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Examination of thin dielectric films with ellipsometric method*

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Ellipsometry in reflected light may be applied to examination of thin dielectric layers on absorbing substrate. The basic optical parameters of the dielectric layers: i.e. their refractive index (n) and thicknesses (d) may be determined from the measurement of the phase difference (Δ) and azimuth (Ψ) for the examined dielectric film – absorbing substrate system. The transition from the measured quantities Δ and Ψ to the film parameters (n and d) may be carried out by using a graphical method (for instance, Shklyarevskii's method) or by using a respective computer programme. In this paper a computational estimation of n and d for ytterbium oxide thin films obtained from the programme elaborated for computer was compared with the respective results obtained by applying the ellipsometric method due to Shklyarevskii. The results obtained show that this programme may be used for the calculation of refractive index and thickness of the dielectric film from the results of ellipsometric measurements.

Introduction

An increasing interest in ellipsometric method observed in the course of last years is connected with the examination of very thin dielectric and absorbing films (several to tens nanometers) deposited on an absorbing substrate. These examinations are important because of metal oxidizing effects, they are also of some meaning in tunnel spectroscopy as well as in investigations of the state of material surface in ultrahigh vacuum. The layers to be examined may be created either in a natural way or deposited artificially.

Ellipsometry exhibits an essential predominance over other methods, since the ellipsometric methods do not require any special preparation of the examined surface and allow to carry out the examinations under different physical conditions (temperature, pressure, type of atmosphere and so on). Nowadays the development of ellipsometry is considerably simplified due to the advances of the computational technique.

The ellipsometric methods in the reflected light are based on the analysis of ellipticity of the light reflected from the examined object.

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If the medium is of absorbing type or a thin film occurs on its surface, then the plane polarized light falling under an angle different from 90° becomes elliptically polarized after reflection.

Results of the experimental examinations

The most common quantities measured experimentally in ellipsometry are: phase difference (Δ) between p- and s-components of the Fresnel coefficients for the light reflected, and the angle Ψ (tan Ψ determines the p- to s-amplitude ratio for the respective Fresnel coefficient components for reflected light).

In all the applications of ellipsometry the interpretation of the values Δ and Ψ (i.e. of the so-called ellipsometric angles) measured directly is reduced to the transition from these quantities to the optical constants n_3, k_3) of the substrate as well as to the optical constants (n_2, k_2) and the thickness (d) of the surface film. Mathematically this means the necessity of solving the inverse ellipsometric problem, i.e. the finding of values of $n_3, k_3; n_2, k_2$ and d on the basis of the values Δ and Ψ measured experimentally.

If the calculation of Δ and Ψ from system parameters ($n_3, k_3; n_2, k_2$ and d) does not present any essential difficulties due to application of computers, an explicit solution of the general equation of ellipsometry with respect to n_3, k_3, n_2, k_2 and d is still unachievable. Therefore, in practice the ellipsometry equation is solved by using either graphical methods or simplified formulae which are valid only for very thin films (some nanometers thick) or finally by using special programmes for computers which allow to solve the general equation of ellipsometry.

The graphical ellipsometric method proposed by Shklyarevskii [1–4] allows to determine simultaneously the refractive index and the thickness of the thin layers, both of dielectric and absorbing type, deposited on an absorbing substrate. In this method the refractive index and the thickness of the surface film are determined from the film-absorbing substrate system. For the given experimental values $\lambda, \varphi, n_3, k_3$ a set of dependences $\Delta(d)$ and $\Psi(d)$ is calculated from the general ellipsometry equation for some reasonably accepted values of the refractive index (n_2) for the examined film. These calculations are carried out on a computer. The intersection points of the curves $\Delta(d)$ and $\Psi(d)$ obtained in this way with the straight lines corresponding to the experimentally measured values of Ψ_{exp} and Δ_{exp} (see fig. 1) give two new dependences $n_\Delta(d)$ and $n_\Psi(d)$. The intersection points for curves n_Δ and n_Ψ determine the sought values of both the refractive index and thickness of the examined film (fig. 2). The Shklyarevskii's method is very laborious and requires plotting of a series of curves. The accuracies achieved with this method for dielectric film

