SPECIFIC FEATURES OF OPTIC QUALITIES OF $Hg_{1-x}Mn_xTe$ AND $Hg_{1-x-y}Cd_xMn_yTe$ SEMIMAGNETIC MATERIALS WITH NARROW GAP COMPARED WITH $Hg_{1-x}Cd_xTe$ NONMAGNETIC SEMICONDUCTOR

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Abstract

In the present work we study the basic laws of component distribution distribution on the epitaxial layer geometry of $Hg_{1-x}Mn_xTe$, $Hg_{1-x}Cd_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ using the micro-X-ray-structural method and the optic method. A curve of standardization was constructed, using the energy band from the experiment to determine the concentration of cadmium and manganese. Analyzing the absorption spectra structure it was determined that in the absence of external magnetic field the energy spectra of the charge carriers of the $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ semimagnetic materials and of $Hg_{1-x}Cd_xTe$ nonmagnetic material with the same energy gap have the same form. The theoretical calculations of absorption spectra were realized within the Kane model with its non-parabolic perturbations specific for indium antimonide as the narrow-gap semiconductor.

1. Introduction

The detailed study in works [1-4] of semimagnetic semiconductors (SMSC) of $Hg_{1-x}Mn_xTe$, $Hg_{1-x}Mn_xSe$ type with narrow gap traced out a set of unusual features of energy spectrum with free charge carriers as: the increase of irradiation intensity within the magnetic field, a higher stability of physical properties in comparison with $Hg_{1-x}Cd_xTe$, etc.

The unusual behavior of SMSC of $Hg_{1-x}Mn_xTe$ type is determined by the influence of the change interaction of charge carriers with localized magnetic moments of manganese ion electrons from $3d^5$ states [3, 5].

The change interaction efficiency in these materials is determined by the content of manganese in respective alloys. This interaction becomes obvious through change integrals for conduction energy band ($N_o\alpha$), for valence energy band ($N_o\beta$) the modification of free charge carrier energy spectrum as well as of localized state energy spectrum.

The investigation of change integral influence on the physical properties of SMSC with narrow energy gap presents both a theoretical and applicative interest. SMSC of the $Hg_{1-x}Mn_xTe$ type can, in perspective, be used in designing some receivers of infrared radiation ($\lambda = 10.6$ μm) with a greater working temperature in comparison with the receivers that function on the basis of optic transitions of the "impure localized energy level – conduction band" type. It is obvious that the influence of change integrals on magnetic field restoring depends on the content of Mn in respective alloy, for instance, in $Hg_{1-x}Mn_xTe$; but the greatest part of manganese content in the $Hg_{1-x}Mn_xTe$ contributes also to the increase of energy band, which, in a way, complicates the separation of change integrals contribution. In these circumstances, better opportunities are offered by study of the quaternary $Hg_{1-x-y}Cd_xMn_yTe$ alloy properties. According to the physical conception of this alloy, we can obtain SMSC with the

same energy band, but with different manganese content. This experimental situation can be created by altering the manganese and cadmium concentration within certain limits. The realized technologic process allows solving this problem [6].

The joint study of the physical properties of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ SMSC and nonmagnetic ones, such as $Hg_{1-x}Cd_xTe$, with the same energy structure is of a special interest for the theory and applicability of the semiconductors with narrow energy band.

This work aims at analyzing the optic properties of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ SMSC and $Hg_{1-x}Cd_xTe$ nonmagnetic material with the same structure of the energy bands and possible modifications in manganese and cadmium concentration.

2. Results and discussion

In the present work we study optic spectra of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ epitaxial layers and $Hg_{1-x}Cd_xTe$ layers with the same structure of energy bands for a temperature range of 4.2÷300 K and a spectral range of 2-50 μm. The basic component of the used installation was a spectrometer of the SPM 2 type with diffraction lattices.

