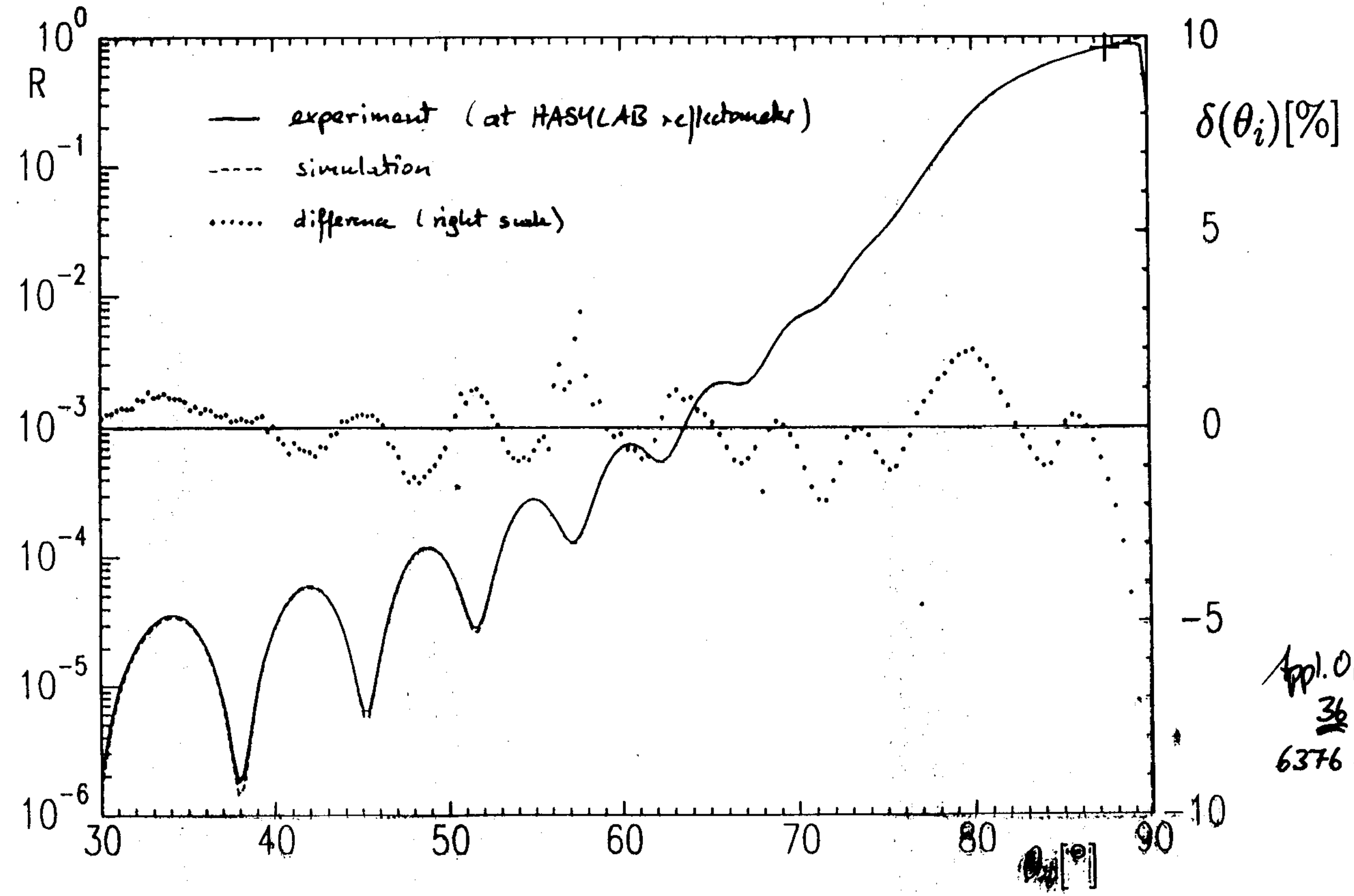


Figure 1. Schematic view of the triple-axis diffractometer: A: 140 mm O.D. goniometer for in-plane detector scan, B: mounting frame, C: base plate for sample rotation goniometer D, D: 80 mm O.D. goniometer for sample rotation, E: sample holder, F: translation stage for sample translation, G: 80 mm O.D. goniometer for out-of-plane detector scan, H: right-angle mount for goniometer G, I: in-plane scan direction, J: detector arm, K: detector housing, L: holder for entrance apertures, O: out-of-plane scan direction, S: incident soft x-rays, V: vacuum stepper motors.

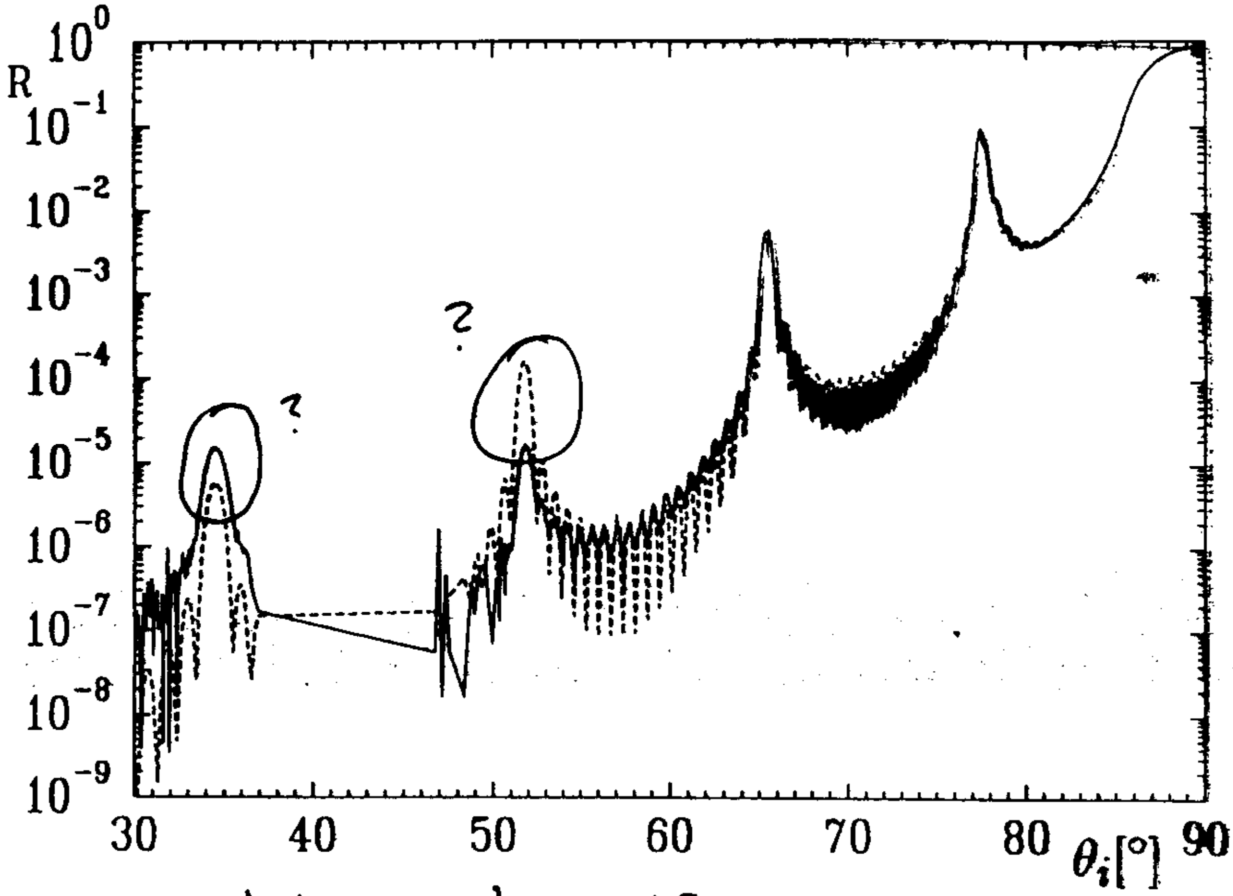
Nucl. Instrum. and Methods, A 266 654 (1988)

