EAST EUROPEAN JOURNAL OF PHYSICS. 1. 197-203 (2025)
DOI:10.26565/2312-4334-2025-1-20 ISSN 2312-4334

OPTICAL INVESTIGATION OF ZnS/GaAs and $CuGaS_2$/GaP SYSTEMS

Kh.N. Ahmadova[a,b,c], M.A. Musayev[b], N.N. Hashimova[b]
[a]*Institute of Physics, Ministry of Science and Education of the Republic of Azerbaijan, Baku, AZ-1143, Azerbaijan*
[b]*Azerbaijan State Oil and Industry University, Baku, AZ-1010, Azerbaijan*
[c]*Khazar University, Baku, AZ 1096, Azerbaijan*
**Corresponding Author e-mail: khuramanahmadova85@gmail.com*
Received October 10, 2024; revised January 4, 2025; accepted January 6, 2025

ZnS and $CuGaS_2$ are materials with a wide range of applications in modern optoelectronics. These materials are used for IR windows as well as lenses in the thermal band, where multispectral maximum transmission and lowest absorption are required. Precisely because of these characteristics, extensive and accurate optical research is necessary. This work has developed an ellipsometric approach for ZnS/GaAs and $CuGaS_2$/GaP film/substrate systems to address direct ellipsometry tasks. The proposed approach enables us to determine the effects of lattice mismatch on the optical indicatrix of the stressed film being considered through ellipsometric parameters.
Keywords: *Lattice mismatch; Thin film; Ellipsometry*
PACS: 42.25. p

INTRODUCTION

In modern optoelectronics, ZnS and CuGaS2 materials are widely used for IR windows, as well as lenses in the thermal band, where multispectral maximum transmission and lowest absorption are required. It is these properties that require extensive and precise optical studies of the materials.

In recent two decades ellipsometric approach has gained a worldwide recognition as the most correct approach for description of light wave [1-5]. The ellipsometry method accurately studies the optical parameters of multilayer systems both theoretically and experimentally. At the same time, it can provide extensive information about the optical parameters of two different liquids [6-8]. Applications of are nowadays very numerous and are spread out from *in-sity* control in planar technologies to precise determination of optical function of solids. Ellipsometry is well known as one of the powerful methods to control thin film and surface parameters [9-12]. A huge variety of problems which are or could be solved by ellipsometric study is very persuasive and has provoked our present trial to explore a possibility of ellipsometric investigation of the photo-elastic effect which should take place in thin film/substrate systems because of lattice mismatch.

In this work ellipsometric approach have been developed for ZnS/GaAs and $CuGaS_2$/GaP film/substrate systems to solve direct ellipsometry task. The proposed approach allows to finding through ellipsometric parameters the lattice mismatch effect on optical indicatrix of the considered stressed film.

1. PHOTOELASTIC EFFECT IN STRESSED FILM

The photoelastic effect due to stress (t) or deformation (r) which corresponds to this stress is written in matrix form as

$$\Delta\eta_{ij} = \pi_{ijkl}t_{kl} = p_{ijkl}r_{kl}, \text{ in tensor form, } \Delta\eta_m = \pi_{mn}t_n = p_{mn}r_n$$

where $\pi_{mn} = \pi_{ijkl}$, n = 1,2,3; $\pi_{mn} = 2\pi_{ijkl}$, n = 4,5,6; and $p_{mn} = p_{ijkl}$, n = 1,2,3; $p_{mn} = 2p_{ijkl}$, n = 4,5,6. Here Δ is the change of the polarization constant η_m due to stress or deformation, π_{mn} and p_{mn} are the piezooptic and photoelastic coefficients, correspondingly; t_n and r_n are the stress and deformation, correspondingly.

To write down the equation of the photoelastic effect in the stressed film it is necessary to know symmetries of the film and substrate, as well as their orientation. For the sake of certainty, let us consider ZnS$(\bar{4}3m)$/GaAs($(\bar{4}3m)$) and $CuGaS_2$($\bar{4}2m$)/GaAs($\bar{4}3m$) [13] systems with interface surface perpendicular to [001] direction (z-direction) in both cases.

