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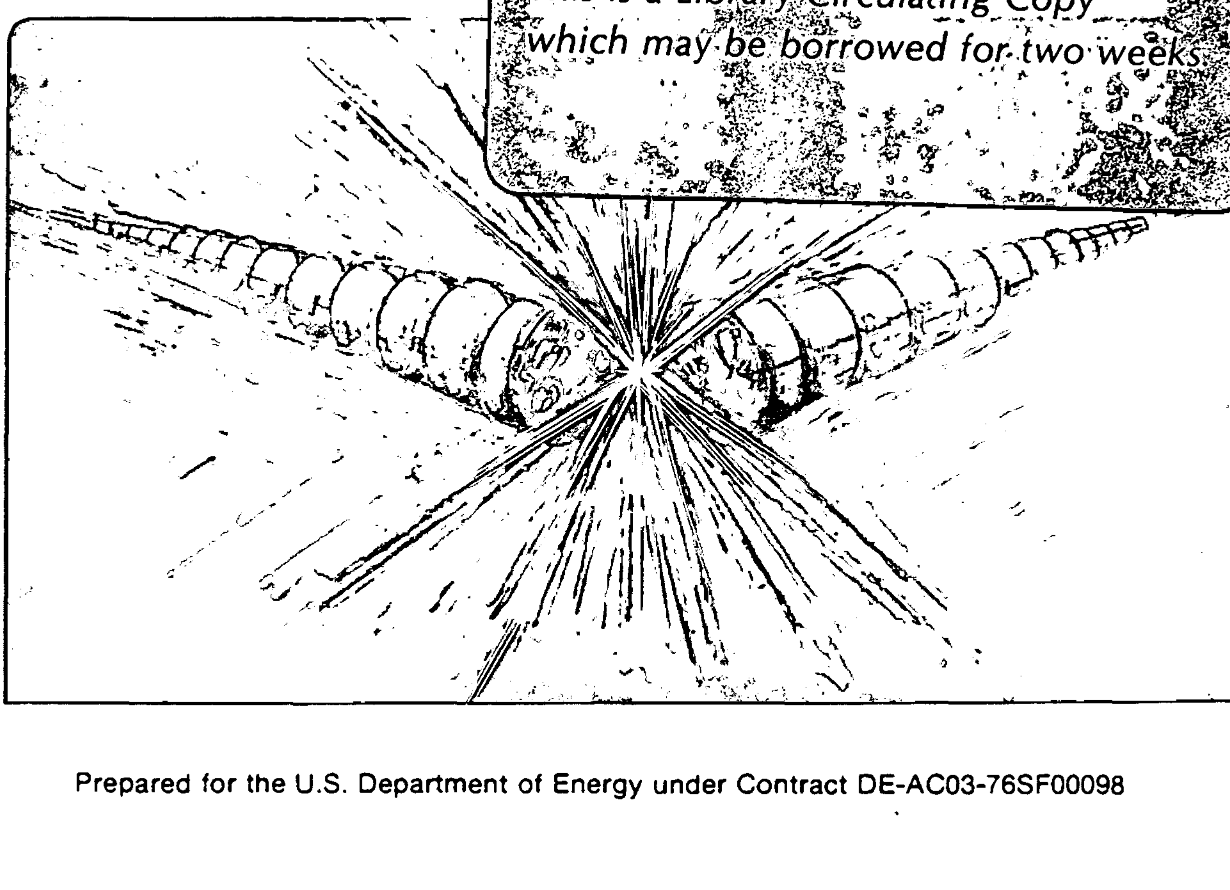

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DISCLAIMER

SPECULAR AND DIFFUSE REFLECTION OF SOFT X-RAYS FROM MIRRORS

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ABSTRACT

Measurements of surface scattering from plane mirrors with different degrees of roughness using soft x-rays are reported. Angle resolved distributions of s-polarized light, scattered in the plane of incidence, were obtained with a precise reflectometer for various angles of incidence and different wavelengths. The influence of the sample preparation and the optical constants on the scattering properties is shown.

Recent monochromator development has more and more filled the energy gap between the VUV and x-ray regions (≈10 - 1500 eV). This progress, on the other hand, imposes severe requirements on the beamline optics: the use of wigglers and undulators requires mirrors which can withstand high power loads and short wavelengths impose the need for supersmooth mirrors since the integral scattering is proportional to λ^{-2} or λ^{-4} [1,2] depending on the average lateral size of the roughness. To accomplish these requirements, there is an increasing need for mirror test facilities to get more experiences on surface scattering and optical and thermal properties of state of the art optical elements. Many surface inspection methods have already been applied to laser mirrors, space telescope mirrors etc. [3] but it is a well-known fact that each method has its limits of spatial frequency bandwidth [4], so that it is desirable to have direct information about the scattering properties of mirrors irradiated with soft x-rays. This has up to now been done only for a few specific samples and with low angular resolution [5]. With our VUV-reflectometer at HASYLAB/DESY in Hamburg [6], which was built for precision measurements of optical properties of solids, we are able to perform angle resolved stray light measurements in the energy range 20 - 1000 eV. The reflectometer can in principle be set up in s and p polarization although up to now it was used only in the s mode of incident light while the detector can measure in and out of the reflection plane. The whole experimental setup used here is shown in figure 1 (side-view) including a monochromator, which since has been replaced by new plane grating monochromator [7] extending the energy range to the above mentioned values.