Real multilayers : a simple Ni - film on float glass

$d = 30.4$ nm $E = 260$ eV

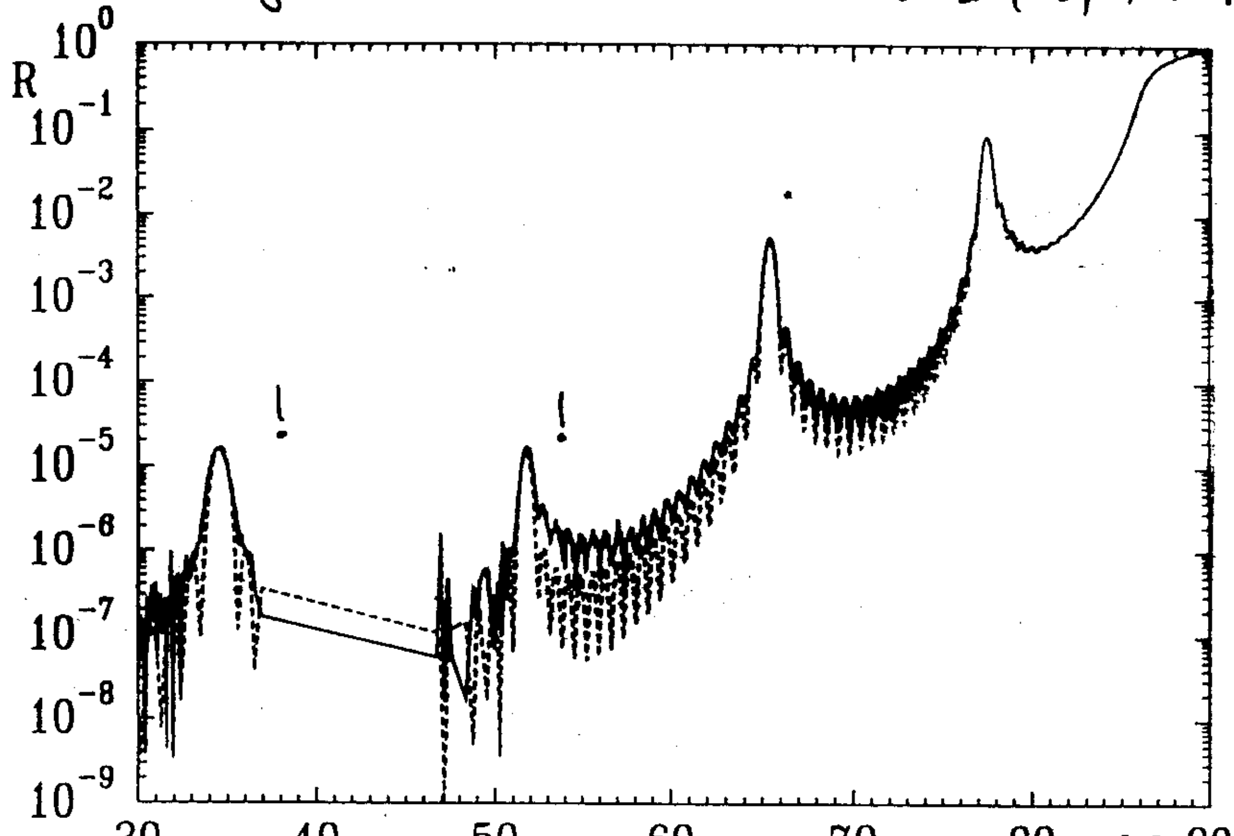


Appl. Opt. 36, 6376 (

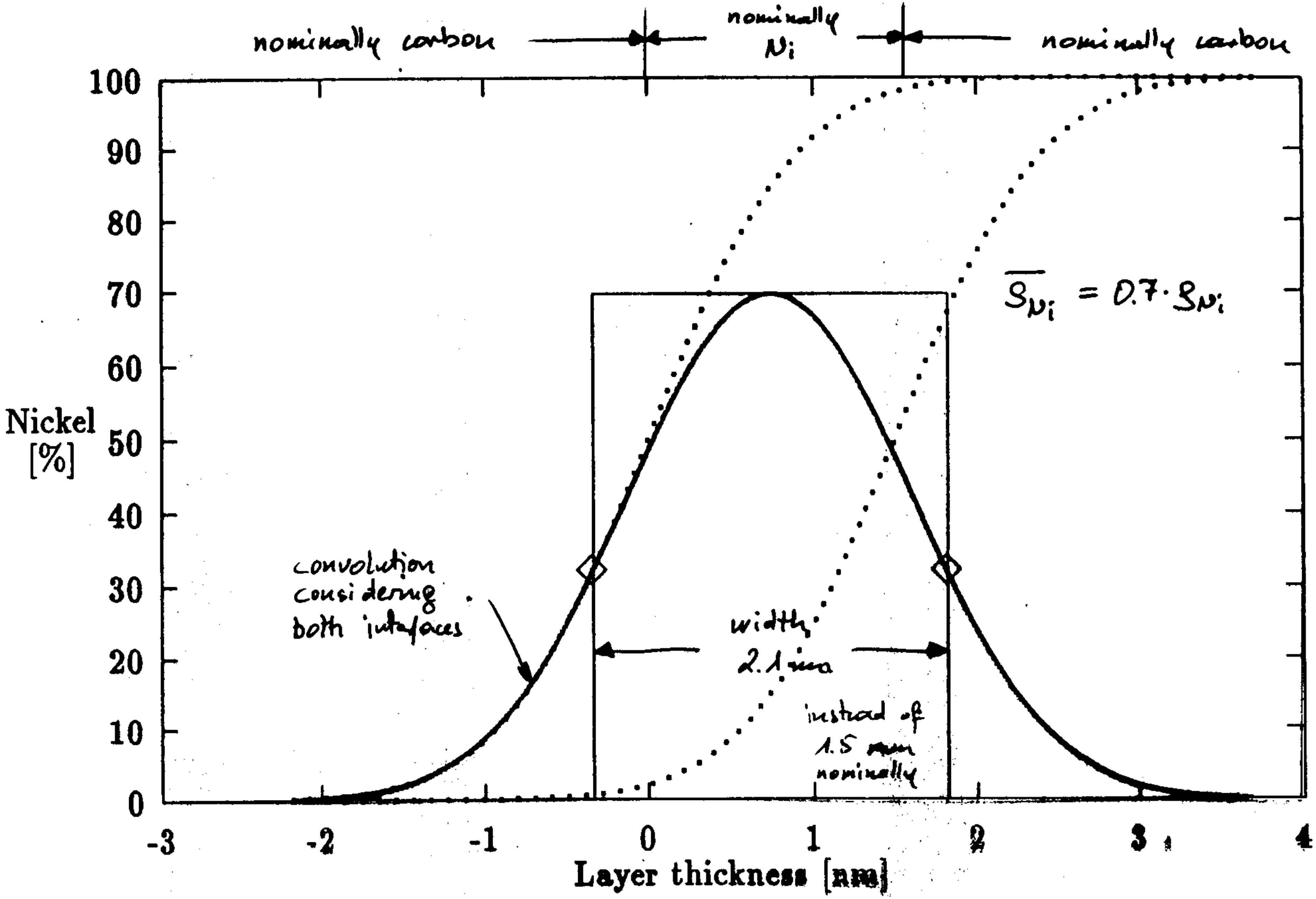


we do have $d_{Ni} = 1.5$ nm
with interface roughness of 0.7 nm RMS

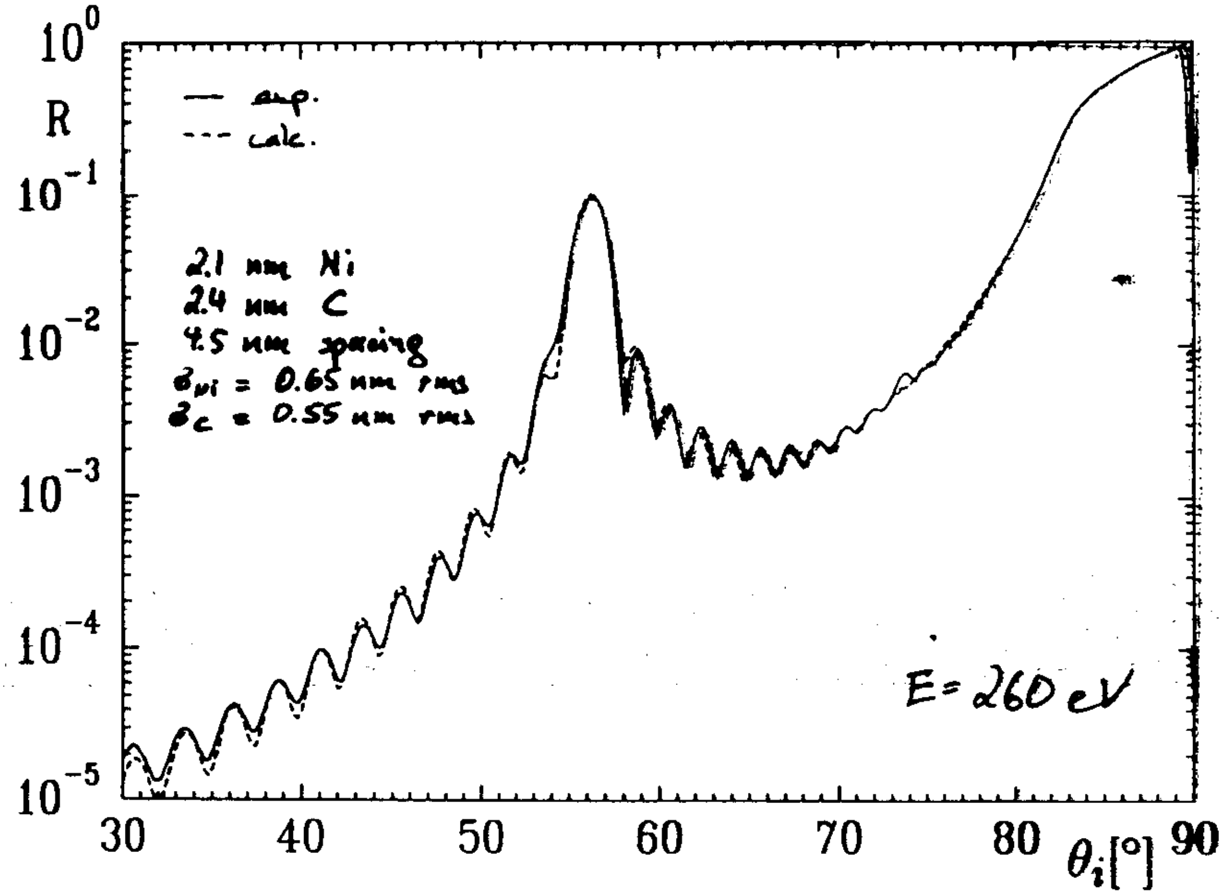
taking into account the reduced density of the Ni-layer



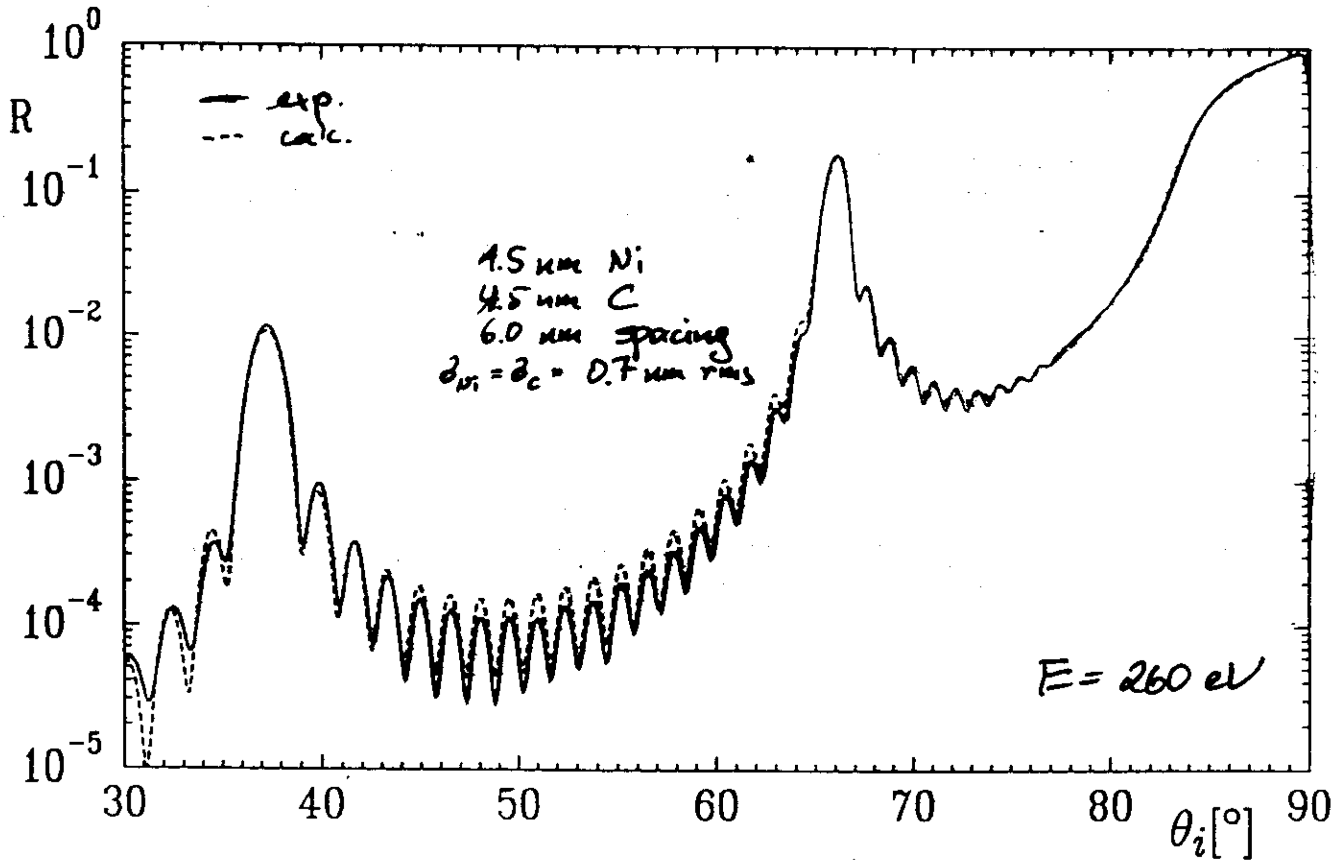
Appl. Opt. 36, 6329 (1997)