1.1. ZnS/GaAs system

Before stress, in a coordinate system where z is directed perpendicular to the interface and x and y axes lie in the plane of interface, the equation for polarization constants in the film can be written as

$$\eta\,(x^2+y^2+z^2) = 1 \tag{1}$$

After the stress, t, due to the lattice mismatch is applied along x and y directions, we have

Cite as: Kh.N. Ahmadova, M.A. Musayev, N.N. Hashimova, East Eur. J. Phys. 1, 197 (2025), https://doi.org/10.26565/2312-4334-2025-1-20

$$\begin{bmatrix} & t & t & 0 & 0 & 0 & 0 \\ \Delta\eta_1 & \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \Delta\eta_2 & \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \Delta\eta_3 & \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ \Delta\eta_4 & 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ \Delta\eta_5 & 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ \Delta\eta_6 & 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \tag{2}$$

and

$$[\eta+(\pi_{11}+\pi_{12})t]x^2+[\eta+(\pi_{12}+\pi_{11})t]y^2+[\eta+(2\pi_{12})t]z^2 = 1 \tag{3}$$

Taking into account the relationship for r_0 [8] and that η equals $1/N^2$ (N is the refractive index) and supposing that everywhere $\Delta\eta \ll \eta$, we have for optical indicatrix that

$$\frac{x^2+y^2}{N^2\left(1-N^2\frac{(p_{11}+p_{12})r}{2}\right)^2}+\frac{z^2}{N^2\left(1-N^2p_{12}r\right)^2}=1 \tag{4}$$

i.e., initially optically isotropic film turned into optically uniaxial film with optical axis **C** along the normal to the interface. The ordinary and extraordinary refractive indexes of the last film are

$$N_0 = N\left(1-N^2\frac{(p_{11}+p_{12})r}{2}\right) \tag{5}$$

and

$$N_e = N\left(1-N^2p_{12}r\right) \tag{5*}$$

respectively.

1.2. $CuGaS_2$/GaP system

CuGaSe film is a uniaxial film, and the equation for polarization constants before stress can be written as $\eta_o(x^2+y^2)+\eta_e z^2=1$.

Stress induced by the lattice mismatch along x and y and the $\Delta\eta_i$ are related as

$$\begin{bmatrix} & t & t & 0 & 0 & 0 & 0 \\ \Delta\eta_1 & \pi_{11} & \pi_{12} & \pi_{13} & 0 & 0 & 0 \\ \Delta\eta_2 & \pi_{12} & \pi_{11} & \pi_{13} & 0 & 0 & 0 \\ \Delta\eta_3 & \pi_{31} & \pi_{31} & \pi_{33} & 0 & 0 & 0 \\ \Delta\eta_4 & 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ \Delta\eta_5 & 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ \Delta\eta_6 & 0 & 0 & 0 & 0 & 0 & \pi_{66} \end{bmatrix} \tag{6}$$

and

$$[\eta_o+(\pi_{11}+\pi_{12})t]x^2+[\eta_o+(\pi_{11}+\pi_{12})t]y^2+[\eta_e+(2\pi_{31})t]z^2=1 \tag{7}$$

For optical indicatrix we then have

$$\frac{x^2+y^2}{N_0^2\left(1-N_0^2\frac{(p_{11}+p_{12})r}{2}\right)^2}+\frac{z^2}{N_e^2\left(1-N_e^2p_{31}r\right)^2}=1 \tag{8}$$

i.e the film is again uniaxial with the same orientation of the principal axes. However, refractive indexes of ordinary and extraordinary beams are changed to

$$N_0^{new} = N_0\left(1-N_0^2\frac{(\ p_{11}+p_{12}\ )r}{2}\right) \text{ and } N_e^{new} = N_e\left(1-N_e^2p_{31}r\right) \tag{9}$$

