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Absorptive CdTe films optical parameters and film thickness determination by the ellipsometric method

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Ellipsometric detective method of refractive index, absorptive index and thickness of the film deposited on the substrate with some optical parameters has been developed. This method is applied for optical parameters and film thickness detecting in visible and near IR spectrum. Refraction index and film thickness dispersion has been studied. It has been determined that film refractive index (2.6 on average) is by 7% less than that of monocrystalline CdTe.

Keywords: ellipsometry, passivation CdTe films, methods of calculating film parameters.

1. Introduction

Semiconductor films are used in micro- and optoelectronics for producing sun energy processing devices, and signal transmitting devices. Cadmium telluride-based devices are used in particular as electroluminescent radiators or for surface passivation of the solid-state sun radiation receiver in the near IR spectral region. The protective ability of films appreciably depends both on the structure and thickness of the films.

Knowledge of the film optical constants and its thickness, film thickness proportional distribution in area extent, film structure radiation and chemical durability are the actual issues of the film technology.

The existing examples of cadmium telluride application indicate the appreciable dependence of the electric and optical properties, and surface structure of CdTe films on the method and technological conditions of its passivation [1–9]. It has been found [3–6] that the value of the refractive index of the film is smaller than that of monocrystalline material. In particular, we have found [6] that refractive index of CdTe films deposited on the monocrystalline silicon substrate is considerably smaller than the refractive index of monocrystalline CdTe. This might be connected with considerable difference between the crystal grate constants of silicon and cadmium telluride. In reference [6], the fact of the refractive index value decreasing is explained by the film porous structure.

So, at the present stage, such technological conditions of film passivation are searched for that would permit obtaining films with perfect structure, homogeneous over the entire working surface of the film. It is, therefore, necessary to have a suitable, accurate and high-precision no contact control method.

Methods based on measures of transmission and reflective spectra at sounding beam normal incidence on the object being studied are widely used for determination of optical parameters and film thickness [1–4, 9]. These methods are used if the substrate is clear, but its accuracy is not high ($\Delta n = 0.01$ [1]). Measuring photoconductivity as an absorption coefficient function we can find thickness with error up to 5% [10].

In the case where substrate is opaque, reflecting methods are used for determination of optical parameters and thickness of CdTe films [4–8], in particular, reflecting ellipsometry, which is based on examination of polarization characteristics of light wave reflected from the sample being studied.

Ellipsometry in some cases allows optical parameters and film thickness to be determined. At the same time, application of computing mathematics methods of measured results calculation to the ellipsometric function, which is nonlinear and transcendental relative to the determinative parameters of the reflective system, is not always successful because of differences between the iteration procedures used or because such determinations appear to be ambiguous and wrong. That is why searching for a suitable algorithm for determination of system parameters from experiment results is relevant in ellipsometry.

The aim of the paper was to develop a method of determination of optical parameters and thickness of semiconductor films, and using this method, to determinate parameters and their heterogeneity in area of CdTe film deposited on the surface of the composite monocrystalline CdHgTe substrate whose lattice constant is close to that of the CdTe lattice.

2. Objects under study and details concerning the experiment

CdTe films were deposited on the surface of monocrystalline CdHgTe fusion by the epitaxy vacuum “hot-wall” method. Before loading into the installation samples were chemically treated in HF acid and washed in acetone for oxide and impurity removing. CdTe film formation was conducted in high vacuum of 10^{-7} mmHg. For obtaining thin film growth conditions that are to the greatest possible extent approximated to the balanced ones, evaporation is conducted in semi-closed space formed by the source, wall and substrate that are kept at different temperatures.

The values of temperature, required for setting conditions of the thin CdTe film growth were the following: source $T_{\text{source}} = 380$ °C, wall $T_{\text{wall}} = 400$ °C, substrate $T_{\text{sub}} = 50–80$ °C. Nominal thickness of CdTe layers was obtained by the continuous growth of a thin layer during the whole time of evaporation, which made up a continuous interval of 8 minutes. We have produced and studied five samples.

Some properties of the given type of the film obtained under the same conditions and at the same plant are described in [11, 12]. In particular, X-ray investigations have shown that CdTe films deposited on CdHgTe have high quality monocrystalline structure with (111) orientation. The data obtained by means of atomic power microscope indicate the flat surface with roughness of 15–100 nm on the base length of 50 μm.

Ellipsometric measurements were conducted on a 632.8 nm wavelength of LEF-3M compensatory zero ellipsometer and on the wavelength of a 579, 546, 435, 405 and 366 nm spectrum of mercury lamp radiation of non-standard photometric ellipsometer, which was calibrated with the help of monocrystalline silicon plate. The ellipsometer is constructed according to the non-compensatory analyzer–sample–polarizer scheme. Measurements were conducted at the incidence angle of $\varphi = 65°$.

The wavelengths were chosen so that on part of them cadmium telluride would have relatively weak absorption (632, 579 and 546 nm) and on the other (435, 405 and 366 nm) would have strong absorption.

Ellipsometric measurements were conducted sequentially on several areas of each sample (up to seven areas) with different interference color, or with different thickness of the film.

