INVESTIGATIONS OF THE SURFACE DIELECTRIC FUNCTION BY MEANS OF THE SCANNING ELLIPSOMETRY AND TRANSITION RADIATION METHODS*

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ABSTRACT. We describe the scanning ellipsometry and transition radiation methods as well as their applications to surface dielectric function measurements. In particular, we present the results for a gadolinium sample in the visible and ultraviolet spectral ranges. We compare our experimental results obtained by both methods.

1. INTRODUCTION

The experimental techniques applied to surface investigations are based on the measurements of parameters describing processes which occur at the nearest neighbourhood of the surface. On the other hand, the surface properties can be detected by analyzing the volume dependent characteristics which are very sensitive to the surface influence which is important when the considered characteristics are spatially inhomogeneous due to the presence of the surface.

The surface experimental techniques chosen for a physical and chemical characterization can be divided into three categories, based on the excitation and

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emission processes in connection with electrons, ions, and photons. Table I contains the most popular and representative techniques for each of the categories mentioned in [1] [3].

TABLE I

Emission \ Excitation	Electrons	Ions	Photons
Electrons	Auger Electron Spectroscopy – AES Low Energy Electron Diffraction – LEED Scanning Electron Microscopy – SEM Scanning Tunneling Microscopy – STM Electron Energy Loss Spectrometry – EELS		Electron Spectroscopy for Chemical Analysis – ESCA
Ions		Secondary Ion Mass Spectroscopy – SIMS Ion Scattering Spectroscopy – ISS	
Photons	Transition Radiation – TR X-ray Microanalysis		Ellipsometry – ELL Optical Interferometry – OI Optical Microscopy – OM

Recently, the variety of methods for surface investigations is still increasing. The present paper is devoted to the scanning ellipsometry and transition radiation methods applied to the surface dielectric function.

2. THE ELLIPSOMETRY OF SOLIDS

When a polarized beam of light is modified by reflection at non-normal incidence from a specularly reflecting surface, its state of polarization is changed. Ellipsometry is the branch of optical spectroscopy that deals with the measurement and interpretation of the change in polarization state in terms of the physical properties of the reflecting surface. These changes can be used with the aid of appropriate models to determine some physical characteristics of the measured

system. For example, a single ellipsometric setting can be used to determine both the real and imaginary parts of the complex dielectric function of a bare reflecting surface or the thickness and refractive index of a transparent film deposited on a substrate, and similar parameters.

The fact that ellipsometry measures the polarization state rather than the intensity, as in the case of reflectometers, makes it inherently a high-precision technique which is relatively unaffected by experimental difficulties caused by source intensity fluctuations or ligh-scattering defects which may occur even on the most carefully prepared surfaces. The capability of measuring phase changes directly gives ellipsometry great sensitivity to the presence of thin films on reflecting surfaces which may be detected to the average thickness of the order of hundredths of a monolayer [2].

The importance of surface conditions can be appreciated on the basis of the fact that the measurements by the ellipsometry method are so sensitive that the influence of a 1 - Å surface layer on various substrate parameters, in particular, the surface dielectric function, can be detected even though the penetration depth of light in opaque materials is about 100–500 Å in the near ultraviolet region [4].

Other advantages of ellipsometry as well as of other optical techniques are the facts that they are nondestructive and can be used for in situ measurements in opaque or any transparent-ambient systems.

3. THE GENERAL ELLIPSOMETER CONFIGURATION

The manipulation and measurement of the polarization state for most ellipsometers is performed by linear optical elements as shown in Fig. 1.

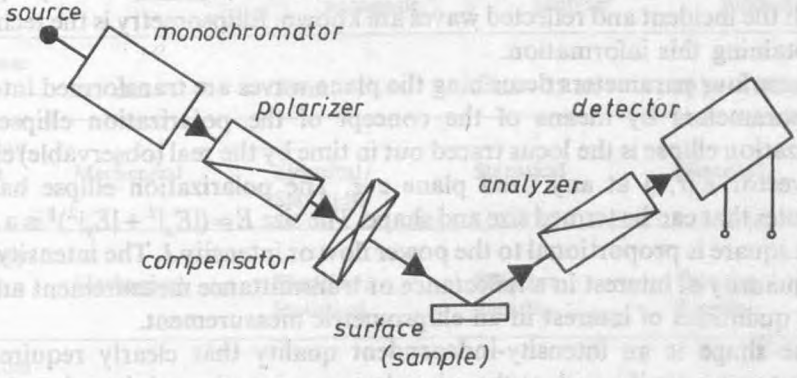

Fig. 1. Schematic diagram of the general ellipsometer configuration.