In this paper we report first measurements of the specular and diffusely reflected soft x-rays from slightly rough plane mirrors (rms-roughness $\sigma \approx 15$–40Å). The theoretical analysis using scalar and vector scattering theories [8,9] will be presented elsewhere [10]. Low normal incidence reflectivity at short wavelengths and the low level of scattered light intensity forced us to perform the stray light measurements at incidence angles $\Theta_1 > 65°$ whereas hard x-ray scattering has to be done at even more grazing incidence. This fact, together with the short wavelengths makes soft x-ray scattering compared to visible and hard x-ray scattering especially sensitive to short lateral surface structures of about 300 to 5000Å as can be estimated from the grating equation. Considering the surface as a grating we also learn that structures with short lateral periodicity scatter far apart from the specular direction resulting in a broad scattering distribution whereas large, wavy structures yield stray light near the specular reflected intensity.

To investigate these properties of stray light and to learn about the influence of different roughnesses we prepared two different types of samples: 1) we evaporated various thicknesses (500/1000/2000Å) of gold on a glass substrate (samples a),b),c) respectively), and 2) polished the glass substrate with diamond paste with grain sizes of 1µm and 15µm in order to roughen it slightly and then coated it with 500Å gold (samples d) and e)). We expected that the thicker coatings of the first type of samples yielded roughnesses with a small lateral structure size roughly equal to the coating thickness. The substrate roughness may then be negligible. Assuming that the thin 500Å gold layer reproduces the substrate roughness of the polished samples, these should exhibit microscopic structure with longer lateral periodicity.

In this first investigation all measurements were carried out in the plane of incidence only using s-polarized light from the storage ring DORIS.

Figure 2 shows a typical measurement of a sample polished with the 1µm - grains (sample d)) for various angles of incidence and λ = 100 Å. The steep specular peak (scattering angle Θ_2 = incidence angle Θ_1) can simply be separated from the diffusely scattered light by comparing with the intensity profile of the incident beam I_o. At steeper angles of incidence the specular intensity is more and more reduced by the roughness itself and by the Fresnel reflectivity R_o of an ideal smooth surface. The two effects are separated in figure 2 by the dashed line. Most of the intensity lost due to the roughness adds to the diffuse background. Consequently, the scattered light distribution raises towards steeper angles of incidence relative to the specularly reflected intensity. In all further figures the spectra are divided by the reflectivity R_o. Nonetheless, the symmetry and shape of the scattered light distribution is still influenced by the optical constants of the scattering material.

Figure 3 shows a complete overview over all our measurements on gold-coated samples at a wavelength of λ = 100Å, while figure 4 presents scattering distributions of some samples carried out at λ = 200Å.

According to BECKMANN [8] the amount of specularly reflected intensity I_{sp} relative to the incident intensity I_o is dependent only on the rms-roughness σ, the wavelength λ and on Θ_1, the dependence is given by $I_{sp} = I_o R_o \exp[-(4\pi\sigma\cos\Theta_1/\lambda)^2]$ (valid only if the radius of curvature of the roughness is large compared to λ). Considering first this intensity fall-off with steeper angles Θ_1 of the specular peaks we see from figure 3 and 4 that sample a) is, as might be expected, the smoothest sample (σ = 18Å), while samples b), d) and e) exhibit a medium range roughness (σ = 27-29Å). Sample c), which has the thickest gold coating (2000Å), shows the highest rms-roughness (σ = 43Å). The σ-values are calculated from the above equation for I_{sp}, which, however, may not be completely correct when σ approaches λ as in the case of sample c).

Looking at the non specularly scattered light distribution, i.e. the diffuse background, we can distinguish two basic types of curves: narrow, concave-shaped ones (a), d), e)) and broad, convex-shaped ones (b), c)). Regarding again the surface as a grating, this experimental result confirms that the scattering from the thick films arises from spatial structures, which are shorter than those of the polished samples. An interesting feature associated with this is that the contrast, i.e. the ratio specular/diffuse intensity near $\Theta_2=\Theta_1$, is much better for sample b) (1000Å Au on smooth glass) than for d) and e), in spite of having nearly the same σ-value. This again indicates that the roughness resulting from the Au films themselves has more short wave components than that of the polished surfaces, in other words, it has a smaller "autocorrelation length".

