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OPTICAL PARAMETER ANALYSIS OF THIN ABSORBING FILMS MEASURED BY THE PHOTOVOLTAGE METHOD

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A special method for measuring the optical parameters of thin absorbing films is presented. Within the method the radiation transmitted through the layer is measured. The transmitted radiation is detected by the space charge region which is located in the substrate at the interface with the layer. The space charge region acts as a photodetector placed just behind the layer. In this paper the method is applied to characterize a system of an absorbing ZnSe film on a GaAs substrate. The values of the optical parameters of the film are evaluated. This means that the value of the thickness and the spectral dependences of both the refractive index and extinction coefficient are determined. The spectral dependences of both optical constants are determined in the visible range. Finally, the comparison of our results obtained by this method with the results obtained from ellipsometric and reflectance measurements is presented.

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The optical parameters are usually measured by standard methods like reflectance, ellipsometry and so on. The measurements can be influenced by some negative factors (e.g., roughness). In this case an alternative method of measurement of optical parameters is being developed. The method is based on the existence of surface space charge region in the semiconductor substrate at the interface between the layer and the substrate. The space charge region acts as a photodetector placed just behind the layer. A measure of the radiant flux passing through the layer is the photovoltage in the space charge region. The principle has been used to observe exciton absorption in a superlattice [1] and has been verified for measurement of non-absorbing thin films [2]. The application of this method to absorbing thin film — semiconductor substrate system measurement is described in this paper. The application of the method to the absorbing layer is the next step to apply this method for the analysis of thin films with rough boundaries.

Standard principles of the method have been described in paper [2] with more details. Some main features of experiments will be referred briefly.

The necessary assumption is the photovoltage effect presence in the substrate. In our case the assumption was fulfilled. The substrate served as a detector of incident optical radiation which passes through the absorbing layer and produces a photovoltage. This voltage is detected by a lock-in nanovoltmeter connected to the electrodes capacitively coupled to the measured system. The voltage was kept constant because the photovoltage is a non-linear function of the radiant flux passing through the layer. For this reason the incident radiant flux from monochromator was changed so as to keep the measured photovoltage constant for different wavelengths. The incident radiant flux from a splitter was measured by an optical thermopile like a conventional radiation detector. The spectral dependence of photovoltage was eliminated by a measurement of sample with two different ambients adjacent to the layer. One of them was air and the second one was pentane, which does not influence the layer.

The investigated sample was a ZnSe layer on a GaAs substrate. To obtain the layer parameters, the spectral dependence of the ratio of the two thermopile readings was treated as described below.

Theoretical expression of parameters evaluation was developed for non-absorbing layers [2]. Furthermore the experimental device has the same configuration then we can only modify some terms. The thin layer under consideration affects the radiant flux I_A absorbed in the substrate which is decreased by the flux absorbed in the layer

$$I_\mathrm{A} = \frac{\tau(1-R-A)}{1-\rho R} I_0, \tag{1}$$

where R and A represent the reflectance [3] and the absorption of system absorbing layer–substrate, I_0 is the radiant flux incident on the measuring cell and the quantities τ, ρ correspond to glass window in experimental setup [2]. In the measurement the value of I_A in Eq. (1) was kept constant and the value of the variable I_0 was being changed at the wavelength of interest. Then the measured ratio P for both ambients (e.g., for air and pentane) equals

$$P = \frac{I_0'}{I_0} = \frac{1-\rho' R'}{\tau'(1-R'-A')} \frac{\tau(1-R-A)}{1-\rho R}, \tag{2}$$

where I_0, R, A, ρ, τ denote the quantities specified above for air and $I_0', R', A', \rho', \tau'$ for pentane, respectively. Value P in Eq. (2) was measured as a spectral function. Since the values of the refractive indices of ambient, substrate and the glass window are known, it is possible to determine the values of the optical parameters of the layer, i.e., the refractive index n_1, extinction coefficient k_1 and thickness d_1 of the layer. Then the complex refractive index was taken in the form $\widehat{n} = n_1 + \mathrm{i}k_1$. The form of spectral dependence of parameters n_1 and k_1 can be written [4] as $n_1 = A_1 + B_1/\lambda^2$ and $k_1 = \alpha_1/\lambda + \beta_1/\lambda^3$ where A_1, B_1, α_1, β_1 are constants and λ is the wavelength of incident light. The optical parameters of the layer can be obtained by experimental data of P carried out using the least square method (LSM) minimization.

A sample for measurement of the optical parameters by this method was GaAs substrate with thin ZnSe layer. The layer is a weakly absorbing semiconductor of II–VI type in the visible spectrum region. Air and pentane were chosen as the non-absorbing ambients of the studied layer. The value of the refractive index of pentane n'_0 was measured using a refractometer. It was found that $n'_0 = 1.346 \pm 0.001$ (dispersion of n_0 was practically negligible in the visible area). For the refractive index of the glass window it was found $\bar{n} = 1.515 \pm 0.005$. From the data of the measured P ratio using the above-mentioned procedure, the optical parameters were found. The P ratio measurement is shown in Fig. 1 and the values of parameters are in Table. In this table the parameter K is a constant in relation with the dielectric constants of the ambient media [2]. The experimental data are in good agreement with theoretical values of the ratio P calculated from Eq. (2) within experimental errors.

