united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR/1270-25

SCHOOL ON SYNCHROTRON RADIATION

6 November - 8 December 2000

Miramare - Trieste, Italy

Supported in part by the Italian Ministry of Foreign Affairs in connection with the SESEME project

Co-sponsors: Sincrotrone Trieste, Società Italiana di Luce di Sincrotrone (SILS) and the Arab Fund for Economic and Social Development

The application of multilayer coatings in synchrotron radiation research

W. Jark
Sincrotrone Trieste
Italy

School on Synchrotron Radiation
ICTP, November 22nd, 2000

The application of multilayer coatings in synchrotron radiation research

Werner Jark

Sincrotrone Trieste
Multilayers and Polarization
S.S. 14 km 163.5 in Area Science Park
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) H[illegible] do we [illegible] 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 [illegible] to use these devices in the soft [illegible] 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: $(1/f) = (n-1)((1/r1) + (1/r2))$ r1, r2 = 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	$6\ 10^{-5}$	$4\ 10^{-7}$
[illegible]	0.37	0.08	0.0014	$1\ 10^{-6}$

[illegible] 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>

E. M. field propagation in film systems:

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

E_{tang} = const at interface

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

d_j = thickness, λ = wavelength,

$g_j = \tilde{n}_j \sin\theta_j \qquad \tilde{\varepsilon}_j = \tilde{n}_j^2 \qquad \tilde{n}_j = 1 - \delta + i\beta$

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

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

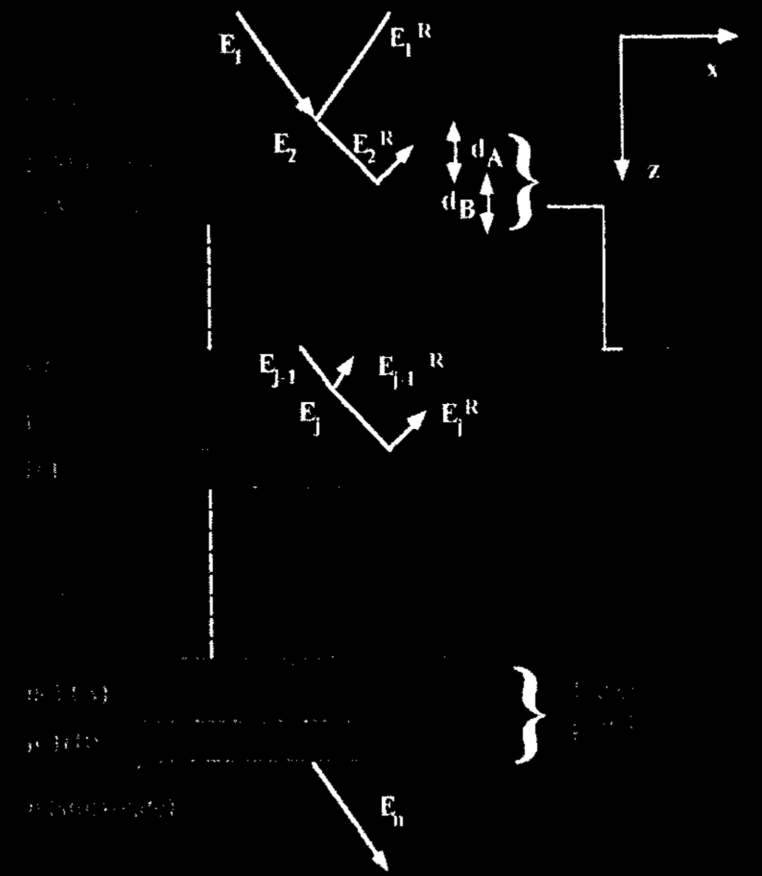
Solution => Recursion equation

$$R_{j,j+1} = a_j^4 \left[\frac{R_{j+1,j+2} + J_{j,j+1}}{R_{j+1,j+2}\, J_{j,j+1} + 1}\right] \qquad \mathbf{R} = \frac{I}{I_0} = |R_{12}|^2$$

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

$$J_{j,j+1}(s-pol) = \frac{E_j^R}{E_j} = \frac{g_j - g_{j+1}}{g_j + g_{j+1}}$$

$$J_{j,j+1}(p-pol) = \frac{g_j/\tilde{n}_j^2 - g_{j+1}/\tilde{n}_{j+1}^2}{g_j/\tilde{n}_j^2 + g_{j+1}/\tilde{n}_{j+1}^2}$$



Do not be afraid!

The job is done already by the Center for X-ray Optics at LBNL at Berkeley, CA (USA):
at
http://www-cxro.lbl.gov/optical_constants
and at
http://www-cxro.lbl.gov/optical_constants/multi2.html

And if you want to analyse data, ask the ESRF for the XOP software package, which contains the program IMD of David Windt.

Production:

[illegible]

NO!!

Evaporation:

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

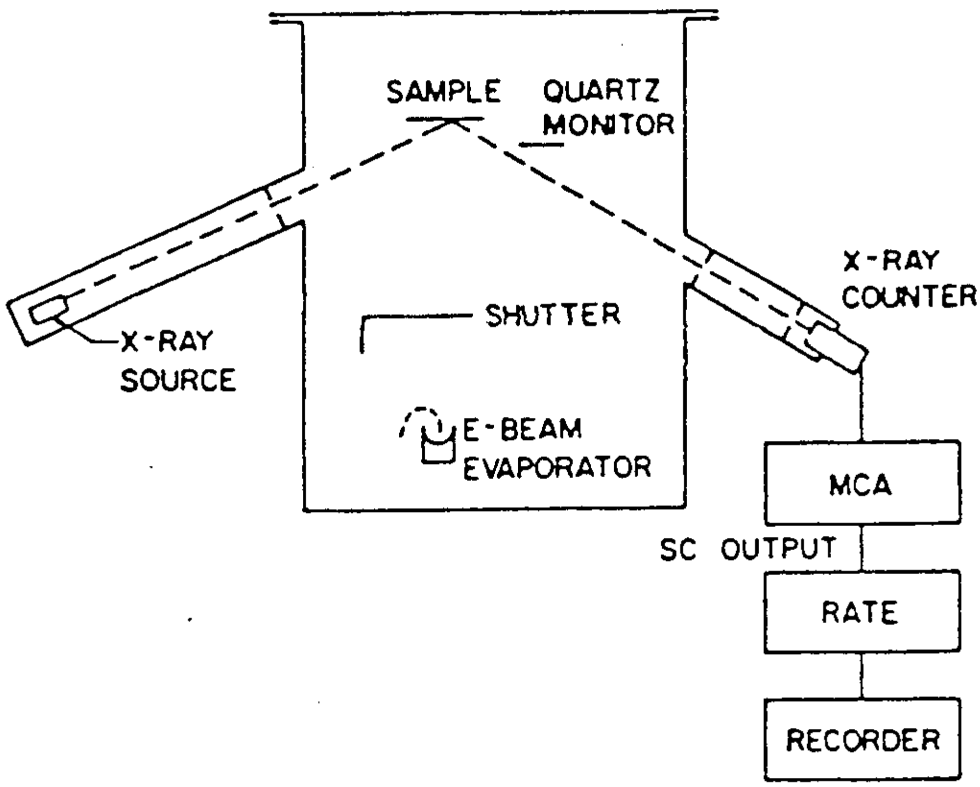
Sputtering:

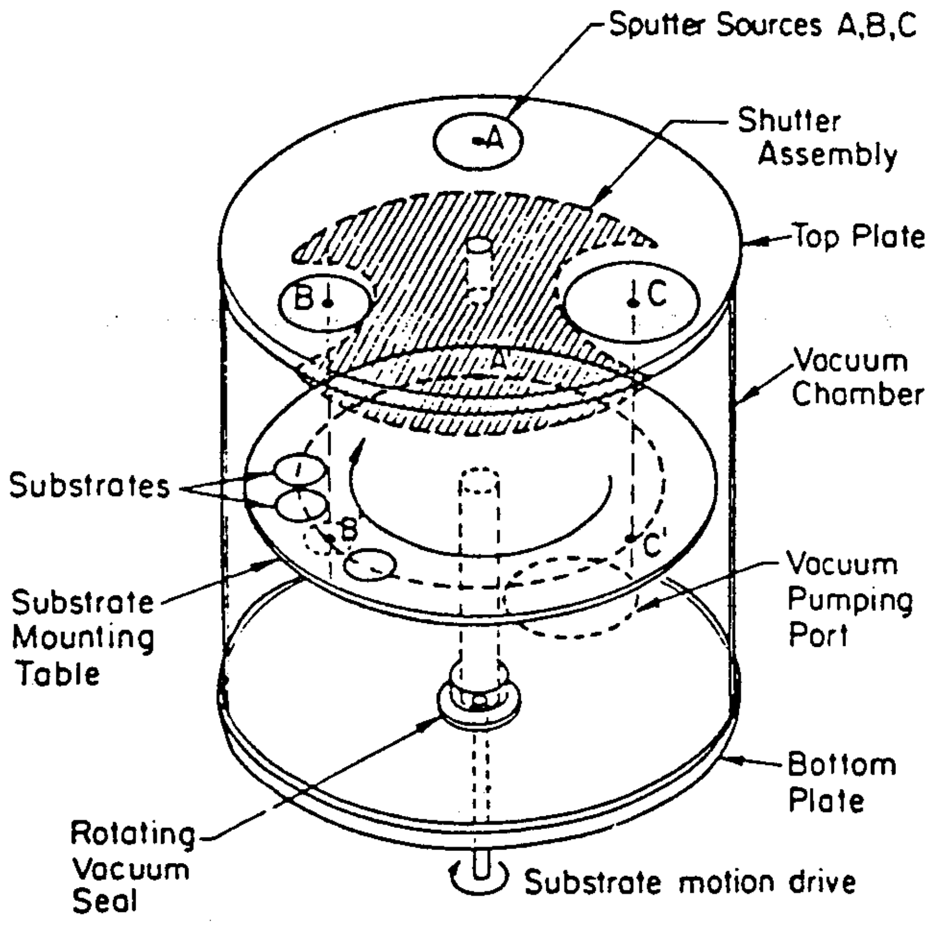
- homogenity over large sample sizes
- simultaneous bombardement of sample with plasma electrons
- plasma gas inclusions ($p \approx 1 \dots 100$ mbar)
- reactions with restgas of vacuum

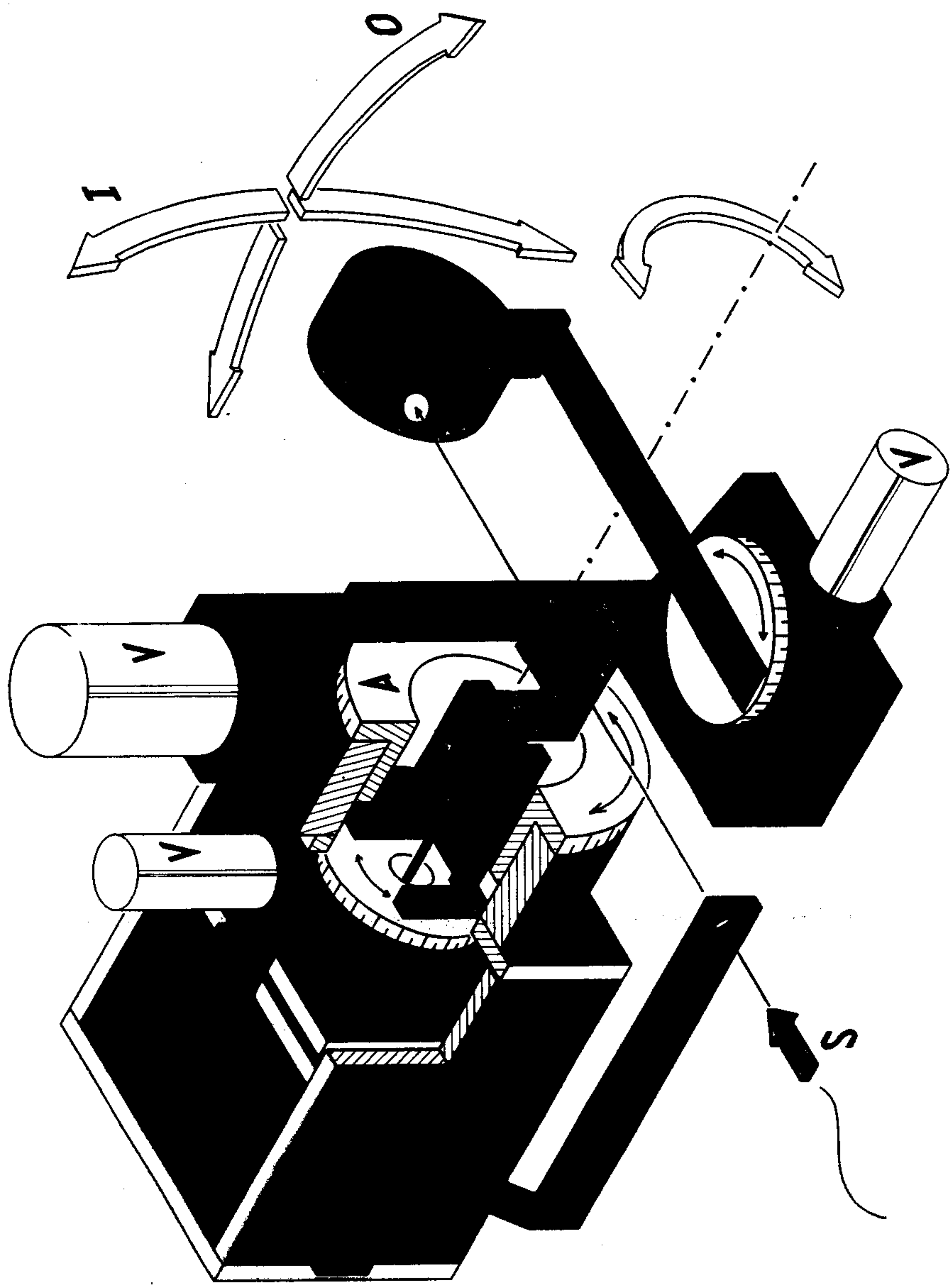
but: easy monitoring and very repeatable due to plasma stability and reproducibility [illegible]