In the applied modification of photoelectric ellipsometric method [13] the measured parameters were $\cos\Delta$ and $\mathrm{tg}\,\psi$, where Δ is the phase difference between *p*- and *s*-components of electric vector of reflected light wave, and $\mathrm{tg}\,\psi$ is the ratio of reflective coefficient in incident plane (*p*-plane) and in the perpendicular *s*-plane. Ellipsometric parameters could be found by measuring the intensities of the radiation reflected from the sample at four azimuths of analyzer: 0°, 45°, 90°, and –45° in relation to the plane of incidence and at the fixed polarizer azimuth. Before measurements the ellipsometer was adjusted according to work [13] and was calibrated with the help of monocrystalline silicon plane in order to get the well known optical constants for silicon.

3. Method of determining film parameters

In the papers presented, ellipsometric measurements were conducted on several areas of the same film, with the thickness being different but unknown. One can expect that the substrate on these areas was the same and its optical parameters n_s and κ_s we obtained from the ellipsometric measurements conducted earlier on the film-free substrate.

From ellipsometric measurements we obtain two parameters, *i.e.*, ellipsometric angles ψ and Δ ($\mathrm{tg}\,\psi$ and $\cos\Delta$ on the photometric ellipsometer) or principal angle Φ

(incidece angle, $\Delta = 90°$) and ellipticity (value of tgψ at the principal angle). Using two values of ellipsometric parameters we can determine two unknown parameters of the film being studied, but in our case, we have to determine a bigger number of indeterminate values (refractive index n, absorptive index κ, and also film thickness on each area under study).

Different calculation procedures based on using ellipsometric function that is set by the basic equation of ellipsometry are used for the determination of reflective system parameters from ellipsometric measurements. General review of numerous papers can be found, for instance, in [14, 15].

A method of obtaining a complete solution to the inverse problem of ellipsometry for one layer isotropic absorptive system relative to the layer and substrate parameters is described in [16]. The method is based on the ellipsometric measurements of Δ and ψ at a constant incidence angle during the process of the film growth at four consistent moments of time, whereby the value of the film thickness increasing (or decreasing) must be known. In our case, this method cannot be used, and that is why one of the aims of the paper was to develop a program for determining system parameters from ellipsometric data.

We have earlier created in [17] a package of programs of ellipsometric data calculation that is based on the Newton iteration method of two equation system determination. The base of the package comprises the ellipsometric function of a two-layer reflective system. Each program permits finding two unknown parameters of the system if the rest of the parameters are known using two values of ellipsometric parameters obtained at the fixed angle of incidence. The existence of such programs allows a method for finding more than two parameters to be created.

This method could be used for calculating ellipsometric data obtained in several areas of the same film with different unknown thickness or for several films with different unknown thickness, deposited on the same substrate with known value of optical constants (refractive index n_s and absorptive index κ_s).

The method includes calculation and graphic procedures; with the help of one of the package programs [17] optical parameters n and κ of the film are calculated for several thickness values (which are chosen arbitrarily within the expected value limits) using a measured ellipsometric parameter couple. Then obtained couples of optical parameters are plotted on the diagram, where, for example, values of the refractive index n are plotted on the vertical scale and values of the absorptive index κ are plotted on the horizontal scale. As a result, a curve is plotted for each area that connects the points obtained and along which the film thickness changes. Let us call such curves thickness curves. If optical parameters of the film are equal in all areas, then the curves would intercross at one point, and the couple of optical parameters corresponding to this point would be general for all the curves. The cross point position on each curve would give us the film thickness on the corresponding areas.

This method could be illustrated by the model calculations. First of all, ellipsometric parameters for a certain one-layer system with optical constants that are close to optical parameters of CdTe film and CdHgTe hybrid crystals, and film thickness in the range of 0–110 nm were calculated. Results of calculations are presented in Fig. 1 as two curves of constant values of optical parameters.

It is seen that the curves look like spiral and they are twisted with the film thickness increasing, with the curve twisting faster when the film absorptive index is bigger.

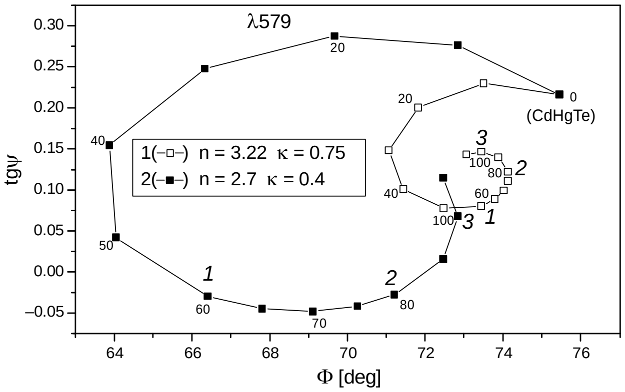

Fig. 1. Theoretical curves ellipticity tgψ–principal angle Φ calculated for different values of optical constants n and κ and film thickness. Film thickness in nm is shown by numbers near the curve marks.