2. ELLIPSOMETRIC APPROACH FOR ZnS/GaAs AND $CuGaS_2$/GaP SYSTEMS

In anizotropic systems we have the most general relationship between p- and s- components of the complex amplitude of the reflected (r) and incident (i) waves [14]

$$E_p^r = R_{pp}\ E_p^i + \ \ R_{sp}E_s^i \tag{10}$$

$$E_s^r = R_{sp}E_p^i + R_{ss}E_s^i \tag{10*}$$

or

$$\frac{E_p^r}{E_s^r}=\frac{\left(\frac{R_{pp}}{R_{ss}}\right)\frac{E_p^i}{E_s^i}+\left(\frac{R_{ps}}{R_{ss}}\right)}{\left(\frac{R_{sp}}{R_{ss}}\right)\frac{E_p^i}{E_s^i}+1}, \qquad (11)$$

where Rpp/Rss, Rps/Rss and Rsp/Rss are the relative coefficients of reflection, which we have to be determine by solving Wave Equation [9]

$$\Delta E\text{-graddiv}E+(2\pi/\lambda)^2 D=0. \qquad (12)$$

It follows from section 1 (see 1.1 and 1.2) that we shall consider an isotropic substrate and a uniaxial film on, with the same z axis for the film and film/substrate system. It follows from Eq. (12) that in this case the x- and y-components of the electrical vector obey the following equations:

$$\varepsilon_e\frac{\partial^2 E_x}{\partial z^2}+\varepsilon_0\left[\left(\frac{2\pi}{\lambda}\right)^2\varepsilon_e-k_x^2\right]E_x=0\text{, and }\frac{\partial^2 E_y}{\partial z^2}+\left[\left(\frac{2\pi}{\lambda}\right)^2\varepsilon_0-k_x^2\right]E_y=0. \qquad (13)$$

Where, k_x=const= $(2\pi/\lambda)\sin\varphi$, and $\varepsilon_o=(n_o-ik_o)^2$ and $\varepsilon_e=(n_e-ik_e)^2$ are the complex diagonal components of the dielectric function tensor. Now let us consider s-component of the incident wave. In this case Ey=Es;Ex=Ez=0; Hy=0. Using the Abbeles method, from solutions of the Eq. (8) the following matrix of tangential components of electric and magnetic field can be constructed:

$$M_s(0,d)=\begin{pmatrix} m_{s11}m_{s12}\\ m_{s21}m_{s22}\end{pmatrix}=\begin{pmatrix}\frac{1}{2}\left[e^{-i\delta_0}+e^{-i\delta_0}\right]\frac{1}{2g_0}\left[e^{-i\delta_0}-e^{i\delta_0}\right]\\ \frac{g_0}{2}\left[e^{-i\delta_0}-e^{-i\delta_0}\right]\frac{1}{2}\left[e^{-i\delta_0}+e^{i\delta_0}\right]\end{pmatrix}, \qquad (14)$$

where $\delta_0=\frac{2\pi}{\lambda}d\sqrt{\varepsilon_0-\sin^2\phi}$ and $g_0=\sqrt{\varepsilon_0-\sin^2\phi}$.

Now tangential components in the interfaces between the film and ambient and between the film and substrate can be connected through matrix

$$Q_s(0)=\begin{pmatrix}E_s(0)\\ H_x(0)\end{pmatrix}=M_s(0,d)\begin{pmatrix}E_s(d)\\ H_x(d)\end{pmatrix} \qquad (15)$$

Hereafter let us distinguish between thick and thin substrate. In the thick or absorptive substrate, we have no waves reflected from the interface between substrate and ambient and this case, as it will be seen afterwards, corresponds to the situation in ZnS/GaAs system. In the thin substrate, we have waves reflected from its bottom boundary and this will modify the total reflected field. (This case will correspond to the experimental situation in $CuGaS_2$/GaP system).

2.1. Thick substrate

$$R_{ss}=\frac{-(m_{s21}+gm_{s22})+g_{sub}(m_{s11}+gm_{s12})}{(m_{s21}-gm_{s22})-g_{sub}(m_{s11}-gm_{s12})}e^{-2ik_z d}, \qquad (16)$$

where:

$$g=\cos\phi\text{, and } g_{sub}=\sqrt{\varepsilon_{sub}-\sin^2\phi}. \qquad (17)$$

2.2. Thin substrate

In this case R_{ss} will be given by the relation (9)

$$M_s(0,d_{sub}+d)=\begin{pmatrix} m_{s11} & m_{s12}\\ m_{s21} & m_{s22}\end{pmatrix}=M(d_{sub},d)M(0,d_{sub}). \qquad (18)$$

Here M (d_{sub},d) is the same as matrix (14), matrix (0, d_{sub}) has the form similar to that of matrix (14) in which δ_0 and g_0 must be replaced by δ_{sub} and g_{sub}, respectively, i.e.