Moreover, there are some characteristic changes in the symmetry of the scattering distribution for different angles of incidence Θ_1 and wavelengths λ which have to be explained by detailed theory [e.g. 8,9]. For example at λ = 100Å, Θ_1 = 70° there is always a more or less pronounced shoulder on the right branch. This may be attributed to the influence of the reflectivity of the sample material near the critical angle, but we don't understand the differences concerning this shoulder in the curves of the different samples in detail.

To elucidate this influence of the optical properties of the sample material we compare in figure 5 scattering distributions of the gold-coated, polished samples d) and e) with the corresponding distributions of the uncoated and also polished glass substrates (at λ = 100Å). First, considering the overall shape of the curves, it can be concluded that the 500Å Au coating seems to reproduce the substrate roughness quite well. Additionally, there occur characteristic distortions of the symmetry of the branches on covering with Au: the left branch is raised while the right branch is lowered. Indeed, according to vector scattering theory [9], the scattering curves for a sample with R=1 have to be multiplied by an "optical factor" $Q=Q(\Theta_2)$ which behaves as a function of

θ_2 quite similar to the behavior of the Fresnel reflectivity as a function of θ_1. This factor has to be applied in order to get the scattering distribution for a sample with $R \neq 1$.

In summarizing, we state that soft x-ray surface scattering proves to be a valuable method for surface characterization. The rms-roughness can be deduced within the bandwidth limits characteristic of this wavelength range. With some more experience quantitative information will be gained about the lateral structure of the surfaces.

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Figure Captions

Figure 1

The experimental setup

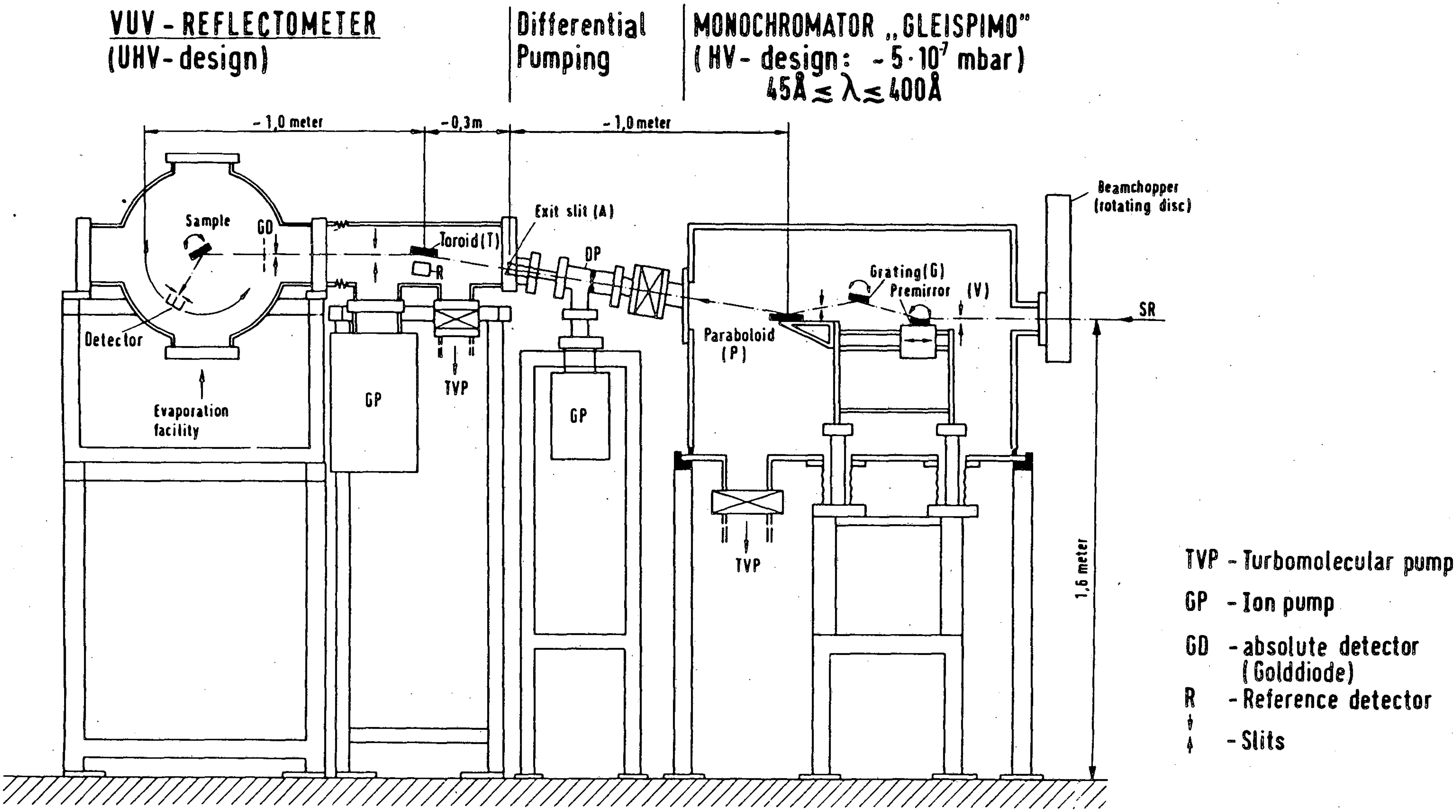
Figure 2 Stray light distribution as measured of a polished sample coated with 500Å gold (sample d)) (θ_2 in plane of incidence, s-polarized light) for different angles of incidence θ_1 and compared to the profile of the incident light I_0. The specularly reflected intensity (the steep peak) is reduced by the surface roughness and the Fresnel reflectivity R_0. The dashed curve indicates the reduction due to the roughness.