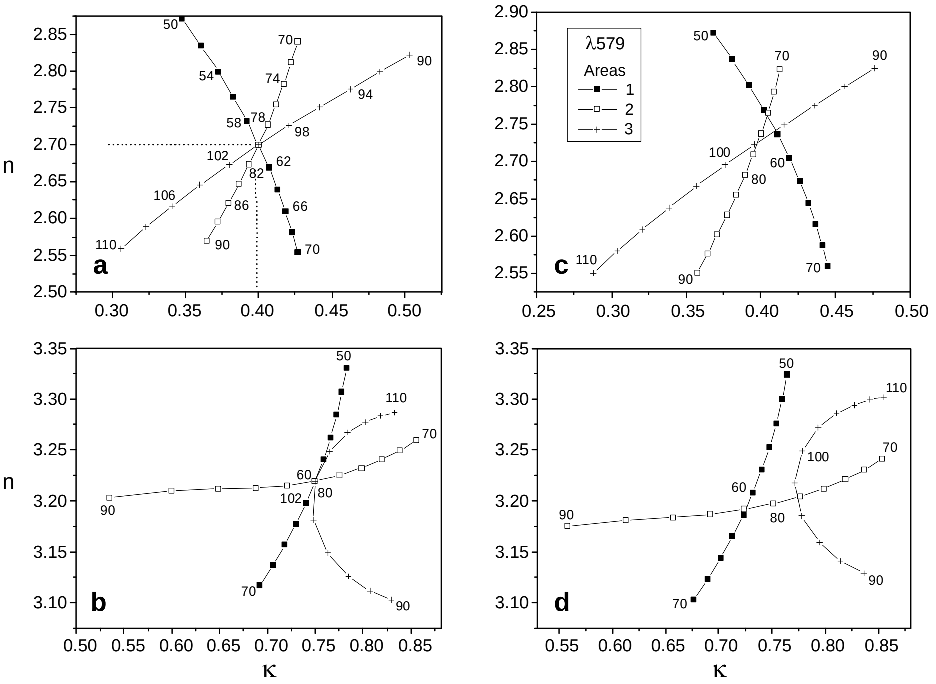

Fig. 2. Curves of probable solutions of film optical parameters obtained for different film thicknesses for three areas of the first (**a**) and second (**b**) curves. Effect of the error of measurement of ellipsometric parameters $\Delta\Phi = 0.2$, $\Delta \mathrm{tg}\psi = 0.01$ on the thickness curves of graphic method (**c**, **d**).

Three areas with fixed thickness of 60 nm (area 1), 80 nm (area 2) and 100 nm (area 3) were chosen on each curve. Then the inverse problem of ellipsometry was solved (film parameters were calculated with the help of the method described earlier) using the couple of values Φ and tgψ that characterized each point.

Calculated results of the optical parameters of the two spirals (Fig. 1) are presented in Figs. 2**a** and 2**b**. In both cases, it was noted that solution curves really intercross at one point, which gives optical parameters of the film and its thickness which coincide with true values of these parameters. Obviously, curves of probable solutions could be noncrossing, they could touch each other at one point, as observed for the second spiral in Fig. 2**b**.

In conditions of real experiment, values of ellipsometric parameters obtained are affected by an experiment error. The experimental error, being typical of each area under study, would lead to the systematic error of detected optical parameters of the film. So, the thickness curves obtained in data calculation would be dislocated and would not intercross at one point in the diagram of detected values, they would converge in a bigger or smaller local region according to the permissible error. This fact is presented in Figs.2**c** and 2**d**.

The values of ellipsometric parameters in areas 1, 2 and 3 were perturbed at $\Delta\Phi = \pm 0.2°$ and $\Delta \mathrm{tg}\psi = \pm 0.01$, which are close to the experimental error and even somewhat bigger. Then thickness curves, similar to those in Figs. 2**a** and 2**b** for the system presented, were calculated with the help of present method using perturbed values of principal angle and ellipticity as analogue of experiment date.

As a result of the error effect, generic intersection points of all thickness curves disappear; curves intercross in pairs, but certain region of the curves converging exists. Under such circumstances solution is found by averaging film parameters obtained from all intersection points in the region of the maximal convergence of the curves.

After averaging the value of the film refractive index would be estimated at 0.04 and thickness value at 3–5 nm for the system with considerably small absorption (curve 1 in Fig. 2). In the case of the system with considerably large absorption (curve 2 in Fig. 2) the film refractive index would be estimated at 0.02 and thickness value at 1–3 nm relative to the true values of these parameters.

So, the error of ellipsometric parameters measured by photometric method can give an error of about 0.05 in the value of refractive index and the error of 5 nm at the most in the value of film thickness.

Model calculations have shown that in some cases several possible solutions may exist for a certain pair of ellipsometric parameters with regard to film optical constants. This conforms to the situation in which in absorptive film model several curves representing constant values of optical parameters could pass through each point in the diagram of the measured values. When we assign film thickness the program chooses that one from possible curves which corresponds to this thickness. However, values of optical constants would be different for each curve. In the model experiment presented, up to three possible solutions were obtained for each area.

So, while searching for solutions with the help of the program one has to determine all possible solutions by modifying initial values of optical parameters within a certain limit. False solutions could be distinguished from the true ones by the fact that their thickness curves have no common intersection point. As a result, experimental measurements must be conducted on as many as possible different thickness areas of the same film.

4. Results of the examination of CdTe/CdHgTe samples

4.1. Optical parameters of CdHgTe substrate

Prior to the deposition of CdTe film on one of the samples ellipsometric measurements were conducted on the substrate of monocrystalline $Cd_{0.2}Hg_{0.8}Te$ and optical constants of the substrate were determined by measured ellipsometric parameters. The obtained values of optical parameters were further used in the program for finding parameters of the films that were deposited on this substrate.

The substrate used for the CdTe film deposition consisted of hybrid three-compound crystal CdHgTe film with relatively big thickness that was deposited on the CdZnTe by epitaxial method. During ellipsometric measurements, it was radiation reflected from the sample surface that was studied, whereas reusable reflection was neglected because of the strong matter absorption. The measurement was conducted at a fixed angle of 65°. Optical constants of matter (refractive index n and absorptive index κ) were found from the ellipsometric measurements. The oxide layer with the thickness of several nanometers was neglected in the calculation.