The light source and monochromator provide a quasiparallel and quasimonochromatic flux. The polarization state of the flux prior to reflection from the sample surfaces is determined by the polarizer and compensator (the compensator is optional in some systems). The polarization state after reflection is measured by a second polarizer, the analyzer, and the resultant intensity converted into electrical form by the photodetector. Ellipsometric data may be obtained either by adjusting the optical elements for zero transmitted flux (null ellipsometry) or by analyzing the time dependence of the transmitted flux that results from the periodic variation of one of the elements (photometric ellipsometry).

An incident plane wave propagating in the z-direction of a local orthogonal coordinate system can be represented as [7]

$$\vec{E};(\vec{r},\, t)=Re\,[(\hat{x}E_x+\hat{y}E_y)\,e^{ikz-i\omega t}] \tag{1}$$

where E_x and E_y are complex field coefficients describing the amplitude and phase dependences of the projections of $\vec{E}_i(\vec{r},\, t)$ along the x and y axes.

If the electromagnetic wave of the light flux is reflected by a smooth surface, the outgoing wave can be represented in the absence of anisotropic effects in another local coordinate systems as

$$\vec{E}_r(\vec{r},\, t)=Re\,[(\hat{x}r_p E_x+\hat{y}r_s E_y)\,e^{ikz-i\omega t}] \tag{2}$$

where in both local coordinate systems the x axes are in the plane of incidence, the y axis is perpendicular to the plane of incidence, and the z axis defines the plane of incidence.

In this approximation the effect of the sample surface is described by two coefficients r_p and r_s. These complex reflectances describe the action of the sample on the field components parallel (p) and perpendicular (s) to the plane of incidence. Thus, four parameters – two amplitudes and two phases – are necessary to describe completely the incoming wave and four more to describe the sample. The properties of the sample therefore are obtainable if the properties of both the incident and reflected waves are known. Ellipsometry is the technique for obtaining this information.

These four parameters describing the plane waves are transformed into four new parameters by means of the concept of the polarization ellipse. The polarization ellipse is the locus traced out in time by the real (observable) electric field vector $\vec{E}(\vec{r},\, t)$ at any fixed plane z–z. The polarization ellipse has two attributes that can be termed size and shape. The size $E=(|E_x|^2+|E_y|^2)^{\frac{1}{2}}$ is a scalar whose square is proportional to the power flow or intensity I. The intensity is the only quantity of interest in a reflectance or transmittance measurement and one of the quantities of interest in an ellipsometric measurement.

The shape is an intensity-independent quality that clearly requires two parameters to specify, such as the minor/major axis ratio and the azimuth angle of the major axis of the polarization ellipse. One convenient representation of the

shape is the polarization state $\chi = E_x/E_y$; since E_x and E_y are complex, χ is also complex and therefore contains the required two parameters.

Given either the intensities or polarization states for the incident and reflected beams, the sample properties can be calculated by taking appropriate ratios. Inellipsometry, the ratio of polarization states yields a somewhat different perspective of the sample. By Eqs. (1) and (2)

$$\chi_r/\chi_i = (r_p E_x/r_s E_y)/(E_x/E_y) = r_p/r_s \tag{3}$$

$$r_p/r_s = \rho(\tan\psi)\, e^{i\Delta} \tag{4}$$

The complex reflectance ratio ρ is often expressed as an amplitude ($\tan\psi$) and a phase Δ.

4. TYPES OF ELLIPSOMETER SYSTEMS

The objective of an ellipsometer system is to determine the change in polarization state of light transformed by reflection from the surface. Two basic types of ellipsometer systems developed for this purpose and now in general use are null ellipsometers and photometric ellipsometers.

The relative advantages and disadvantages of three representative types of ellipsometers – one null and two photometric – are summarized in Table II.

TABLE II

	Null		Photometric	
	Manual	Modulated automatic	Rotating-analyzer	Phase-modulated
Response time	>1 min	10 ms – 10 s	5 ms – 25 ms	20 μs – 100 μs
Precision limit	Mechanical	Electrical/ Statistical	Statistical	Electrical
Accuracy limit	Mechanical	Electrical/ Statistical	Detector linearity	Detector linearity
Optimum reflecting surface	Any	Any	Metal	Metal

Table II contd.

Scanning range	No practical	Compensator-limited	Source/detector limited	Modulator limited
Disadvantages	Tedious to operate; poor signal-to-noise	Sensitivity to dark current noise	Requires linear detector	Requires linear detector
Advantage	Mechanical simplicity	Accuracy	High precision; no wavelength dependence	High precision; high speed

4.1. *Null ellipsometer*

The null ellipsometer consists of a polarizer, compensator, sample (reflecting surface) and analyzer. Measurements are performed usually by adjusting the polarizer azimuth so that the ellipticity produced by the polarizer-compensator combination is exactly cancelled by reflection, leaving a linearly polarized beam that can be extinguished completely by suitably adjusting the analyzer azimuth. The symmetry of the instrument implies that the same null will be obtained with the source placed at either end of the instrument.