Appl. Opt. 36, 6329 (199



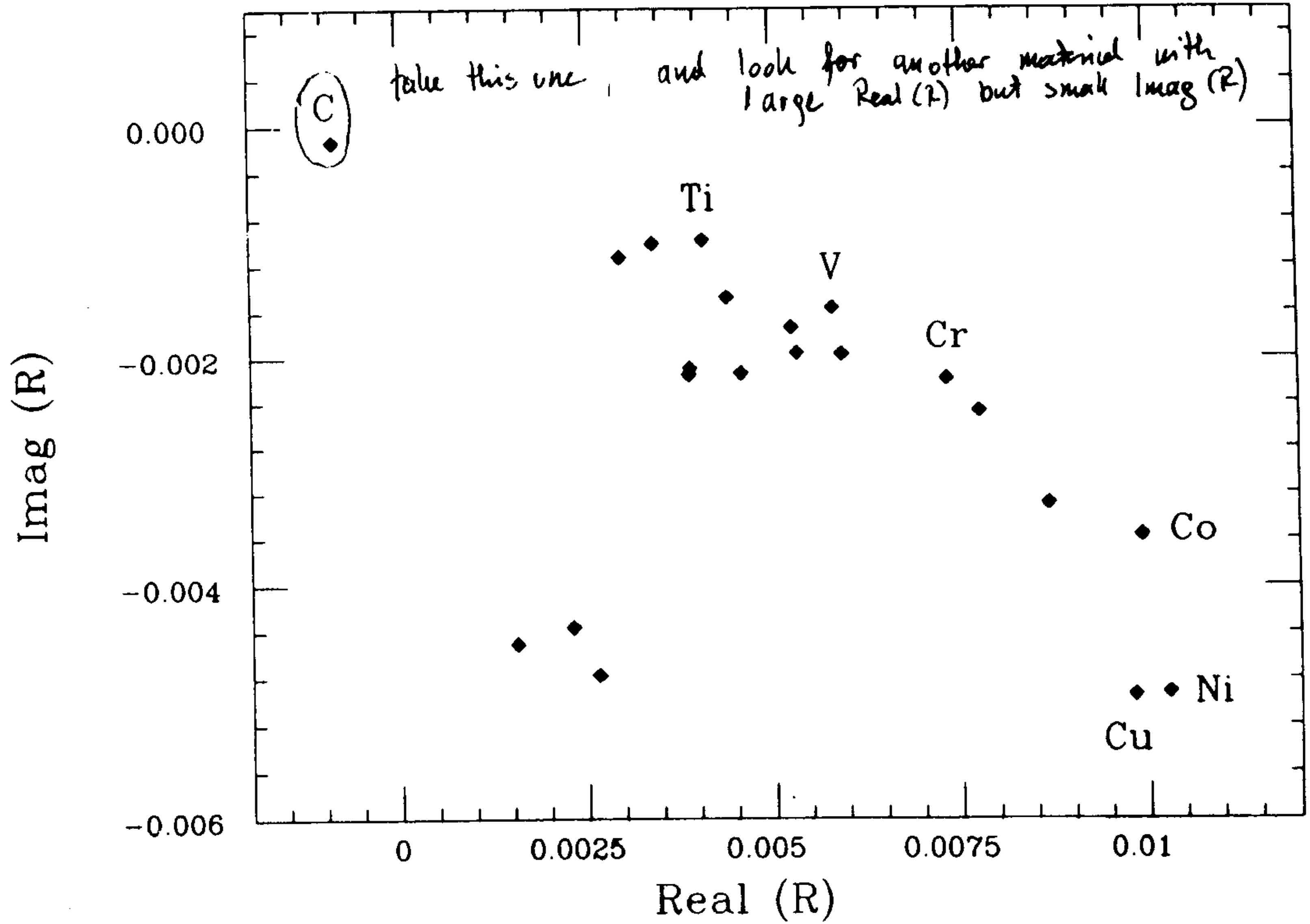
Real multilayer : N = 20 periods Ni / C

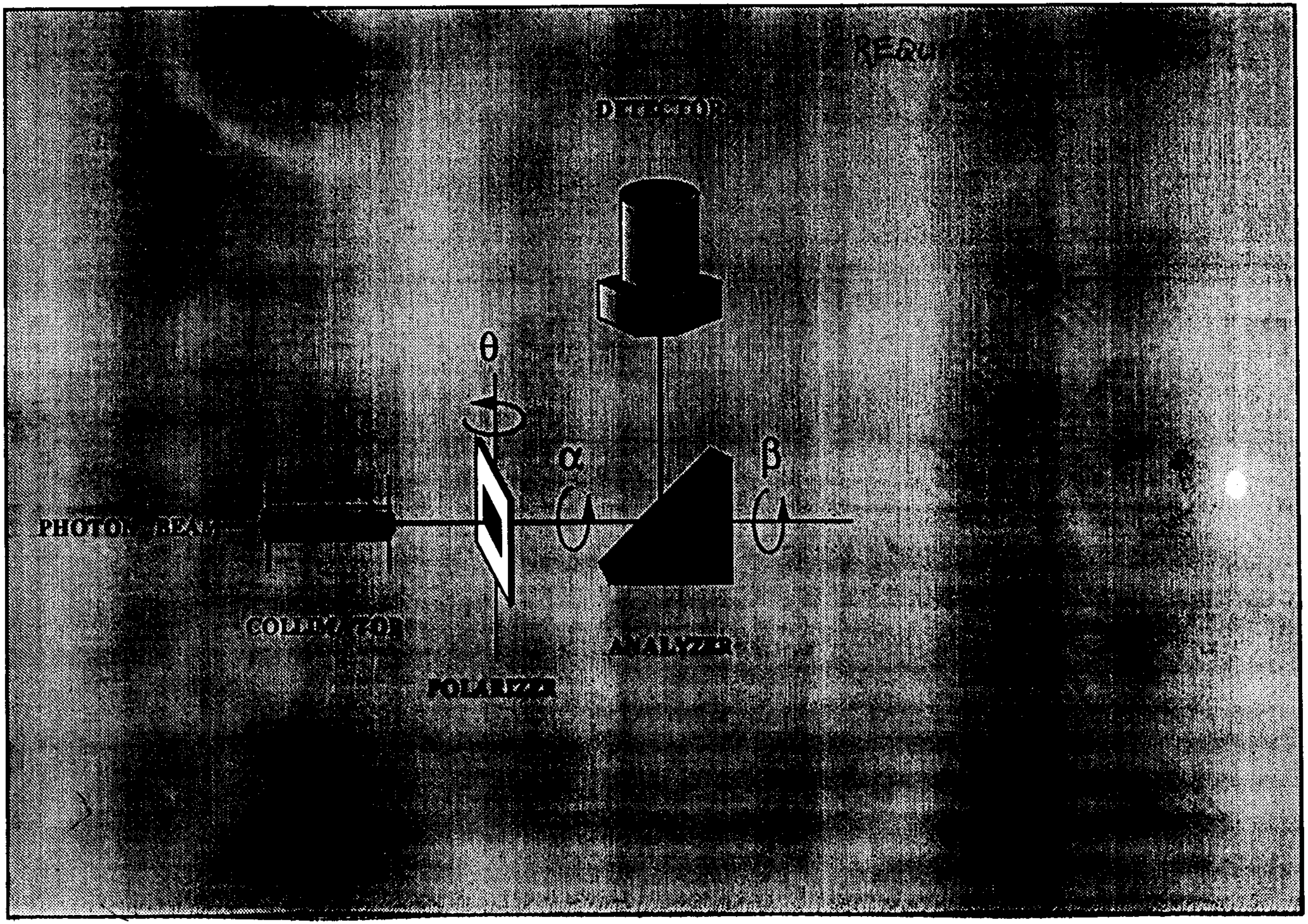


Appl. Optics, 36. 6329 (1997)

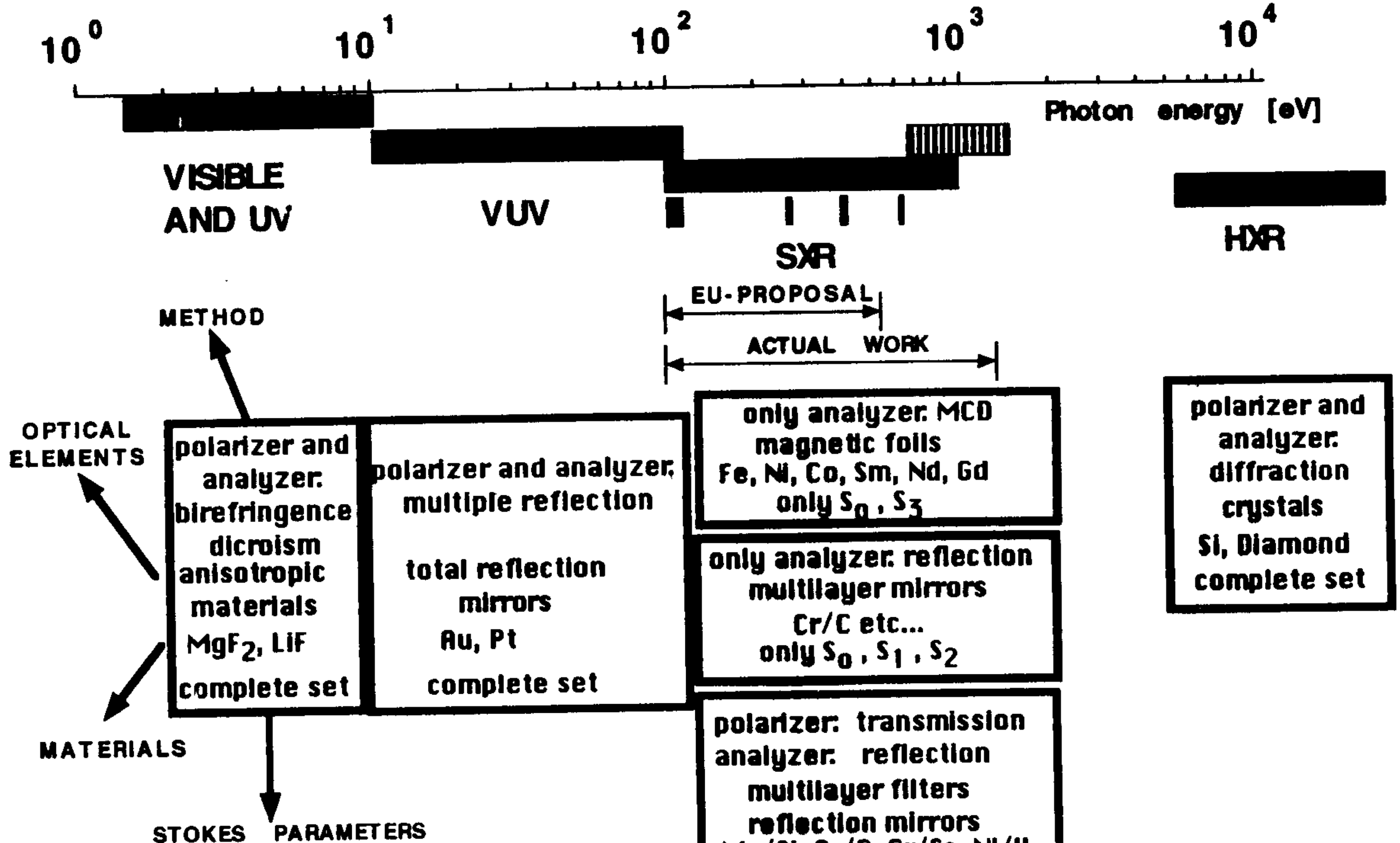
Components of reflexion coefficient · Performance optimization