Measurements of ellipsometric parameters were conducted by studying the beam reflected from different areas of the sample in order to control the similarity of the substrate properties on the sample surface. The obtained values of optical parameters are presented in Fig. 3.

The high-strength doublet maximum is observed in the spectrum of absorptive index, and a wide region of anomaly dispersion that corresponds to this absorptive maximum is observed in the spectrum of refractive index.

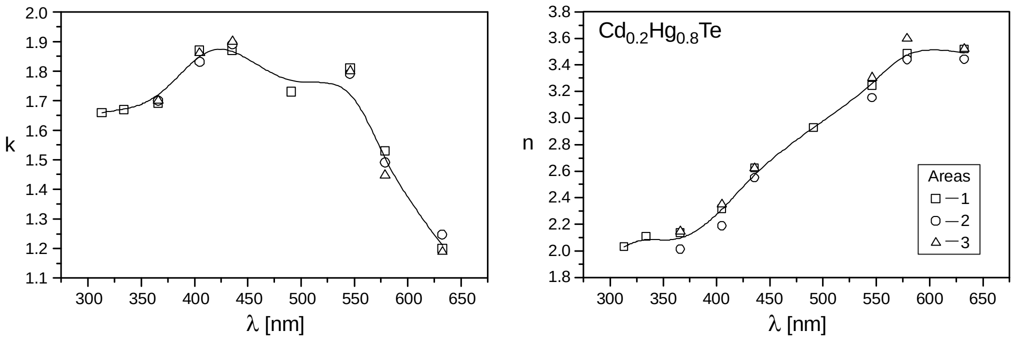

Fig. 3. Refractive index n and absorptive index κ of mixed CdHgTe crystals.

According to the customary interpretation of the semiconductor properties which are crystallized in the zinc blend structure [18], the obtained spectrum of the optical constants conforms to intrinsic electron transition from the valence band that is split by the spin-orbit interaction to the lower conduction band. Such transitions occur in the wide region of the quasi-momentum towards the Brilluen zone Λ. The refractive index spectrum splitting conforms to the spin-orbit splitting of the valence band in the corresponding direction.

Values of the optical constants that we obtained coincide with the accuracy of 5–10% with values presented in [19] for the matter of the given composition. Deviation could be explained by the imperfection of sample surface and it indicates that the optical constants obtained have physical meaning of some effective parameters, which characterizes not only the substrate matter but geometry of the reflective surface.

From the analysis of the data obtained one can draw conclusion that the difference in the values of optical constants in different areas of the sample surface does not exceed 1% that is close to the experimental error. The obtained values of the substrate optical parameters were used for calculating the parameters of CdTe films deposited on this substrate.

4.2. CdTe film parameters

This series contains 4 samples obtained by depositing CdTe film on the substrate from the hybrid monocrystals of CdHgTe under the same conditions of the hot-wall epitaxy method; time of the evaporation time was the same and equalled 8 minutes. Up to 7 areas with different interference color and different thickness of deposited film were chosen on the sample surface.

Measurements were conducted at the wavelength of 632.8 nm and incidence angle of 60°. In ellipsometric data calculation film parameters were detected for each sample separately by the method of thickness curves that was described earlier. Thickness curves of one of the samples that illustrate film parameters detection are presented in Fig. 4 as an example.

It was found that for each couple of ellipsometric parameters the program gave two possible solutions: two couples of film optical constants for the area under study. So, two couples of thickness curves, one of which contained true solution and another contained false solutions were obtained for each area.

All solutions, both true and false are presented in Fig. 4**a**. The region where the greatest number of curves intercross is marked with rectangle. Thickness curves that correspond to the false solutions are mostly almost parallel to each other. Curves in the outlined region where film parameters were obtained are presented in Fig. 4**b**. Optical constants and film thickness were detected as the average values of those obtained from the diagram as intersection points of all thickness curves of the sample. The average dispersion of parameters was detected, it possible (provided that the number of intersection points was sufficient). Results of calculation are presented in Tab. 1.

Table 1. Refractive index n and absorptive index κ of the film, and its thickness in different areas of the sample, thickness scatter in terms of sample surface (as a degree of film homogeneity).

			Film thickness in areas [nm]								
Sample	n	κ	1	2	3	4	5	6	7	8	Δd [nm]
100-2	2.5 ± 0.04	0.23 ± 0.03	52 ± 4	57 ± 4.5	68 ± 4	73	67 ± 5	—	—	—	21
104-4	2.14 ± 0.02	0.47 ± 0.005	78 ± 1	88.5	92	76 ± 2	97.5	—	—	—	21.5
81-3	2.52 ± 0.02	0.385 ± 0.01	50.5	63	71.5	68	66	—	58	57	21
81-5	2.66 ± 0.02	0.31 ± 0.01	44±1	52 ± 2	54.5	59	61 ± 1	57	60	—	17

