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ANISOTROPIC REFRACTIVE INDICES OF CADMIUM SULFIDE THIN FILM ON A SLAB-TYPE OPTICAL WAVEGUIDE


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Résumé - Les indices de réfraction anisotropes de couches minces de sulfure de cadmium déposées par évaporation sous vide sur des guides d'onde optiques, ont été déterminés par l'analyse croisée des ondes TE et TM.

Abstract - Anisotropic refractive indices of vacuum evaporated cadmium sulfide thin films on slab-type optical waveguides were determined by an incorporated analysis of the TE and the TM waves.

1. Introduction

There have been many methods to determine optical constants of thin solid films. Ellipsometry/1/, Abeles' method/2/ and Male's method/3/ are famous because of their availabilities. In ellipsometry, degrees of freedom in polarization are skillfully joined to determining optical constants of isotropic films. Majority of other methods are also concerned with optically isotropic films.

In the present study a new method to determine anisotropic refractive indices of vacuum evaporated cadmium sulfide thin films is proposed. This method is an extended application of the previously reported guided wave method with tapered isotropic films on slab-type optical glass waveguides/4,5/. In the present method an anisotropic cadmium sulfide thin film was used as an example. Vacuum evaporated cadmium sulfide thin film deposited on fused quartz substrate at appropriate temperature has microcrystalline wurtzite structure with the c-axis of each microcrystal oriented perpendicular to the substrate.

Other two axes are ambiguous in each crystal and can be averaged over as isotropic in the plane. This situation is expressed by a diagonal dielectric tensor. Optical guided waves for each polarization mode (the TE and the TM) in a single propagation mode slab-type waveguide have each inherent propagation constants corresponding to a specific waveguide thickness. Smooth guidings of those waves through a region covered with a cadmium sulfide top layer film are prevented, except for specific top layer thicknesses (resonant thicknesses).

These situations are analyzed theoretically by dispersion relations considered as equations for unknown refractive indices in both polarization modes with an unknown dielectric tensor of the cadmium sulfide thin film. Incorporation of both dispersion relations can give rise to determining the anisotropic refractive indices by substitutions of experimentally given resonant thicknesses of both modes into the relations.
2. Theory

Theoretical analysis is performed by a slab-type single propagation mode waveguide with a high index top layer film to be determined as shown in Fig 1.

![Diagram of waveguide with layers labeled](image)

\[ n_3 = 1.00 \]
\[ n_1 = 1.55 \]
\[ n_0 = 1.46 \]

Fig 1. A model waveguide used in the analysis.

It is supposed that anisotropic property of the top layer is expressed by a following dielectric tensor (1).

\[
\tilde{\varepsilon}_2 = \varepsilon_0 \begin{bmatrix}
\varepsilon_{2e} & 0 & 0 \\
0 & \varepsilon_{2o} & 0 \\
0 & 0 & \varepsilon_{2o}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_0^2 & 0 & 0 \\
0 & n_{2e}^2 & 0 \\
0 & 0 & n_{2o}^2
\end{bmatrix}
\]

(1)

Dispersion relations of the region II are given by the following two equations,

**TE:**

\[
\lambda E_2 d = \tan^{-1} \left( \frac{\lambda_1}{\lambda_2} \tan \left\{ \tan^{-1} \left( \frac{\lambda_0}{\lambda_1} \right) - \lambda_1 \pi \right\} \right)
\]

+ \tan^{-1} \left( \frac{\lambda_3}{\lambda_2} \right) + m \pi

(2)

where \( \lambda_0 = \beta E^2 \), \( \lambda_1 = (k_0n_1)^2 - \beta E^2 \), \( \lambda_2 = (k_0n_1)^2 - \beta_0^2 \), \( \lambda_3 = (k_0n_2o)^2 - \beta E^2 \), \( \lambda_3 = (k_0n_3)^2 \), \( k_0 = 2\pi/\Lambda \), \( \Lambda \) is a wavelength of guided wave and \( m \) is positive integer.