=> monitoring by timing

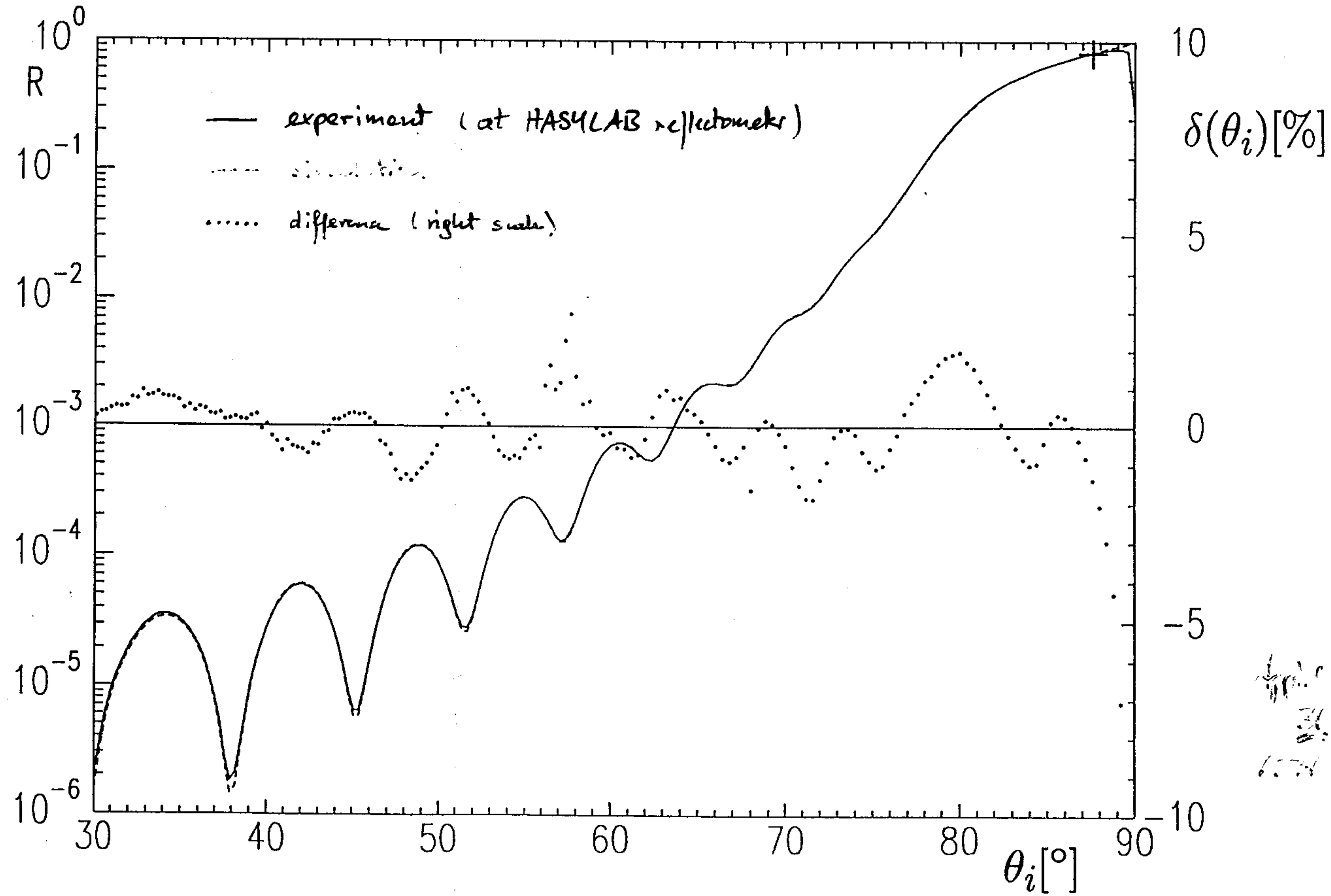
[illegible]

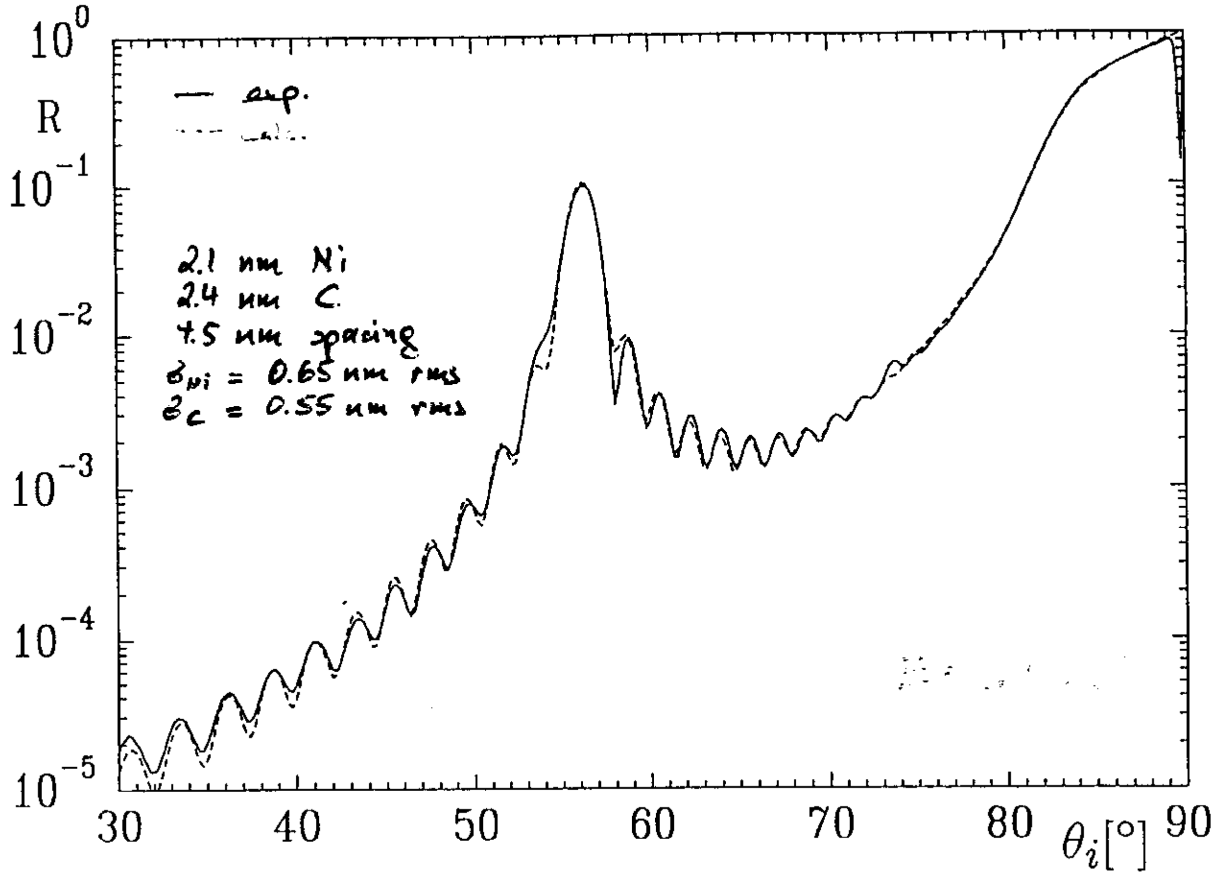

SAMPLE
QUARTZ MONITOR
X-RAY COUNTER
SHUTTER
X-RAY SOURCE
E-BEAM EVAPORATOR
MCA
SC OUTPUT
RATE
RECORDER


Sputter Sources A,B,C
A
Shutter Assembly
Top Plate
B
C
A
Vacuum Chamber
Substrates
B
C
Substrate Mounting Table
Vacuum Pumping Port
Bottom Plate
Rotating Vacuum Seal
Substrate motion drive