for 280 eV photon energy



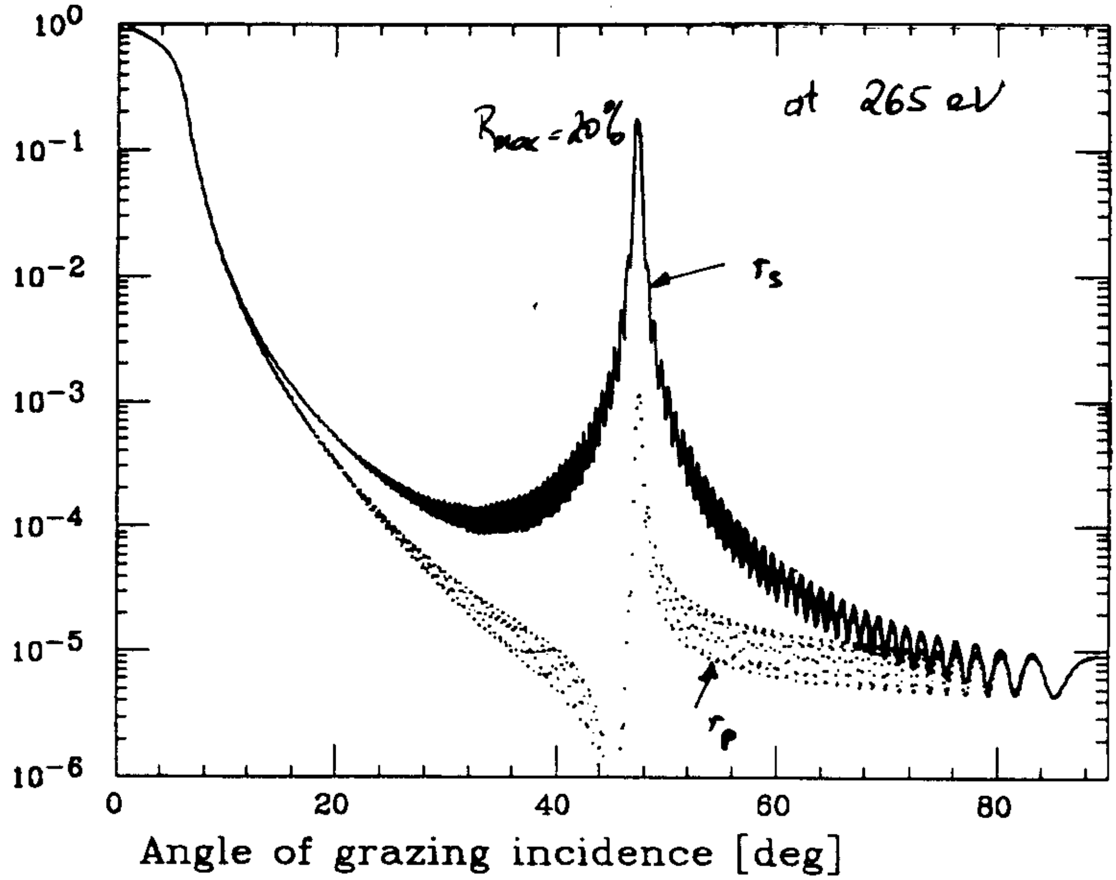

θ
α
β
POLARIZER
ANALYZER

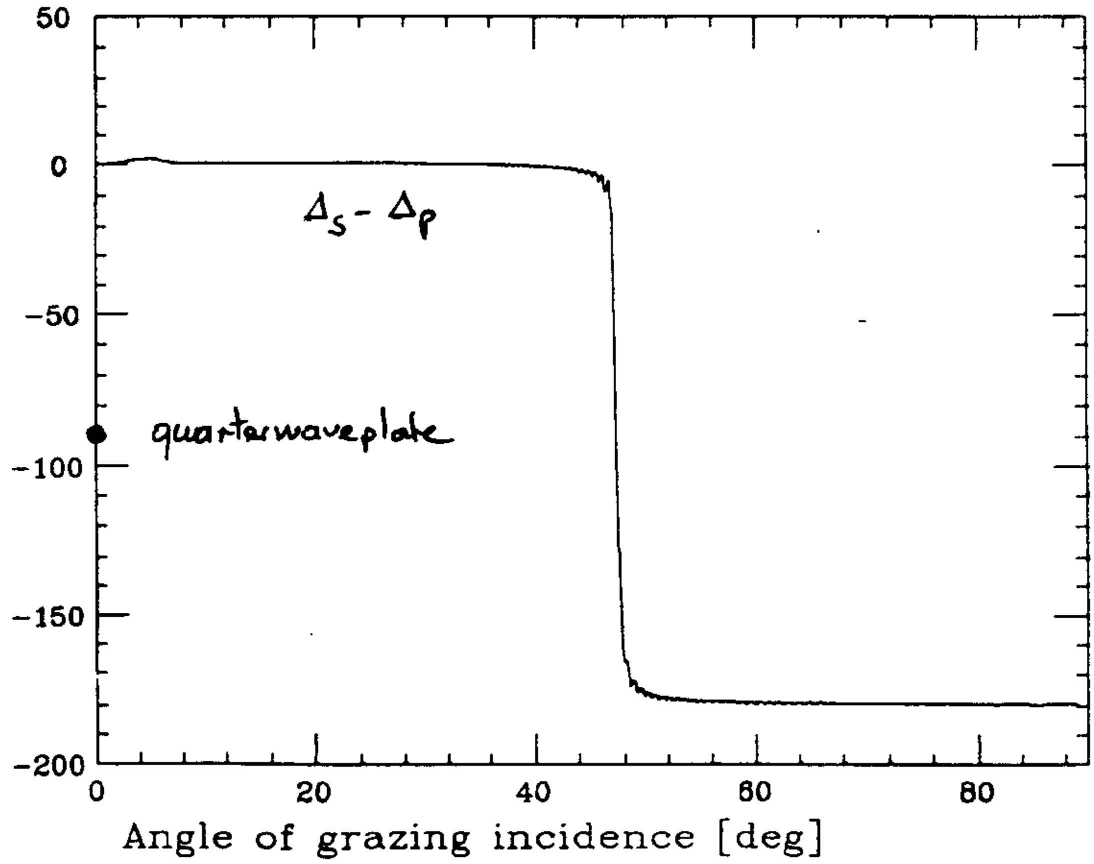
POLARIZATION ANALYSIS



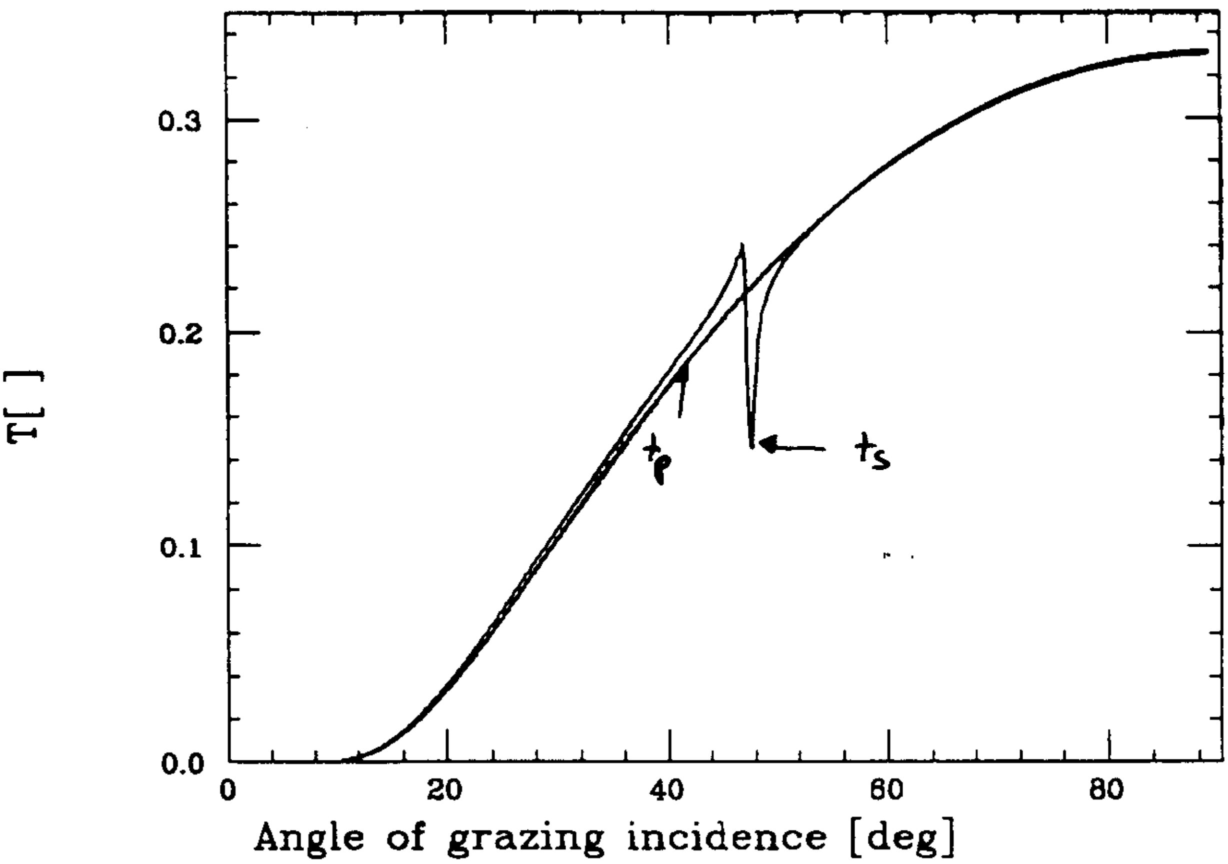
$$S_0 = (S_1^2 + S_2^2 + S_3^2)^{1/2} + S_4$$

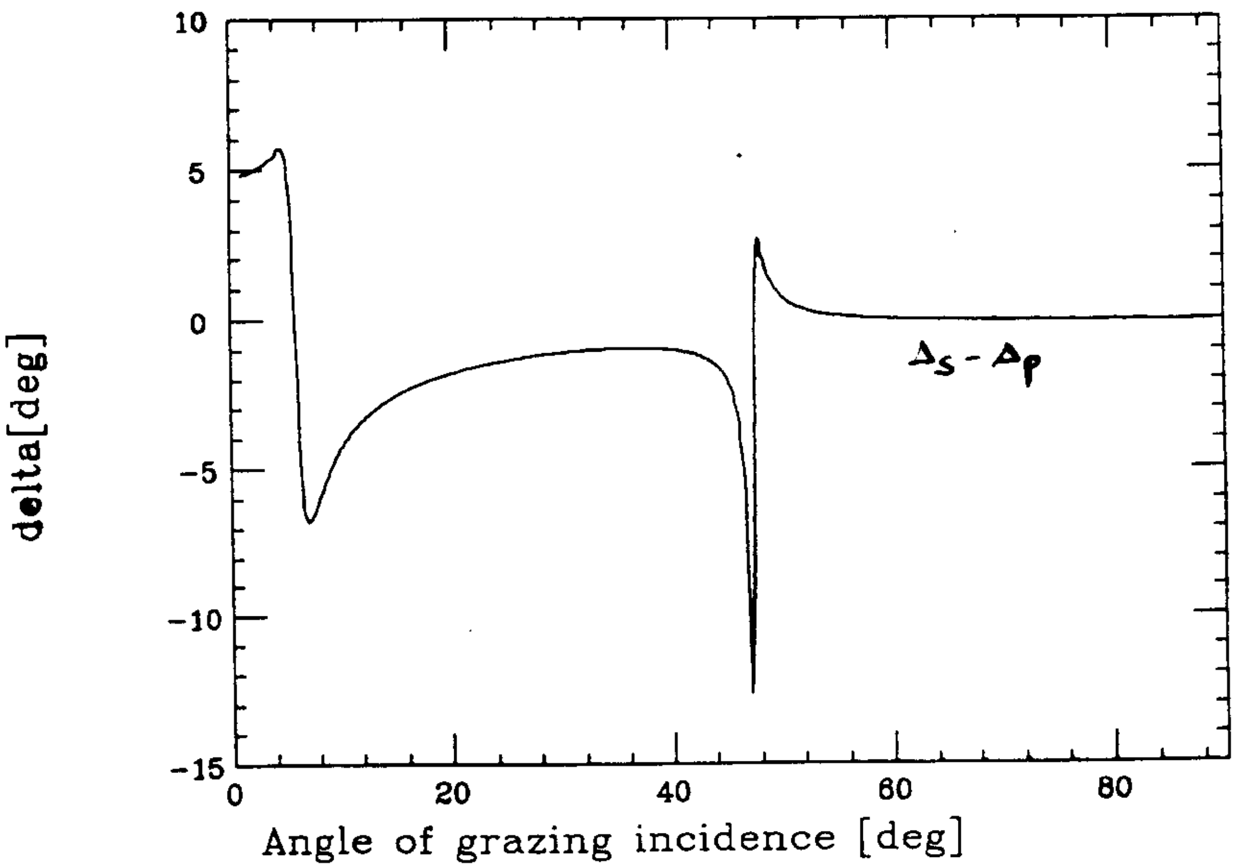
σ = 0.5 nm rms   3.21 nm spacing





Simulation for the same objects.