Figure 3 Stray light distribution of all gold-coated samples for λ = 100Å. The spectra are divided by the reflectivity R_0 corresponding to the angle of incidence θ_1 of each distribution. The intensity fall-off of the steep specular peaks relative to I_0 is then a measure for the rms-roughness of the different samples.

(a) 500Å Au on smooth glass substrate
(b) 1000Å Au on smooth glass substrate
(c) 2000Å Au on smooth glass substrate
(d) 500Å Au on polished glass substrate (1μ)
(e) 500Å Au on polished glass substrate (15μ)

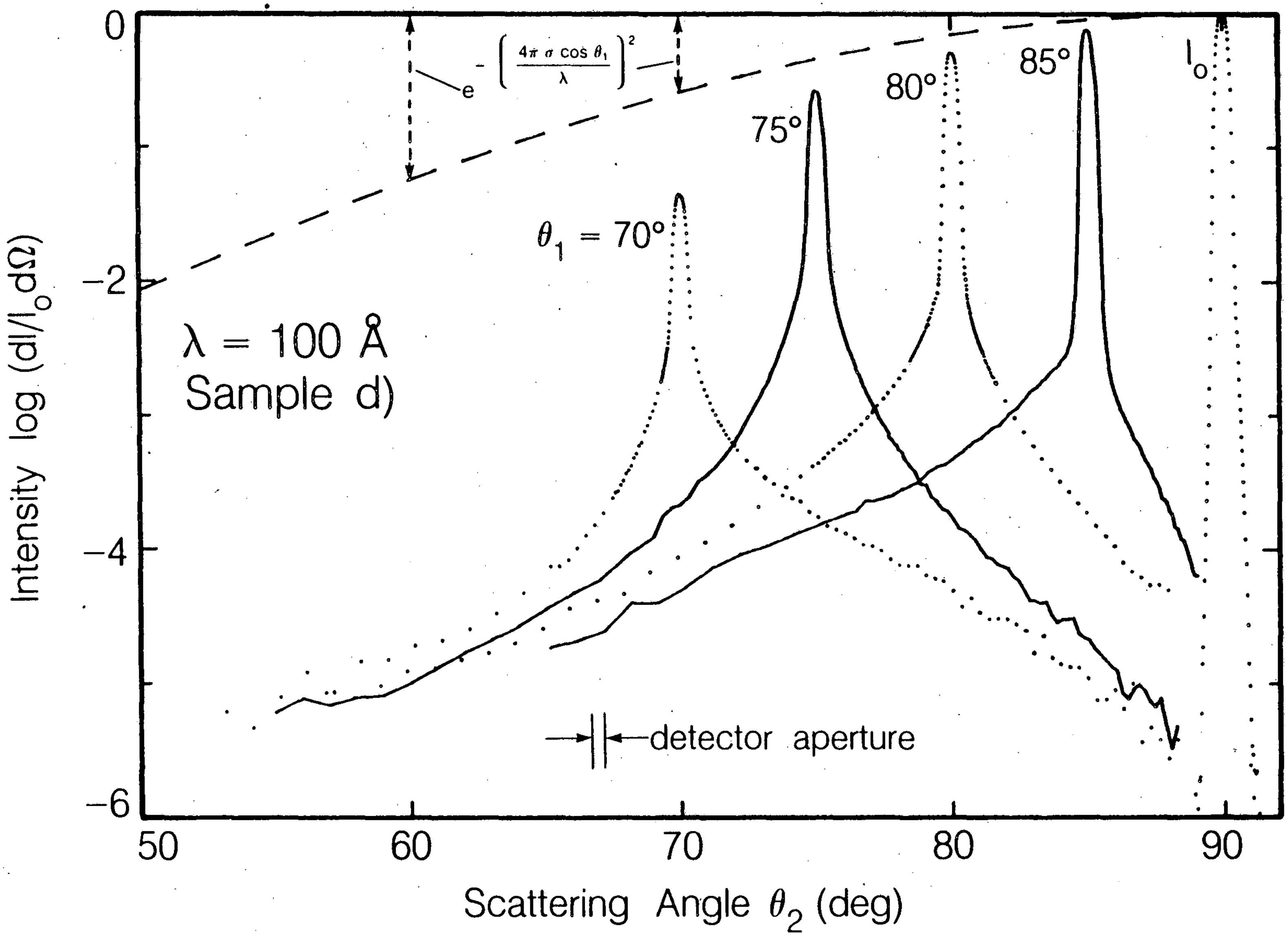
Figure 4 Same as figure 3) for samples c), d), and e), λ = 200Å