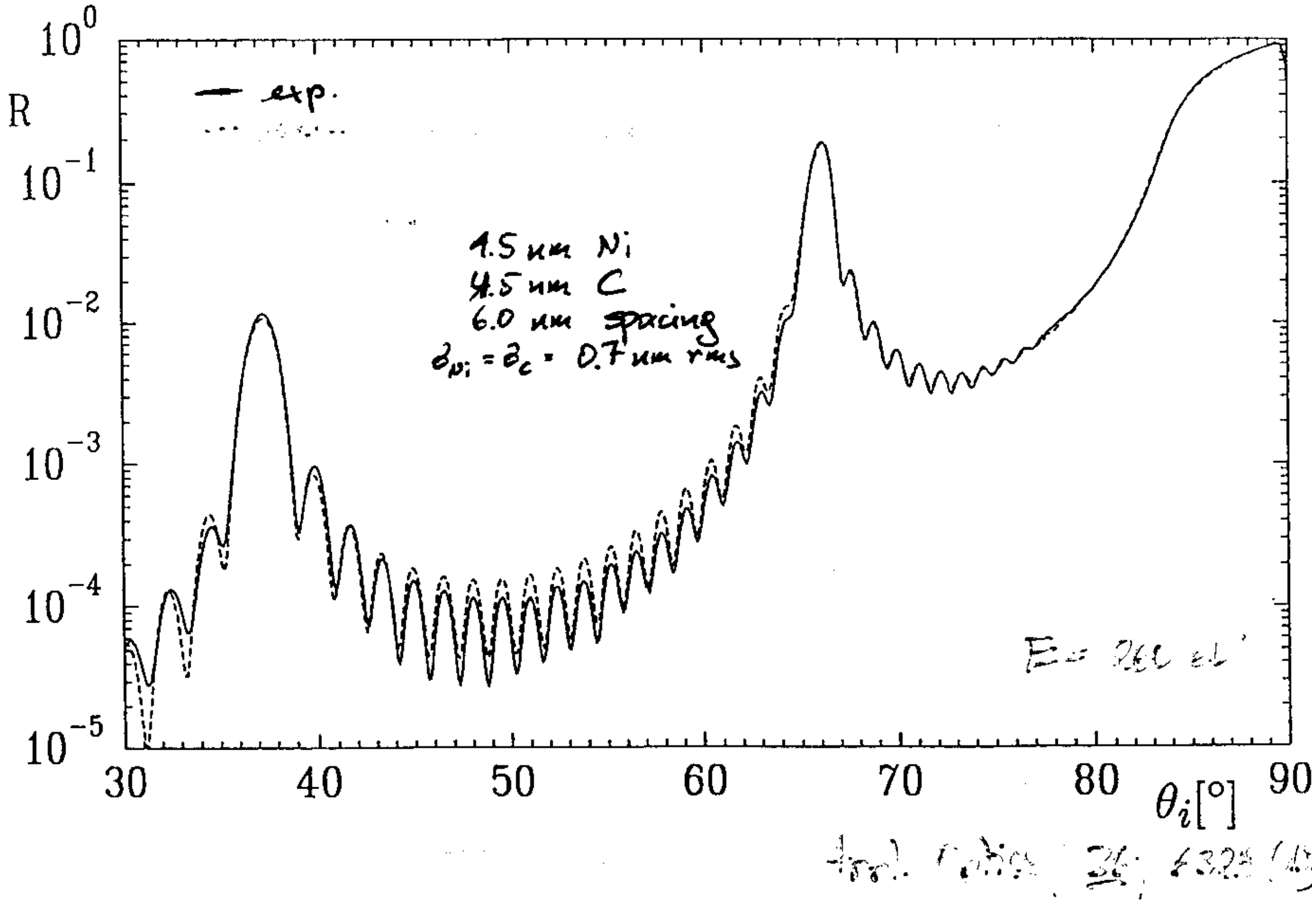

I
O
V
A
S

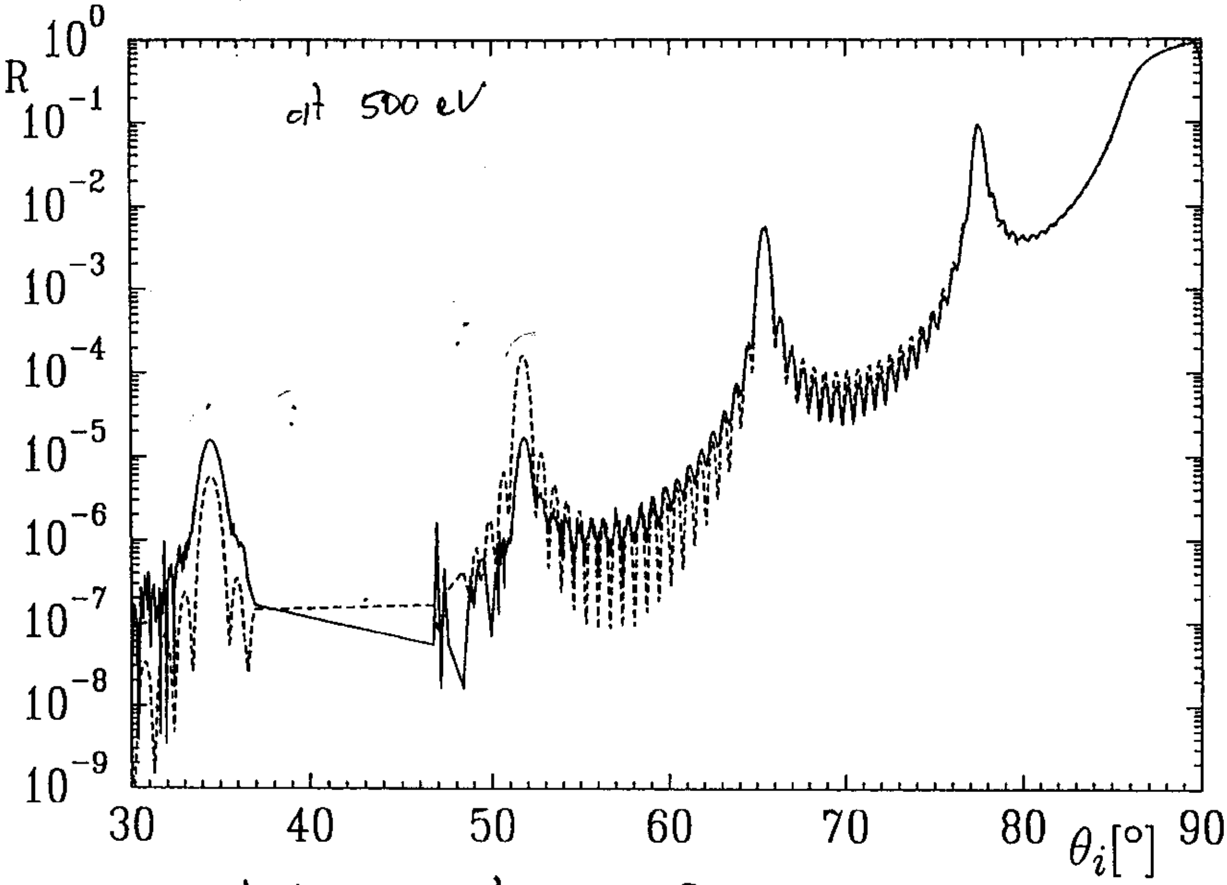
a simple Ni - film



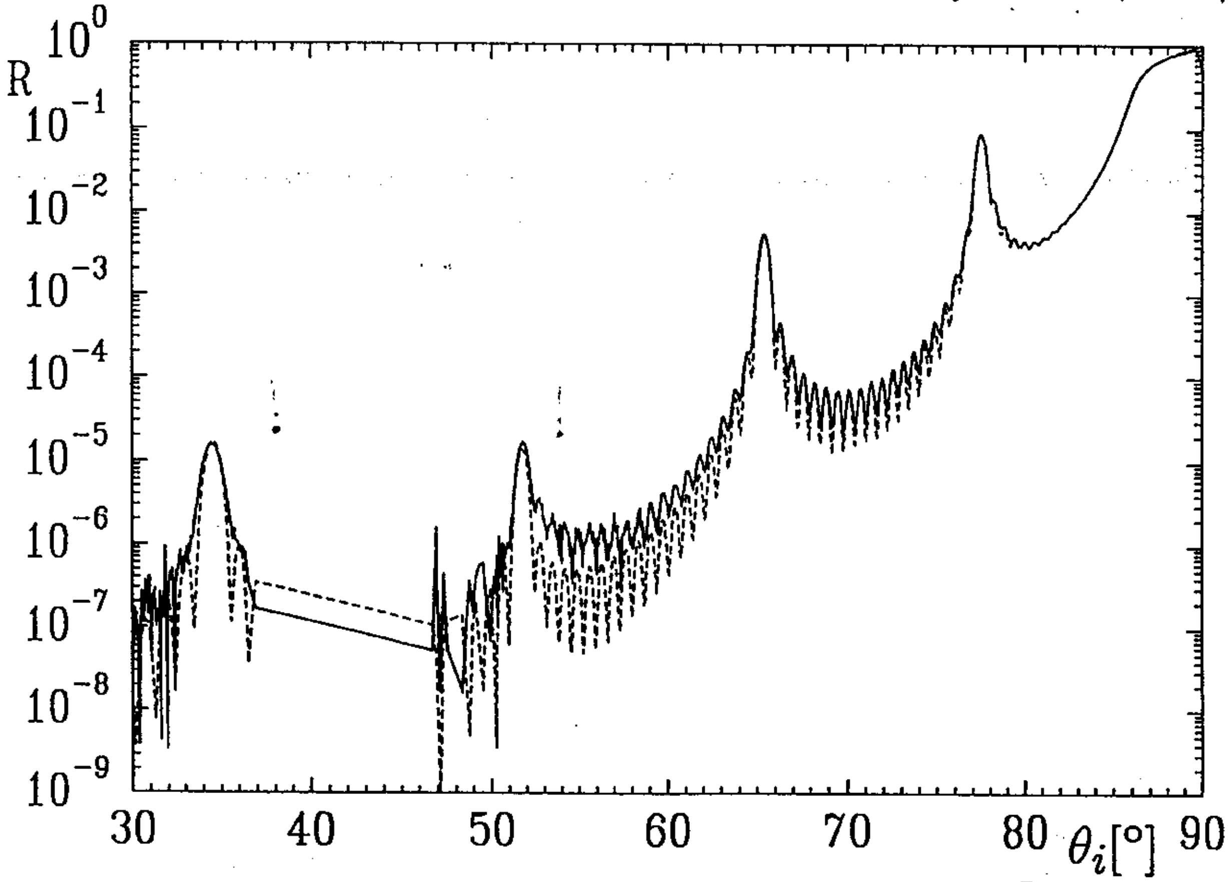


N = 20 periods Ni / C

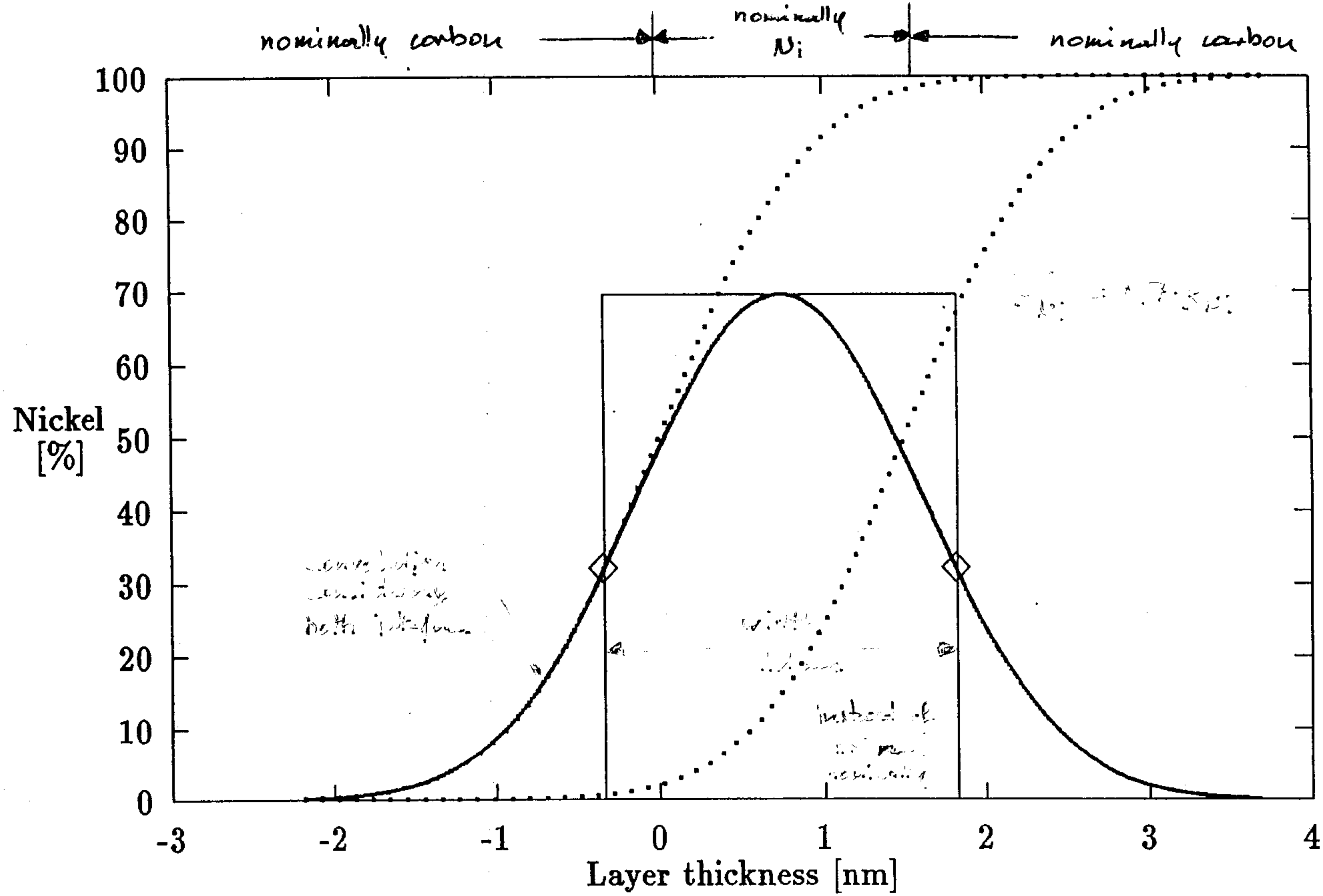




we do have d_{Ni} = 1.5 nm
with interface roughness of 0.7 nm (RMS)

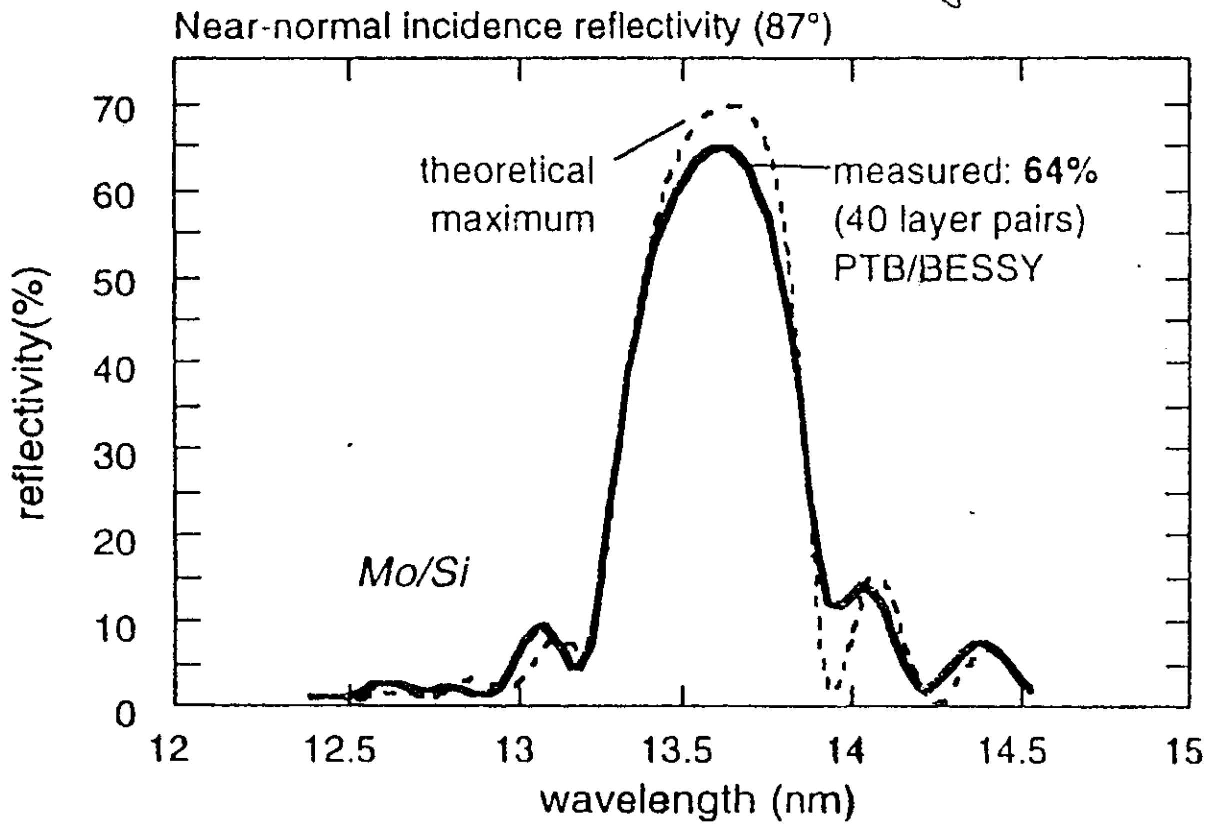


Appl. Opt. 36, 6395 (1997)


nominally carbon
nominally Ni
nominally carbon
Nickel [%]
Layer thickness [nm]
100
90
80
70
60
50
40
30
20
10
0
-3
-2
-1
0
1
2
3
4

Multilayer coatings

FOM Rijnhuizen, NL



method

- *e-beam evaporation + in-situ monitoring*
  - *reproducibility: 0.1% run-to-run*
- *ion-beam smoothening of interfaces*
  - *no accumulation of roughness through stack*
  - *ability to correct thickness errors*
  - *extra research tool: e.g. H implantation*
- *substrate temperature controlled deposition*