The null ellipsometer is the simplest system in the sense that if the operator is willing to read the azimuth angles and perform the calculations, the only equipment needed is the mechanical/optical system comprising the ellipsometer itself and a strong monochromatic light source such as a laser or a suitably filtered spectral line source. It is not particularly well suited for scanning purposes, but can be useful for repetitive measurements on a small scale.

4.2. *Modulated null ellipsometer*

The ease and precision of the null settings of the azimuth angles of the polarizer and analyzer prism can be determined by using Faraday cells or Pockels cells to modulate the planes of polarization of light emerging from the polarizer and entering the analyzer.

The principal disadvantage in this method is the sensitivity of the attainable precision to even small amounts of stray light or detector dark current as a consequence of operation at low light levels.

4.3. *Phase-modulated ellipsometer*

A phase-modulated ellipsometer is a photometric system obtained by replacing the compensator with a large-amplitude birefringent modulator such as a Pockels cell or piezobirefringent plate.

The significant advantage of phase-modulated ellipsometers compared with other systems lies in their speed of measurement. Since piezobirefringent modulators operate in the 100 kHz range, measurement times of the order of 10 μs are possible in principle. Thus, these systems should be particularly useful for monitoring fast reactions at interfaces.

4.4. *Rotating-analyzer ellipsometers*

The rotating-analyzer ellipsometer is a photometric instrument where information is carried in the time dependence of the transmitted flux. In its simplest form, a rotating-analyzer system consists of a polarizer, reflecting surface, and rotating-analyzer. These systems are ideal for scanning purposes since high precision is easily achieved and, in the absence of a compensator, the only wavelength-dependent element is the reflecting surface itself.

Such an ellipsometer has been used for the dielectric function measurements presented in this paper; therefore, we shall consider its construction and principle of operation in more detail.

A scheme of the ellipsometer is presented in Fig. 2.

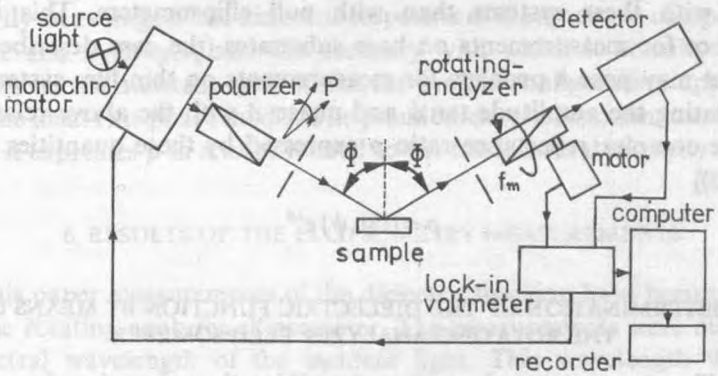

Fig. 2. Experimental arrangement of the rotating-analyzer ellipsometer.

The continuum source used here was a high pressure xenon short-arc lamp. A light beam from the Xe lamp passed through the monochromator and next (with a definite wavelength) fell on the polarizer prism, which was a Rochon

prism. That linearly polarized light beam fell on a measurement sample under an incidence angle Φ. Next, the reflected light beam passed through an analyzer (a Rochon prism as well). The analyzer, rotating about its axis, analysed the polarization degree of the reflected beam whose intensity was measured with a photomultiplier tube. The current variations of the output of the photomultiplier tube as well as the variations of the light beam on the photocathode of the photomultiplier tube (of the light reflected on the sample) are described by the formula (9):

$$J(t)=J_0(1+\alpha\cos 2ft+\beta\sin 2ft) \tag{5}$$

where J_0 is the mean light intensity and α, β are normalized Fourier coefficients describing the phase and relative complex amplitude of the ac component of the flux incident on the detector, whereas f is the optical frequency, equal to twice the mechanical analyzer rotation frequency f_m.

The normalized Fourier coefficients α and β are determined experimentally from the values of the dc, cosine, and sine components of the transmitted intensity and are given from output of the lock-in nanovoltmeter (see Fig. 2).

In terms of α and β we find that [2]:

$$\tan\psi=\left(\frac{1+\alpha}{1-\alpha}\right)^{1/2}\tan P \tag{6}$$

$$\cos(\Delta-\delta)=\beta/(1-\alpha)^{1/2} \tag{7}$$

where P is the azimuth angle which locates the plane of polarization of the polarizer prism with respect to the incident light plane. Since rotating-analyzer ellipsometers measure $\cos(\Delta-\delta)$ rather than Δ, intrinsically less information is available with these systems than with null ellipsometers. This is of no consequence for measurements on bare substrates (the case described in this paper), but may pose a problem for measurements on thin-film systems.