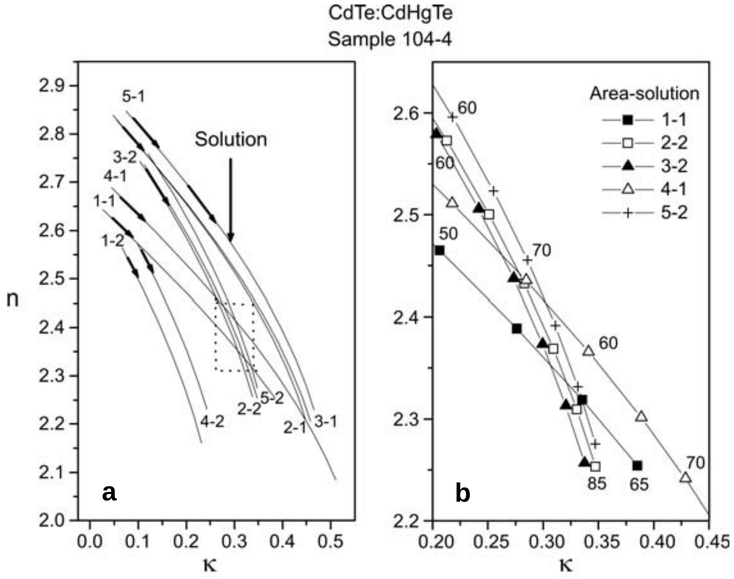

Fig. 4. Finding refractive index n and absorptive index κ by the method of thickness curves. Arrows on the curves (**a**) show direction of the film thickness increasing over the interval of 40–85 nm, numbers near each curve show the area number and solution number over dash. Curves in the region of the greatest number of their intercrosses are presented in (**b**), numbers near the marks show the film thickness in nm.

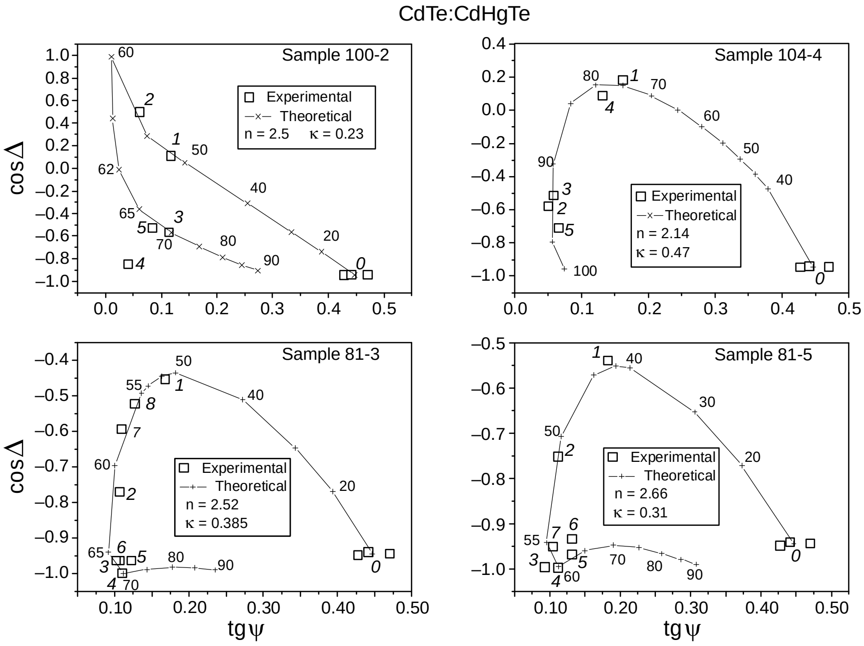

Fig. 5. Comparison of experimental values of principal angle *Φ* and ellipticity tg*ψ* with theoretical calculations. Film thickness in nm is shown by numbers near the theoretical curves marks.

The obtained values of optical parameters range (0.01–0.05) and thickness (1–4 nm) are close to those burdened with the measuring error of the ellipsometric parameters.

It was found that values of the film optical parameters for different samples differ from each other by the value that exceeds the experimental error. Particularly, film refractive indexes of three samples (100-2, 81-3, 81-5) are almost similar and lie within the limit of 2.6, whereas the film refractive index of sample 104-4 is appreciably smaller and equals 2.14.

Experimental data distribution for different areas of the samples under study and theoretical curves that describe this distribution are presented in Fig. 5. Curves are plotted according to the values of film parameters obtained, which are presented in Tab. 1. It is obvious that theoretical curves pass close to the experimental points.

Ellipsometric measurements were conducted at several wavelengths of the mercury lamp radiation on one of the samples (time of evaporation was 8.5 minutes) in order to determine optical parameters dispersion. These measurements were conducted with the use of the photometric ellipsometer by the method described in Section 3.

Measurements were conducted on several areas with different thickness at fixed incident angle of 65° and in a wide region of incident angles. Principal angle was detected from the multiangular measurements. Optical constants and film thickness were determined by the method described earlier, using ellipsometric parameters at a fixed angle and applying the values of principal angle and ellipticity.