$$M_S\left(0,d_{sub}\right)=\begin{pmatrix} \frac{1}{2}\left[e^{-i\delta_{sub}}+e^{i\delta_{sub}}\right] & \frac{1}{2g_{sub}}\left[e^{-i\delta_{sub}}-e^{i\delta_{sub}}\right] \\ \frac{g_{sub}}{2}\left[e^{-i\delta_{sub}}-e^{i\delta_{sub}}\right] & \frac{1}{2}\left[e^{-i\delta_{sub}}+e^{i\delta_{sub}}\right] \end{pmatrix}, \tag{19}$$

where $\delta_{sub}=\frac{2\pi}{\lambda}d_{sub}\sqrt{\varepsilon_{sub}-\sin^2\phi}$ and $g_{sub}=\sqrt{\varepsilon_{sub}-\sin^2\phi}$

Similary to R_{ss} it is easy to show that R_{pp} can be written in both cases (thin and thick substrate) so as it is shown in the next subsection.

2.3. Thick substrate

$$R_{pp}=\frac{-\left(m_{p21}-gm_{p22}\right)-\frac{g_{sub}}{\varepsilon_{sub}}\left(m_{p11}-gm_{p12}\right)}{\left(m_{p21}+gm_{p22}\right)+\frac{g_{sub}}{\varepsilon_{sub}}\left(m_{p11}+gm_{p12}\right)}e^{-2ik_zd} \tag{20}$$

$$M_p\left(0,d\right)=\begin{pmatrix} \frac{1}{2}\left[e^{-i\delta_e}+e^{i\delta_e}\right] & -\frac{\varepsilon_e}{2g_e}\left[e^{-i\delta_e}-e^{i\delta_e}\right] \\ -\frac{g_e}{2\varepsilon_e}\left[e^{-i\delta_e}-e^{i\delta_e}\right] & \frac{1}{2}\left[e^{-i\delta_e}+e^{i\delta_e}\right] \end{pmatrix}, \tag{21}$$

where,

$$\delta_e=\frac{2\pi}{\lambda}d\sqrt{\varepsilon_0-\left(\frac{\varepsilon_0}{\varepsilon_e}\right)\sin^2\phi}\ \text{and}\ g_e=\sqrt{\varepsilon_e-\left(\frac{\varepsilon_0}{\varepsilon_e}\right)\sin^2\phi} \tag{22}$$

2.4. Thin substrate

In this case $M_p(d_{sub},d)$ equals

$$M_p\left(0,d_{sub}\right)=\begin{pmatrix} \frac{1}{2}\left[e^{-i\delta_{sub}}+e^{i\delta_{sub}}\right] & -\frac{\varepsilon_{sub}}{2g_{sub}}\left[e^{-i\delta_{sub}}-e^{i\delta_{sub}}\right] \\ -\frac{g_{sub}}{2\varepsilon_{sub}}\left[e^{-i\delta_{sub}}-e^{i\delta_{sub}}\right] & \frac{1}{2}\left[e^{-i\delta_{sub}}+e^{i\delta_{sub}}\right] \end{pmatrix} \tag{23}$$

The ratio of $g_{sub}/\varepsilon_{sub}$ must be replaced by $g=\cos\varphi$. The coefficients m can then be obtained from

$$M_p\left(0,d_{sub}+d\right)=\begin{pmatrix} m_{p11} & m_{p12} \\ m_{p21} & m_{p22} \end{pmatrix}=M_p\left(d_{sub},d\right)M_p\left(0,d_{sub}\right). \tag{24}$$

3. DIRECT ELLIPSOMETRY TASK FOR ZnS/GaAs AND $CuGaS_2$/GaP

Direct ellipsometry task implies a computation of ellipsometric angles ψ and Δ of the system under consideration using analytic expressions obtained in Section 2. Our main target is the photoelastic effect in stressed film/substrate system. To calculate the magnitude of the effect in ψ-and Δ-units we will do the following. First, we will calculate ψ and Δ for unstressed film/substrate systems at different thicknesses of the film d. After that we will calculate ψ and Δ for stressed film/substrate system with above values of the thicknesses and different values ($p_{mn}r$, r is known) of the photoelastic effect. In both cases we will constract Δ=f(ψ) dependencies and will estimate the smallest value of the photoelastic effect, which we are still be able to detect.