Figure 5 Comparison of the stray light from uncoated glass substrates and corresponding gold-coated polished samples. Assuming that the thin gold coating does not change the topology of the roughness, the effect of different optical constants of the surface is showing up.



VUV - REFLECTOMETER
(UHV- design)
Differential
Pumping
MONOCHROMATOR „GLEISPIMO"
(HV- design: ~5·10⁻⁷ mbar)
45Å ≲ λ ≲ 400Å
~1,0 meter
~0,3m
~1,0 meter
Sample
GD
Toroid(T)
R
Exit slit (A)
DP
Beamchopper
(rotating disc)
Grating(G)
Premirror
(V)
SR
Paraboloid
(P)
Detector
Evaporation
facility
GP
TVP
GP
TVP
1,6 meter
TVP - Turbomolecular pump
GP - Ion pump
GD - absolute detector
(Golddiode)
R - Reference detector
- Slits

Fig. 1



0
−2
−4
−6
50
60
70
80
90
Intensity log $(dI/I_o d\Omega)$
Scattering Angle θ_2 (deg)
$e^{-\left(\frac{4\pi\sigma\cos\theta_1}{\lambda}\right)^2}$
$\theta_1 = 70°$
75°
80°
85°
I_o
$\lambda = 100$ Å
Sample d)
detector aperture