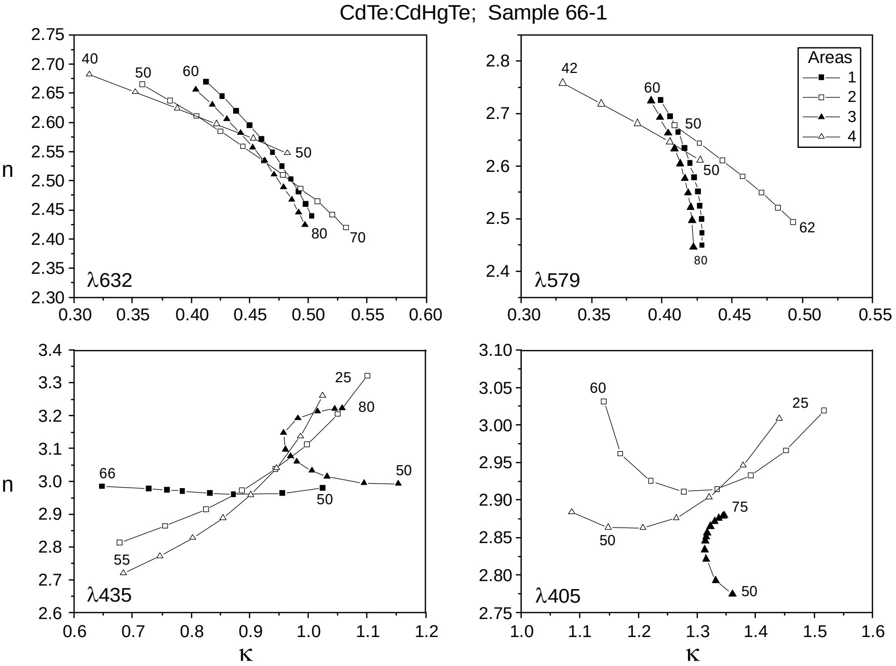

Fig. 6. Determination of film parameters by principal angle and ellipticity.

An example of data calculation for the principal angle, where sensibility of the ellipsometric parameters to the film characteristics is somewhat higher than for the angle $\varphi = 65°$, is presented in Fig. 6 (the data for an angle of 65° are similar to those of the principal angle, so a diagram that describes it is not presented in the paper). These data are effective for estimating of the accuracy of the method.

From the data of Fig. 6 it is obvious that thickness curves in the shortwave region become twisted and diverge like in Fig. 2**d**. So, the film thickness for the wavelengths of 405 nm and 366 nm was not exactly determined. Such a character of the curves is explained by the fact of the film absorption being rather high in the short-wave region and considerably big film thickness. As a result, experimental points obtained at these

Table 2. Comparison of 66-1 sample optical parameters obtained by different methods.

	Measurements at angle of 65°		Measurements at principal angle	
λ [nm]	n	κ	n	κ
632.8	2.68±0.015	0.308±0.005	2.56±0.02	0.45±0.01
579	2.62±0.01	0.422±0.002	2.66±0.01	0.41±0.003
546	2.51±0.01	0.423±0.001	—	—
435	3.03±0.02	0.994±0.01	3.02±0.025	0.93±0.015
405	2.83±0.03	1.34±0.015	2.90	1.34
366	2.35	1.4	—	—

Table 3. Film thickness in different areas.

	Film thickness [nm]	
Area	Measurements at angle of 65°	Measurements at principal angle
1	68±2	62
2	51±4	44±3
3	64±3.5	662
4	44±5	39.5±5
Thickness dispersion [nm]	24	26

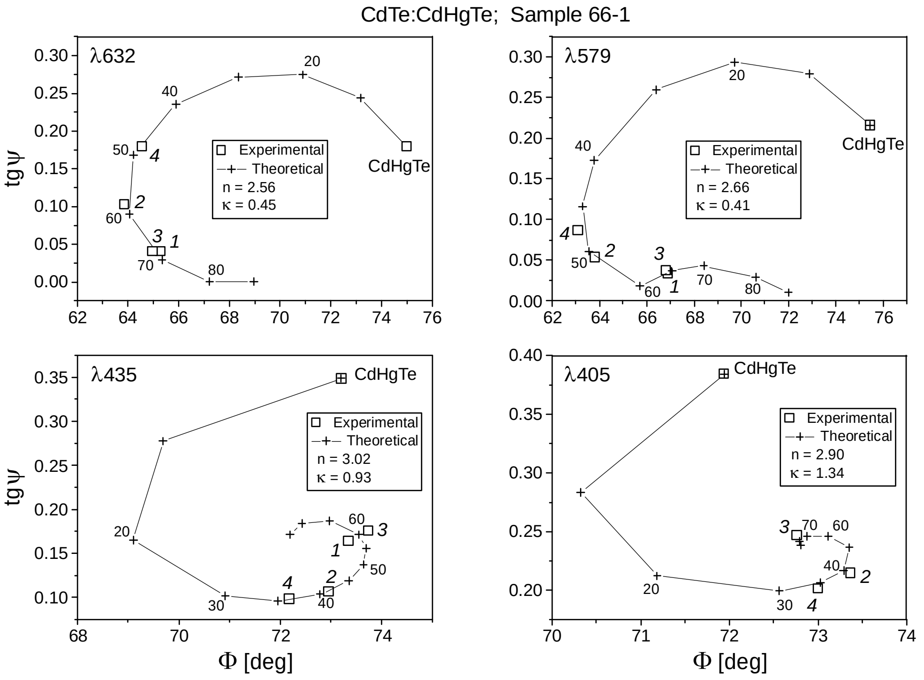

Fig. 7. Comparison of experiment values of principal angle *Φ* and ellipticity tg*ψ* with theoretical calculations. Film thickness in nm is shown by numbers near the theoretical curves marks. Numbers near squares indicate the numbers of areas on the sample surface.

wavelengths were found to lie close to the pole of corresponding spiral theoretical curve (curve 1 in Fig. 1), and sensitivity of ellipsometric parameters particularly to the thickness in different areas appeared to be small.

The obtained values of film parameters are presented in Tables 2 and 3; besides, the values of optical parameters obtained at a fixed and principal angles are compared in Tab. 2. The coincidence of optical parameters is satisfactory.