this Mo/Si mirror

- *polished: Si, 300 eV, Kr+, 45°*

➡ **>90% of maximum theoretical reflectivity achievable**

ref Louis et al, Microelectr. Engin. 27 (1995) 235-238

Eiliptical Wiggler

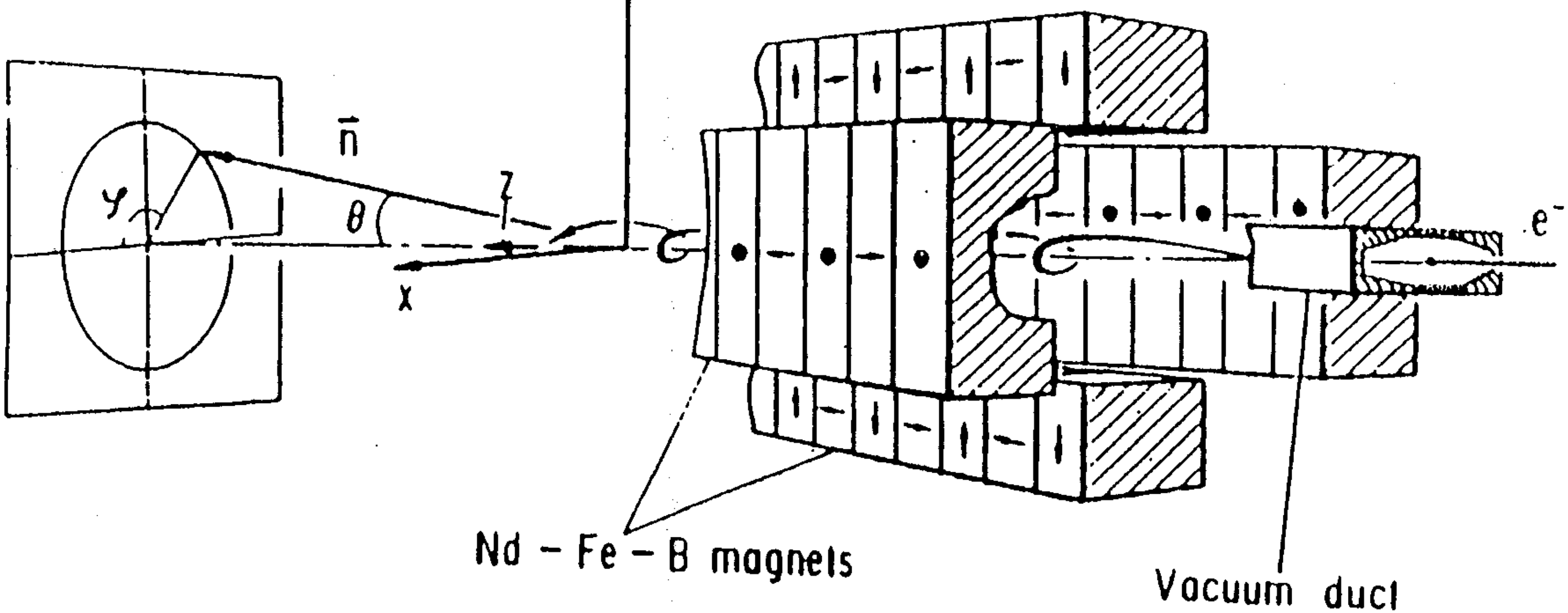
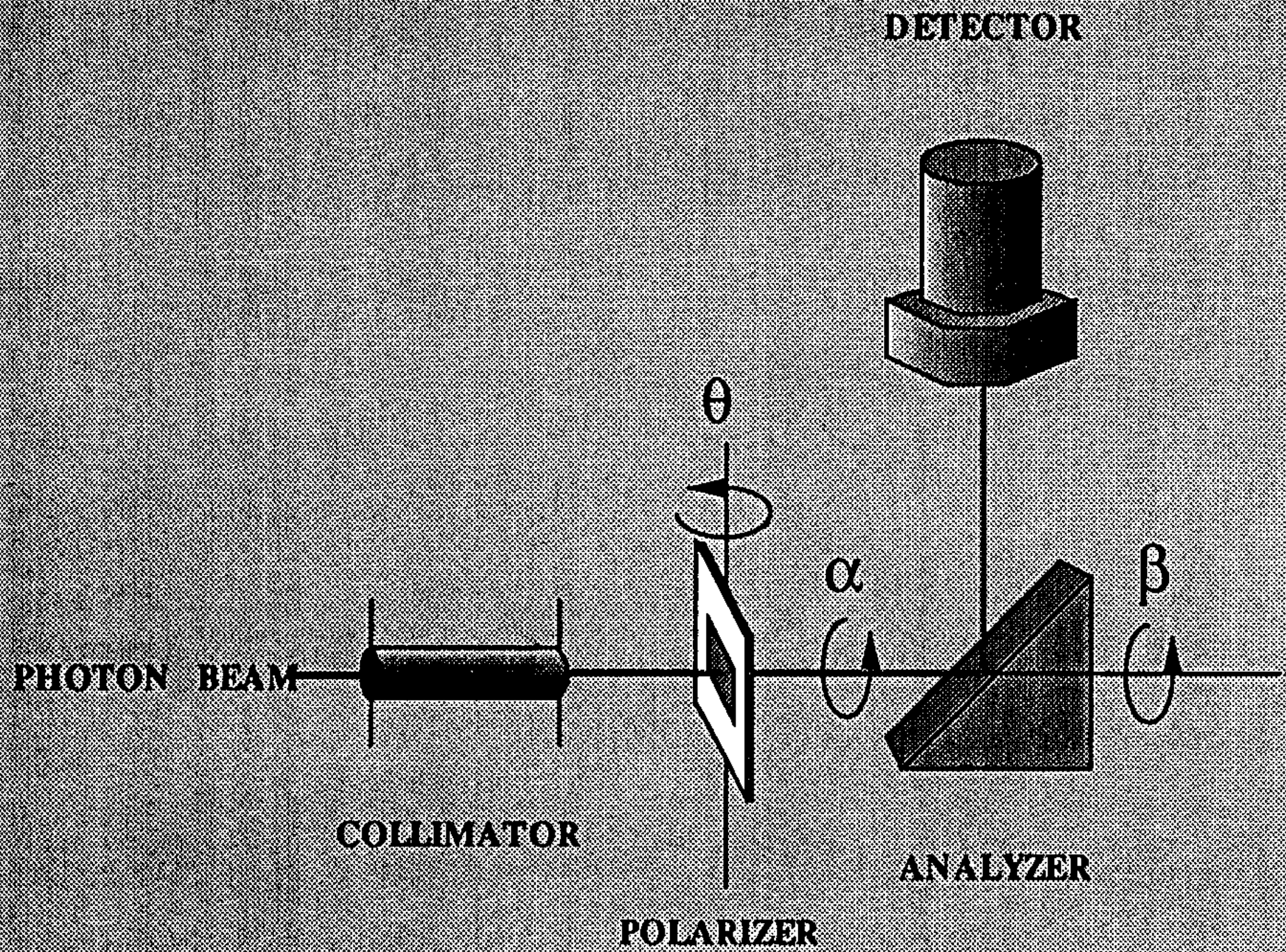


FIG. 2. Schematic illustration of the mechanism of the present insertion devices. Arrows denote the magnetization direction of each magnet, which totally forms the magnetic field given by Eq. (1) on the axis of the device.

$$\mathbf{B} = \pm \mathbf{e}_x B_{x0} \cos(2\pi z/\lambda_u) - \mathbf{e}_y B_{y0} \sin(2\pi z/\lambda_u) \quad (1)$$

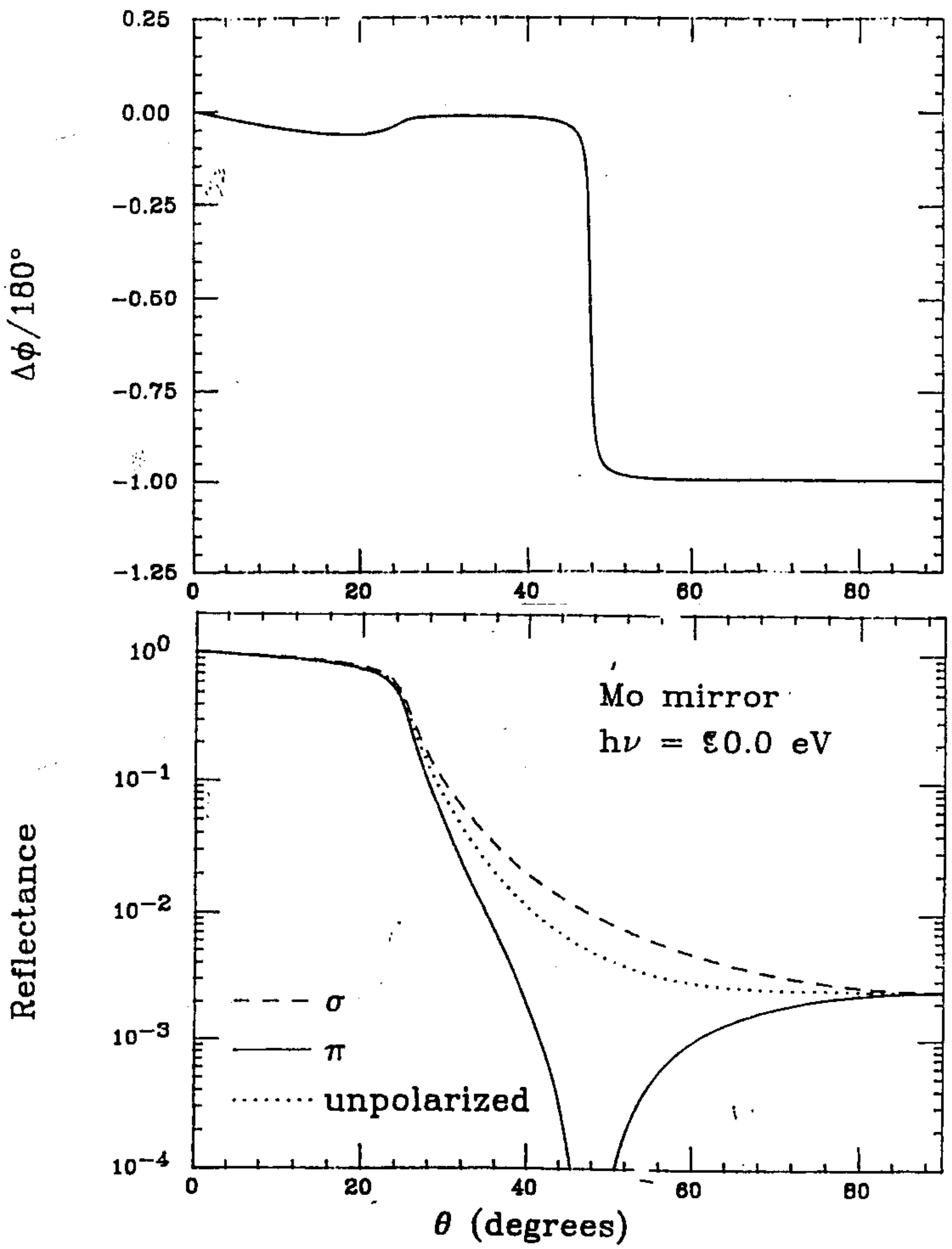
REQUIRED DETECTION SCHEME



90 eV PHASE RETARDATION in SIMPLE mirrors:

J.B. Kortright and J.H. Underwood

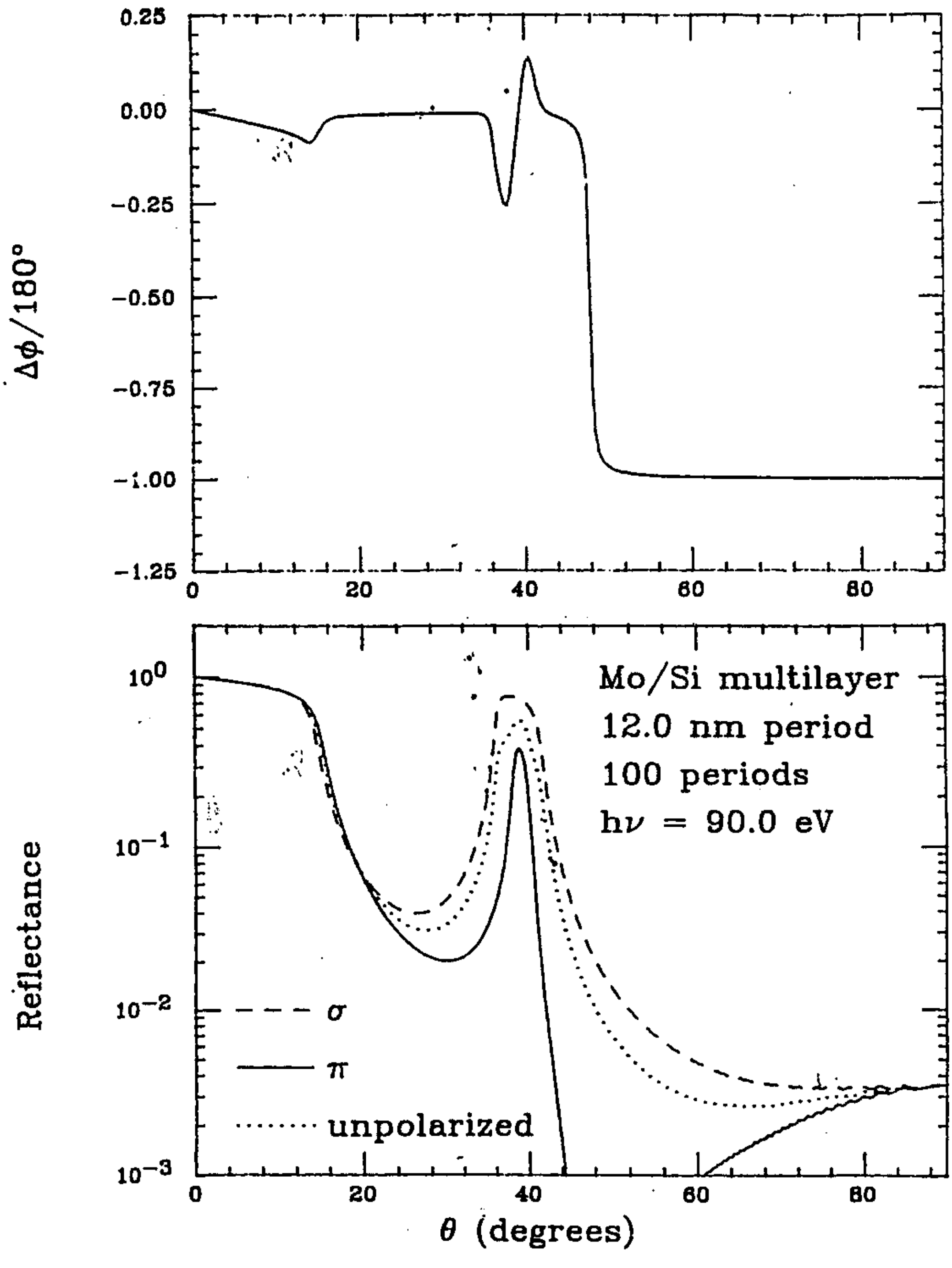
Nucl. Instrum. Methods A291, 272 (1990)



90 eV PHASE RETARDATION in MULTILAYER mirrors:

J.B. Kortright and J.H. Underwood

Nucl. Instrum. Methods A291, *272 (1990)*

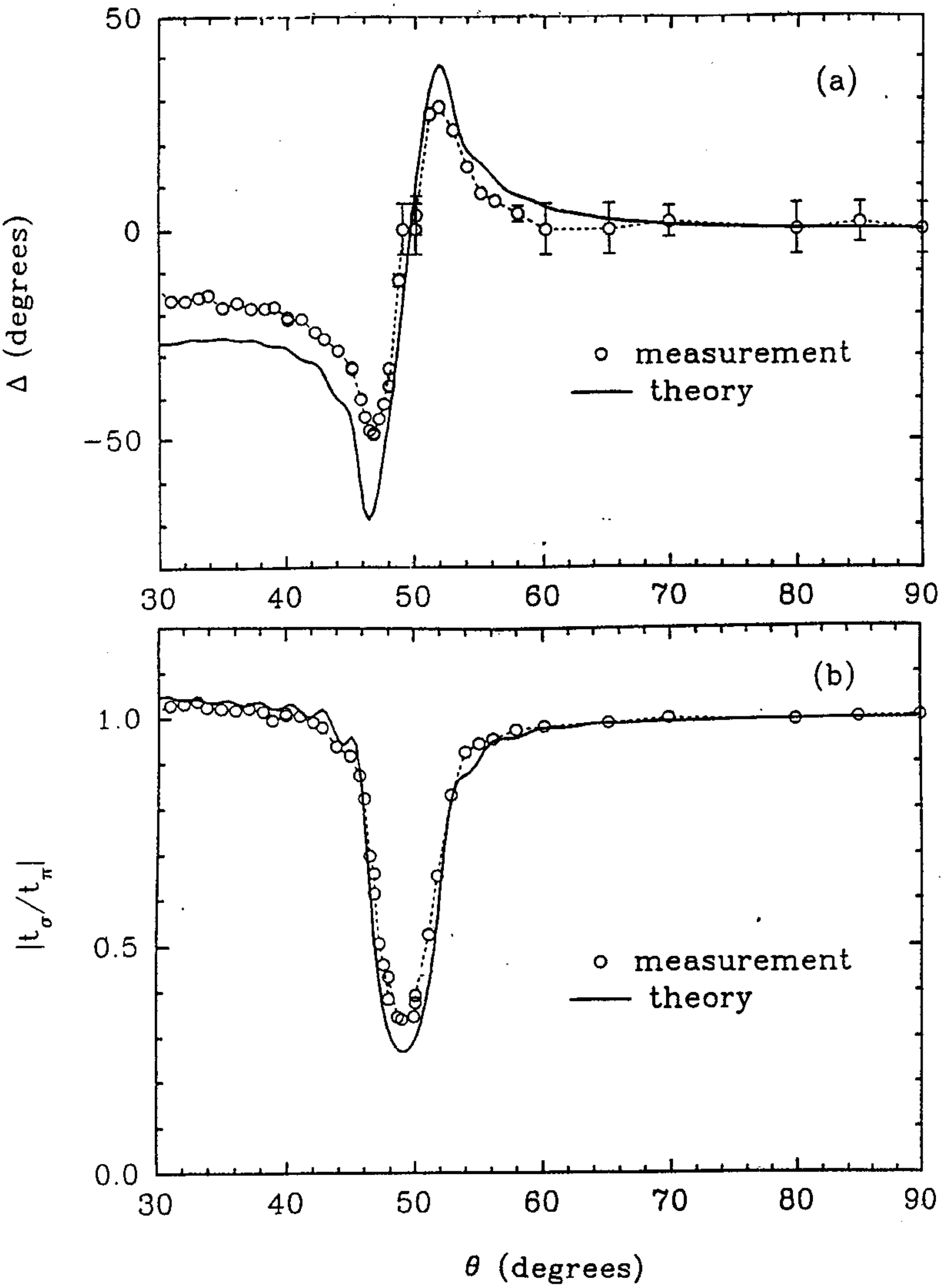


100 periods Mo/Si with d = 12 nm (2/3 Si and 1/3 Mo)

97 eV PHASE RETARDATION:

J.B. Kortright, H. Kimura, V. Nikitin, K. Mayama, M. Yamamoto and M. Yanagihara

Appl. Phys. Lett. 60, *2963 (1992)*



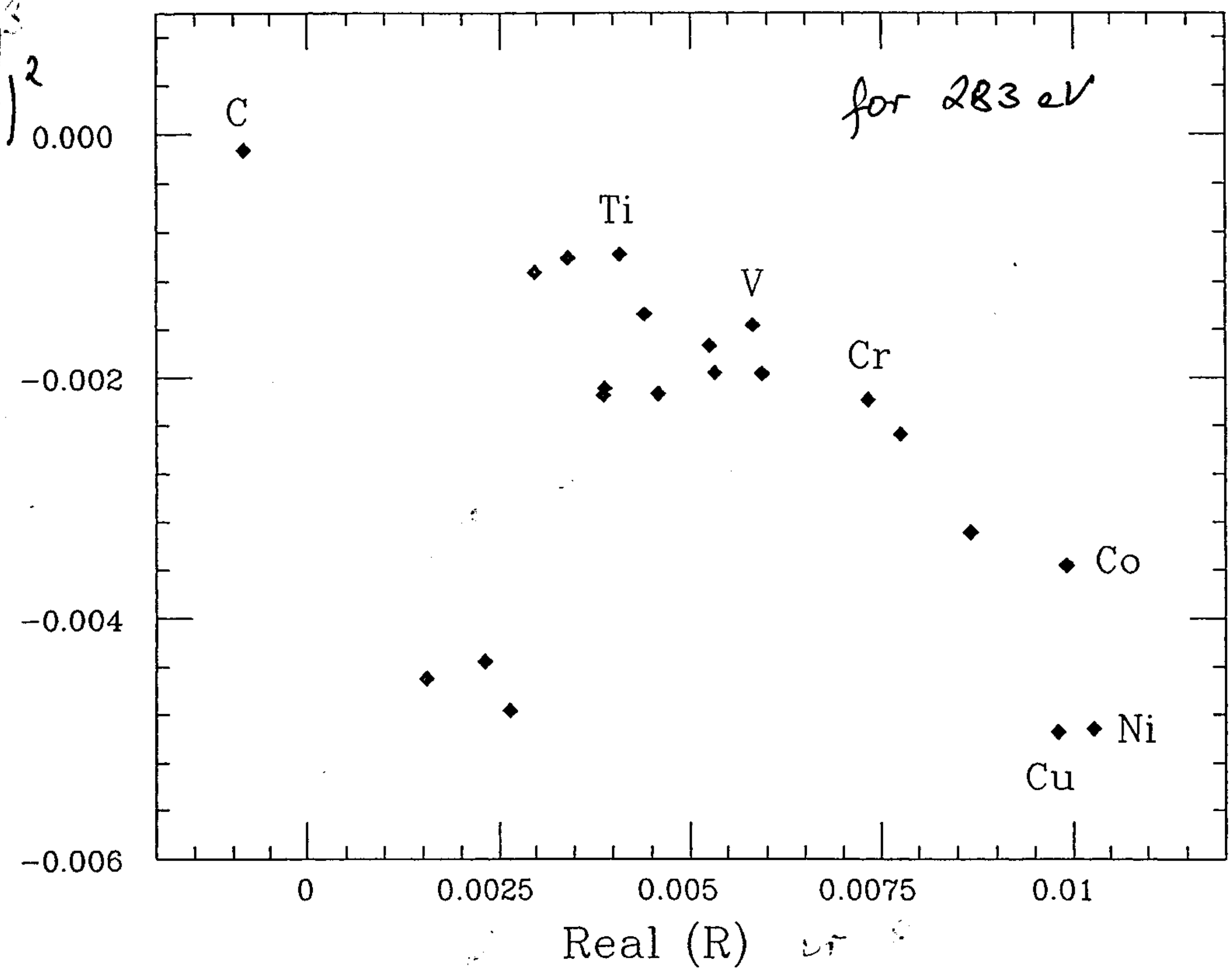
20 periods Mo/Si with d = 8.75 nm (2/3 Si and 1/3 Mo)

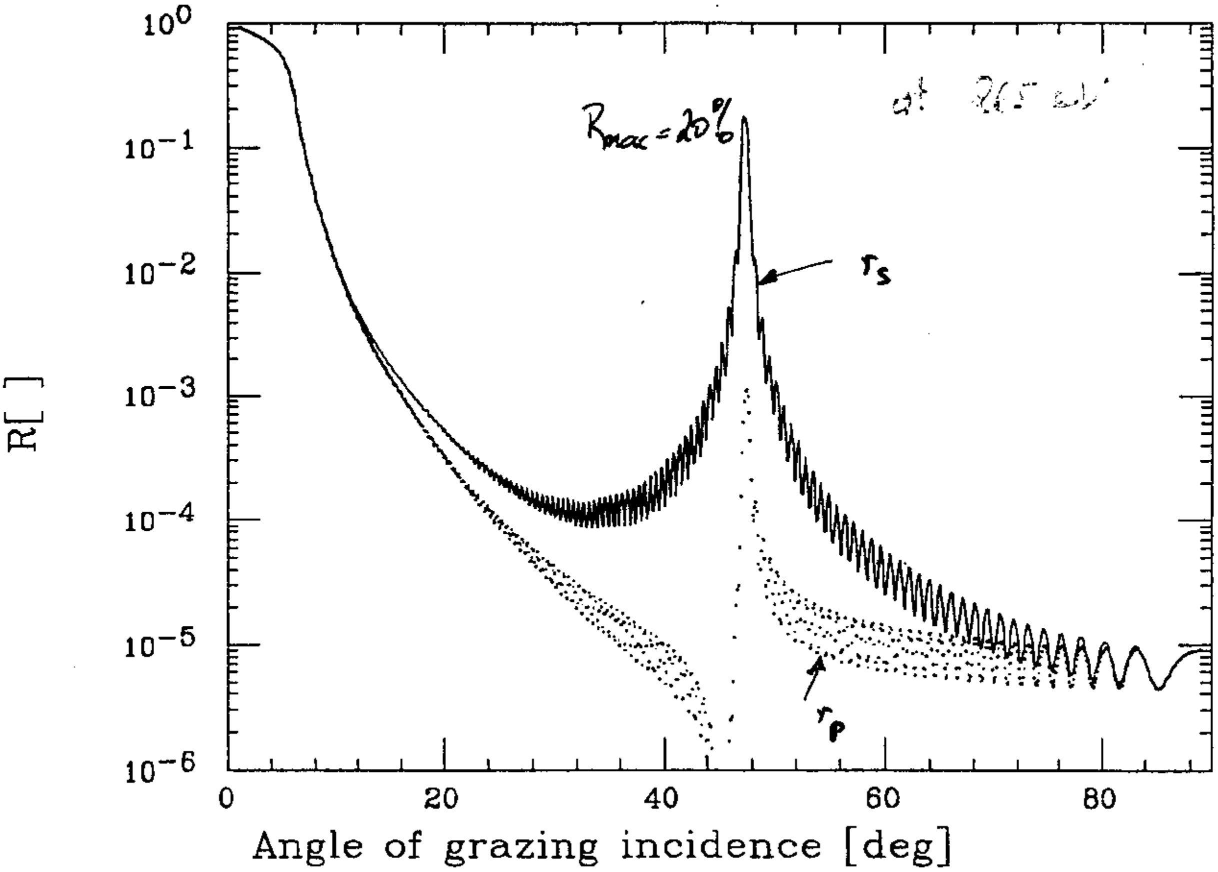
effect 2/3 of theory wi[illegible]0% transmission