Samples of $Hg_{1-x}Mn_xTe$, $Hg_{1-x-y}Cd_xMn_yTe$, and $Hg_{1-x}Cd_xTe$ with different manganese and cadmium concentration, studied in this work, were obtained by the method of phase epitaxy in thermodynamic systems closed by oriented sublevels of cadmium telluride <111> in absolute accordance with state diagram. The technology for obtaining of epitaxial layers is described in work [6]. The technological process realized in this work also allows, resulting from the experiment needs, doping of the layers. The concentration of unidentified impurities was determined from galvanic-magnetic measurements and varied within ($2\div5\cdot10^{14}cm^{-3}$) and ($3\div6\cdot10^{15}cm^{-3}$).

The composition and homogeneity of the epitaxial layers was checked up with the help of the micro-X-ray spectral analyzer. The results of the epitaxial layer homogeneity study in geometry structure are represented in Figs. 1a and 1b. Figure 1a presents the diagram of thickness distribution of the components (Mn, Hg, and Te) within the epitaxial layers for the $Hg_{1-x}Mn_xTe$ alloy.

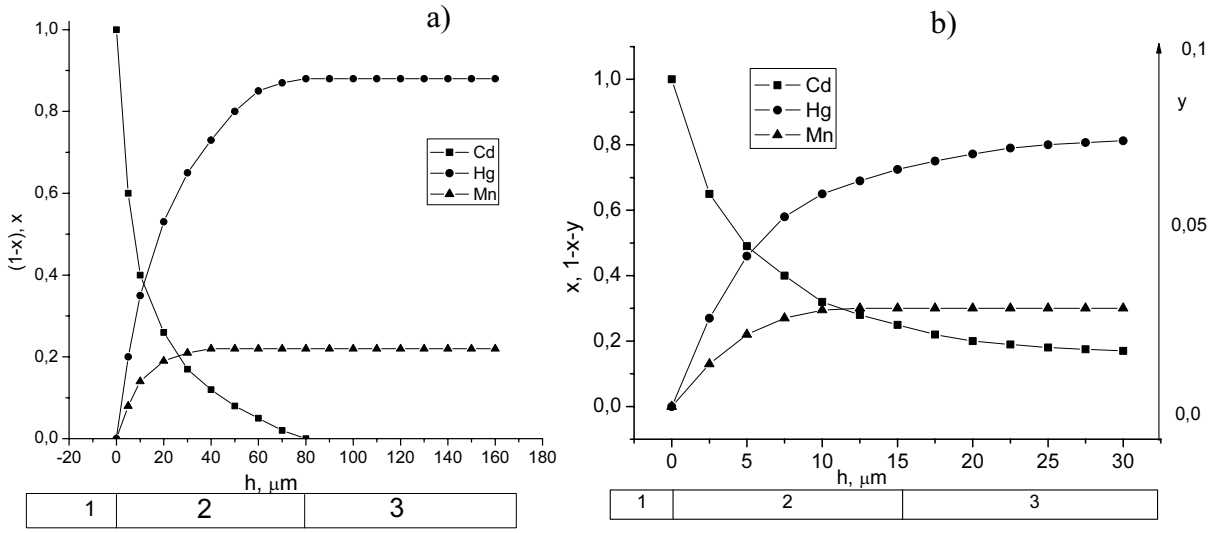

Fig. 1. The diagram of component thickness distribution in epitaxial layers of $Hg_{1-x}Mn_xTe$ (a) and $Hg_{1-x-y}Cd_xMn_yTe$ (b); (1) CdTe oriented sublayer; (2) Transition layer; (3) Layers of $Hg_{1-x}Mn_xTe$ (a) and $Hg_{1-x-y}Cd_xMn_yTe$ (b) with the determined composition.

From these results we can emphasize that at a depth of 80 μm from the layer surface we practically have a constant distribution of the components. These results confirm the high degree of studied layer homogeneity. A similar situation is presented in Fig. 1b for the quaternary $Hg_{1-x-y}Cd_xMn_yTe$ alloy. For this alloy, as the experiment confirms it, we have a high degree of layer homogeneity at a depth of 20 μm. A favorable argument for layer homogeneity is also the data presented in Table 1.