Comparison of experimental data with theoretical curves in the principal angle–ellipticity diagram, which are calculated using the data from Tab. 2, is presented in

Fig. 7. Clearly, the experimental points fit well appropriate places on the theoretical curves.

Values of the film thickness in different areas and also thickness dispersion on the sample surface calculated as a difference between maximal (the center) and minimal (the periphery) thicknesses are presented in Tab. 3. Thickness scattering of the sample surface depends on technological conditions of film evaporation in a given device. Particularly, in our case, we can see that the heat field in conditions of film depositing by the hot-wall epitaxy was not sufficiently isotropic in the region of substrate allocation, hence the film growth with the thickness being heterogeneous.

5. Discussion of the results

As can be easily seen from the data of Fig. 2, the error relative to film parameters induced by the error of ellipsometric parameters measurement by means of the method presented amounts to $\Delta n = \pm 0.05$, $\Delta\kappa = \pm 0.02$, $\Delta d = \pm 2$ nm. Values of optical constants dispersion obtained experimentally are located within the above-mentioned limits (as is seen from data presented in Tabs. 1 and 2).

So, the present method of absorptive film parameters detection was found to be suitable for CdTe films on the surface of mixed crystals CdHgTe. In all the cases, these parameters were found by thickness curves obtained for different areas of the sample surface. This means that the film obtained by the hot-wall epitaxy under conditions of evaporation described above is homogenous enough; in certain limits optical parameters are similar within the surface extent.

Moreover, the film thickness is different in different areas of the same sample and varies within the limits of 20 nm increasing from the periphery to the center of the sample. Besides, this error of the thickness determination in the same sample (Tab. 3) was somewhat greater than the value mentioned above, which characterizes the error of the method presented. This means that the film is heterogeneous as regards the thickness.

In the method applied, film thickness is determined by the temperature field and the time of evaporation. So, it is expected that certain temperature distribution in the working volume exists in a given setup for film deposition; the temperature (most probably of the substrate) increasing from the periphery to the center.

The refractive index of the CdTe films is appreciably smaller than that of the monocrystalline cadmium telluride (~2.8 in the visible spectrum [20, 21]) when absorptive indexes for both systems are equal.

As refractive index value is sensitive to the technological conditions of film depositing, its deflection from the refractive index of the monocrystalline matter could be the measure of perfection of the film obtained under given conditions.

Thickness dispersion of the sample surface (which changes in the limit of 20 nm, as seen from Tabs. 2 and 3) could be a certain characteristic of the film deposition process. It can be seen that the thickness dispersion for sample 66-1 is 17 nm which is the smallest value obtained for all the samples from this series. The refractive index value of this sample is the nearest to the refractive index of the monocrystalline CdTe. This fact could be explained by the quality of the film obtained for this sample.

In [3, 4], it was also observed that in the case of glass, the CdTe films have refractive index which is smaller than that of the monocrystalline CdTe; this might be caused by the polycrystalline structure of the film. In [6], we have found that refractive index of CdTe film on the monocrystalline Si in the visible spectrum makes up 2.1, which is appreciably smaller than average value 2.5 of CdTe films on the CdHgTe substrate obtained under similar conditions. Such refractive index decreasing is explained by the varied structure of the film (which among single grids of basic matter contains porous ones), which is the result of big difference in lattice constants (5.4282 Å for Si and 6.477 Å for CdTe).

In the present work, measurements were conducted for high-quality films with monocrystalline structure, which is testified by the X-ray diffraction [11, 12]. Bigger values of refractive index which, however, are smaller than refractive index of monocrystalline CdTe were obtained, though lattice constants of CdTe and solid solution of $Cd_{0.2}Hg_{0.8}Te$ (6.464) are practically equal. This means that refractive index values obtained from ellipsometric data are affected by different factors.

Roughness of the film surface is one of the factors that can appreciably change values of film parameters, and particularly refractive index that is obtained from ellipsometric data. As is shown in [12], films of such type, obtained under the same conditions as ours, have roughness equal to 50–100 nm. Neglecting roughness in ellipsometric data calculation could lead to a decrease in the values of refractive index obtained. In this case, film parameters have physical meaning of some effective parameters which characterizes not only the film matter but the geometry of the reflective surface. So, ellipsometric data calculation has to be conducted in the model with roughness boundaries of the layers. This task is rather hard because of the incompleteness of the theory of electromagnetic wave formation by the matter with roughness surface.

6. Conclusions

A method of the determination of optical constants and absorptive film thickness by thickness curves, each containing a great number of possible solutions for film area (or films) with its thickness, was found to be suitable for determination of the parameters of monocrystalline CdTe films, obtained on monocrystalline CdHgTe substrate. Experiments and model calculations have proved that in conditions of measuring error existing the thickness curves have no generic intersection point but they intercross in pairs. In such circumstances, refractive index n, absorptive index κ, and film thickness d are found by averaging all intersection points of thickness curves. In our case, the other film parameter errors were obtained: $\Delta n = \pm 0.02-0.04$, $\Delta\kappa = \pm 0.01$, $\Delta d = \pm 1-4$ nm.

This method allows elimination of false solutions that could appear as a result of the main ellipsometric equation properties – thickness curves of false solutions do not intercross and/or are situated far from the basic.

The films under study are homogeneous with respect to refractive index and heterogeneous with respect to thickness which decreases from the center to the periphery. Refractive index of CdTe film deposited on CdHgTe substrate is somewhat bigger than refractive index of films obtained on Si substrate in the same conditions, but is 7% smaller than refractive index of monocrystalline cadmium telluride.