Components of reflexion coefficient

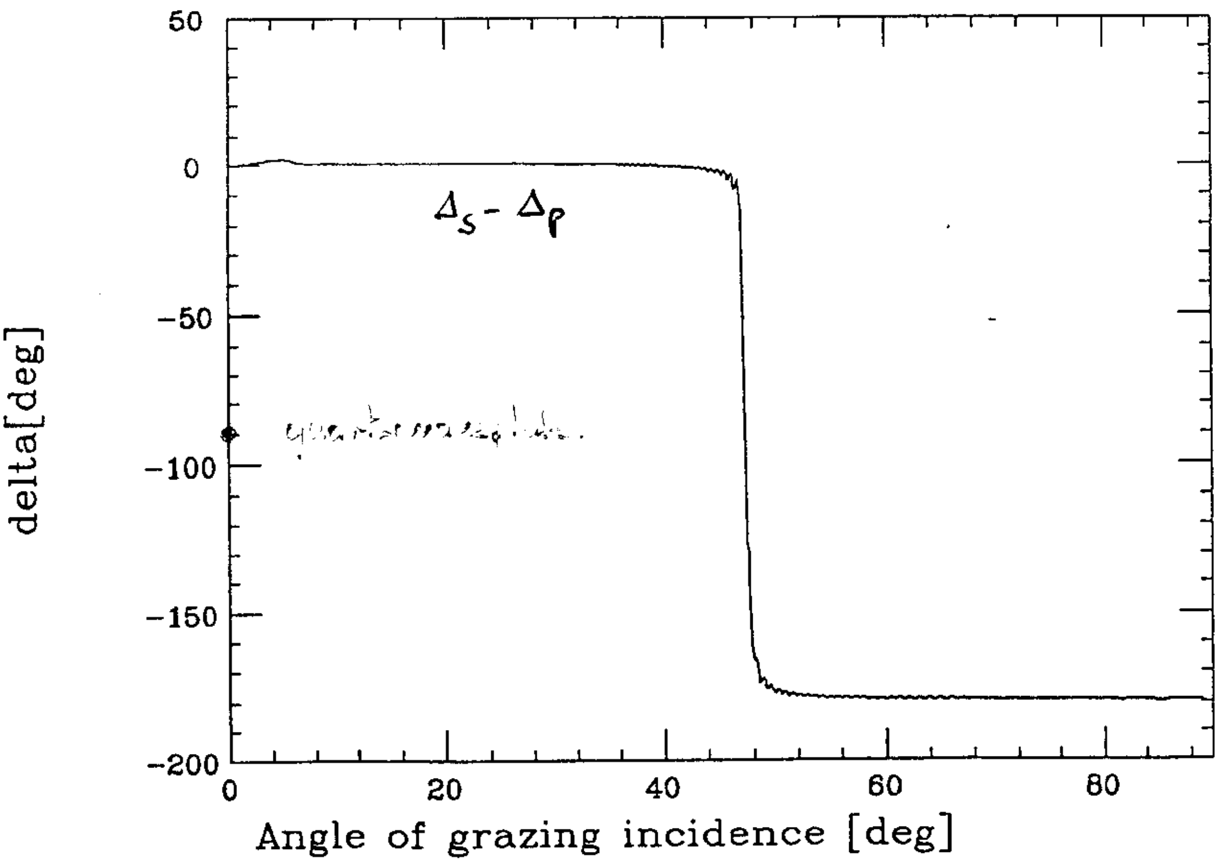
$n = 1 - \delta + i\beta$

$R = \left(\frac{n-1}{n+1}\right)^2$

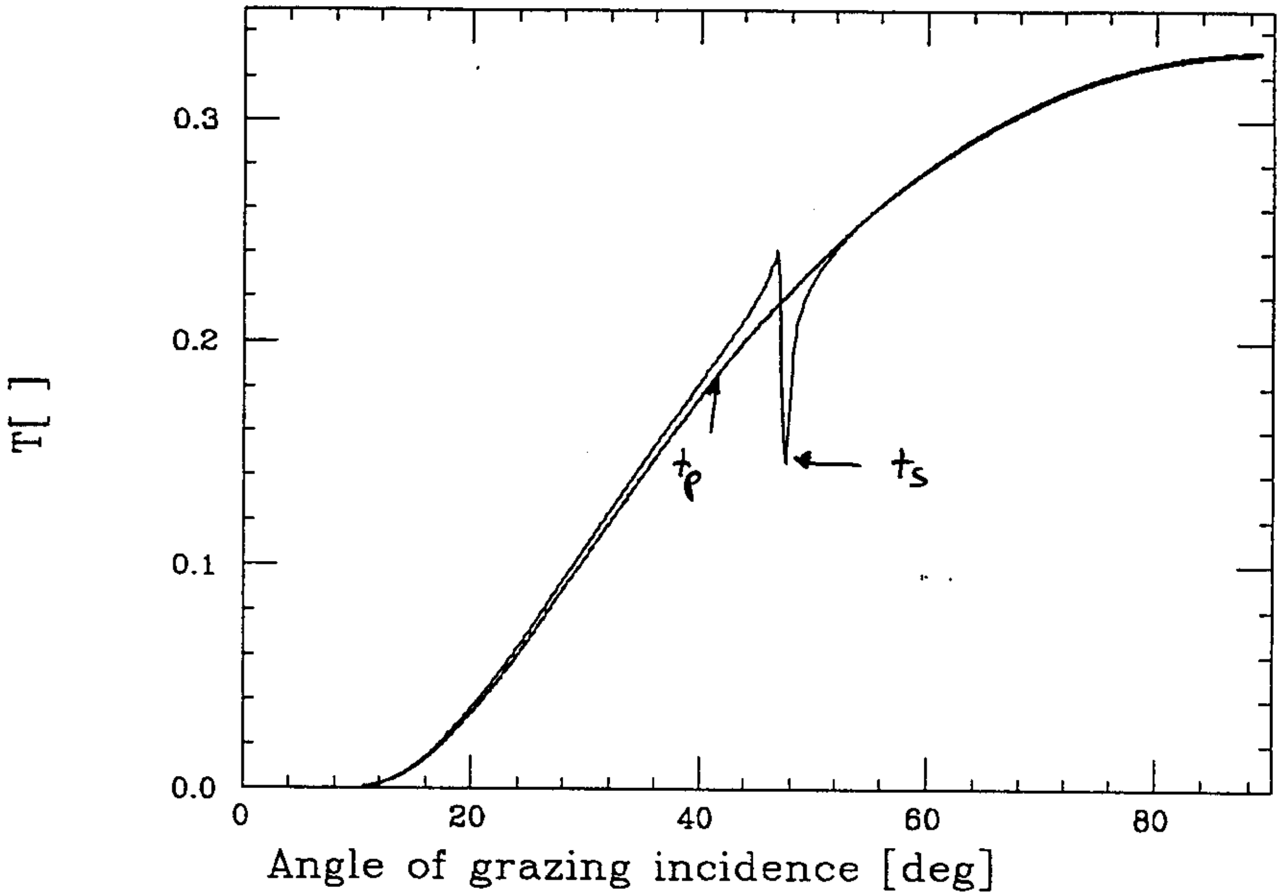




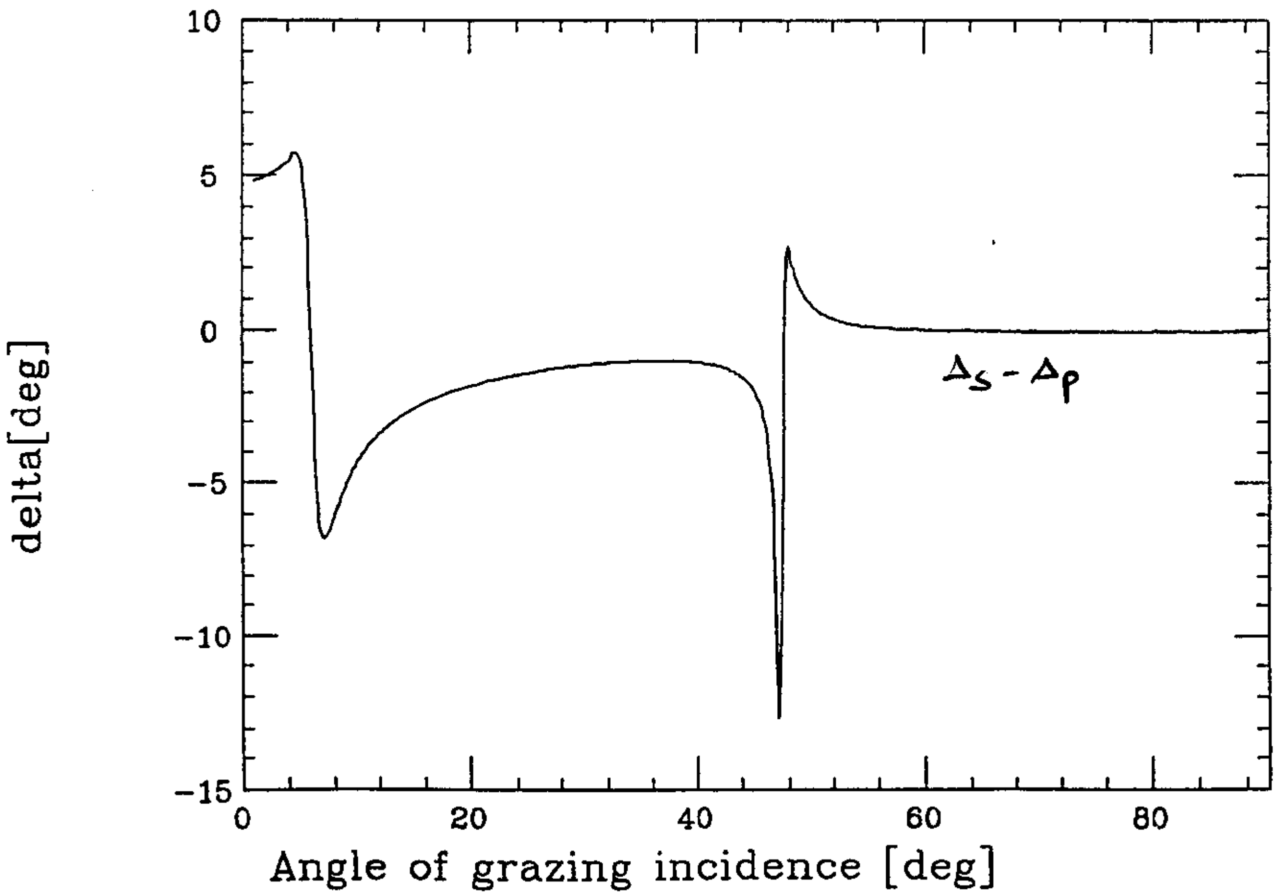
R[ ]
Angle of grazing incidence [deg]
$R_{max}=20\%$
r_s
r_p



delta[deg]
Angle of grazing incidence [deg]
$\Delta_s - \Delta_p$

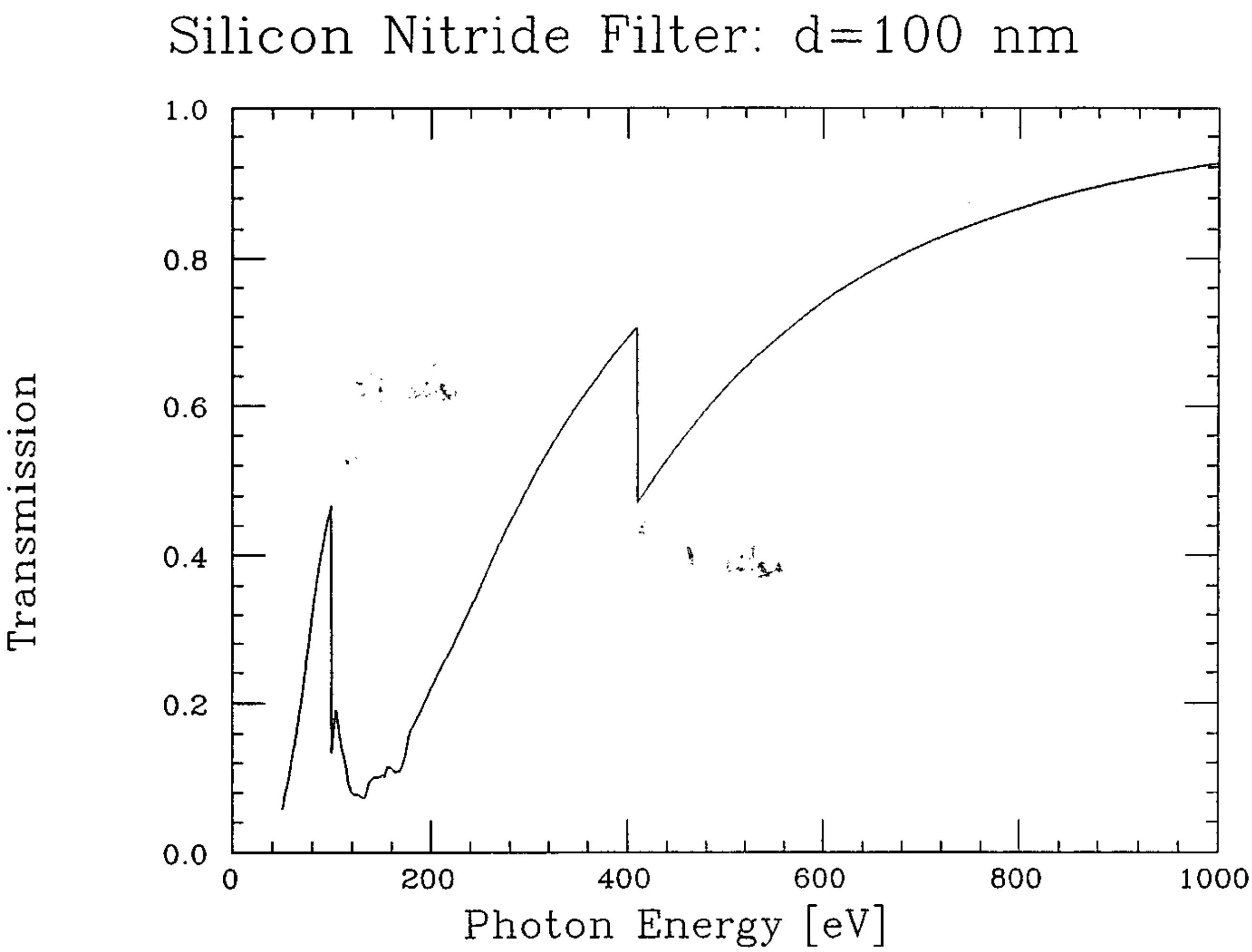


T[ ]
0.0
0.1
0.2
0.3
0
20
40
60
80
Angle of grazing incidence [deg]
t_p
t_s



delta[deg]
10
5
0
−5
−10
−15
0
20
40
60
80
Angle of grazing incidence [deg]
$\Delta_s - \Delta_p$

calculated with recent collection of f_1 and f_2



Collaboration project for polarization characterization

S. Di Fonzo* E.R. Müller*
G. Soullie'*
W. Jark*
R. P. Walker

SINCROTRONE TRIESTE, Trieste, Italy
(* Multilayer Technology Laboratory)

F. Schäfers H. [illegible] (?)
H. C. Mertins
A. Gaupp
W. Gudat
I. Packe
M. Mertin
F. Schmolla

BESSY mbH, Berlin, Germany

H. Grimmer
P. Böni
D. Clemens
M. Horisberger

Institute for Neutron Scattering
ETH and PSI, Villigen, Switzerland

N. N. Salashchenko
E. A. Shamov

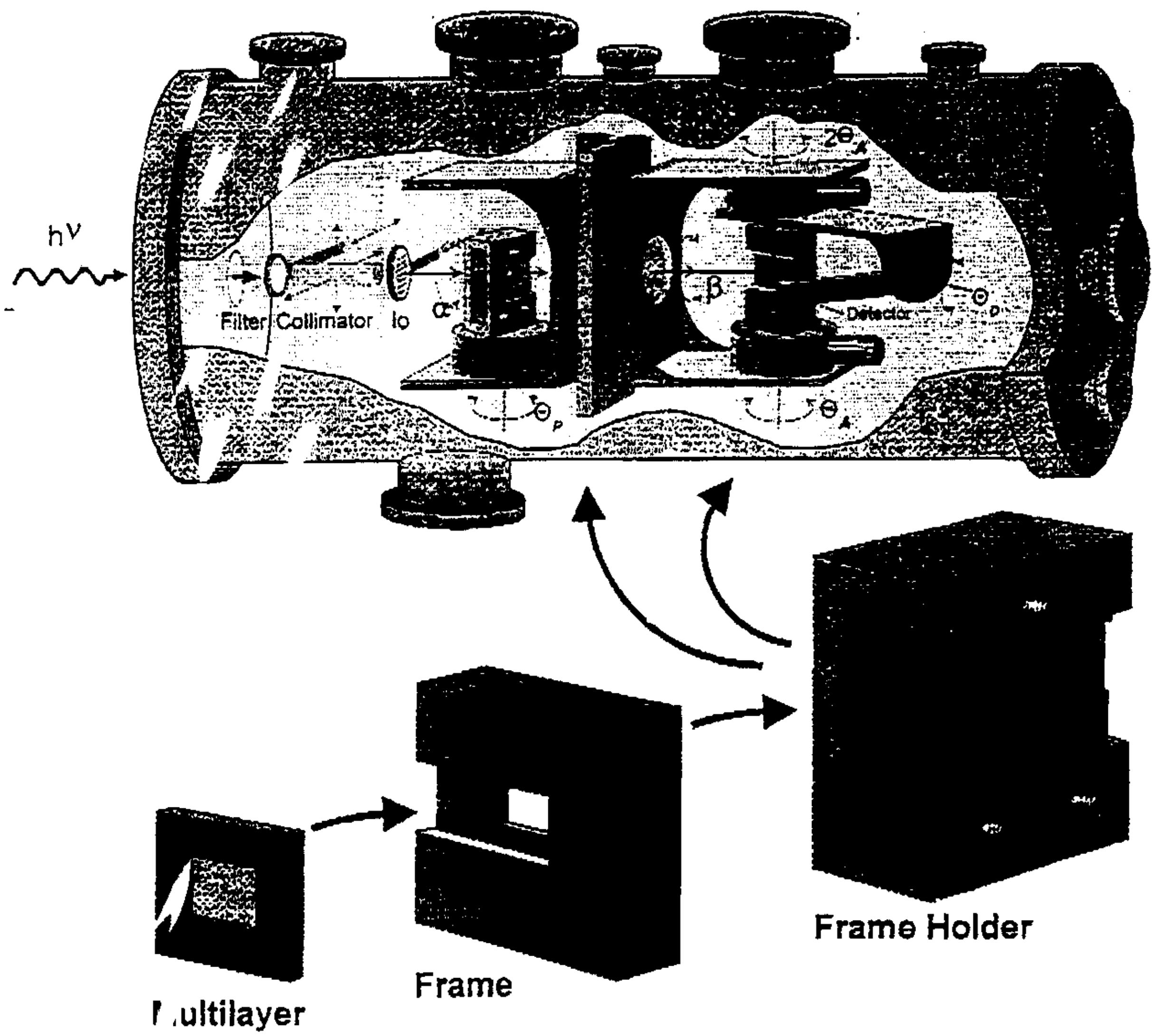
Institute for Physics of Microstructures
Nizhny Novgorod, Russia