Table 1. Component structure in $Hg_{1-x}Mn_xTe$ layers determined by different methods.

Sample	Sample code	Mn content (experiment), at %	Mn content (microanalyzer), at %	E_g, eV (experiment)	Cd content in $Hg_{1-x}Cd_xTe$ at %
$Hg_{1-x}Mn_xTe$	MPT-43	0.150	0.145	0.29	0.30
$Hg_{1-x}Mn_xTe$	MPT-29	0.135	0.127	0.21	0.24
$Hg_{1-x}Mn_xTe$	MPT-13-11	0.110	0.110	0.19	0.22
$Hg_{1-x}Mn_xTe$	MPT-13-1	0.110	0.105	0.16	0.20

This table presents the following: the manganese composition introduced into the technologic process; manganese concentration determined with the help of micro-analyzer; cadmium concentration necessary in the $Hg_{1-x}Cd_xTe$ alloy to obtain the material with the same energy band as $Hg_{1-x}Mn_xTe$. The energy band presented in this table is determined from transparency spectra at a temperature of 300 K. The presented data analysis confirms a satisfactory correlation in determining the layer composition. It is also confirmed that for obtaining of an $Hg_{1-x}Cd_xTe$ layer with the same energy band width as $Hg_{1-x}Mn_xTe$ we need a concentration of cadmium twice as big as the concentration of manganese. Table 2 presents the diagram of the components (cadmium and manganese) according to the thickness after 6 chemical processings. For the $Hg_{1-x-y}Cd_xMn_yTe$ layers the chemical processing was realized in bromine solution (8%) and butanol (82%). The data confirm a respective thickness distribution of the components. It is obvious that the change of component concentration also modifies the energy band structure; this is confirmed in the table.

Table 2. Depth distribution of Mn and Te components in $Hg_{1-x-y}Cd_xMn_yTe$ layers after chemical processing.

Sample	Nr. chemical processing	Thickness, μm	E_g, eV (experiment)	Components at %	
				Mn	Cd
$Hg_{1-x-y}Cd_xMn_yTe$ CMRT-13	1	70	0.130	0.055	0.050
	2	60	0.160	0.058	0.063
	3	50	0.200	0.056	0.077
	4	40	0.198	0.055	0.078
	5	30	0.220	0.046	0.255
	6	20	0.250	0.0095	0.659

The stability in time of physical characteristics of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ layers relate to $Hg_{1-x}Cd_xTe$ was also checked up, measuring the galvanic-magnetic properties in different time intervals, namely, 6 months after the end of the technological process. The obtained experimental data confirm a 20% higher stability than that of the physical characteristics of $Hg_{1-x}Cd_xTe$. It is a conclusion that corresponds to the physical conceptions of the authors of [7, 8].

For the study of the transparency spectra, $Hg_{1-x}Cd_xTe$, $Hg_{1-x}Mn_xTe$, and $Hg_{1-x-y}Cd_xMn_yTe$ epitaxial layers were freed from the CdMn substrate either mechanically or chemically. The transparency spectra were measured at different temperatures from the (4.2÷300 K) range in the absence of magnetic field. The results of the optic effect study, the photoconduction of the materials with energy band semiconductor properties calculated within the well-known Kane model demonstrate that $\lambda_{1/2}$ in photoconduction spectra correlates with the absorption coefficient of 500 cm^{-1} value. This experimental affirmation convinces us that it is possible to determine the fundamental absorption edge from absorption spectra at this level of absorption coefficient for the studied alloys with the thickness ≤ 150 μm. So, from these experiments we calculated the energy band relative to the temperature and the component concentration. The experiment confirms a linear dependence on temperature and a more complicated dependence on alloy composition. Nowadays, in reference literature, for instance, for $Hg_{1-x}Cd_xTe$ 9 analytical forms for $E_g=E_g(x, T)$ are known. Using the standardization curves constructed for $Hg_{1-x}Cd_xTe$, using the definition from [9] we determined the alloy composition. More exact data were obtained for the temperature of 300 K. As to the errors of this experiment, we proceeded from the fact that the linear dispersion of the used spectrum constitutes 0.18 μm/mm (for λ = 10 μm) and the spectrometer diaphragm (≤1 mm) allowed us to determine the fundamental edge position with an accuracy of 0.2 μm, which corresponds to the accuracy of cadmium concentration determination in the alloy at 300 K an is on the order of ±0.005. An argument for this accuracy is the high absorption spectra from the layer surface determined by virtue of a diagram with the sizes 100÷200 μm.