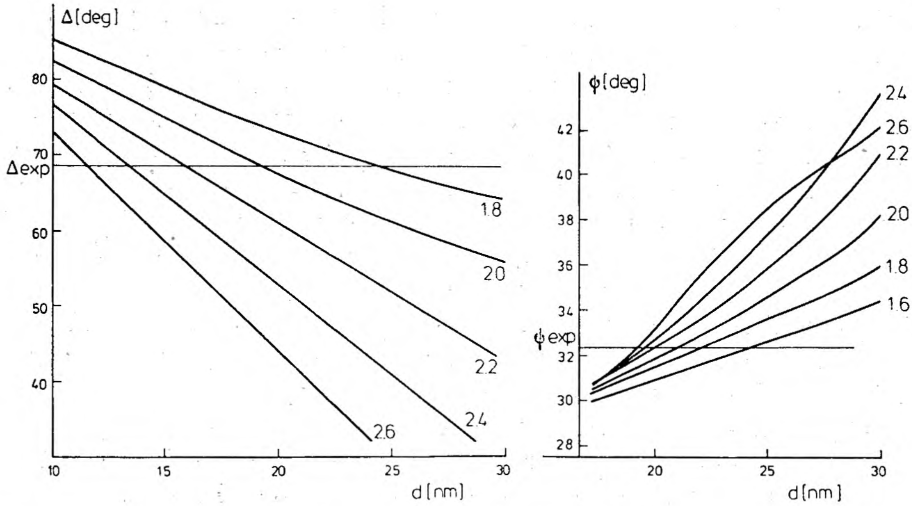

Fig. 1. The calculated family of curves $\Delta(d)$ and $\Psi(d)$ for the layers Yb_2O_3 on chromium. The incidence angle 70°, optical constant of chromium for $\lambda = 500$ μm, $n_3 = 2.11$, $k_3 = 2.10$. The horizontal lines represent experimental data (Δ_{exp}, Ψ_{exp}), while the numbers close to curves denotes the values of n_2

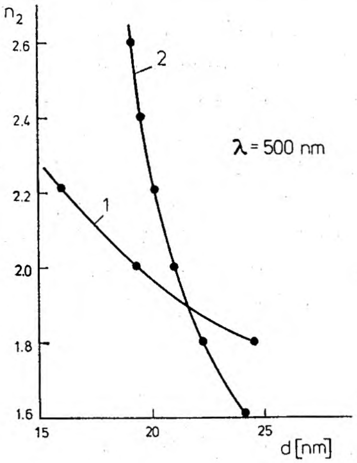

Fig. 2. Determination of the refractive index (n_2) and the thickness (d) for the ytterbium oxide layers: 1) $n_\Delta(d)$ found from the fig. 1, 2) $n_\Psi(d)$ found from the fig. 1

on chromium substrate are of order of some percent both for the refractive index and thickness of the layer.

Therefore, a programme for computer has been elaborated which allows to determine from the experimental data of Δ and Ψ the refractive index and the thickness of the dielectric layer deposited on an absorbing substrate [5].

The programme elaborated requires the measurement of ellipsometric angles Δ and Ψ for the given incidence angle (φ) for the examined film-absorbing substrate system as well as the knowledge of the optical constants (n_3, k_3) or ellipsometric angles (Δ, Ψ) of the substrate.

The programme has been written for R-32 computer in Fortran IV. It has been verified for a number of tabularized values taken from the work by Gergely [6] for the system SiO_2 on Si. First when the obtained numerical results were consistent with the corresponding tabularized data this programme was applied to calculation of the refractive index and the different thicknesses of this ytterbium layers on the chromium substrate. To be sure that the programme works correctly the results obtained had to be verified by comparing them with those obtained by a different method. The Shklyarevskii's method the correctness of which seems to be unquestionable was chosen as a reference method.

The ytterbium oxide films were obtained by thermal evaporation in vacuum, opaque chromium films being used as the substrates. The ellipsometric measurements have been carried out on a EL-6 ellipsometer [7] in the visible spectral range 450–650 nm.

In the table the results obtained from the computer and those given by Shklyarevskii's method have been collected. The comparison of these data indicates that the elaborated programme may be considered as a correct one since the compared data do not differ practically from each other. The accuracies of evaluations of n and d are conditioned by the accuracy of ellipsometric angle measurement. The ellipsometer applied by us allows to measure the ellipsometric angles with the accuracy not better than 3′, which results in the 1 % accuracy of calculation of n and 0.5 % accuracy of the thickness for a definite wavelength.

