Total Internal Reflection Ellipsometry with Transition Layer

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Abstract - The paper is devoted to the modeling of the total internal reflection ellipsometry (TIRE) of periodic structures with ferromagnetic stripes. The influence of garnet film located on contact surface of coupling prism, different values of prism refractive indices, and induced anisotropy of grating lamellas are discussed in detail. The interaction of electromagnetic field with lamellar periodic structures and their diffraction properties are determined by coupled wave method implemented as the Fourier modal method. The simulations of the ellipsometric response under internal reflection for different geometrical and material configurations are presented.

Index Terms - ellipsometry, total reflection, evanescent waves, scatterometry

I. INTRODUCTION

The total internal reflection model on the base of coupling prism has been described more thirty years ago. There are many fields in optical research, sensorics or nano-technology, where this experimental set-up and its applications made themselves useful [1]. Recently, the theory of attenuated total reflection on corrugated semi-infinite media and experimental data related to near-field magneto-optical microscopy have been presented [2]. Also, this experimental technique can be advantageously combined with ellipsometry. A concept of total internal reflection ellipsometry (TIRE) at a dielectric interface with a semi-transparent layer and two thin layers has been presented in [3]. The reorientation dynamics of surface-stabilized ferroelectric liquid crystals at the substrate surface have been studied by time-resolved spectro-ellipsometry [4]. The total reflection experimental arrangement has been used for the study of interfacial liquid crystal orientation [5]. This approach combines evanescent waves and a metal-coated optical fiber probe. Time-resolved spectro-ellipsometry (TRSE) can selective isolate the liquid-crystal director orientation dynamics in the close vicinity of substrate surfaces [6]. The importance of the cladding layer on coupling prism for the absorption measurement of liquid samples and a novel sensitive chemical sensor probe are described in [7,8]. Simulations and results of experiments show greatly enhanced thin film and grating sensitivity compared with ordinary ellipsometry [3].

In our previous paper [9] the theoretical model of the evanescent waves coupling with dielectric and metallic strip gratings has been described. The attention was concentrated in the study of coupling strength influence, effects connected with stripes geometry, and with absorption in metallic elements of grating.

In this paper the interaction of electromagnetic field with lamellar periodic structures and their diffraction properties are determined by coupled wave method implemented as the Fourier modal method. The simulations of ellipsometric response under internal reflection are presented for the cases, when the magneto-optical coating layer, different coupling prisms, and magneto-optical effects are included.

II. THEORY

The studied TIR periodic structure is composed from the iron lamellar grating deposited on the SiO₂ substrate, total internal reflection is realized by prism coupling. To simulate various forms of evanescent wave the different materials of prism
are considered, and, thin anisotropic garnet film on the bottom side of prism was supposed. The coordinate system and basic parameters of the optical structure are obvious by the Fig. 1. The geometry of diffraction system is characterized by period \( \Lambda = 260 \text{ nm} \) and by the breadth to height ratio of lamellas 130/10 nm. These parameters as well as air gap thickness \( h^{(2)} = 30 \text{ nm} \) were constant in the course of numerical experiments. The thickness \( h^{(1)} \) of garnet film was changed from 25 to 150 nm.

![Fig. 1. TIR diffraction system scheme.](image)

Incident monochromatic plane wave with free-space wavelength \( \lambda \) propagates in homogeneous isotropic superstrate with refractive index \( n^{(0)} \) in the plane perpendicular to lamellar system. In the \( \kappa \)-th layer, the space-dependent part of electrical intensity vector is expanded into Rayleigh modes (the time factor \( \exp\{i \omega t\} \) is assumed),

\[
E^{(k)} = \sum_n u_n^{(k)} e_n e^{-i k_0 (\beta_n x_1 + \gamma^{(k)}_n x_3)}.
\]  

(1)

The terms \( u_n^{(k)} \), \( e_n^{(k)} \) denote amplitude coefficients and polarization vectors of the \( n \)-th mode, respectively, and \( \beta_n = n^{(0)} \sin \phi + \lambda n / \Lambda \) for the incidence angle \( \phi \).

Propagation constants \( \gamma^{(k)}_n \) in the semi-infinite lossless homogeneous superstrate and substrate are given by Rayleigh formula

\[
\gamma^{(k)}_n = \pm \sqrt{(n^{(k)})^2 - \beta_n^2}.
\]

(2)

Related eigenvectors can be derived analytically in the closed form. In the inner layers, the Maxwell’s system is solved using Fourier modal method to find propagation constants and polarization states. The rigorous formulation of governing equation system is applied to obtain correct results for Laurent product of Fourier series [10], when the practical computations are performed over truncated mode set \( -N \leq n \leq N \).

For the layer coupling the so called “S-matrix” algorithm was implemented [11]. In the case of the grating system with \( K \) finite layers the resulting formula for amplitude coefficients has the form

\[
u^{(0)} = (D^{(0)})^{-1} SD^{(K+1)} u^{(K+1)}.
\]

(3)

The coefficients of incident and reflected field in the superstrate are associated in the vector \( u^{(0)} \). For the transmitted field in the substrate we introduce the vector \( u^{(K+1)} \). Any layer of thickness \( h^{(k)} \) contributes to the matrix \( S \) in the special way by the blocks of diagonal propagation matrix with the elements

\[
\exp\{i k_0 \gamma^{(k)}_n h^{(k)} \},
\]

(4)

and by the blocks of polarization matrix \( D^{(k)} \). The last is composed from columns of Fourier coefficients of polarization vectors by distinguishing of forward (+) and backward (-) modes. Moreover, the specification of \( s \)- and \( p \)-polarized modes must be possible in the superstrate and substrate.