Fig. 2

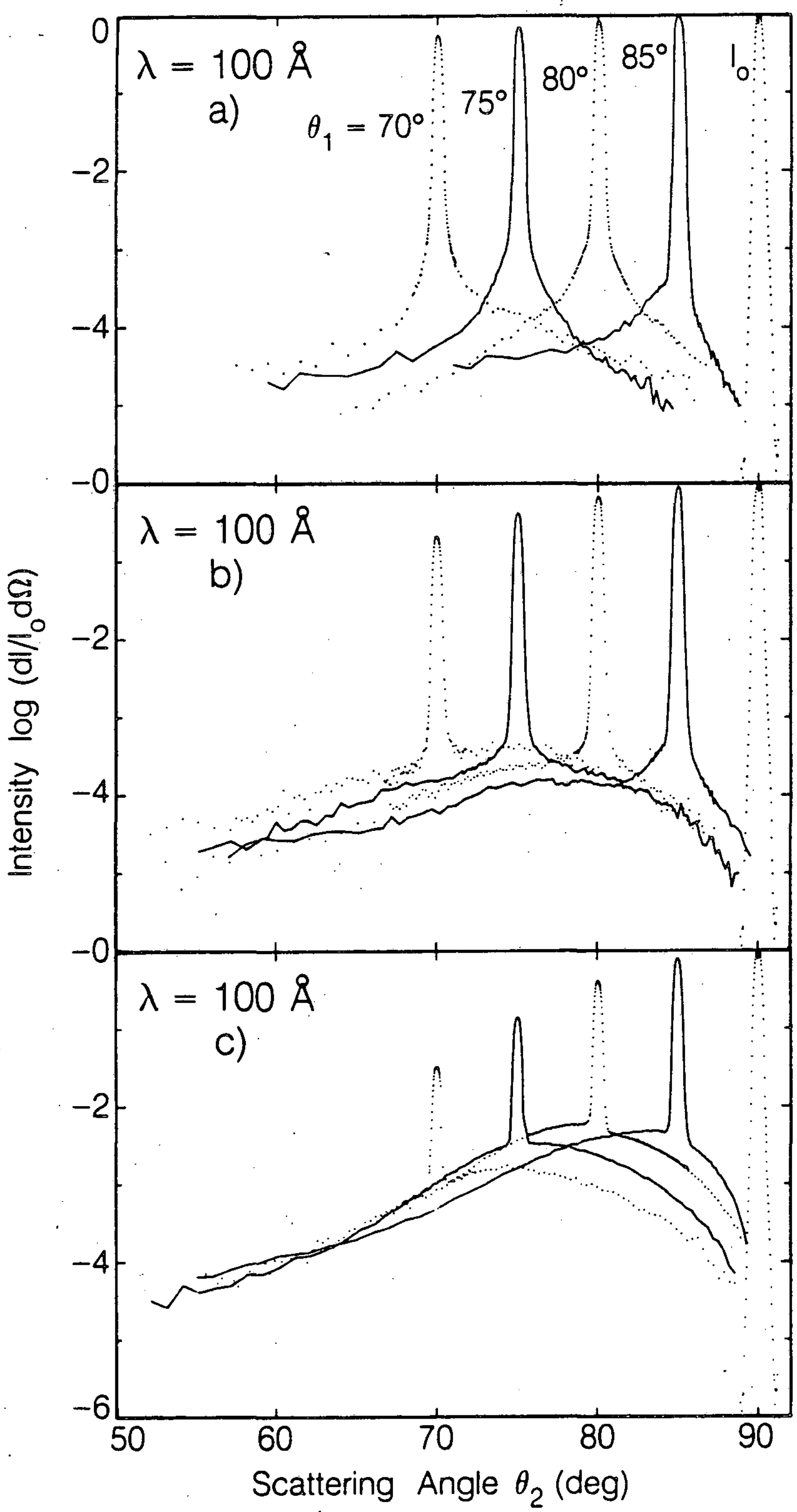

λ = 100 Å
a)
θ_1 = 70°
75°
80°
85°
I_o
λ = 100 Å
b)
λ = 100 Å
c)
Intensity log (dI/I_odΩ)
Scattering Angle θ_2 (deg)
0
-2
-4
-0
-2
-4
-0
-2
-4
-6
50
60
70
80
90