In this paper the ellipsometric measurements have been carried out for 9 different wavelengths from the visible spectral range. The deviations from the mean value of the thicknesses of the same film for different wavelengths ranged between 2 and 4 %.

Conclusions

The results obtained in this paper indicate that the elaborated programme allowing to evaluate simultaneously the refractive index and the thickness of a dielectric layer on an absorbing substrate is correct and may be applied to calculations of the parameters of the dielectric films from the ellipsometric measurements.

In the future a further development of the programme is forseen to make it applicable to absorbing films on absorbing substrate, too*.

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Table

A comparison of the results obtained from the computer with those given by Shklyarevskii's method for thin ytterbium layers on chromium

nm	n	d nm	n	d nm	n	d nm	n	d nm	n	d nm	n	d nm	n	d nm	
450	–	–	–	–	2.20	8.70	–	–	1.89	22.70	1.84	44.60	2.12	64.00	*
			2.19	8.59	2.19	8.59	1.53	19.63	1.89	22.86	1.83	45.07	2.65	60.75	**
475	2.56	3.33	2.10	7.69	2.15	7.65	1.98	12.10	1.89	23.10	1.82	44.80	1.95	76.00	*
	2.57	3.32	2.15	7.60	2.15	7.60	1.95	12.20	1.89	23.23	1.83	44.41	1.93	76.68	**
500	–	–	2.04	7.81	2.08	6.62	2.03	11.00	1.83	23.90	1.81	44.70	1.85	81.80	*
			2.07	6.56	2.07	6.56	2.03	11.07	1.81	24.27	1.81	44.41	1.83	84.25	**
525	–	–	1.93	8.12	2.02	8.09	1.87	11.90	1.84	22.40	1.83	44.10	1.86	80.40	*
			2.03	7.99	2.03	7.99	1.87	11.91	1.83	22.53	1.81	44.82	1.83	83.15	**
550	2.46	2.80	1.92	7.18	2.08	8.15	1.76	14.10	1.84	23.30	1.80	45.30	1.86	80.00	*
	2.47	2.64	2.09	8.21	2.09	8.21	1.77	14.00	1.85	23.14	1.81	45.00	1.85	81.27	**
575	2.45	3.21	1.68	8.50	1.90	9.25	1.62	15.50	1.79	25.30	1.81	44.70	1.82	84.00	*
	2.47	3.19	1.91	9.23	1.91	9.23	1.61	15.55	1.79	25.32	1.81	44.83	1.81	84.13	**
600	2.23	3.62	1.81	8.91	2.02	8.80	1.62	15.65	1.84	24.20	1.89	43.40	1.85	78.20	*
	2.17	4.40	2.01	9.62	2.01	9.62	1.63	16.47	1.85	24.84	1.85	43.05	1.81	83.06	**
625	2.09	3.83	1.72	11.63	1.88	10.20	–	–	1.81	26.70	1.81	44.50	1.80	84.60	*
	2.11	5.03	1.89	10.15	1.89	10.15	1.53	19.43	1.81	26.49	1.81	44.47	1.81	83.28	**
650	1.97	4.71	1.70	9.05	2.06	8.70	1.60	17.00	1.81	26.60	1.83	44.20	1.80	85.00	*
	1.97	5.00	2.07	8.75	2.07	8.75	1.59	16.98	1.81	26.63	1.83	43.81	1.79	86.01	**

* – experimental results obtained by Shklyarevskii's method,
** – computer results.

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Исследования диэлектрических тонких пленок методом эллипсометрии

Эллипсометрия в отраженном свете может применяться для исследования диэлектрических тонких пленок, находящихся на поглощающей подложке. Основные оптические параметры диэлектрической пленки, коэффициент преломления (n) и её толщина (d), могут быть вычислены из измерения разности фазы Δ и азимута ψ для исследуемой системы диэлектрическая пленка — поглощающая подложка. Переход от измеренных величин Δ и ψ к параметрам пленки (n и d) может быть выполнен либо графическим методом (например, методом Шкляревского), либо созданием программы для ЭЦВМ. В работе сравнены результаты расчета n и d тонких пленок окиси итербия, полученных из разработанной программы вычислений на ЭЦВМ и эллипсометрического метода Шкляревского. Полученные результаты показывают, что программа ЭЦВМ может применяться для вычисления коэффициента преломления и толщины диэлектрической пленки из эллипсометрических измерений.