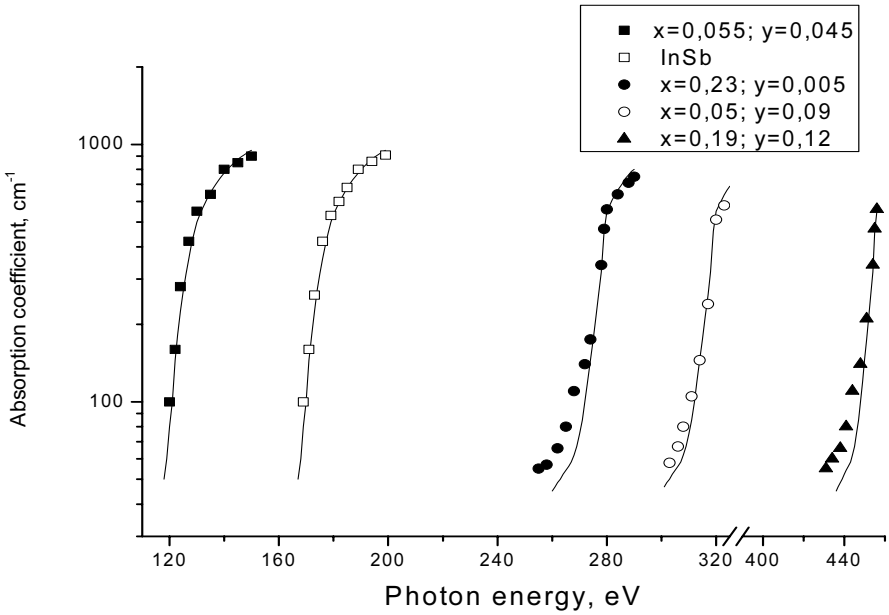

Fig 2. Absorption spectra of $Hg_{1-x-y}Cd_xMn_yTe$ epitaxial layers measured at a temperature of 300 K in comparison with different content of cadmium and manganese; magnetic field induction B = 0.

Figure 2 presents segments from absorption spectra that express optic transitions of "energy band heavy holes – conduction energy band" type of $Hg_{1-x-y}Cd_xMn_yTe$ layers measured at a temperature of 300 K relative to different content of cadmium and manganese in the absence of magnetic field. At the absorption coefficient level α = 500 cm^{-1} the energy band was determined. The obtained results for a set of alloys are presented in Table 3 for $E_g=E_g(x, y, T)$ in comparison with the manganese and cadmium concentration determined by the micro-X-ray analyzer.

Table 3. Components structure of $Hg_{1-x-y}Cd_xMn_yTe$ layers (T = 300 K).

sample	Type of conductivity	x, at % (Cd)	y, at % (Mn)	E_g, eV experiment	E_g, eV theory
KMPT-4	p	0.200	0.042	0.310	0.360
KMPT-36	p	0.074	0.088	0.270	0.250
KMPT-46	p	0.230	0.050	0.270	0.240
KMPT-56	p	0.190	0.120	0.440	0.420
KMPT-13	n	0.050	0.055	0.140	0.130
KMPT-41	n	0.050	0.090	0.300	0.310
KMPT-18	n	0.110	0.085	0.250	0.260
KMPT-8	n	0.055	0.045	0.124	0.078
MB-156	p	0.220	0.040	0.320	0.340