TABLE

The comparison of the results obtained from the measurement of P ratio and of reflection.

Parameter	From P ratio	From reflection
d_1 [μm]	0.058 ± 0.004	0.052 ± 0.002
A_1	2.1 ± 0.2	2.3 ± 0.4
B_1 [μm^2]	0.12 ± 0.03	0.1200 ± 0.0001
α_1 [μm]	$(17 \pm 6) \times 10^{-3}$	$(16 \pm 9) \times 10^{-3}$
β_1 [μm^3]	$(400 \pm 200) \times 10^{-6}$	$(300 \pm 3) \times 10^{-6}$
K	0.93 ± 0.01	

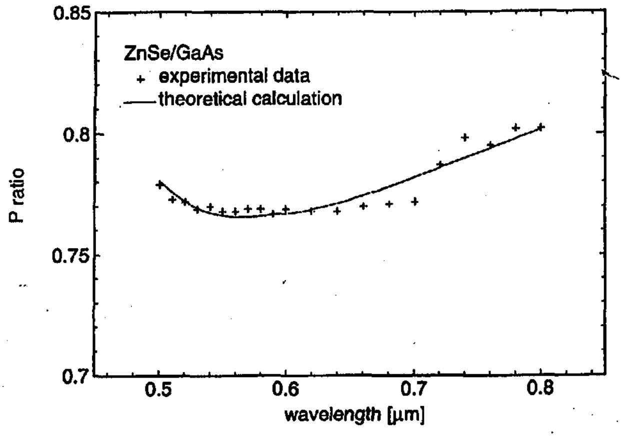

Fig. 1. The spectral dependence of measured and calculated P ratio.

The reflection and ellipsometric data were measured on the sample for comparison too. The parameters were evaluated according to Ref. [3] with a form of the optical parameters n_1, k_1 as above. The measured values of relative reflectance is shown in Fig. 2 and the optical parameters are in Table. From the found parameters the dependences of n_1 and k_1 were calculated and shown in Fig. 3. Ellipsometric data are corresponding to monochromatic ellipsometry ($\lambda = 632.8$ nm). The result is shown in Fig. 3. The values of the optical parameters of ZnSe obtained from these independent measurements and the calculated ones from the method proposed by us are in agreement. ZnSe bulk values were taken from Ref. [5] for comparison (in Fig. 3).

In conclusion, we have presented experimental results of the measurement of optical parameters of thin absorbing films by the technique based on the surface photovoltage in a substrate. The experiments verified the method extension on absorbing layers.

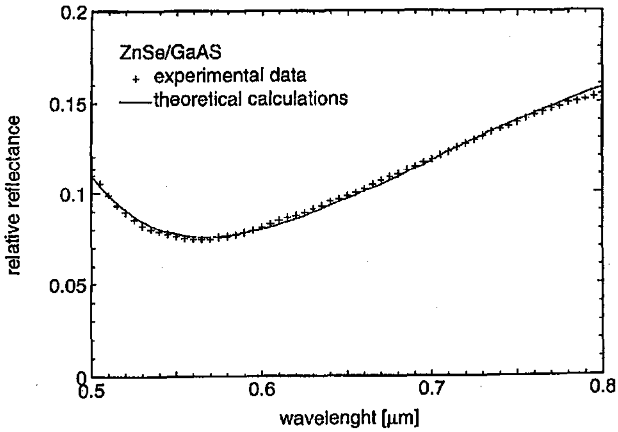

Fig. 2. The spectral dependence of measured and calculated relative reflectance.

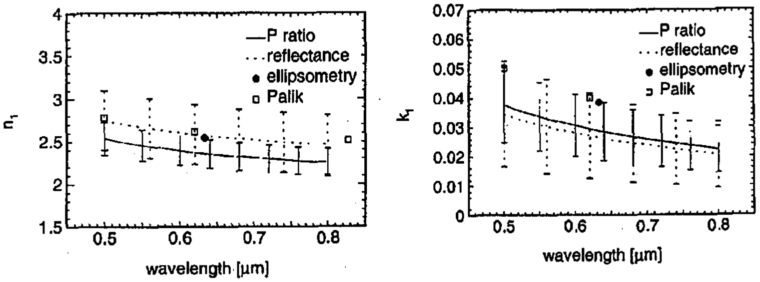

Fig. 3. The comparison of n_1 and k_1 values obtained from the measured P ratio, reflection, ellipsometry and data from Palik [5].

It should be noted that the method cannot be employed for layers whose properties are influenced by the immersion liquid (chemical reaction, etc.). This fact and the existence of a substrate photovoltage are the main limitations of the method.

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