3.1. Unstressed ZnS/GaAs system

ZnS/GaAs system presents an isotropic film/substrate system for which the principal equation of the ellipsometry ($\tan\psi e^{i\Delta}=R_p/R_s$) is very well known and given by

$$\tan\psi\times e^{i\Delta}=\frac{r_{01p}+e^{-2\delta_2}e^{-2i\delta_1}r_{12p}}{1+e^{-2\delta_2}e^{-2i\delta_1}r_{01p}r_{12p}}\times\frac{1+e^{-2\delta_2}e^{-2i\delta_1}r_{01s}r_{12s}}{r_{01s}+e^{-2\delta_2}e^{-2i\delta_1}r_{12s}}, \tag{25}$$

$$r_{12s}=\frac{\sqrt{\varepsilon_{film}-\sin^2\phi}-\sqrt{\varepsilon_{sub}-\sin^2\phi}}{\sqrt{\varepsilon_{film}-\sin^2\phi}+\sqrt{\varepsilon_{sub}-\sin^2\phi}},\ r_{12p}=\frac{\sqrt{\varepsilon_{sub}-\dfrac{\varepsilon_{sub}\sin^2\phi}{\varepsilon_{film}}}-\sqrt{\varepsilon_{film}-\dfrac{\varepsilon_{film}\sin^2\phi}{\varepsilon_{sub}}}}{\sqrt{\varepsilon_{sub}-\dfrac{\varepsilon_{sub}\sin^2\phi}{\varepsilon_{film}}}+\sqrt{\varepsilon_{film}-\dfrac{\varepsilon_{film}\sin^2\phi}{\varepsilon_{sub}}}},\ r_{01s}=\frac{\cos\phi-\sqrt{\varepsilon_{film}-\sin^2\phi}}{\cos\phi+\sqrt{\varepsilon_{film}-\sin^2\phi}},$$

$$\delta_1=\frac{\sqrt{2}\pi}{\lambda}\times d\times\sqrt{\sqrt{a^2+b^2}+a},\ \delta_2=\frac{\sqrt{2}\pi}{\lambda}\times d\times\sqrt{\sqrt{a^2+b^2}-a},$$

$$a=n_{film}^2-k_{film}^2-\sin^2\phi,\ \varepsilon_{film}=n_{film}^2-k_{film}^2-i2n_{film}k_{film},\ \varepsilon_{sub}=n_{sub}k_{sub}^2-i2n_{sub}k_{sub}.$$

Let us select the experimental wavelength in region where sensitivity of a Jobin-Ivon spectroscopic ellipsometer is high and the substrate is absorptive enough to avoid formation of the reflected beam from the bottom boundary of the substrate.

3.2. Unstressed $CuGaS_2$/GaP system

There exists a possibility to simplify the problem by selecting the experimental wavelength at λ=6400 Å where $N_0=N_e$ (isotropic point) and uniaxial optical idicatrix turns into sphere. It is easy to show that in this case,

$$\tan\psi\times e^{i\Delta}=\frac{r_{01p}+e^{-2\delta_2^{film}}e^{-2i\delta_1^{film}}r_{12p}+e^{-2\delta_2^{sub}}e^{-2i\delta_1^{sub}}r_{01p}r_{12p}r_{23p}+e^{-2(\delta_2^{film}+\delta_2^{sub})}e^{-2i(\delta_1^{film}+\delta_1^{sub})}r_{23p}}{1+e^{-2\delta_2^{film}}e^{-2i\delta_1^{film}}r_{01p}r_{12p}+e^{-2\delta_2^{sub}}e^{-2i\delta_1^{sub}}r_{12p}r_{23p}+e^{-2(\delta_2^{film}+\delta_2^{sub})}e^{-2i(\delta_1^{film}+\delta_1^{sub})}r_{01p}r_{23p}}\times$$
$$\times\frac{1+e^{-2\delta_2^{film}}e^{-2i\delta_1^{film}}r_{01s}r_{12s}+e^{-2\delta_2^{sub}}e^{-2i\delta_1^{sub}}r_{12s}r_{23s}+e^{-2(\delta_2^{film}+\delta_2^{sub})}e^{-2i(\delta_1^{film}+\delta_1^{sub})}r_{01s}r_{23s}}{r_{01s}+e^{-2\delta_2^{film}}e^{-2i\delta_1^{film}}r_{12s}+e^{-2\delta_2^{sub}}e^{-2i\delta_1^{sub}}r_{01s}r_{12s}r_{23s}+e^{-2(\delta_2^{film}+\delta_2^{sub})}e^{-2i(\delta_1^{film}+\delta_1^{sub})}r_{23s}}. \tag{26}$$

