Frequency spectra in the ATR mode of ellipsometric parameters of a periodic medium with a resonant defect in which polaritons are excited

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Abstract. The work is devoted to the study of ellipsometry parameters of elliptically polarized light reflected from a layered system in the ATR mode. Two cases were considered. In the first case, reflection occurs from an ideal periodic layered system of 10 pairs of layers. In the second case, the 10th layer is replaced with a resonant semiconductor InSb, which acts as a defect in the periodic structure. The dielectric constant of this layer exhibits a strong resonant frequency dependence, resulting in the excitation of polaritons with a mixed electromagnetic and mechanical nature. The study demonstrates that the presence of a resonant defect significantly affects the ellipsometric parameters of light reflected from the layered system. This phenomenon can be utilized to investigate the optical properties of resonant semiconductors in which polaritons are excited. Furthermore, in this layered system with an embedded foreign object, a change in the nature of polarization occurs when circularly polarized light is reflected from it. Under certain conditions, it is shown that left-handed circularly polarized light initially incident on the layered system transforms upon reflection into elliptically polarized light with right-handed polarization. This effect has potential applications in devices designed for light polarization conversion.

1 Introduction

Recently, diagnostics of various materials using elliptical and circular polarized light has attracted increasing attention from researchers and engineers. The reason is that with such radiation it is possible to analyze not only the energy coefficients of reflection and transmission, but also to study the change in the polarization ellipse upon reflection. Thus, in [1], circularly polarized light was used to analyze the periodic nanostructure. A nanocomposite was considered in the structure of the surface plasmon resonance spectroscopy method. The combination of the ellipsometric method and the attenuated total internal reflection method has proven to be a very promising method for diagnosing various materials. The works [2-4] use ATR and the ellipsometric method to analyze the polaritons

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of resonant micro objects. The works [5-8] use the ATR and Fourier ATR methods to study thin films of polymer and biological materials.

In this work, we analyze the influence of a foreign inclusion in a periodic structure on its optical properties using circularly polarized light. In this case, the foreign inclusion is a semiconductor layer of InSb, which has a resonance at frequency, and in which polaritons can therefore be excited. The latter are of a mixed electromagnetic and mechanical nature. Polaritons attract the attention of researchers because their group velocity of propagation depends significantly on frequency.

1.1 Formulation of the problem

Elliptically polarized light is incident on the boundary of a periodic layered medium at an angle θ_i. The layered medium consists of 10 pairs of layers with parameters $\varepsilon_2, d_2, \varepsilon_3, d_3$. The dielectric constant of the first medium is $\varepsilon_1 = 8$ (ATR mode), and the substrate is $\varepsilon_L = 2.3104$. $\varepsilon_2 = 23.67$, $d_2 = 3.23$, $\varepsilon_3 = 5.29$, $d_3 = 6.85$. It is necessary to calculate both ellipsometry parameters for a periodic structure. At the second stage, instead of the 10th layer, a foreign object made of InSb semiconductor material is introduced. It is required to evaluate the influence of this object on the spectra of ellipsometry parameters.

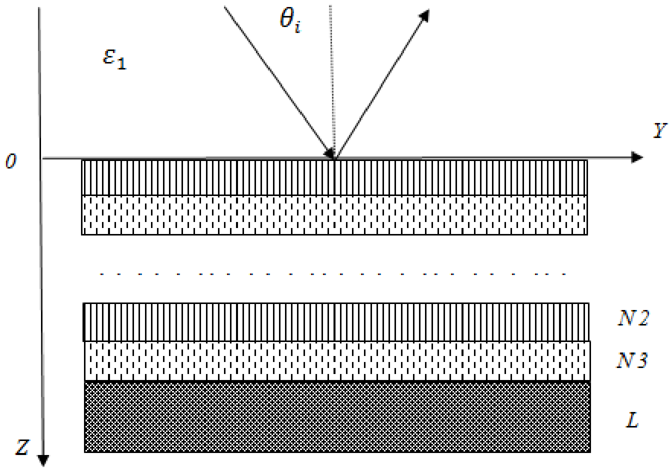

Fig. 1. Problem geometry.