Reflection properties of the structure at the zero-th mode order and for normalized input are defined by complex ratio \( \Omega \), from which we determine ellipsometric angles \( \psi \) and \( \Delta \):

\[
\Omega = \frac{u_{0, p}^{(0)}}{u_{0, s}^{(0)}}
\]

(5)

\[
\psi = \arctan |\Omega|, \quad \Delta = -\arg \Omega.
\]

(6)

Ellipsometric angles were computed for the wavelength 632.8 nm with the incidence angle step 0.5°. The number of used diffraction orders was truncated by the value \( N = 6 \). The own Matlab code operated on standard PC has been tested in usual
way, i.e. through the unit value of total efficiency for a lossless case, and, by the stability test for increased $N$ for general absorbing structure.

III. RESULTS AND DISCUSSION

In our previous paper [9] the some aspects of TIRE have been discussed in detail. The attention has been focused on the influence of ferromagnetic thin film covering of the dielectric gratings on ellipsometric angles. The importance of coupling gap thickness has been demonstrated and analyzed.

The proposed experimental set-up consists of a single coupling prism with magnetic garnet layer coating on its coupling surface, as shown in Fig. 1. The coupling area is realized by air gap. The lamellar ferromagnetic stripes (1D grating) on SiO$_2$ substrate have been applied as an inspected structure. In this paper the influences of garnet film thickness, refractive index of prism, and magneto-optical effects on ellipsometric angles for TIRE are studied.

The ellipsometric angles $\psi$ and $\Delta$ as function of incidence angle for different magnetic garnet film thicknesses located on the prism base have been computed. The relative permittivity tensor for magnetic garnet film has been specified in our early paper [12]. For this case two different coupling prisms have been chosen. In the first situation the modeling has been realized for the prism with refractive index of 2.87 (see Figs. 2a,b).

The chosen relationship between refraction indices of the coupling prism and garnet coating enables us to generate the total reflection on the prism-magneto-optical layer interface. From the condition of the continuity of tangential field components on the boundaries the critical angle for garnet layer-air gap interface can be specified. Its value is about 20.4 degrees. This situation is clearly demonstrated on the left side of Fig. 2a. We can observe the amplitude and angle modulation of $\psi$ ellipsometric angle by the thickness of garnet film. This thickness change has been modeled in the range from 25 nm to 150 nm. As result the shift of minima for $\psi$ angles is more than 10 degrees in the incidence angle scale. As regards the condition of total reflection on prism-garnet film interface, its position in $\psi$ dependence on the incidence angle is not too bold. It can be clearly specified from angle distribution of $r_{pp}$ reflection coefficient. The shifts in ellipsometric angles distribution due to different thickness of coating layer enable us to solve the technical problems in TIRE experimental arrangement – for example to change the angle of incoming light beam. In all situations the thicknesses of air gap and lamellar pitch have been chosen 30 nm and 10 nm, respectively.

The Fig. 3 describes the same situation for the case of glass coupling prism (index of refraction 1.515). In this case we observe expressive modulation of ellipsometric angles distribution as a function of coating garnet film thickness. For the incidence angle 41.30 degrees the total reflection condition on the interface garnet layer-air gap is realized. The presence of garnet coating layer

Fig. 2. Ellipsometric angles vs. thickness of anisotropic garnet film (high refractive index prism)

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alternates the minima positions of $\psi$ dependencies as function of incidence angles. The comparison of presented figures (Figs. 2 and 3) implies the expressive modulation of dependencies of ellipsometric angles up prism index of refraction. This result can be advantageously applied in the scatterometry of deep gratings.

For the mathematical simulation of magneto-optical effects we used the rutile prism coated by magnetic thin film garnet structure. Among other, the characteristic matrices were derived for prism coupler to structures with magnetic ordering for linear magneto-optical effects (will be published). The following parameters were applied: on-diagonal permittivity element $\varepsilon_0(1) = (2.22 - 0.02i)^2$, off-diagonal element $\varepsilon_1(1) = 10^{-3}\varepsilon_0(1)$ [12]. It is known that for transverse geometry of magnetization the conversion reflection coefficients cannot be observed for linear magneto-optical effects [12].

The effect of refractive index of coupling prism is summarized in Fig. 4. For three different values of this refractive index the ellipsometric angles $\psi$ and $\Delta$ at fixed magneto-optical layer thickness (50 nm) are illustrated. Because the value $1.515$ (glass prism) is less than garnet film refractive index, the behaviors of $\psi$ and $\Delta$ are radically transmuted in comparison with using of rutile or BiGe prisms.

The magneto-optical contribution of iron grating stripes is taken into account. The thickness has been selected to be 50 nm for garnet film and 10 nm for iron stripes.

Fig. 3. Ellipsometric angles vs. thickness of anisotropic garnet film (glass prism).

Fig. 4. Ellipsometric parameters vs. prism refractive index.
The influence of induced anisotropy is demonstrated graphically for the area around minimum of the $\psi$ angles - see Fig. 5. The $\psi$ angles are modulated in the frame of 0.2 degree. The same result can be observed for $\Delta$ ellipsometric angles. It means this effect can be elaborately used in TIRE measurements.

Fig. 5. The influence of induced anisotropy on the $\psi$ ellipsometric angle.

Total internal spectral ellipsometry has provided new opportunities for nondestructive testing and detail analysis of thin films systems and periodic structures. The using of transition layer in the coupling area of TIRE extends the experimental possibilities of this measuring approach. The more attention has to be devoted to the detail analysis of the implementation of anisotropic planar and periodic structures in the frame of TIRE. The integration of spectral ellipsometry operating at internal reflection with anisotropic materials is very promising in sensor engineering.

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