Calculating the amplitude $\tan\psi$ and phase Δ with the above relations, we obtain the complex reflectance ratio ρ expressed by these quantities (see also formula (3))

$$\rho=(\tan\psi)\,e^{i\Delta} \tag{8}$$

5. DETERMINATION OF THE DIELECTRIC FUNCTION BY MEANS OF THE ROTATING-ANALYZER ELLIPSOMETER

A significant parameter given when describing the properties of a solid is the complex dielectric permittivity, defined as a function of the frequency ω as:

$$\varepsilon(\omega)=\varepsilon_1(\omega)+i\varepsilon_2(\omega) \tag{9}$$

where $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ are real and imaginary parts, respectively. The quantity presented in such a way appears often in the literature as the dielectric function [2].

In the general case the dielectric function is a second order tensor. Since we restrict ourselves to the investigation of the polycrystalline, isotropic medium the dielectric function can be represented here by a scalar quantity only which is sufficient to express the results of our measurements.

In the ideal case, in which the specimen (substrate) is homogeneous and isotropic and the surface is mathematically sharp, the dielectric function $\varepsilon(\omega)$ is given by the two-phase (substrate-ambient) model [4]:

$$\frac{\varepsilon(\omega)}{\varepsilon_a(\omega)} = \sin^2 \Phi + \sin^2 \Phi \tan^2 \Phi \left[\frac{(1-\rho(\omega))}{(1+\rho(\omega))}\right]^2 \tag{10}$$

where Φ is the angle of incidence, and $\varepsilon(\omega)$, $\varepsilon_a(\omega)$ are the complex dielectric functions of the specimen (substrate) and ambient, respectively.

The accurate determination of the dielectric function and other optical parameters of a material in its pure bulk form requires not only accurate instrumentation but also well-characterized samples.

For real samples, the assumption of a mathematically sharp interface leads to immediate practical difficulties. Transition-region widths are finite even if the lattice termination is atomically perfect. Under typical laboratory conditions, surfaces are covered with oxides or adsorbed contaminations. Surfaces are usually microscopically rough, often as a result of preparation processes used to remove the contaminations for other overlayers. If such effects are not taken into account, the dielectric function calculated from (10) may be considerably in error. However, in the analysis of ellipsometric data it is often useful to assume perfection anyway and to convert the measured quantity ρ into a derived quantity, the pseudodielectric function $\langle\varepsilon\rangle$. The pseudodielectric function is necessarily an average of the dielectric responses of the specimen composed of the substrate and overlayer, and the accuracy with which it actually represents ε depends on the accuracy with which the sample configuration approximates that of the ideal two-phase model. The pseudodielectric function is useful simply because it expresses ρ in a form related to the fundamental quantity of interest.

6. RESULTS OF THE ELLIPSOMETRY MEASUREMENTS

In this paper measurements of the dielectric function have been carried out using the rotating-analyzer ellipsometer. The measurements were made versus the spectral wavelength of the incident light. This wavelength was varied automatically by computer control during the one at a time working cycle of the ellipsometer system. Such a procedure is referred to as scanning along the wavelength and this ellipsometer arrangement is called a scanning ellipsometer system [9].

The present ellipsometric results have been obtained using the apparatus of the Department of Physics of the Universidad Autonoma de Puebla in Mexico.

6.1. *Testing of the scanning ellipsometer equipment*

In order to check the correctness of the ellipsometric method used as well as the functioning of a measuring system, testing measurements for a monocrystal Ag have been performed.

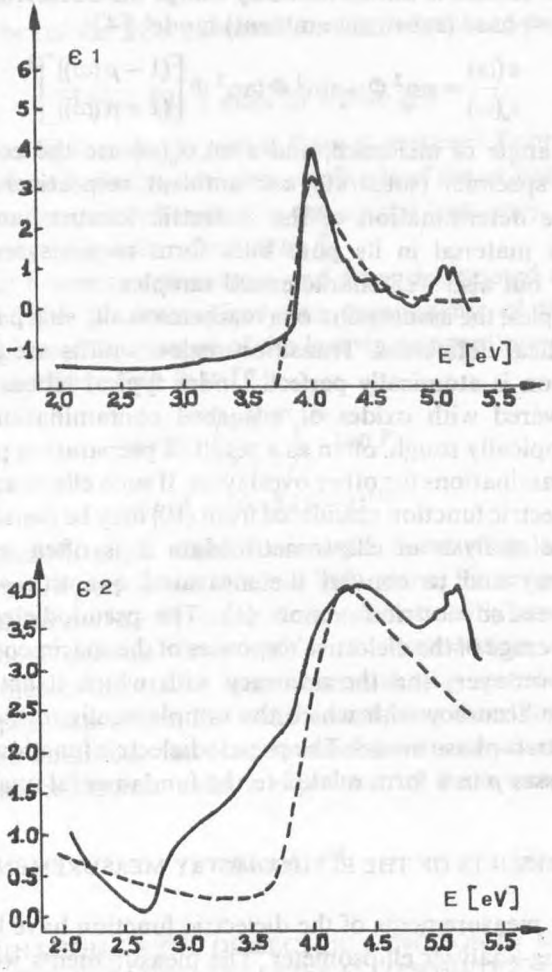

Fig. 3. Dielectric function for Ag monocrystal:
ε_1 – real and ε_2 – imaginary parts of the dielectric function; —— full line – results of testing measurements; – – – – dashed line – data from the literature [10].