Fig. 3

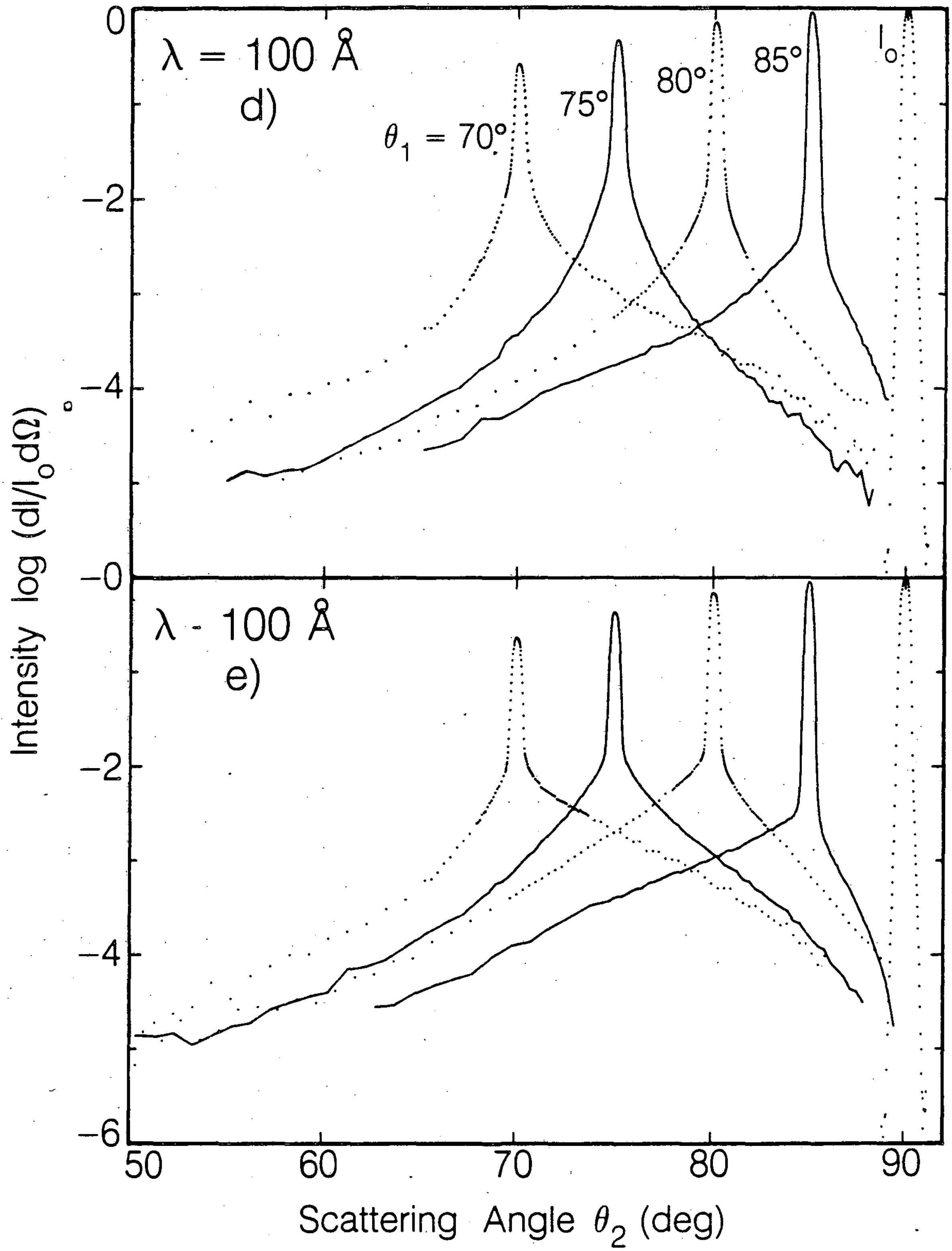

λ = 100 Å
d)
θ_1 = 70°
75°
80°
85°
I_o
λ - 100 Å
e)
Intensity log (dI/I_odΩ)
0
-2
-4
-0
-2
-4
-6
50
60
70
80
90
Scattering Angle θ_2 (deg)

Fig. 3 (cont.)

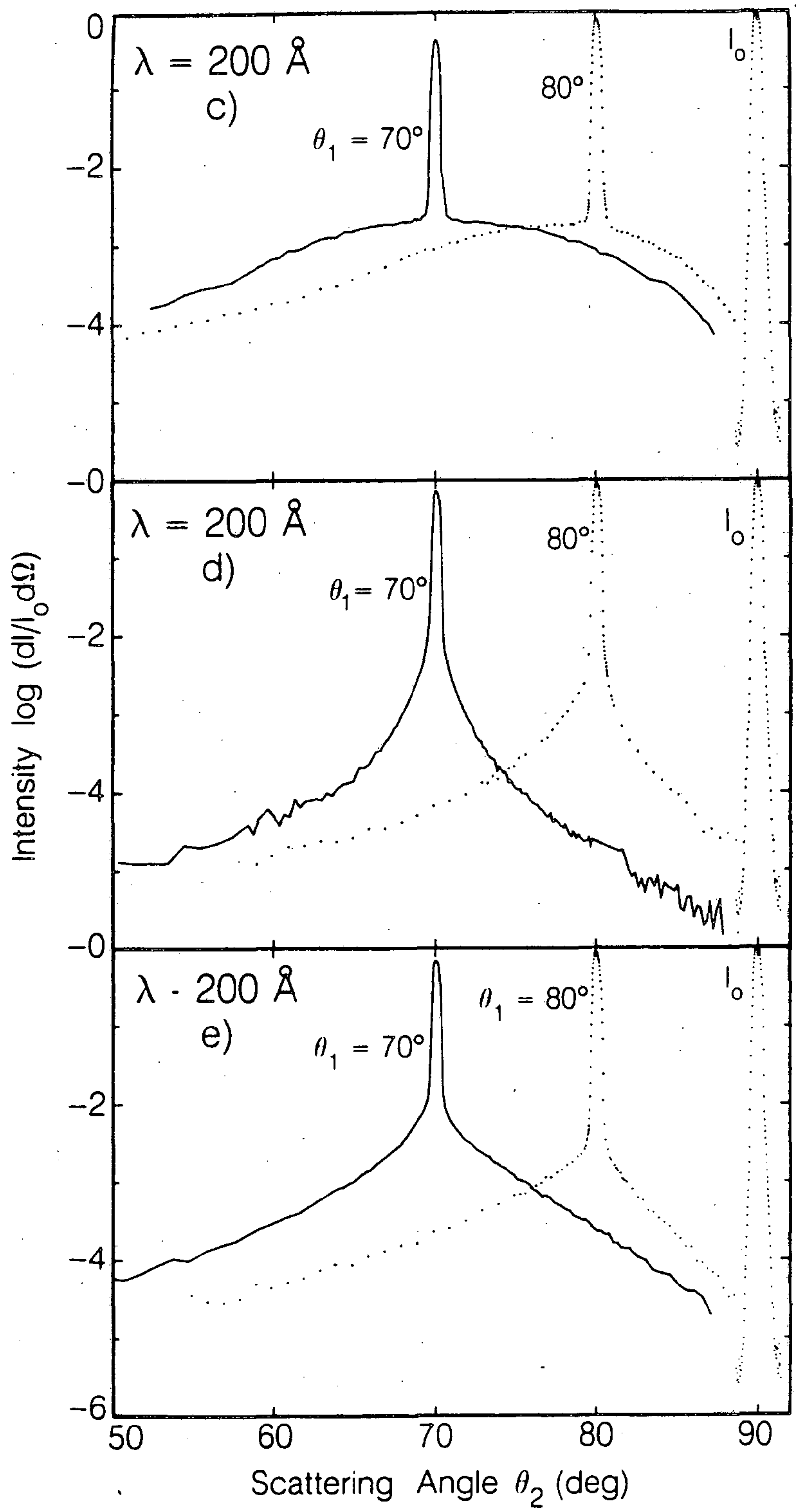

λ = 200 Å
c)
θ1 = 70°
80°
Io
λ = 200 Å
d)
θ1 = 70°
80°
Io
λ - 200 Å
e)
θ1 = 70°
θ1 = 80°
Io
Intensity log (dI/Io dΩ)
Scattering Angle θ2 (deg)
0
-2
-4
-0
-2
-4
-0
-2
-4
-6
50
60
70
80
90