**TM:**

\[
\lambda M_2 d = \tan \left\{ \tan^{-1} \left( \frac{n_{2o}^2 \lambda_1}{n_{2o}^2 \lambda_{M2}} \right) \right\}
\]

+ \tan^{-1} \left( \frac{n_{2e}^2 \lambda_3}{n_{2o}^2 \lambda_{M2}} \right) + m \pi

(3)

where \( \lambda_0 = \beta M^2 \), \( \lambda_1 = (k_0n_1)^2 - \beta M^2 \), \( \lambda_2 = (k_0n_2o)^2 - (n_{2o}/n_{2e})^2 \), \( \lambda_3 = (k_0n_3)^2 \), \( n_{2o} \) and \( n_{2e} \) correspond to ordinary and extraordinary respectively. Calculated dispersion curves for each mode are shown in Fig 2. In the figure, vertical straight lines corresponding to the incident propagation constants \( \beta_{0E} \) and \( \beta_{0M} \) in the regions I and III intersect every dispersion curve at specific top layer thicknesses (resonant thicknesses) \( d_{1E}, d_{2E}, d_{3E}, \ldots \) and \( d_{1M}, d_{2M}, d_{3M}, \ldots \) for the respective modes. At these resonant thicknesses, for the TE mode Eq. (2) is reduced and an unknown index \( n_{2o} \) for the
ordinary wave can be given by:

\[ \lambda_{E2d_{mM}} = m\pi, \quad n_{2o} = \sqrt{\left(\frac{m\lambda}{2d_{mM}}\right)^2 + \left(\frac{\beta_{0E}}{k_0}\right)^2} \quad (4) \]

Then from Equ. (3) at resonant thicknesses for the TM mode, another index for the extraordinary wave \( n_{2e} \) can be given as:

\[ \lambda_{M2d_{mM}} = m\pi, \quad n_{2e} = \left(\frac{\beta_{0M}}{k_0}\right)/\left[1 - \left(m\lambda/2d_{mM}n_{2o}\right)\right]^{1/2} \quad (5) \]

3. Experiment

(A) Sample preparation

Tapered cadmium sulfide thin film was deposited on a single propagation mode slab-type waveguide at 80°C from an alumina crucible with a tungsten heater, at 170Å/min deposition rate. Tapered structure was realized by diffraction of evaporated molecular beam with a knife edge. It was found that the film had polycrystalline wurtzite structure by x-ray analysis as depicted in Fig 3.

(B) Measurement of resonant thicknesses

Resonant thicknesses for each mode were measured by an experimental setup illustrated in Fig 4. Damped oscillations with continuous variation of the tapered top layer thickness were recorded by translational movement of the waveguide with a synchronous gear motor.

Typical traces of oscillations are sketched in Fig 5 with a cross-section of the tapered top layer film. Used wavelength of the guided wave was an Ar laser 5145Å.

4. Results and discussion

Substitutions of resonant thicknesses \( d_{mM} \) in Fig 5 for the TE mode and the propagation constant \( \beta_{0E}/k_0 = 1.332 \) for the 1st mode in the
region I into Equ. (4) gave \( n_{20} = 2.66 \) for the ordinary wave. In the same way, substitution of each parameter in Equ. (5) by the propagation constant \( \beta_0 / k_0 = 1.530 \) for the TM mode in Fig 5 gave rise to determining another unknown index for the extraordinary wave \( (n_{ze} = 2.33) \). We can hardly find papers on optical constants of anisotropic cadmium sulfide thin films though there are several reports on bulk single crystals/6,7,8/. Determined indices in the present study are smaller than those of bulk crystal, as known generally for solid materials. For the bulk crystal, it was reported that \( n_e > n_o \) for wavelength longer than the absorption edge \( (5200\text{Å}) \) and \( n_o > n_e \) for shorter wavelength \( /9/ \). Ar laser 5145Å used in the present study is located near the absorption edge, but detailed comparison or discussion is not given here. The problem will be clarified by measurement of dispersion and temperature dependence of the indices. Absorption coefficient of the film resulting in the damping oscillation in Fig 5 could be determined by introduction of complex refractive indices and complex propagation constants though cutting down in the present paper.

Fig 4. Experimental setup.
1; polarizer, 2; slab-type waveguide, 3; fused quartz substrate, 4,6; prism, 5; tapered top layer CdS film, 7; detector, 8; pen-recorder.

Fig 5. Oscillation traces and film cross section.

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