The results obtained were then compared with the results of other authors, (e.g., [10]). In our case, silver was chosen as a material of well-defined optical

parameters, and served as reference specimen. The results obtained in the testing measurements for the dielectric function of silver (for its imaginary and real parts) are presented in Fig. 3. The full line shows suitable data. From [10] we can observe the similarity in shape and character of the graphs compared. From both graphs we conclude that with the same energies (about 4 eV) the dielectric function in its real and imaginary parts behaves characteristically for the dispersion properties of silver. The differences occurring in the left-hand side of the graphs, in low energy regions (e.g., the visible region) are interpreted as due to the influence of roughness of the sample under investigation. As it is seen, the method of preparation used here has made it impossible for us to obtain a surface of a quality as good as in [10]. Finally, we observe an increase in the determined properties of the dielectric function in its real and imaginary parts by comparison with the results of [10].

The differences observed in the graphs in question in great energy regions (ultraviolet region – the right - hand of the graphs) are caused by trace impurities on the sample surface. These impurities remained after the process of polishing of the sample surface.

All in all, the measuring system can be said to work correctly. The occurring irregularities are connected only with the surface of the sample which had not been prepared properly enough.

6.2. *Results of the measurements for gadolinium*

In the experimental arrangement described above we measured the dielectric function for a solid sample of polycrystalline gadolinium of purity 99,97%, polished mechanically and cleaned chemically.

The measurements were carried out within a spectral range of the incident light from 1,5 eV to 5,3 eV, which corresponds to a wavelength from 820 nm to 234 nm, respectively.

The accuracy of measurement equalled 1% of the experimental result in the whole range. Such a high accuracy enabled us to observe subtle properties of the measured dielectric function of the gadolinium. In Fig. 4 the results of the measurements are presented separately for the real an imaginary parts of the dielectric function.

Because of the rapid changes in the surface state of the investigated sample which characterize materials like gadolinium, we carried our measurements directly after bringing to an end the process of preparing the sample as well as after long periods from the moment of its installation in the measurement chamber. The first measurement referred to the purest surface of the sample and by means of it the qualities in question were determined.