1.2 Theoretical analysis

To solve our problem, we introduce a column vector containing components of the electromagnetic field that are continuous across the interface. In the case of s-polarization these will be projections E_x and H_y

$$\vec{Q} = \begin{pmatrix} E_x \\ H_y \end{pmatrix} \tag{1}$$

When light falls on a layered system at the boundary z = 0, the boundary condition of continuity of the tangential components of the field vectors is satisfied

$$\left.\begin{aligned} E_x|_{0-} &= E_x|_{0+} \\ H_y|_{0-} &= H_y|_{0+} \end{aligned}\right\} \tag{2}$$

Inside each layer we obtain the following connection between the column vectors through the characteristic matrix

$$\vec{Q}_0\,(0+) = \widehat{M}(d)\,\vec{Q}\,(d^-) \tag{3}$$

Next, at each interface of one layer, the boundary conditions are satisfied

$$\begin{gathered}\vec{Q}_0\,(0+) = \vec{Q}_0\,(0-)\\ \vec{Q}_0\,(d-) = \vec{Q}_0\,(d+)\end{gathered} \tag{4}$$

Therefore, using these relations, relationship (3) can be represented in the form

$$\vec{Q}_0\,(0\,-) = \widehat{\mathrm{M}}(\mathrm{d})\,\vec{\mathrm{Q}}\,(\mathrm{d}^+) \tag{5}$$

This formula establishes a connection between the components E_x and H_y in the first medium with dielectric constant ε_1 ($\mathrm{z} = 0-$)and similar components at the output of the first layer ($\mathrm{z} = 0+$). Further

$$\begin{pmatrix} A+R \\ p_1(A-R) \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} T \\ p_l T \end{pmatrix} \tag{6}$$

$$\begin{cases} A+R = m_{11}T + m_{12}p_l T \\ p_1(A-R) = m_{21}T + m_{22}p_l T \end{cases} \tag{7}$$

From this system of algebraic equations it is easy to obtain expressions for the amplitude reflection and transmission coefficients

$$r = \frac{R}{A} = \frac{(m_{11}+m_{12}p_l)p_1 - (m_{21}+m_{22}p_l)}{(m_{11}+m_{12}p_l)p_1 + (m_{21}+m_{22}p_l)} \tag{8}$$

$$t = \frac{T}{A} = \frac{2p_1}{(m_{11}+m_{12}p_l)p_1 + (m_{21}+m_{22}p_l)} \tag{9}$$

Here we introduced the notation

$$p_i = \sqrt{\varepsilon_i} cos\theta_i\,, \qquad i = 1, l$$

For the case of a layered structure with characteristic matrices of layers M_1, M_2 , ... M_N, the resulting matrix can be calculated as the product of the characteristic matrices of the layers

$$M(z_N) = M_1(z_1)M_2\,(z_2 - z_1) * \ldots * M_N(z_N - z_{N-1}) \tag{10}$$

Similar reasoning is carried out to obtain the characteristic matrix of a layered system in the case of p – polarization.

Ellipsometry parameters are determined through the amplitude reflection coefficients for s- and p-polarization as follows

$$\hat{\rho} = \rho \cdot e^{i\Delta} = \frac{R_p}{R_s} \tag{11}$$

The parameter ρ, which is the modulus of a complex quantity $\hat{\rho}$, will be called the first parameter of ellipsometry, and the argument Δ of the complex number $\hat{\rho}$ - the second parameter.

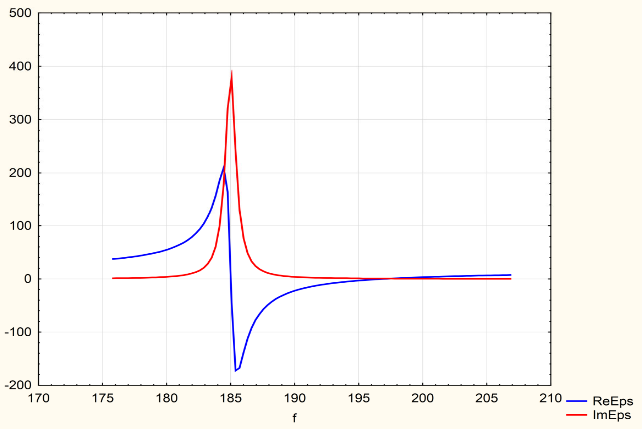

Fig. 2. Dependence of the real and imaginary parts of the complex dielectric permittivity of InSb on frequency. The abscissa axis shows the frequency in cm^{-1}.

We will consider the InSb semiconductor layer as a defect. The frequency dependence of the real and imaginary parts of the dielectric constant of the InSb is presented in Figure 2.

2 Results of analysis

As a result of the analysis, we obtained frequency spectra of both ellipsometry parameters, the graphs of which are shown in Figures 3-11.

2.1 First ellipsometric parameter

In Figures 3-5 we present frequency dependence of the first ellipsometric parameter ρ for a periodic system and a periodic system with a foreign layer.