Decreasing of refractive index of the film on the substrate could be explained by the imperfect film surface, roughness presence in particular.

References

[1] LAAZIZ Y., BENNOUNA A., CHAHBOUN N., OUTZOURHIM A., AMEZIANE E.L., *Optical characterization of low optical thickness thin films from transmittance and back reflectance measurements*, Thin Solid Films **372**(1–2), 2000, pp. 149–55.

[2] MUTHUKUMARASAMY N., BALASUNDARAPRABHU R., JAYAKUMAR S., KANNAN M.D., RAMANATHASWAMY P., *Compositional dependence of optical properties of hot wall deposited* $CdSe_xTe_{1-x}$ *thin films*, Physica Status Solidi A **201**(10), 2004, pp. 2312–8.

[3] RUSU M., RUSU G.G., *On the optical properties of evaporated CdTe thin films*, Physics of Low Dimensional Structures No. 3/4, 2002, pp. 105–15.

[4] THUTUPALLI G.K.M., TOMLIN S.G., *The optical properties of thin films of cadmium and zinc selenides and tellurides*, Journal of Physics D: Applied Physics **9**(11), 1976, pp. 1639–46.

[5] PAULSON P.D., XAVIER MATHEW, *Spectroscopic ellipsometry investigation of optical and interface properties of CdTe films deposited on metal foils*, Solar Energy Materials and Solar Cells **82**(1–2), 2004, pp. 279–90.

[6] KORNIENKO K.N., ODARYCH V.A., POPERENKO L.V., VUICHIK M.V., *Determination of optical parameters of CdTe films by principal angle ellypsometry*, Functional Materials **13**(1), 2006, pp. 179–82.

[7] MEHTA B.R., KUMAR S., SINGH K., CHOPRA K.L., *Application of spectroscopic ellipsometry to study the effect of surface treatments on cadmium telluride films*, Thin Solid Films **164**, 1988, pp. 265–8.

[8] PEIRIS F.C., WEBER Z.J., CHEN Y., BRILL G., *Optical properties of* $CdSe_xTe_{1-x}$ *epitaxial films studied by spectroscopic ellipsometry*, Journal of Electronic Materials **33**(6), 2004, pp. 724–7.

[9] BHATTACHARYA D., CHAUDHURI S., PAL A.K., *Determination of optical constants and band gaps of bilayered semiconductor films*, Vacuum **46**(3), 1995, pp. 309–13.

[10] POHORYLES B., MORAWSKI A., *Photoconductivity – a novel method of evaluation of thin semiconducting film thickness*, Thin Solid Films **301**(1–2), 1997, pp. 122–5.

[11] BILEVYCH YE.O., BOKA A.I., DARCHUK L.O., GUMENJUK-SICHEVSKA J.V., SIZOV F.F., BOELLING O., SULKIO-CLEFF B., *Properties of CdTe thin films prepared by hot wall epitaxy*, Semiconductor Physics, Quantum Electronics and Optoelectronics **7**(2), 2004, pp. 129–32.

[12] BILEVYCH YE., SOSHNIKOV A., DARCHUK L., APATSKAYA M., TSYBRII Z., VUYCHIK M., BOKA A., SIZOV F., BOELLING O., SULKIO-CLEFF B., *Influence of substrate materials on the properties of CdTe thin films grown by hot-wall epitaxy*, Journal of Crystal Growth **275**(1–2), 2005, pp. e1177–e1181.

[13] ODARYCH V.A., , Zavod. Labor. **43**(9), 1977, p. 1093 (in Russian).

[14] AZZAM R.M.A., BASHARA N.M., *Ellipsometry and Polarized Light*, North-Holland Publ., Amsterdam, New York, Oxford, 1977, p. 583.

[15] GORSHKOV M.M., *Ellipsometry*, Sov. Radio, Moscow, 1974, p. 200 (in Russian).

[16] Dagman E.E., *Complete solution of the inverse problem in ellipsometry for a single-layer system with variations in film thickness*, Optics and Spectroscopy **66**(1), 1989, pp. 101−4; (original: Optika i Spektroskopiya **66**(1), 1989, pp. 174−9).

[17] Odarych V.A., Panasyuk V.I., Staschuk V.S., Zhurnal Prikladnoi Spektroskopii **56**(5/6), 1992, p. 827 (in Russian); Byatec M.A., Kusch V.T., Odarych V.A., Panasyuk V.I., Visn. Kiev Univ. (Fiz.-Mat.) No. 7, 1992, p. 7 (in Ukrainian).

[18] Chadi D.J., Walter J.P., Cohen M.L., Petroff Y., Balkanski M., *Reflectivities and electronic band structures of CdTe and HgTe*, Physical Review B: Solid State **5**(8), 1972, pp. 3058−64.

[19] Johs B., Herzinger C.M., Dinan J.H., Cornfeld A., Benson J.D., *Development of a parametric optical constant model for* $Hg_{1-x}Cd_xTe$ *for control of composition by spectroscopic ellipsometry during MBE growth*, Thin Solid Films **313/314**(1–2), 1998, pp. 137−42.

[20] Marple D.T.F., Ehrenreich H., *Dielectric constant behavior near band edges in CdTe and Ge*, Physical Review Letters **8**(3), 1962, pp. 87−9.

[21] Adachi S., Kinura T., Suzuki N., *Optical properties of CdTe: experiment and modeling*, Journal of Applied Physics **74**(5), 1993, pp. 3435−41.

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