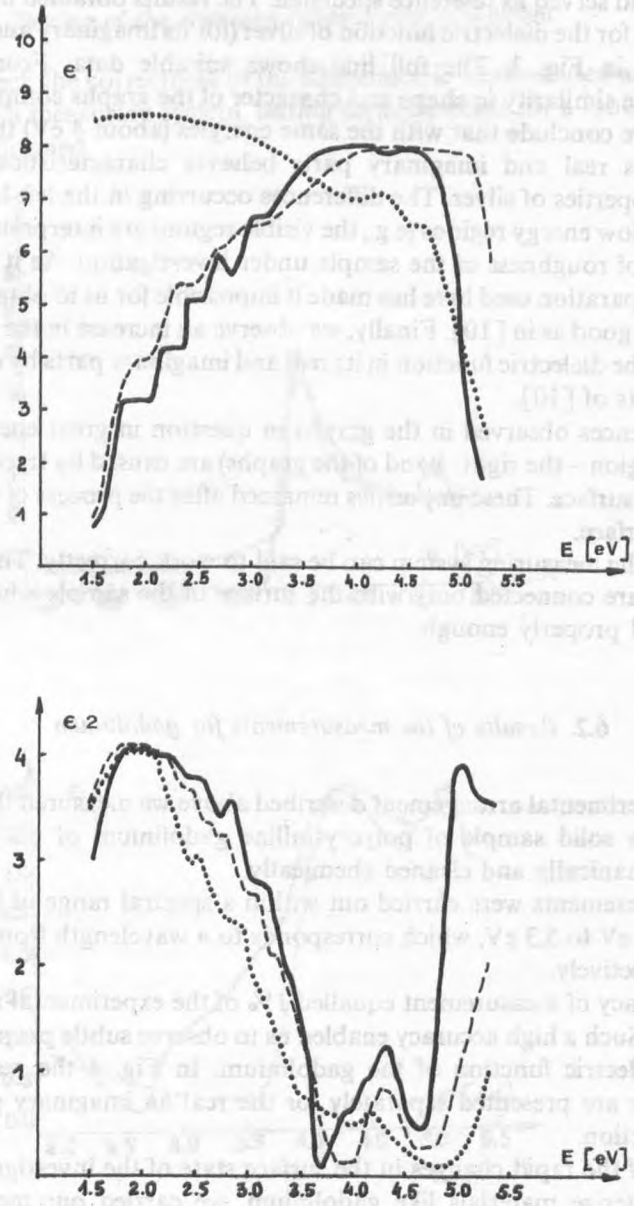

Fig. 4. Dielectric function for gadolinium sample:
ε_1 – real and ε_2 – imaginary parts of the dielectric function; full line – measurement results directly after the process of preparing; dashed line – measurement results obtained 24 hours after the process of preparing; .... dotted line – measurements 48 hours after the process of preparing.

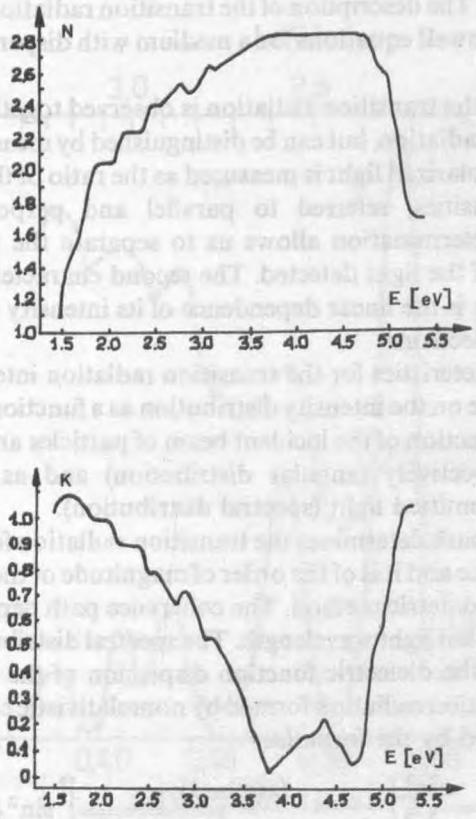

Fig. 5. Refractive index N and index of extinction K.

The surface variations in time, occurring in the sample under investigation, are especially well apparent in the graphs of the real part of the dielectric function and concern the raising (in low energy regions) of the left-hand side of the graphs. Simultaneously, the step character of the graph observed till now vanished. In fact, two days after the preparation of the sample its surface state made it impossible to carry out ellipsometric measurements.

In Fig. 5 we present such optical parameters of gadolinium as its index of refraction N and index of extinction K as functions of frequency.

7. THE TRANSITION RADIATION PHENOMENON

The transition radiation predicted by Ginzburg and Frank [11] is emitted as an electromagnetic radiation produced when a charged particle moves with constant velocity and crosses the interface between two media with different

dielectric functions. The description of the transition radiation properties is based on the classical Maxwell equations for a medium with dispersion of the dielectric susceptibility [12].

In experiments the transition radiation is observed together with other kinds of electromagnetic radiation, but can be distinguished by means of its polarization. The degree of the polarized light is measured as the ratio of the difference and the sum of two intensities, referred to parallel and perpendicular planes of polarization. Its determination allows us to separate the transition radiation from other kinds of the light detected. The second characteristic identifying the transition radiation is the linear dependence of its intensity on the energy of the incident beam of electrons.

The main characteristics for the transition radiation intensity are connected with the dependence on the intensity distribution as a function of the angles Φ and ϑ referred to the direction of the incident beam of particles and to the direction of emitted light, respectively (angular distribution) and as a function of the wavelength of the emitted light (spectral distribution).

The coherence path determines the transition radiation formation area at the vicinity of the surface and it is of the order of magnitude of the penetration depths of light in the ellipsometric method. The coherence path depends on the particle energy and the emitted light wavelength. The spectral distributions are of various shapes and reflect the dielectric function dispersion of the sample. The energy density of the transition radiation formed by nonrelativistic electrons (for the case $\Phi = \pi/2$) is described by the formula:

$$\frac{d^2w}{d\Omega\, d\omega} = \frac{e^2v^2}{\pi^2c^3}\left|\frac{(\varepsilon(\omega)-1)}{\varepsilon(\omega)\cos\vartheta+\sqrt{\varepsilon(\omega)-\sin^2\vartheta}}\right|^2 \sin^2\vartheta\cos^2\vartheta \tag{11}$$

where $\varepsilon(\omega)$ is the complex dielectric function of the sample (the ambient medium is, in typical cases, vacuum i.e. $\varepsilon_a(\omega)=1$); e and v are the charge of the electron and its velocity, respectively.