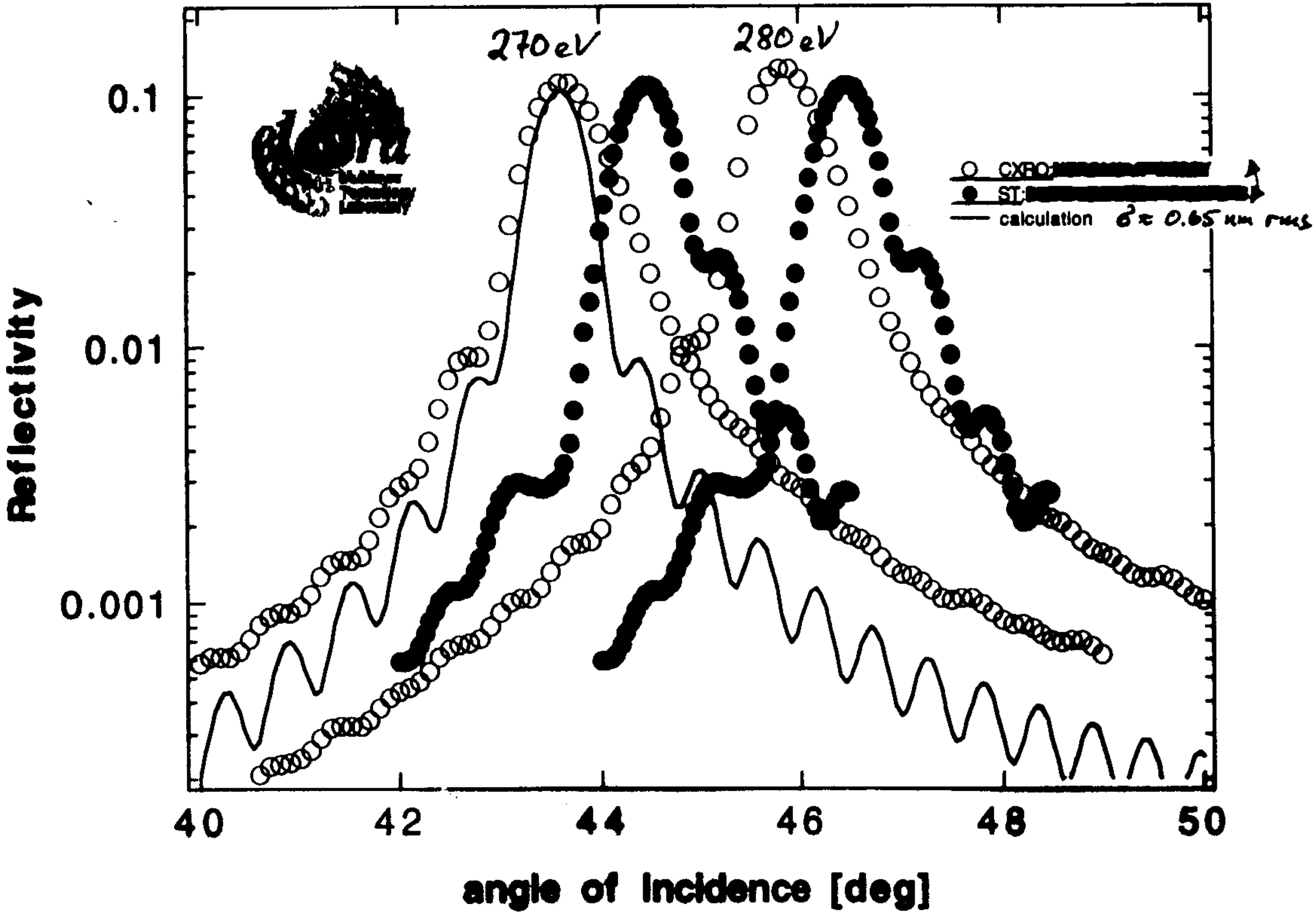




100 period multilayers with 1.07 nm Cr / 2.14 nm C sputtered onto silicon

○ produced at Center for x-ray optics, LBL

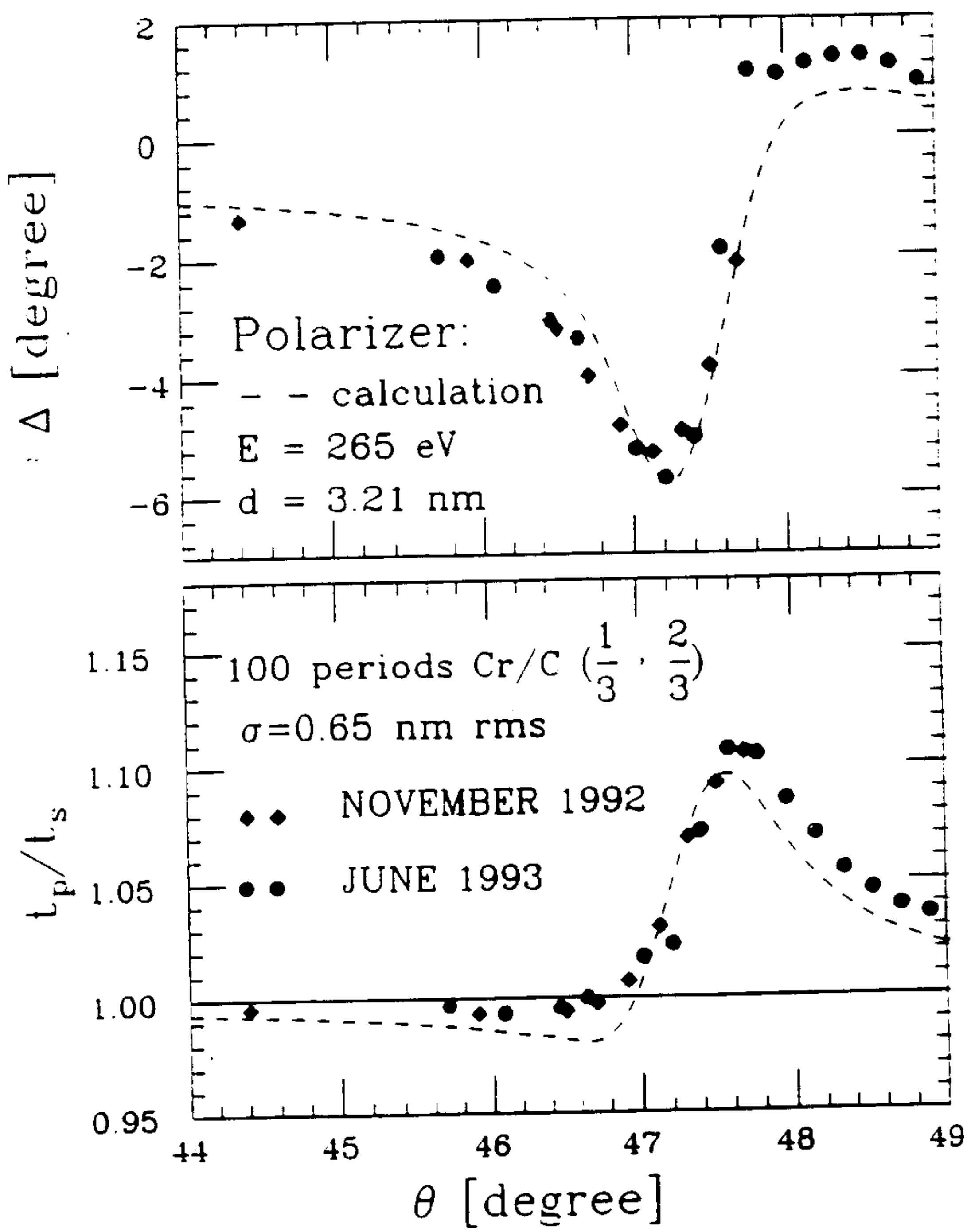
● produced at SINCROTRONE TRIESTE



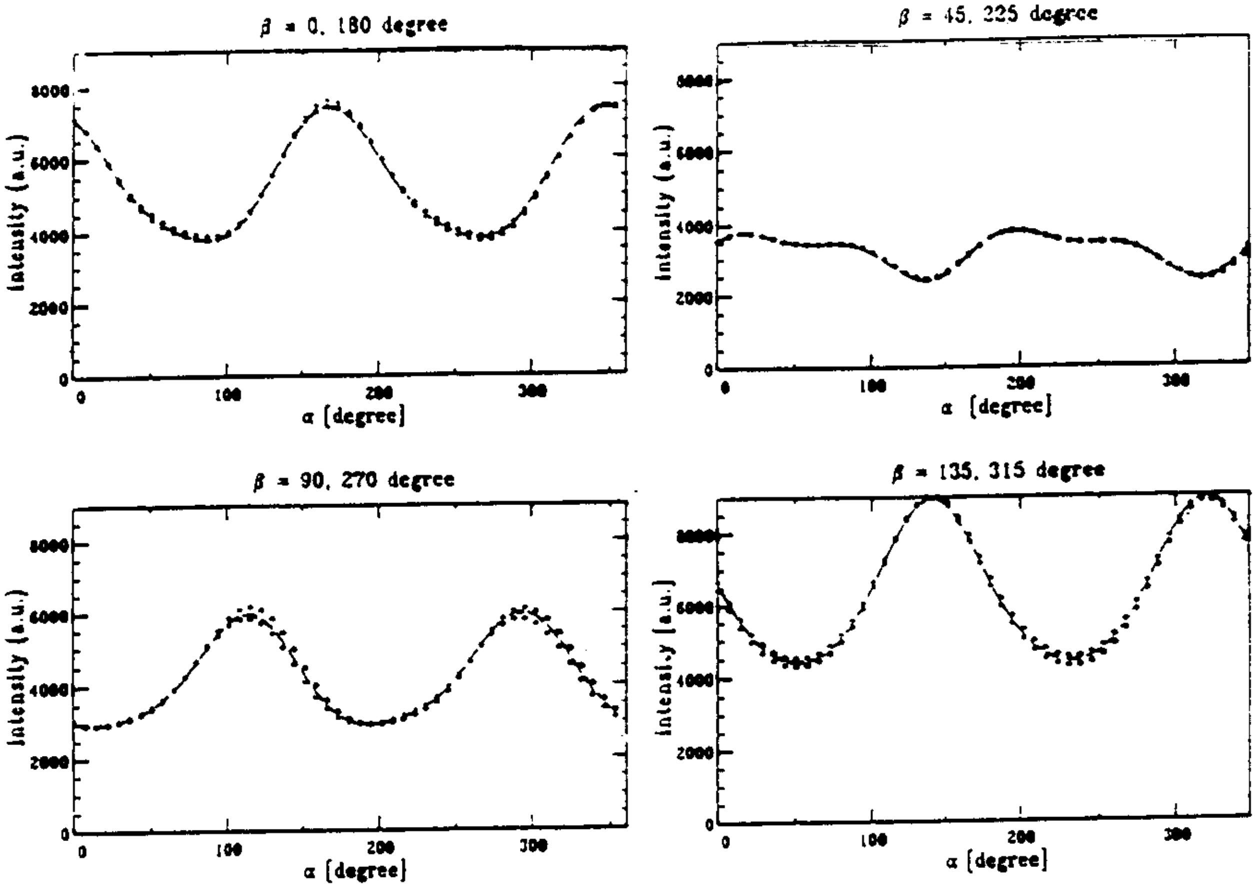
Soft x-ray phase retarders:

SINCROTRONE TRIESTE: Silvia Di Fonzo, Bernd R. Müller, Werner Jark
BESSY: Andreas Gaupp, Helmut Petersen, Franz Schäfers
CXRO, LBL: Jim Underwood

Appl. Opt. 33, 2624 (1994)



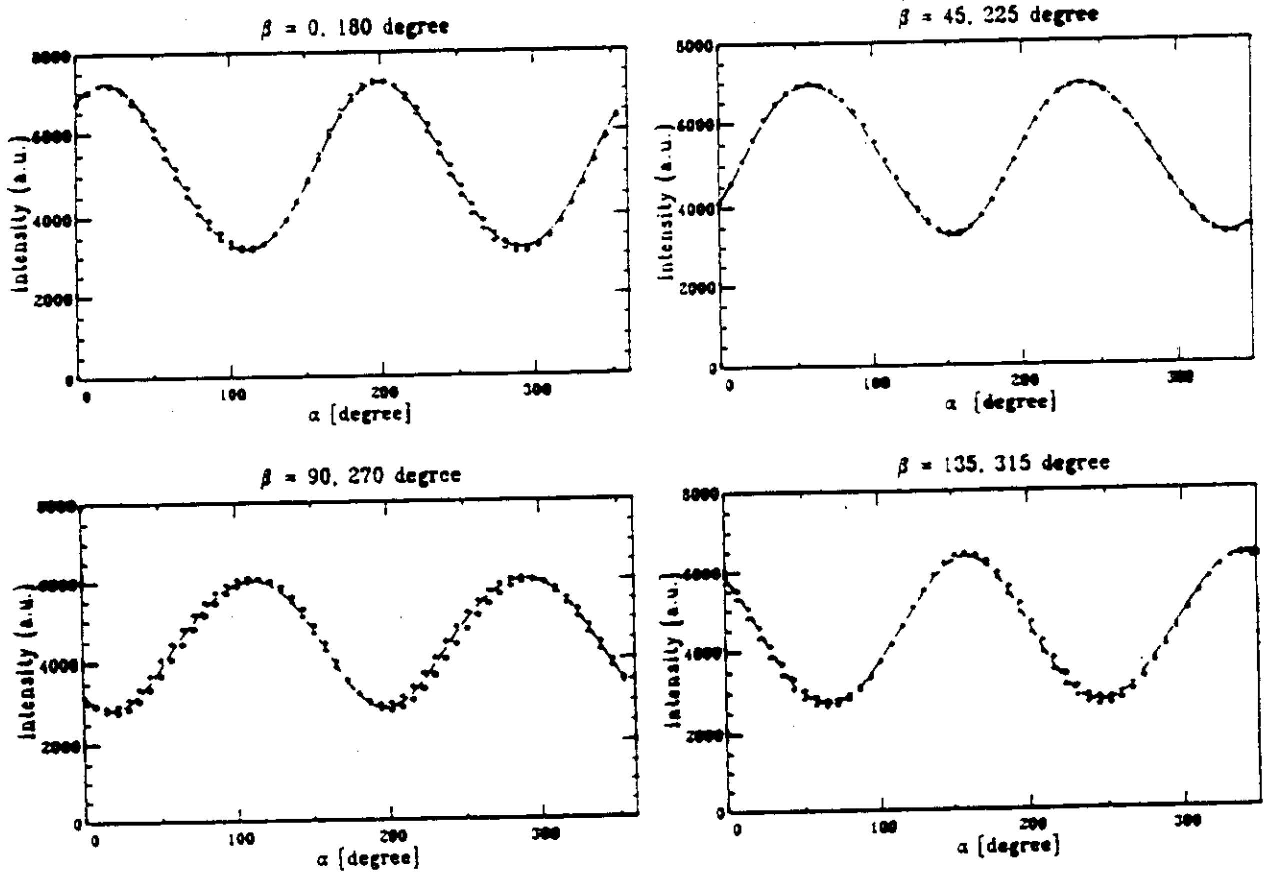
ACP2.02 ε_h=53.35, ε_v=54.5, I_{max}=39.9 Amp 91/09/14 S_1 = +.17 S_2 = −.[illegible] S_3 = .09



20:12:36 Gauss

10-JAN-92

ACP2.05 ε_h=53.35, ε_v=54.5, I_{max}=8.5 Amp 92/09/14 S_1 = .10 S_2 = .09 S_3 = .45



The BESSY polarimeter

(A. Gaupp and M. Mast: Rev. Sci. Instrum. **60**, 2213 (1989)

$t_{s1} = |t_{s1}| \exp(i\delta_{s1})$ $\qquad$ $r_{s2} = |r_{s2}| \exp(i\delta_{s2})$

$t_{p1} = |t_{p1}| \exp(i\delta_{p1})$ $\qquad$ $r_{p2} = |r_{p2}| \exp(i\delta_{p2})$

$\Delta_1 = \delta_{p1} - \delta_{s1}$ $\qquad$ $\Delta_2 = \delta_{p2} - \delta_{s2} = 0$

$\tan \Psi_1 = |t_{p1}|/|t_{s1}|$ $\qquad$ $\tan \Psi_2 = |r_{p2}|/|r_{s2}|$

Stokes-parameters: $\qquad$ S_0, S_1, S_2 and S_3

$I_{pass} =$ $\quad$ $^1/_2 (ts1^2 + tp1^2) *$ $\quad$ $^1/_2 (rs2^2 + rp2^2) *$

{	S_0		
$+ \cos 2\alpha$	$[-S_1 \cos 2\Psi_1]$	$+ \sin 2\alpha$	$[-S_2 \cos 2\Psi_1]$
$+ \quad \cos 2\beta$	$[-S_1 \cos 2\Psi_2 * (1 + \sin 2\Psi_1 \cos \Delta_1)/2]$	$+ \quad \sin 2\beta$	$[-S_2 \cos 2\Psi_2 * (1 + \sin 2\Psi_1 \cos \Delta_1)/2]$
$+ \cos 2\alpha \cos 2\beta$	$[+S_0 \cos 2\Psi_1 * \cos 2\Psi_2]$	$+ \sin 2\alpha \cos 2\beta$	$[+S_3 \sin 2\Psi_1 * \cos 2\Psi_2 \sin \Delta_1]$
$+ \cos 2\alpha \sin 2\beta$	$[-S_3 \sin 2\Psi_1 * \cos 2\Psi_2 \sin \Delta_1]$	$+ \sin 2\alpha \sin 2\beta$	$[+S_0 \cos 2\Psi_1 * \cos 2\Psi_2]$
$+ \cos 4\alpha \cos 2\beta$	$[-S_1 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$	$+ \sin 4\alpha \cos 2\beta$	$[-S_2 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$
$+ \cos 4\alpha \sin 2\beta$	$[+S_2 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$	$+ \sin 4\alpha \sin 2\beta$	$[-S_1 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$}

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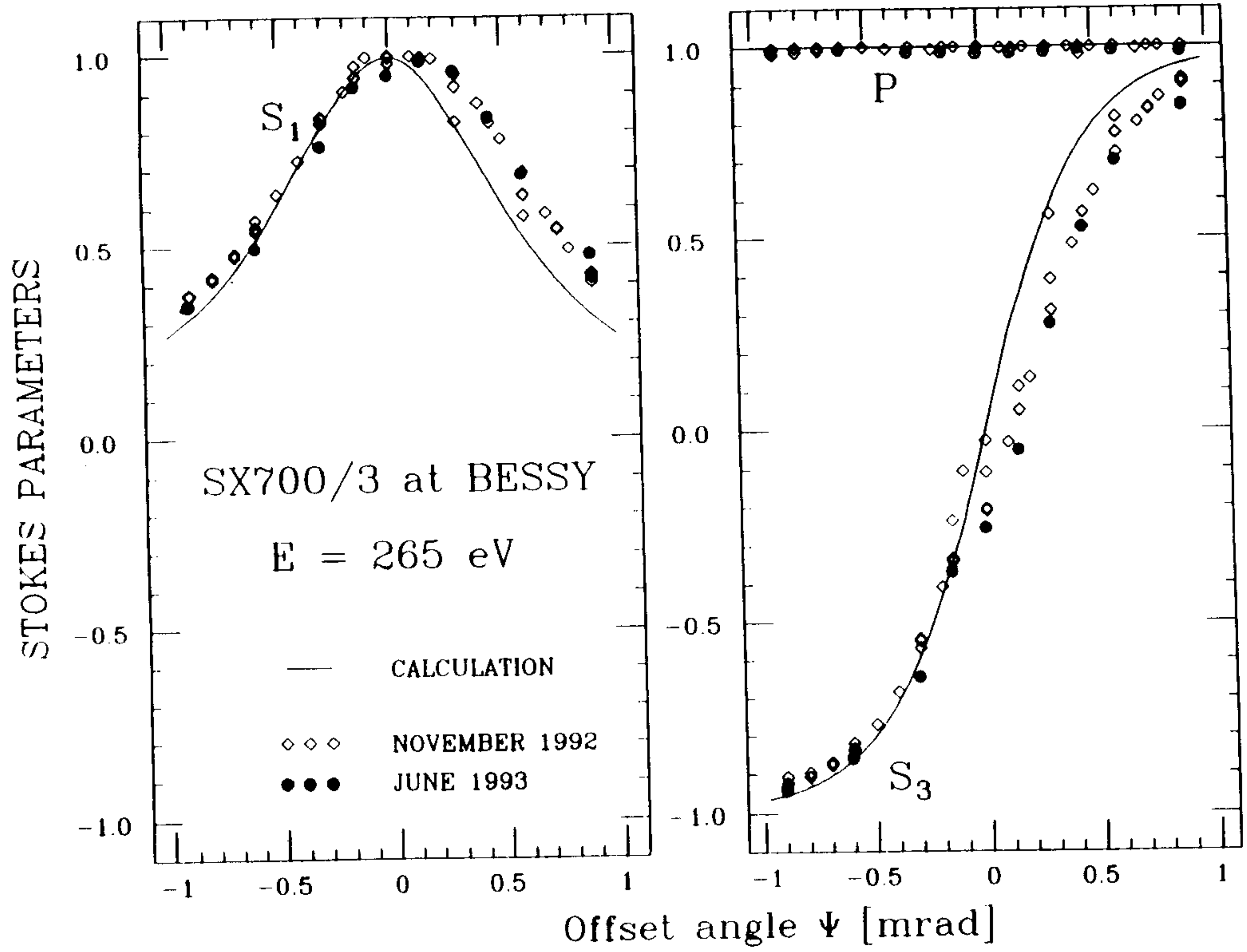


calculation does not consider polarizing and depolarizing effects in the monochromator