R. Nyholm
X. Le Cann

MAX-Laboratory, Lund, Sweden

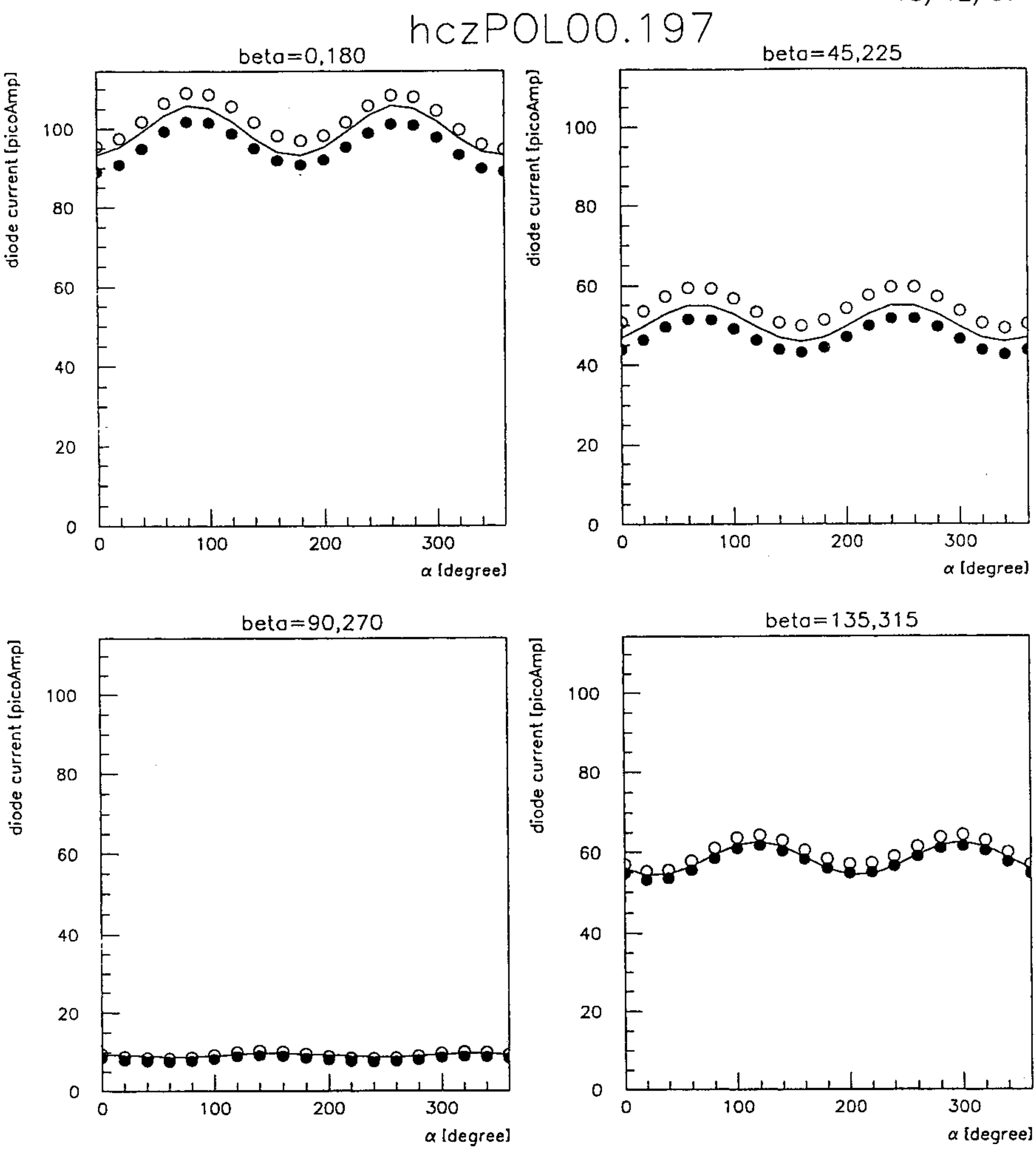
J. H. Underwood
Center for X-ray Optics, Berkeley, CA

BESSY Soft-X-Ray Polarimeter



Applications / features	Technical features
• Determination of all Stokes parameters	• **8-axes polarimeter:**
S_0 (Intensity), S_1, S_2, (lin.pol.), S_3 (circ.pol.)	- **Collimator** (pinholes Ø: 0.5 – 2 mm)
• **Optical elements**	Translation in x, y ±12 mm
- Polarizer: transmission multilayers,	- **Polarizer / analyzer:**
λ/4-plates (MgF_2)	Azimuthal angle: $0° \leq \alpha, \beta \leq 370°$
- Analyzer: reflection multilayers, mirrors,	Incidence angle: $0° \leq \Theta_P, \Theta_A \leq 90°$
(Mo/Si, Cr/C, Cr/Sc, Ni/Ti)	- **Detector** (GaAsP diode):
• **Working energy:** visible to soft X-ray range	scan range: in plane $0° \leq 2\Theta_A \leq 180°$
determined by optical elements in use	off plane $-27°\ \Theta_D \leq +27°$
• **Characterization of optical elements:**	• **UHV compatible,** $p \leq 10^{-8}$ mbar
- Multilayers, transmission foils, crystals	• **UHV-goniometers, motors f.** positioning (>0.001 °)
- Reflectance, transmission	• **Sample size:** $10 \times 10 \times 0.5\ mm^3$ to $140 \times 50 \times 11\ mm^3$
- Phase retardation	• **Magazine** for 10 samples, alignable in situ
- s- and p-polarization geometry	• **Filter** for higher order: Be, C_6H_8, Ti, Cr, Fe, Cu

18/12/97 22.36



37

The BESSY polarimeter

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

$$t_{s1} = |t_{s1}| \;\exp(i\delta_{s1}) \qquad r_{s2} = |r_{s2}| \;\exp(i\delta_{s2})$$
$$t_{p1} = |t_{p1}| \;\exp(i\delta_{p1}) \qquad r_{p2} = |r_{p2}| \;\exp(i\delta_{p2})$$

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

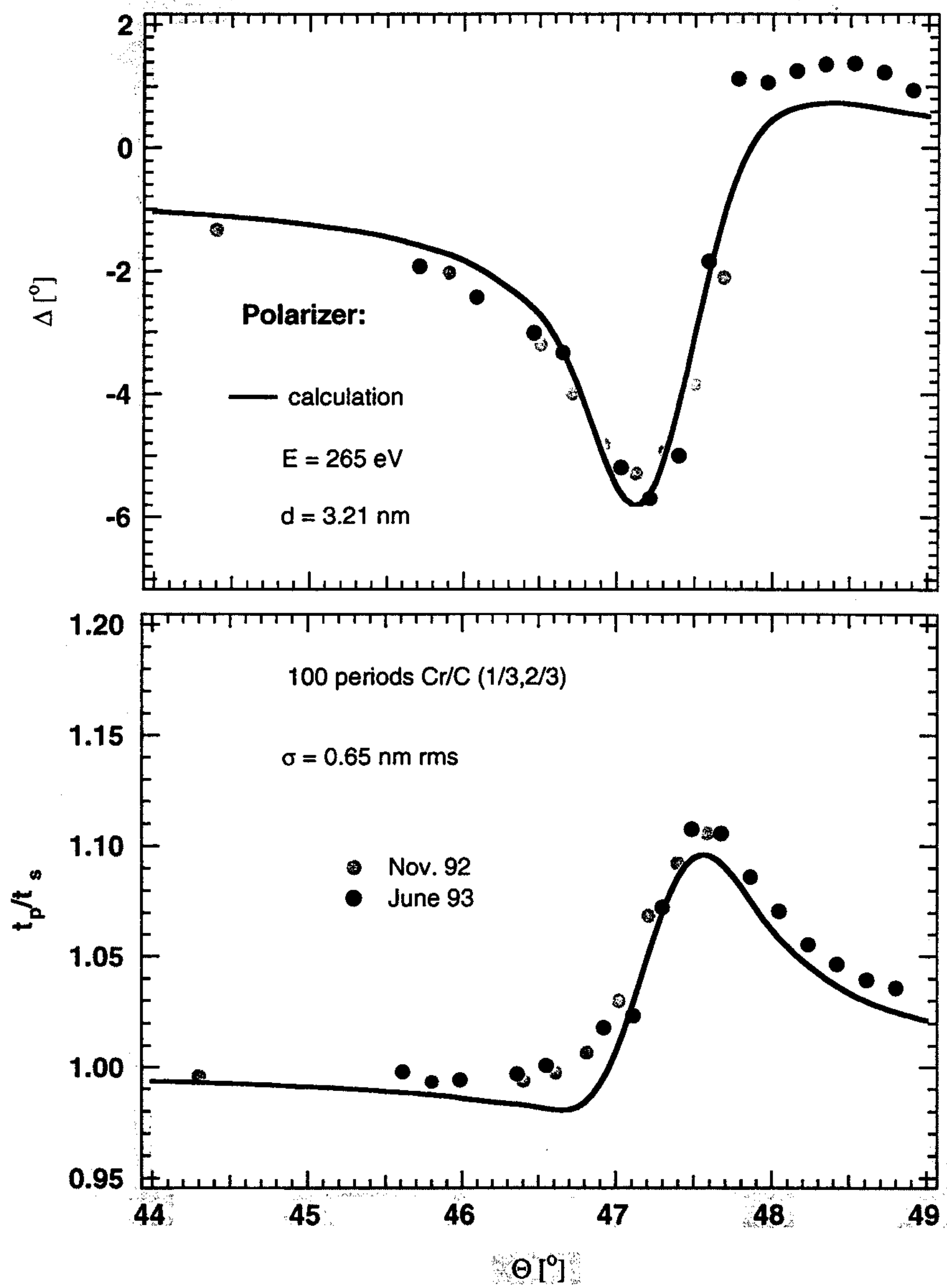
$$\tan \Psi_1 = |t_{p1}|/|t_{s1}| \qquad \tan \Psi_2 = |r_{p2}|/|r_{s2}|$$

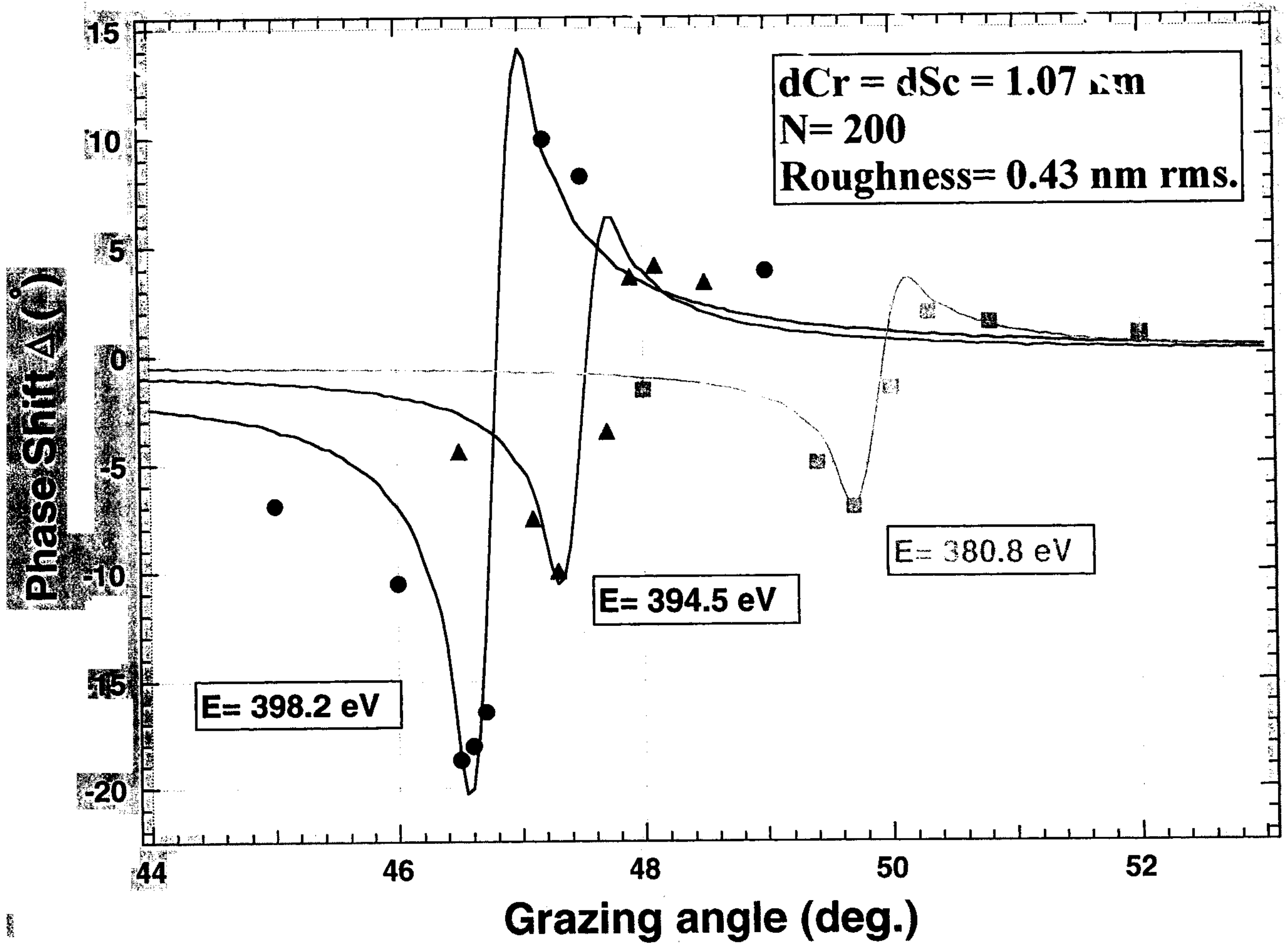
Stokes-parameters: S_0, S_1, S_2 and S_3