8. APPLICATION OF TRANSITION RADIATION TO THE DISCUSSION OF THE SURFACE DIELECTRIC FUNCTION

The transition radiation emitted from a surface sample depends mainly on the optical parameters of the medium in which it is created [12] [3]. In particular, the intensity of this radiation, measured by the fixed energy of the charged particle and by the fixed observation angle ϑ, depends exclusively on the sample dielectric function. This direct relationship between the phenomenon of the transition radiation intensity and the dielectric function enables us to measure the latter by the intermediate method, i.e. by investigation of the transition radiation and, later, by calculations from formula (11) of the suitable dielectric function [13].

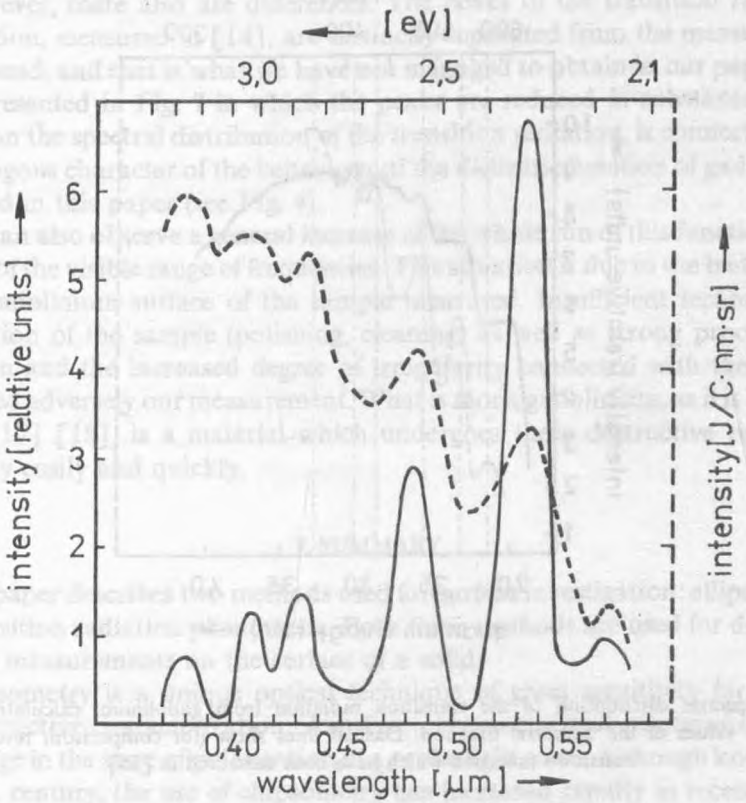

Fig. 6. Dependence of the transition radiation intensity on the wavelength of the observed radiation: —— full line is a result from [14]; - - - - dashed line is a result from [15].

This method has been used in this paper for the investigation of the dielectric function in a gadolinium sample. We calculated the spectral distribution of the transition radiation for the gadolinium dielectric function which had been measured in this paper by the ellipsometric method (see subsec. 6.2). The results obtained will be compared with the corresponding experimental measurements in [14], where the transition radiation on the gadolinium sample has been investigated. The directly measured spectral distribution of the transition radiation for the gadolinium which has been presented in [14] is shown in Fig. 6. We also show this result after normalization to absolute units from [15].

The spectral distribution of the transition radiation obtained there contains several peaks of the intensity of this radiation for wavelengths in the visible region. The calculation results from formula (11) (for dielectric function evidence with ellipsometry method) are presented in Fig. 7.

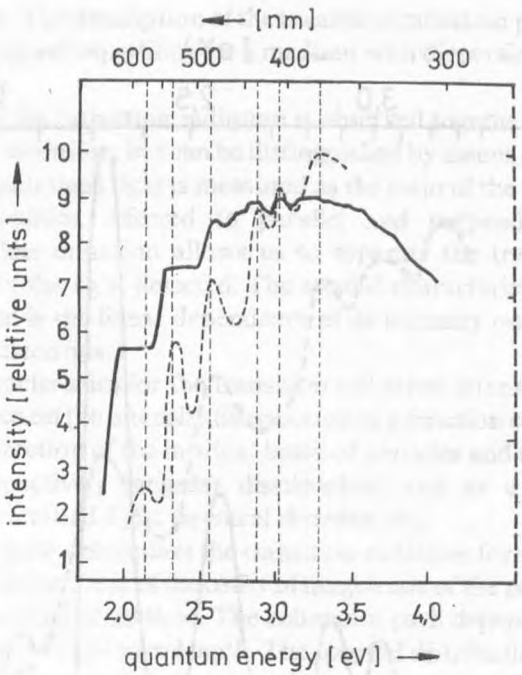

Fig. 7. Spectral distribution of the transition radiation from gadolinium calculated for the measured values of the dielectric function: Dashed lines show (for comparison) results of the transition radiation which have been measured in [15].