Phase-shifter of group of ... in ...
(University of Bielefeld) for use at BESSY

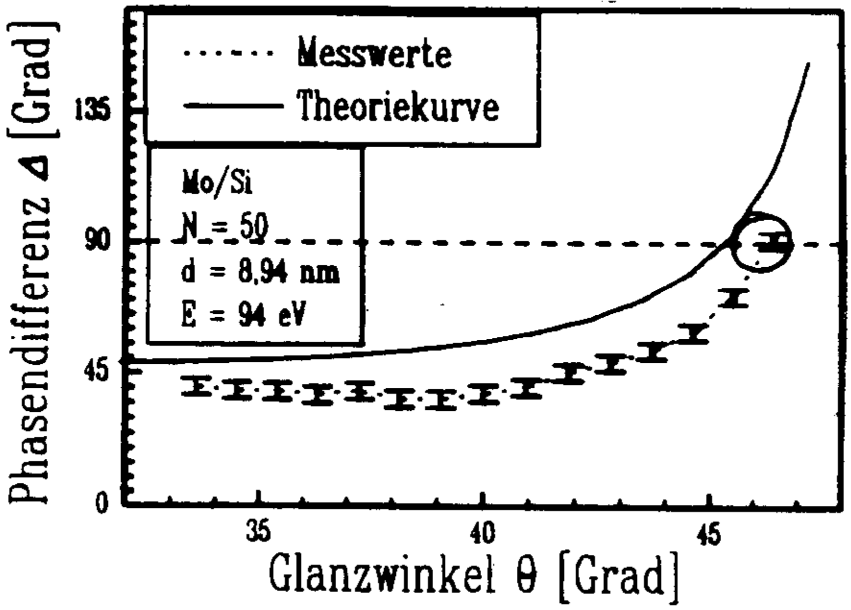
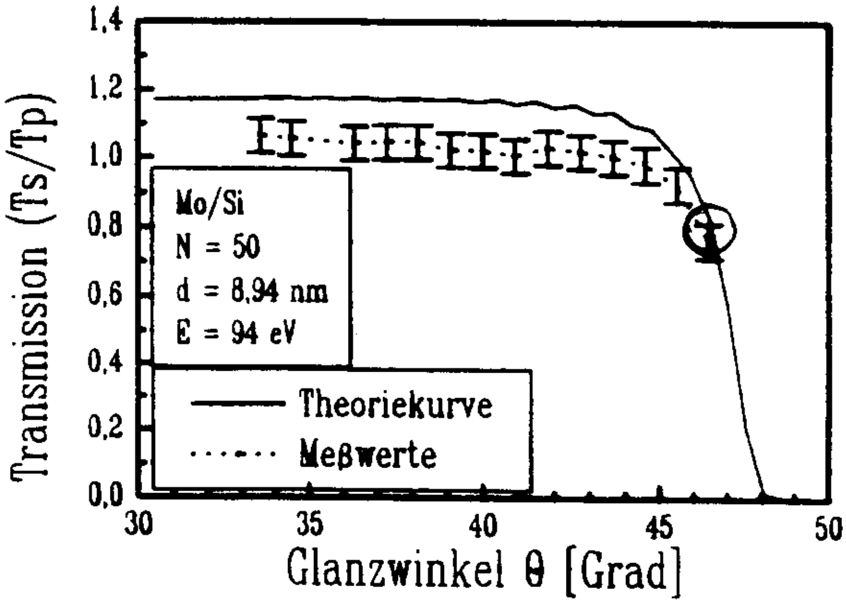


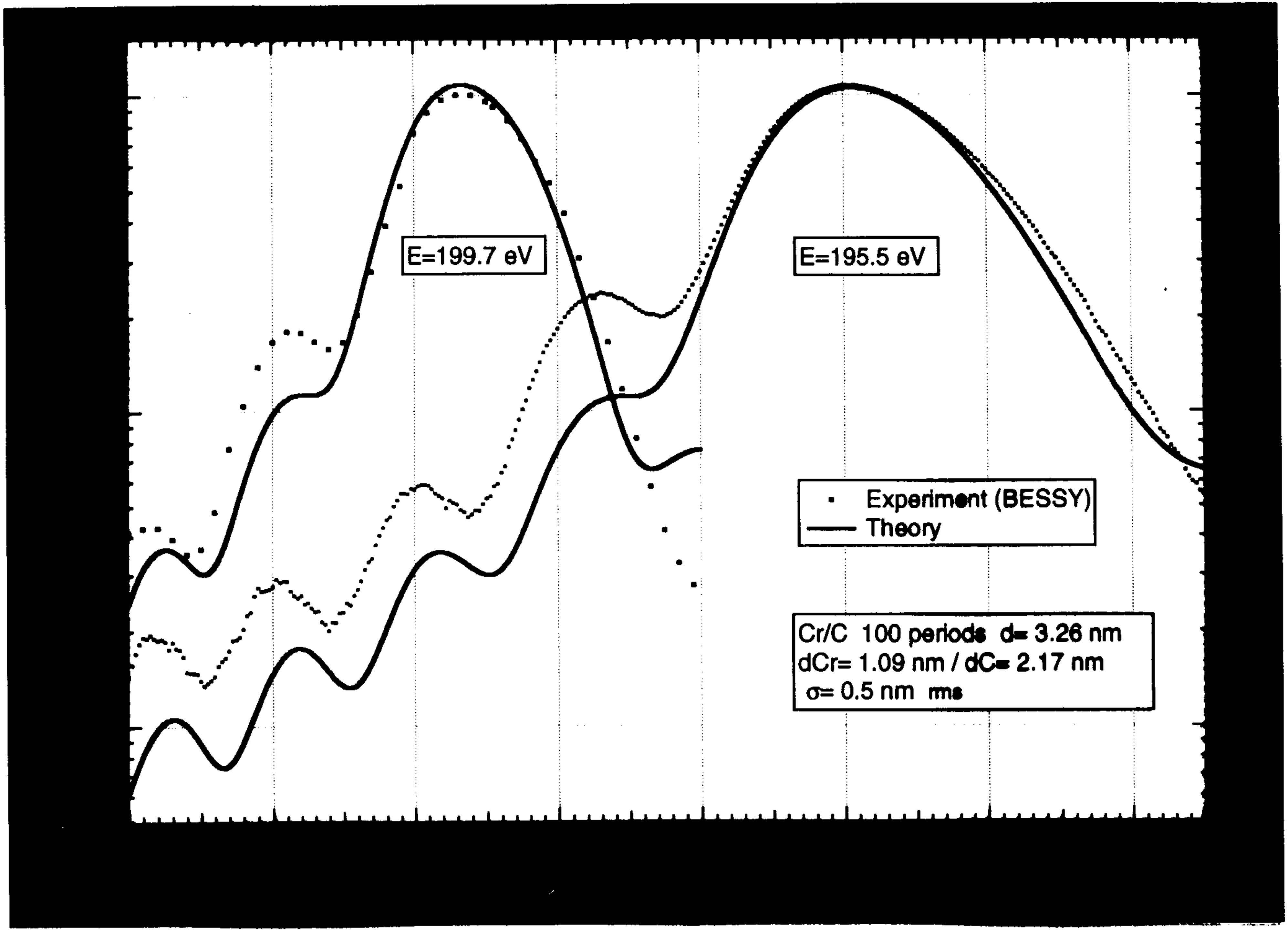
Abbildung 3: Phasenschiebung Δ des TML aufgetragen über den Glanzwinkel θ



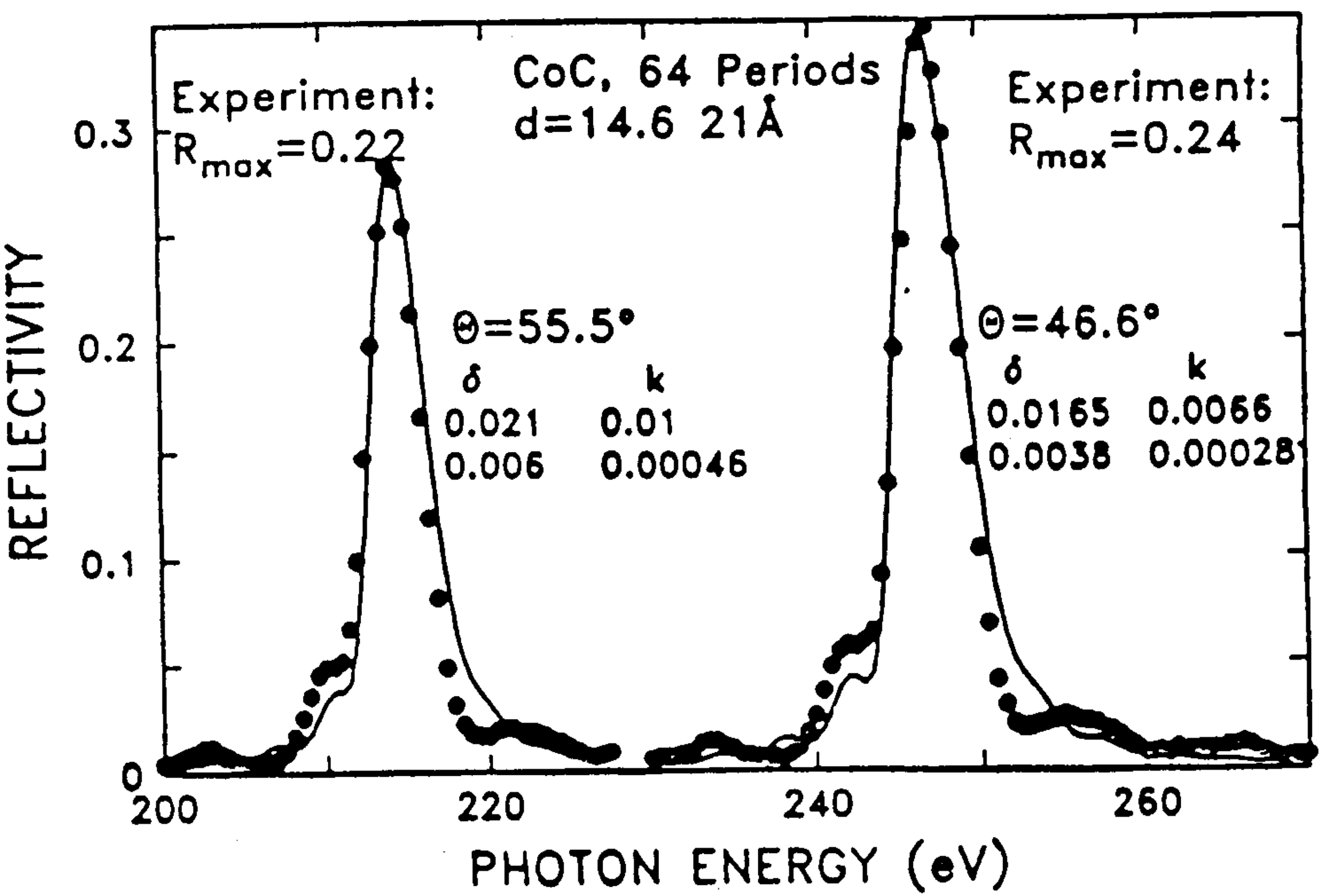
$T \approx$ %

Abbildung 4: Transmissionsverhältniss des TML von s– zu p–polarisierter Komponente aufgetragen über den Glanzwinkel θ