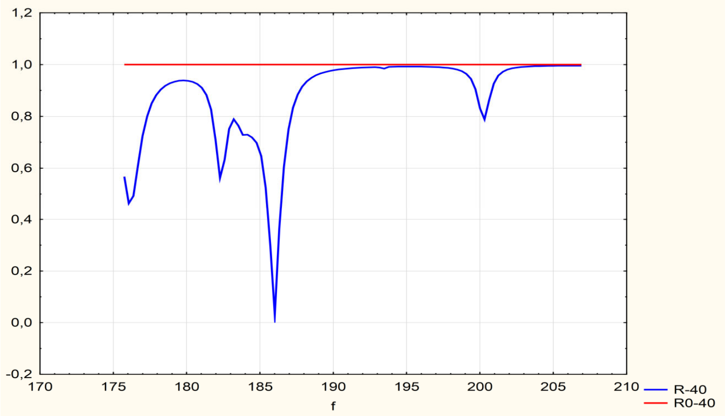

Fig. 3. Frequency dependence of the first ellipsometric parameter of reflected light for a periodic system R0-40 and a periodic system with a foreign layer R-40. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 40°$.

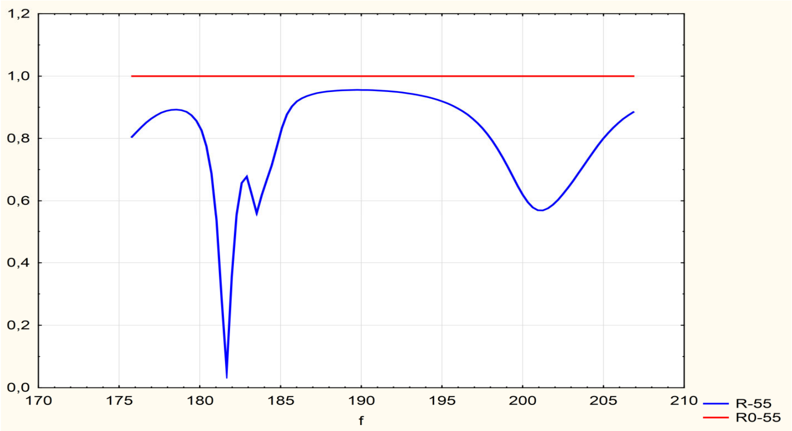

Fig. 4. Frequency dependence of the first ellipsometric parameter of reflected light for a periodic system R0-55 and a periodic system with a foreign layer R-55. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 55°$.

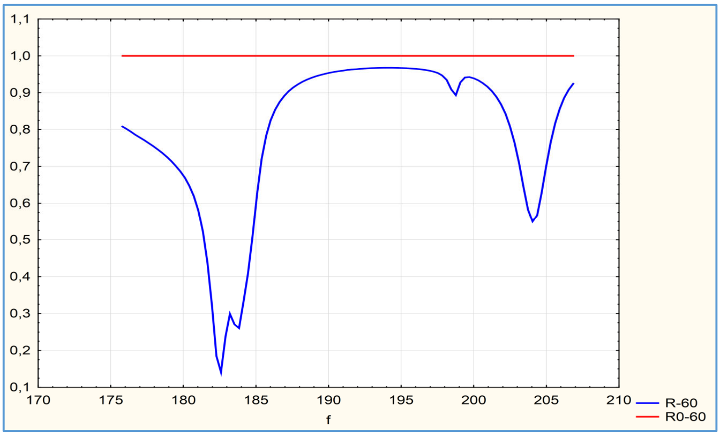

Fig. 5. Frequency dependence of the first ellipsometric parameter of reflected light for a periodic system R0-60 and a periodic system with a foreign layer R-60. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 60°$.

2.2 Angular spectrum of the ellipse parameter Δ

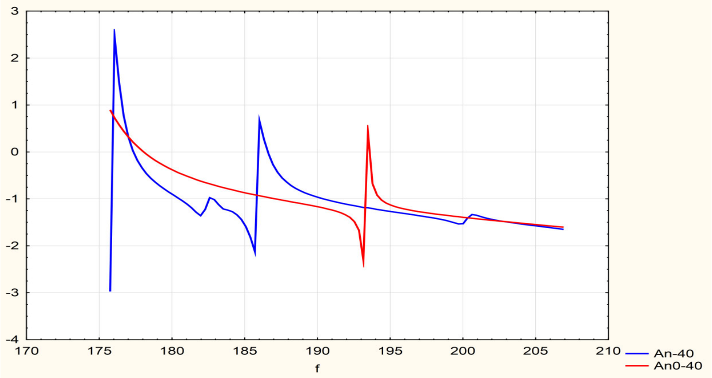

Fig. 6. Frequency dependence of the second ellipsometric parameter of reflected light for a periodic system An0-40 and a periodic system with a foreign layer An-40. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 40°$.