We note a great similarity between the peaks shown in Fig. 6 and the irregularities of the last graph of the spectral distribution of the transition radiation calculated here on the basis of the dielectric function obtained in this paper (see subsec. 6.2). This comparison is of a qualitative nature and concerns exclusively the comparison of the frequency at which there exist variations of the character of the peaks of the transition radiation intensity. In this way these results confirm the theoretical model assumed which describes the dielectric function of the gadolinium presented in [14].

The results for the dielectric function of gadolinium versus frequency shows, as far as the general character of variability is concerned, a behaviour typical for many metals. However, when analyzing the graph exactly, we can observe its irregular, step-like shape in the visible region, both in its real and imaginary parts. Such irregularities of the graph (on its left-hand side) cause, among other things, that the spectral distribution of the transition radiation, calculated for such a dielectric function, has an analogous irregular character.

These irregularities are identical (as for their position on the frequency axis) with the peaks of this distribution as measured directly in [14] [16].

However, there also are differences. The peaks of the transition radiation distribution, measured in [14], are distinctly separated from the measurement background, and that is what we have not managed to obtain in our paper. The result presented in Fig. 7 in which the peaks are reduced in substance to flat "steps" on the spectral distribution of the transition radiation, is connected with an analogous character of the behaviour of the dielectric function of gadolinium measured in this paper (see Fig. 4).

We can also observe a general increase of the whole run of this function from the side of the visible range of frequencies. This situation is due to the bad quality of the gadolinium surface of the sample measured. Insufficient technological preparation of the sample (polishing, cleaning) as well as strong processes of oxidation and the increased degree of irregularity connected with them have influenced adversely our measurement. What is more, gadolinium, as it is pointed out in [17] [18], is a material which undergoes these destructive processes especially easily and quickly.

9. SUMMARY

The paper describes two methods used for surface investigation: ellipsometry and transition radiation phenomena. Both these methods are used for dielectric function measurements on the surface of a solid.

Ellipsometry is a unique optical technique of great sensitivity for in situ non-destructive characterization of surface phenomena and reactions utilizing the change in the state of polarization of a probe light wave. Although known for almost a century, the use of ellipsometry has increased rapidly in recent years. Among the most significant recent developments are new automated instrumentation and techniques for error-free data analysis.

In this paper we have determined exactly, by means of the ellipsometry method, the dielectric function of gadolinium. Only such a high accuracy of measurement, typical of the rotating-analyzer ellipsometer, has allowed us to obtain a more interesting shape of the dielectric function.

This interesting shape of the dielectric function in the gadolinium sample has also been confirmed by the transition radiation measurements. In this way the transition radiation method has become a convenient tool of surface dielectric function observation supplementary to ellipsometric methods.

REFERENCES

[1] G. B. Larrabee; Scanning Electron Microscopy, vol. I (1977) 639.

[2] D. E. Aspnes; in Optical Properties of Solids – New Developments, (North–Holland, Amsterdam, 1976), Ch. 15.

[3] L. Wojtczak, Conf. "Trends in Physics" Prague 1984.

[4] D. E. Aspnes, in Handbook of Optical Constants of Solids (Academic Press – INC 1985) Ch. 5.

[5] K. Brudzewski, Scientific Bulletin of the Technical University of Warsaw, 30 (1983) (in Polish).
[6] A. V. Rzhanov et al., Principles of Ellipsometry (Nauka, Novosibirsk, 1979) (in Russian).
[7] J. D. Jackson, Classical Electrodynamics (Wiley, New York, 1962) Ch. 7.
[8] R. M. A. Azzam, N. M. Bashara, Ellipsometry and Polarized Light (North–Holland, Amsterdam, 1987).
[9] D. E. Aspnes, A. A. Studna, Appl. Opt., 14 (1975) 220.
[10] H. Ehrenreich, H. R. Philipp, Phys. Rev., 4 (1962) 1622.
[11] W. L. Ginzburg, J. M. Frank, Zh. Eksp. Teor. Fiz. 16 (1946) 15 (in Russian).
[12] F. G. Bass, W. M. Jakovenko, Uspekhi Fiz. Nauk., 86 (1965) 189 (in Russian).
[13] S. Michalak, K. Polański, J. Rutkowski, Acta Univ. Lodz, Folia Physica 3 (1984) 61.
[14] S. Michalak, Nguyen Chau, K. Polański, Acta Phys. Pol. 1–2 (1981) 39.
[15] K. Polański, Doctor's Thesis, University of Lódź, 1982 (in Polish).
[16] A. P. Kobziev, A. .Krawczyk, K. Polański, J. Rutkowski, Proceedings IVth School – Symposium "Physics of Metals" Piechowice, April 23–28 (1987) p. 91, Poland.
[17] O. Singh, A. E. Curzon, Thin Sol. Film, 44 (1977) 233.
[18] A. A. Hussain, Thin Sol. Film, 77 (1981) 330.