The other coefficients are given by

$$r_{23p}=\sqrt{1-\frac{\sin^2\phi}{\varepsilon_{sub}}}-\sqrt{\varepsilon_{sub}}\cos\phi\Big/\sqrt{1-\frac{\sin^2\phi}{\varepsilon_{sub}}}+\sqrt{\varepsilon_{sub}}\cos\phi,\ r_{23s}=\frac{\sqrt{\varepsilon_{sub}-\sin^2\phi}-\cos\phi}{\sqrt{\varepsilon_{sub}-\sin^2\phi}+\cos\phi},$$

$$\delta_1^{film(sub)}=\frac{\sqrt{2}\pi}{\lambda}\times d_{film(sub)}\times\sqrt{\sqrt{a_{film(sub)}^2+b_{film(sub)}^2}+a},\ \delta_2^{film(sub)}=\frac{\sqrt{2}\pi}{\lambda}\times d_{film(sub)}\times\sqrt{\sqrt{a_{film(sub)}^2+b_{film(sub)}^2}-a},$$

$$a_{film(sub)}=n_{film(sub)}^2-k_{film(sub)}^2-\sin^2\phi,\ b_{film(sub)}=2n_{film(sub)}k_{film(sub)}.$$

3.3. Selection of experimental angle of incidence

The change of polarization angles due to the change of the dielectric constant of the film is observable if the following conditions is fulfilled:

$$\delta\psi_{\min}=\left|\delta n_{film,\min}^{(\psi)}\left(\frac{\partial\psi}{\partial n_{film}}\right)-\delta\psi_{el}\right|>0,$$

and

$$\delta\Delta_{\min}=\left|\delta n_{film,\min}^{(\Delta)}\left(\frac{\partial\Delta}{\partial n_{film}}\right)-\delta\Delta_{el}\right|>0 \tag{27}$$

Where $\delta_{film\min}^{(\psi,\Delta)}$ are the minimal value of the change of the dielectric constant of the film, $\partial\psi/\partial n_{film}$ and $\partial\Delta/\partial n_{film}$ are the first derivatives, $\delta\psi_{el}$ and $\delta\Delta_{el}$ are the threshold sensitivities of the employed ellipsometer. As seen from Fig.1, the optimum sensitivity for ψ and Δ is attained at around pseudo-Brewster angle for all considered systems. It is natural (Fig.1) that the higher the film thickness the larger response of the ellipsometric angles is.

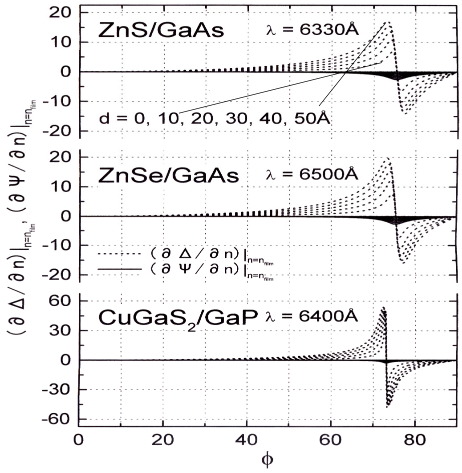

Figure 1. First derivatives of the ellipsometric parameters as function of incidence angle ϕ at various film thicknesses d