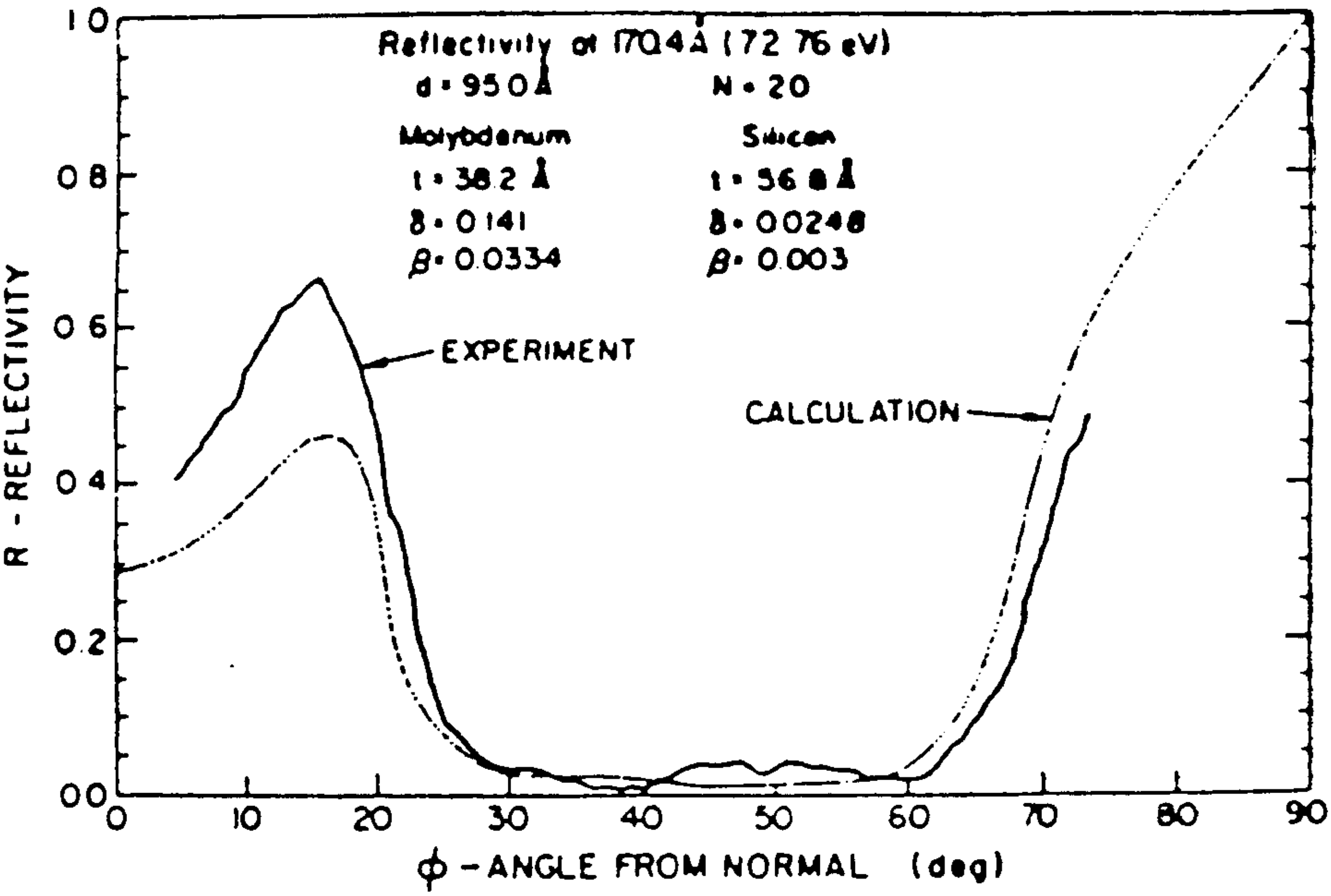
similar objects produced also by
Kimura (SPRING 8) and by
Hortright (Center for x-ray optics, LBL)


E=199.7 eV
E=195.5 eV
Experiment (BESSY)
Theory
Cr/C 100 periods d= 3.26 nm
dCr= 1.09 nm / dC= 2.17 nm
σ= 0.5 nm rms

E. Spiller et al.



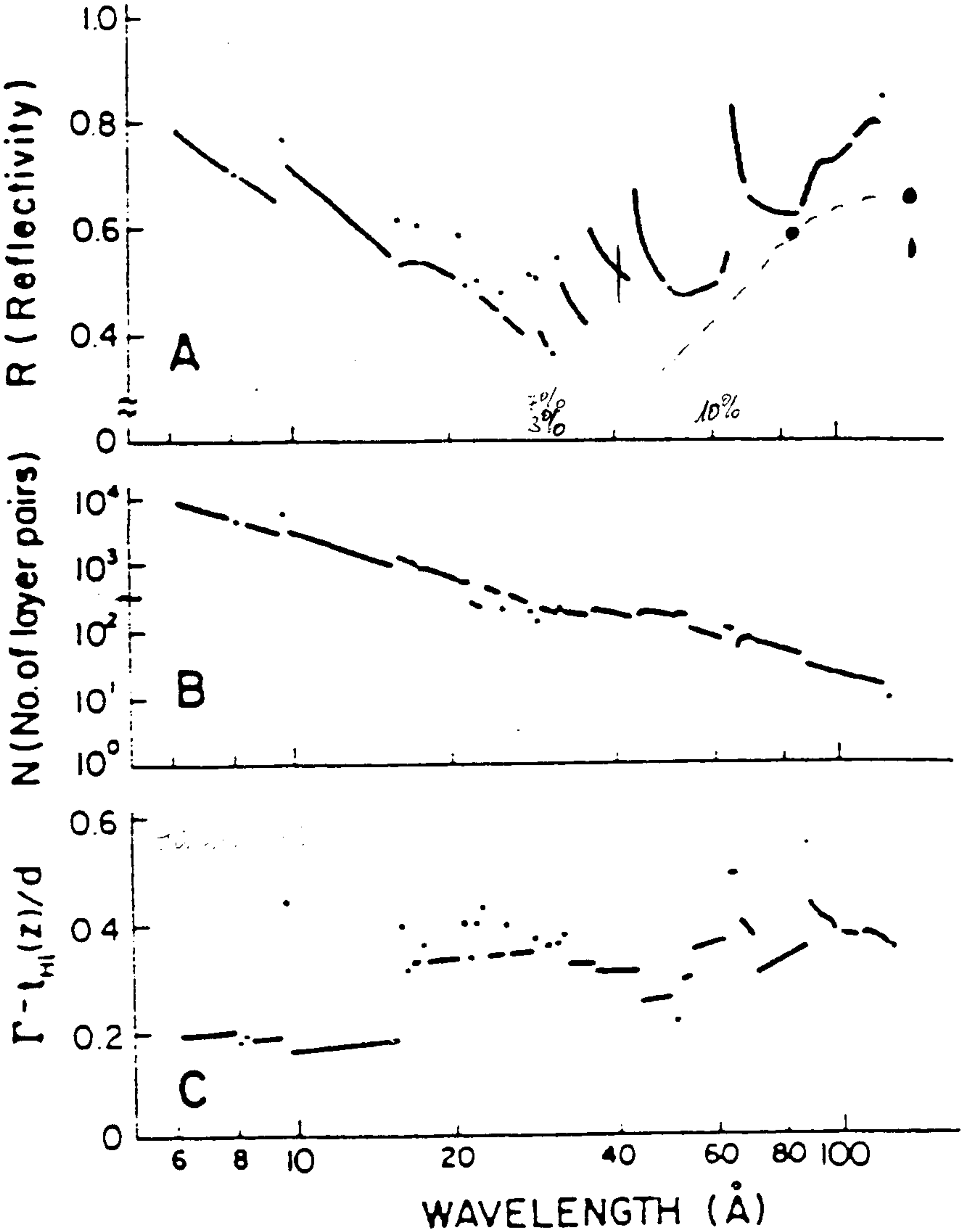
T. W. Barbee et al



Rosenbluth - Tables

A.E. Rosenbluth, Ph. D. Thesis, Rochester (1982)

for normal incidence



Imaging with normal incidence optics with multilayers

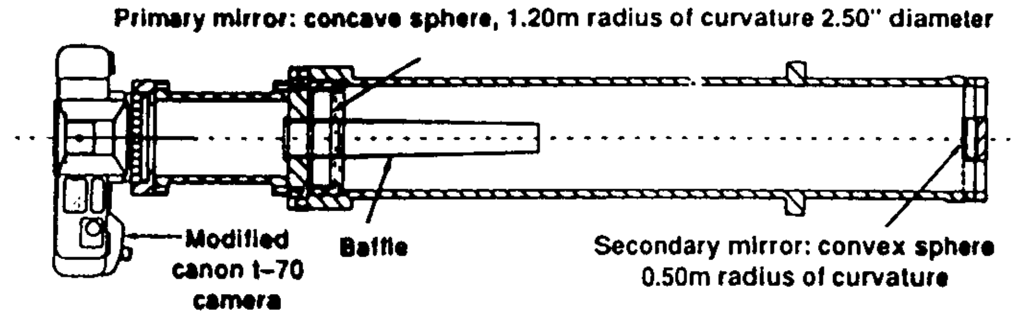


Fig. 9. Schematic of the normal incidence Cassegrain multilayer telescope.[56] Angular resolution is 1.2 arcsec, effective focal length is 2m, and bandpass is 6.5% at 175 Å.

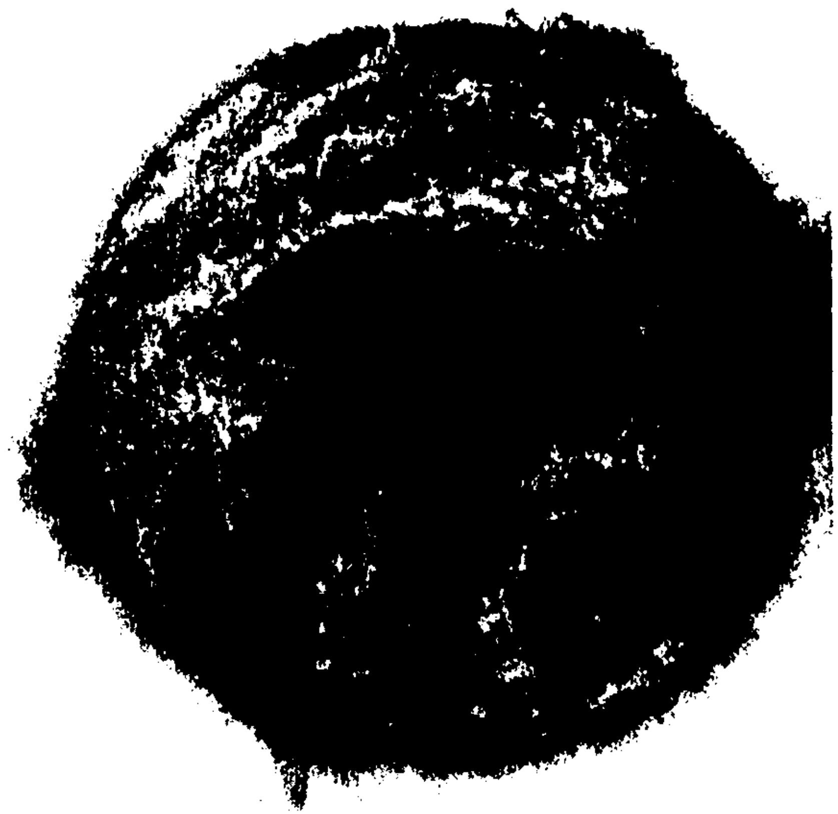


Fig. 10. Photograph of the solar corona at 1,000,000 K obtain[ed] with a multilayer Cassegrain telescope. The multilayers w[ere] molybdenum-silicon deposited using magnetron sputter co[...] physical vapor deposition technology.

The work which has been performed at the
SINCROTRONE TRIESTE
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