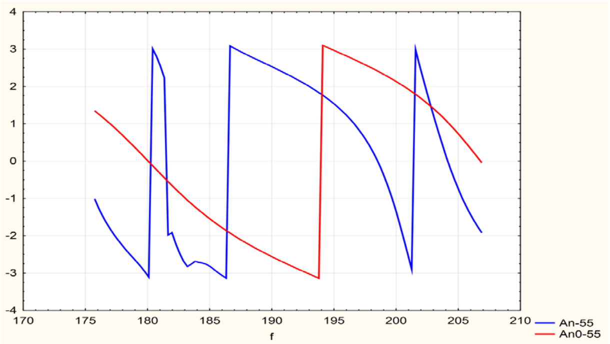

Fig. 7. Frequency dependence of the second ellipsometric parameter Δ of reflected light for a periodic system An0-55 and a periodic system with a foreign layer An-55. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 55°$.

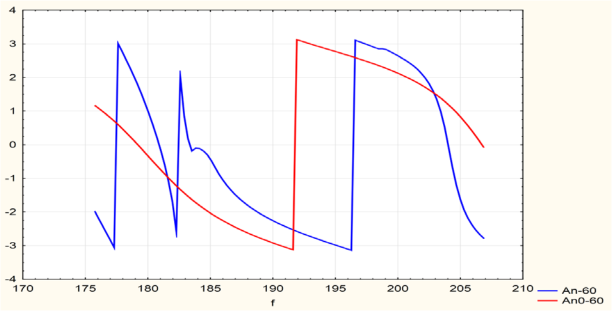

Fig. 8. Frequency dependence of the second ellipsometric parameter Δ of reflected light for a periodic system An0-60 and a periodic system with a foreign layer An-60. The abscissa axis shows the frequency in cm^{-1}. Angle of incidence $\theta_i = 60°$.

3 Conclusion

From Figures 3-5 it is clear that for an ideal layered structure total reflection is observed, while the parameter ρ for a layered system with a defect exhibits noticeable variability. A similar conclusion can be drawn from Figures 6-8 regarding the ellipsometric parameters Δ. Thus, against the background of an ideal layered periodic system, the presence of a resonant defect leads to significant differences in the spectra of ellipsometric parameters.

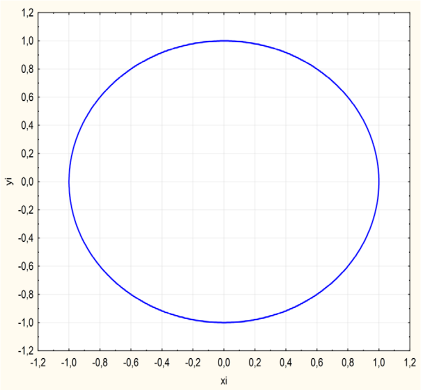

Fig. 9. Left circular polarization of incident light.

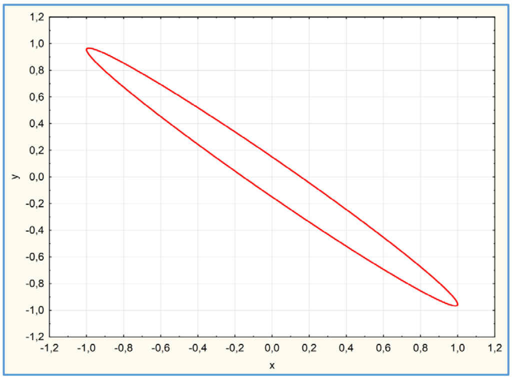

Fig. 10. Right elliptically polarized light reflected from a layered medium with a resonant InSb layer. Parameters θ_i=60°, frequency ω=195.032 cm^{-1}, ρ=0.967, Δ= - 2.986.

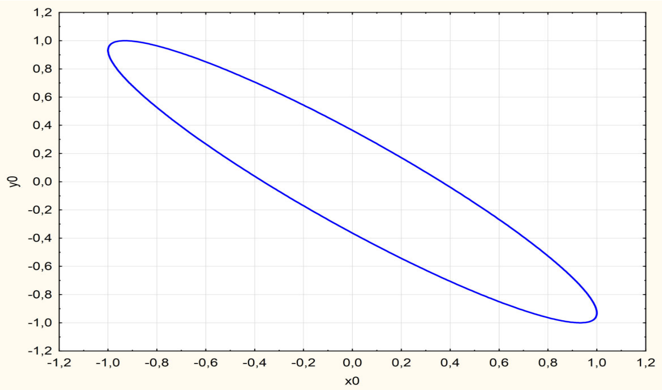

Fig. 11. Left elliptically polarized light reflected from a layered medium. Parameters θ_i=60°, frequency ω=195.032 cm^{-1}, ρ =1, Δ= 2.769.

The frequency dependence of the second ellipsometric parameter Δ actually determines the change in the nature of polarization. Indeed, Figures 9–11 present comparative characteristics of polarization ellipses for incident light reflected from a periodic layered system and a layered system with a resonant defect.

References

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