3.4. ZnS/GaAs after stress

It follows from Sections 2.3 and 2.4 that after stress the principal ellipsometry equation can be rewritten as

$$\tan\psi e^{i\Delta} = \frac{\left(\cos\phi - \dfrac{g_{sub}}{\varepsilon_{sub}}\right)\cos\delta_e + i\left(\dfrac{g_{sub}}{\varepsilon_{sub}}\dfrac{\varepsilon_e}{g_e} - \dfrac{g_e}{\varepsilon_e}\right)\sin\delta_e}{\left(\cos\phi + \dfrac{g_{sub}}{\varepsilon_{sub}}\right)\cos\delta_e + i\left(\dfrac{g_{sub}}{\varepsilon_{sub}}\dfrac{\varepsilon_e}{g_e} + \dfrac{g_e}{\varepsilon_e}\right)\sin\delta_e} \times \frac{(\cos\phi + g_{sub})\cos\delta_0 + i\left(g_0 + \dfrac{g_{sub}}{g_0}\right)\sin\delta_0}{(\cos\phi - g_{sub})\cos\delta_0 + i\left(g_0 - \dfrac{g_{sub}}{g_0}\right)\sin\delta_0}. \tag{28}$$

Here

$$\delta_e = \frac{2\pi}{\lambda} d_{eff}\sqrt{\varepsilon_0 - \left(\frac{\varepsilon_0}{\varepsilon_e}\right)\sin^2\phi}\,,\ \delta_0 = \frac{2\pi}{\lambda} d_{eff}\sqrt{\varepsilon_0 - \sin^2\phi}\,, \tag{29}$$

and

$$\varepsilon_e = n_{film}^2(1 - n_{film}^2 p_{12} r_{eff})^2 \quad , \quad \varepsilon_0 = n_{film}^2(1 - n_{film}^2\frac{p_{11}+p_{12}}{2} r_{eff})^2. \tag{30}$$

In similar way the principal ellipsometry equation is obtained for a stressed $CuGaS_2$/GaP system.

4. CONCLUSIONS

The ellipsometric description of the lattice parameter mismatch effect consists of the results of solving the ellipsometric straight problem for ZnS/GaAs and $CuGaS_2$/GaP semiconductor systems. The photoelastic effect resulting from the elastic deformation of materials with different lattice parameters in contact with each other (at the atomic level) is described in this work. The thicknesses of dislocation-free layers in which the photoelastic effect is observed due to the mismatch of the lattice parameters (pure photoelastic effect occurs only in such layers due to the mismatch of the lattice parameters) were evaluated. Amplitude coefficients of reflection from (ZnS/GaAs or $CuGaS_2$/InP) internal boundary and (vacuum/ZnS or $CuGaS_2$) external boundary were determined. The relationship between the optical anisotropy and the optical parameters of the initially isotropic ZnS layer after straining was studied in detail. Analogously, the relationship between the new value of the optical anisotropy of the $CuGaS_2$ layer, which was initially uniaxial, but retained the uniaxial character of the optical anisotropy even after applying the voltage, and the variable parameters of the system was found. The calculated photoelastic effect and its dependence on the thickness of the layers are given in the ellipsometric image, which is more convenient for conducting an ellipsometric experiment.

ORCID
Kh.N. Ahmadova, https://orcid.org/0000-0001-5974-5400

REFERENCES

[1] A. Kitano, Y.G. Shim, K. Wakita, Kh. Khalilova, N. Mamedov, A. Bayramov, E. Huseynov, and I. Hasanov, "Optical characterization of non-annealed CdS:O films for window layers in solar cells," Phys. Status Solidi C, **10**, 1107-1110 (2013). https://doi.org/10.1002/pssc.201200834
[2] Kh. Khalilova, Y.G. Shim, I. Hasanov, R. Asaba, K. Wakita, and N. Mamedov, "Spectroscopic ellipsometry studies of as-prepared and annealed CdS:O thin films," Physica Status Solidi C, **12**, 592-595 (2015). https://doi.org/10.1002/pssc.201400272