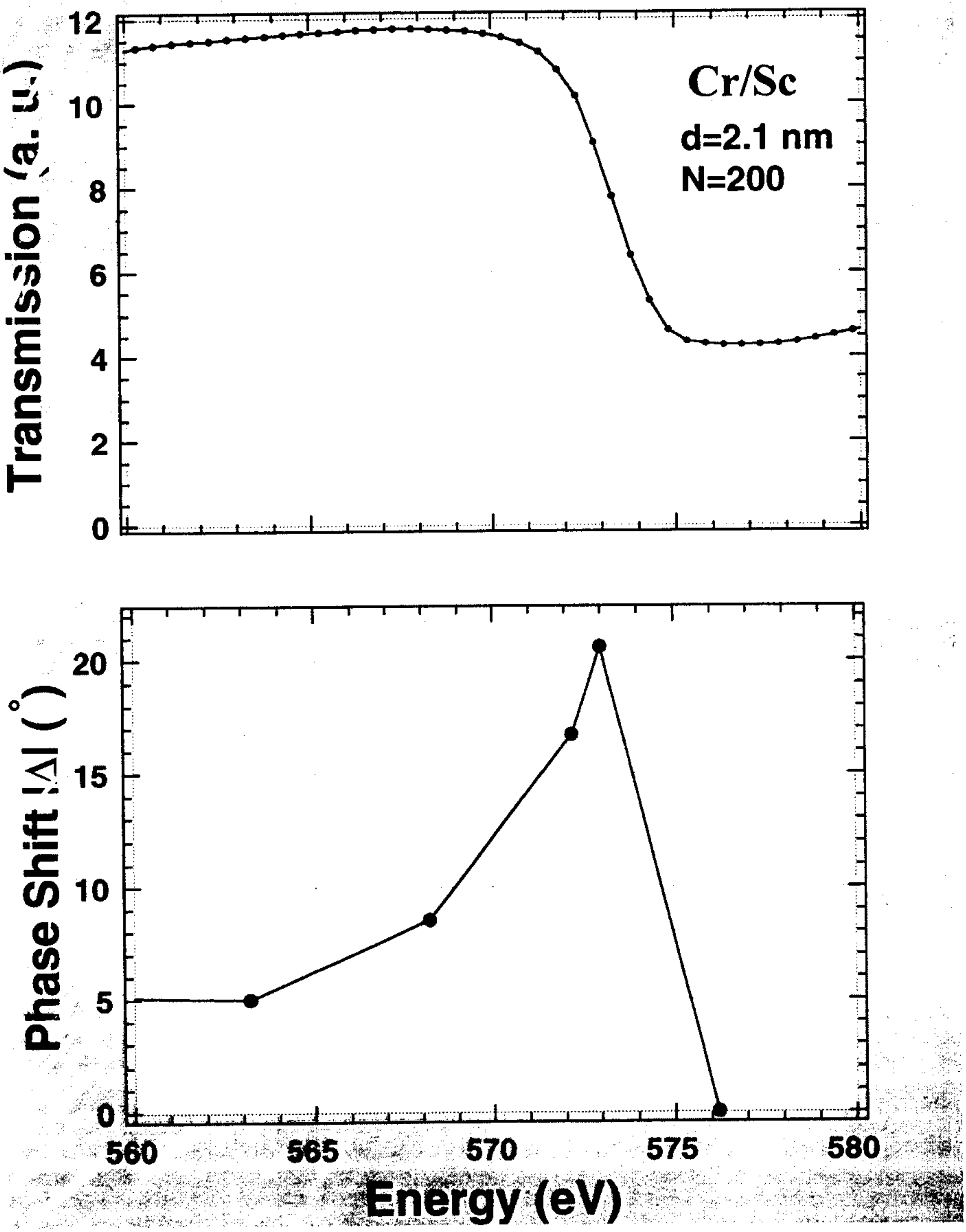
$$\mathbf{I}_{pass} = \tfrac{1}{2}\,(ts1^2 + tp1^2) * \qquad \tfrac{1}{2}\,(rs2^2 + rp2^2) *$$

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

Di Fonzo et al, Appl. Opt. 33, 2624 (1994)



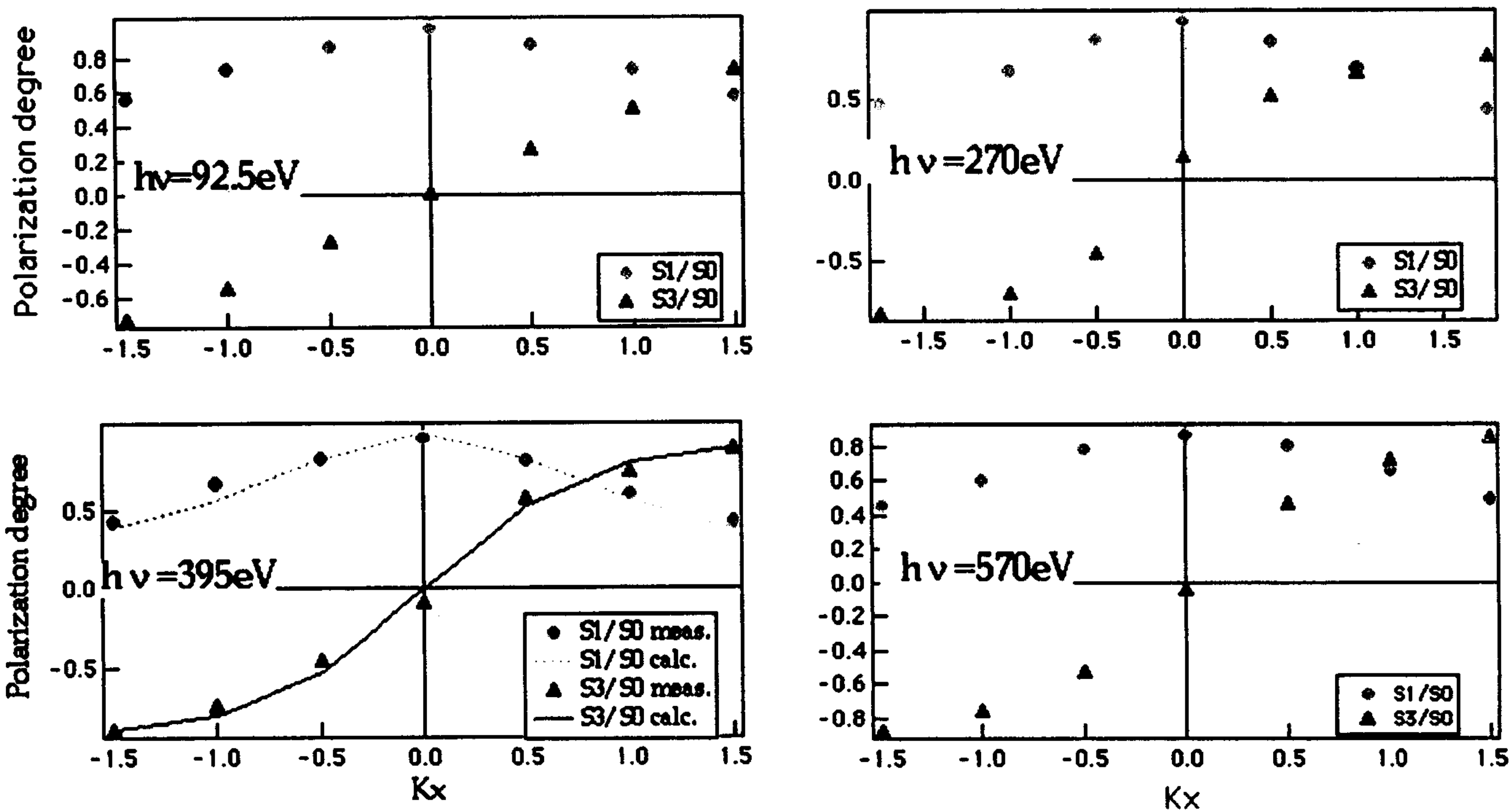

dCr = dSc = 1.07 nm
N= 200
Roughness= 0.43 nm rms.
E= 398.2 eV
E= 394.5 eV
E= 380.8 eV
Phase Shift Δ (°)
Grazing angle (deg.)
15
10
5
0
-5
-10
-15
-20
44
46
48
50
52



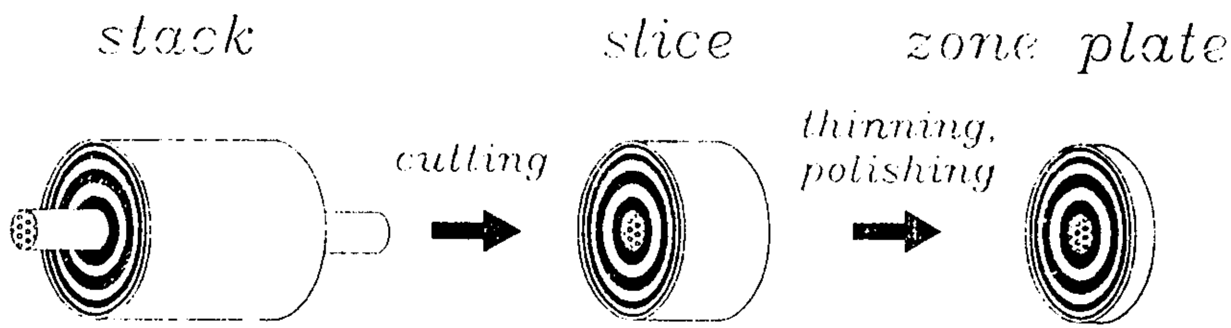
Cr/Sc
d=2.1 nm
N=200
Transmission (a. u.)
Phase Shift |Δ| (°)
Energy (eV)

Wiggler mode

Mo/Si 92.5 eV (edge of Si)
Cr/C 270 eV (edge of C)
Cr/Sc 395 eV (edge of Sc)
Cr/ Sc 574 eV (edge of Cr)



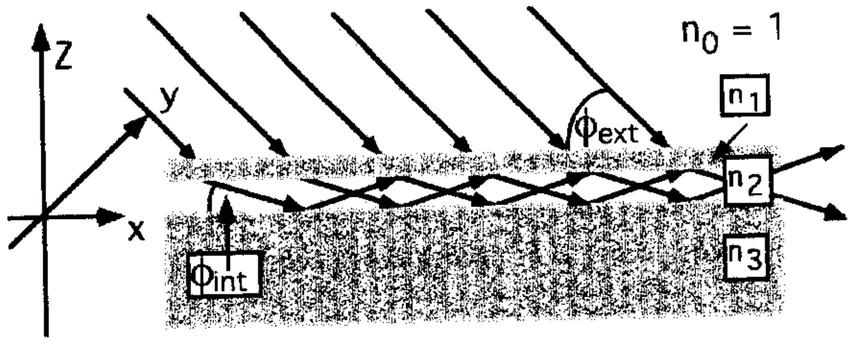
Sputtered Sliced Zone Plate Technology: [11, 8]



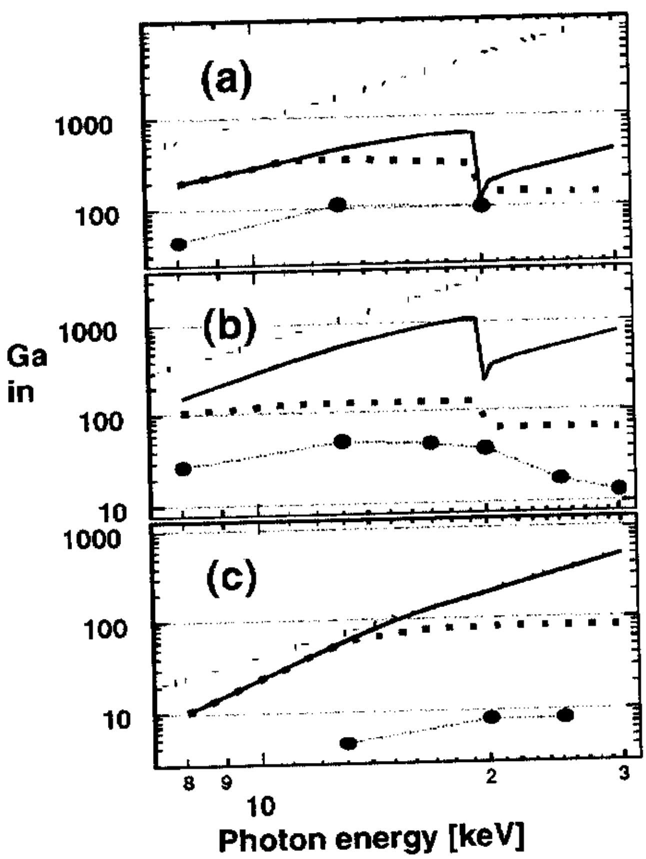
- combination of highest aspect ratios and high resolution is possible
- optimal thickness of zone plates can be used for high efficiencies
- no restriction by reactive ion etching methods if the spacer material has not to be removed
- the limitation in outermost zone width is given by roughness and interdiffusion of the layers

Field intensity enhancement in thin film

W. Jark et al, to be publ.



enhancement = gain   if $n_2 > n_1, n_3$



Dots: ideal interfaces, no absorption in top and bottom layer
Line: rigorous calculation
Dashes: rigorous calculation correct for finite beam divergence

The data is presented as function of photon energy for different materials and thickness:

A) 74 nm Be between 5.5 and 20 nm Mo.

B) 110 nm Be between 5.5 and 20 nm Mo.

C) 160 nm C (with relatively 1% inclusions of Ar) between 4 and 20 nm Cr.