Fig. 4

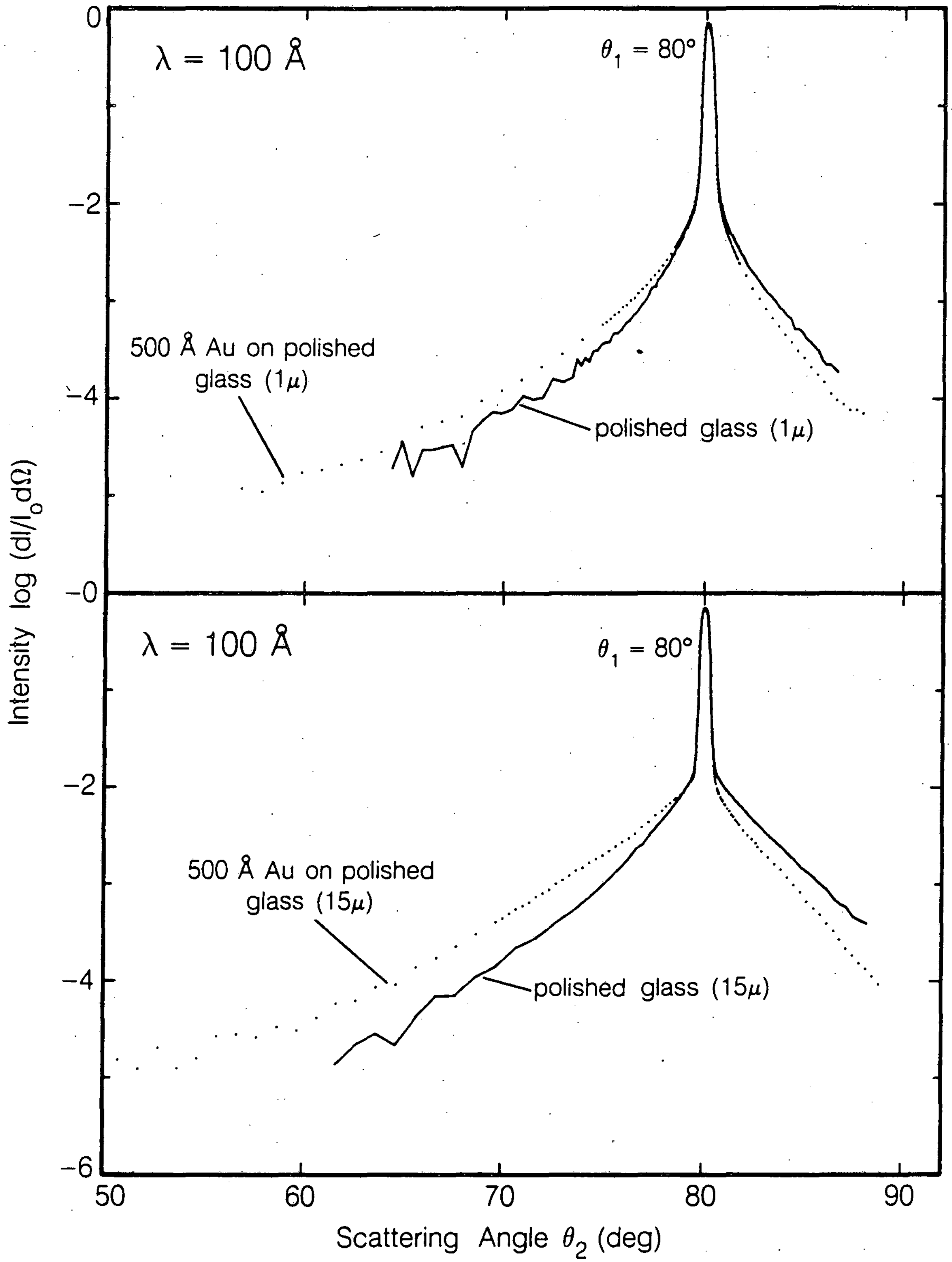

λ = 100 Å
θ1 = 80°
500 Å Au on polished glass (1μ)
polished glass (1μ)
λ = 100 Å
θ1 = 80°
500 Å Au on polished glass (15μ)
polished glass (15μ)
Intensity log (dI/I0dΩ)
0
-2
-4
-0
-2
-4
-6
50
60
70
80
90
Scattering Angle θ2 (deg)

Fig. 5

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