[3] Kh.N. Ahmadova, and S.H. Jabarov, "Obtaining of Al nanosized thin layers and their structural properties," Arabian Journal for Science and Engineering, **48**, 8083-8088 (2023). https://doi.org/10.1007/s13369-022-07449-2
[4] Kh.N. Ahmadova, S.H. Jabarov, Y.I. Aliyev, Sh.N. Aliyeva, A.V. Trukhanov, S.V. Trukhanov, and M.N. Mirzayev, "Design, production and investigation of structural singularities of layered metal-oxide nanostructures," International Journal of Nanoscience, (2024). https://doi.org/10.1142/S0219581X24500157
[5] Kh.N. Ahmadova, and S.H. Jabarov, "Obtaining of Al nanolayers and crystal structure," International Journal on Technical and Physical Problems of Engineering, **52**, 116-120 (2022). https://www.iotpe.com/IJTPE/IJTPE-2022/IJTPE-Issue52-Vol14-No3-Sep2022/16-IJTPE-Issue52-Vol14-No3-Sep2022-pp116-120.pdf
[6] Kh.N. Ahmadova, "Spectroscopic ellipsometric investigation of optical parameters of oil-water thin multiple systems," International Journal of Modern Physics B, **34**, 2050058 (2020). https://doi.org/10.1142/S0217979220500587
[7] T.K. Nurubeyli, and Kh.N. Ahmadova, "The role of the spectral matrix effect in the element analysis of biological fluids in ICP-MS," Modern Physics Letters B, **35**, 2150094 (2021). https://doi.org/10.1142/S0217984921500949
[8] Kh.N. Ahmadova, "The new innovative optic complete method of identification of oil and its fraction," International Journal of Modern Physics B, **35**, 2150241 (2021). https://doi.org/10.1142/S0217979221502416
[9] D. Datta, V. Tripathi, P. Gogoi, S. Banerjee, and S. Kumar, "Ellipsometric studies on thin film CuPC: C60 blends for solar cell applications," Thin Solid Films, **516**, 7237 (2008). https://doi.org/10.1016/j.tsf.2007.12.043
[10] Y. Shim, H. Hasegawa, K. Wakita, and N. Mamedov, "$CuAl_{1-x}In_xSe_2$ solid solutions. Dielectric function and inter-band optical transitions," Thin Solid Films, **517**, 1442 (2008). https://doi.org/10.1016/j.tsf.2008.09.013
[11] Y. Shim, W. Okada, K. Wakita, and N. Mamedov, "Refractive indices of layered semiconductor ferroelectrics $TlInS_2$, $TlGaS_2$ and $TlGaSe_2$ from ellipsometric measurements limited to only layer-plane surfaces," J. Appl. Phys. **102**, 083537 (2007). https://doi.org/10.1063/1.2800827
[12] H. Fujiwara, *Spectroscopic Ellipsometry: Principles and Applications*, (John Wiley & Sons, Ltd, 2007), https://doi.org/10.1002/9780470060193
[13] S. Iida, H. Icinokura, Y. Toyama, and A. Kato, "Photoluminescence of site-selectively Zn-doped $CuGaS_2$/GaP epitaxial layers," Journal of Physics and Chemistry of Solids, **64**(9-10), 2017-2020 (2017). https://doi.org/10.1016/S0022-3697(03)00093-3
[14] U. Rossow, "Spectroscopic Ellipsometry," in: *Epioptics. Esprit Basic Research Series*, edited by J.F. McGlip, D. Weaire, and C.H. Patterson, (Springer, Berlin, Heidelberg, 1995). pp. 39-76. https://doi.org/10.1007/978-3-642-79820-7_3

ОПТИЧНІ ДОСЛІДЖЕННЯ СИСТЕМ ZnS/GaAs ТА CuGaS2/GaP

Х.Н. Ахмадова[a,b,c], М.А. Мусаєв[b], Н.Н. Хашімова[b]
[a]*Інститут фізики Міністерства науки і освіти Азербайджанської Республіки, Баку, AZ-1143, Азербайджан*
[b]*Азербайджанський державний університет нафти та промисловості, Баку, AZ-1010, Азербайджан*
[c]*Хазарський університет, Баку, AZ 1096, Азербайджан*

ZnS і $CuGaS_2$ є матеріалами з широким спектром застосування в сучасній оптоелектроніці. Ці матеріали використовуються для ІЧ-вікон, а також для лінз у тепловому діапазоні, де потрібне багатоспектральне максимальне пропускання та найменше поглинання. Саме через ці характеристики необхідні обширні та точні оптичні дослідження. У цій роботі розроблено еліпсометричний підхід для систем плівка/підкладка ZnS/GaAs і $CuGaS_2$/GaP для вирішення завдань прямої еліпсометрії. Запропонований підхід дозволяє через еліпсометричні параметри визначити вплив неузгодженості ґрат на оптичну індикатрису напруженої плівки.

Ключові слова: *неузгодженість решітки; тонка плівка; еліпсометрія*