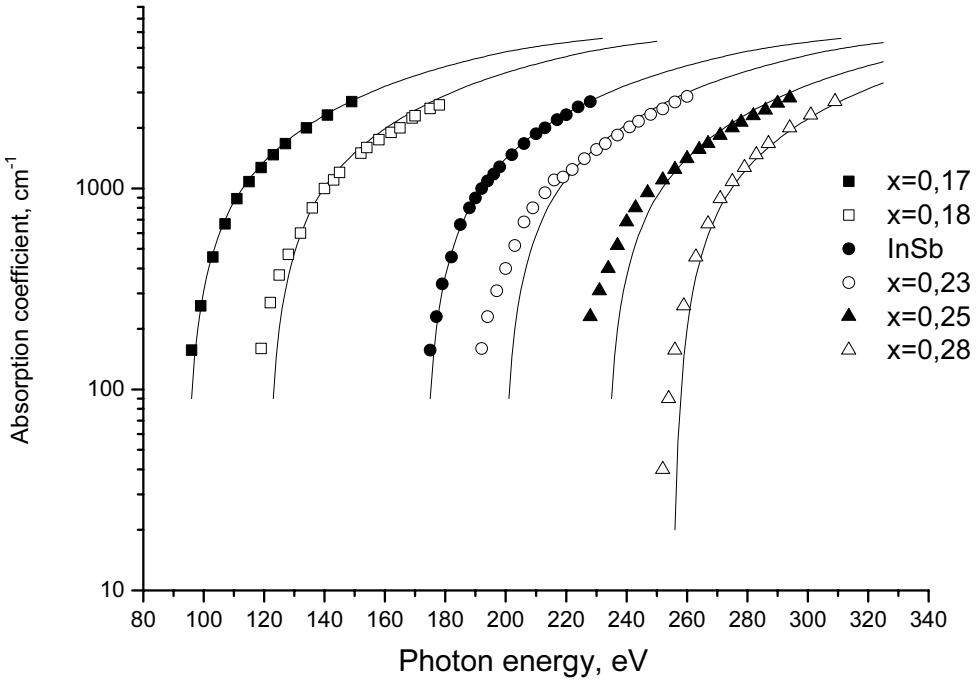

Fig. 3. Absorption spectra of $Hg_{1-x}Cd_xTe$ and InSb epitaxial layers measured at a temperature of 300 K in comparison with cadmium content. Magnetic field induction B=0. Continuous lines show the calculated absorption spectra.

Table 4. Some parameters of $Hg_{1-x}Cd_xTe$ epitaxial layers determined from the optical transparence and electrical-magnetic phenomena.

sample	code	Energy gap, eV, absorption, 300 K	Component, x, at %	n, cm^{-3} T=300K	n, cm^{-3} T=77K	Type of conduc.
1 $Hg_{1-x}Cd_xTe$	KPT-17	0.120	0.17	$9.0*10^{16}$	$1.4*10^{16}$	n
2 $Hg_{1-x}Cd_xTe$	KPT-18	0.135	0.18	$3.5*10^{16}$	$2.3*10^{15}$	n
3 $Hg_{1-x}Cd_xTe$	KPT-25	0.220	0.25	$8.2*10^{16}$	$6.7*10^{16}$	n
4 $Hg_{1-x}Cd_xTe$	KPT-26	0.240	0.26	$2.3*10^{16}$	$1.1*10^{16}$	p
5 $Hg_{1-x}Cd_xTe$	KPT-28	0.270	0.28	$2.5*10^{16}$	$3.5*10^{15}$	n
6 $Hg_{1-x}Cd_xTe$	KPT-32	0.321	0.32	$3.0*10^{16}$	$2.3*10^{15}$	n
7 $Hg_{1-x}Cd_xTe$	KPT-46	0.520	0.46	$2.0*10^{16}$	$1.8*10^{15}$	p
8 $Hg_{1-x}Cd_xTe$	KPT-69	0.855	0.69	$4.1*10^{16}$	$3.0*10^{16}$	p
9 $Hg_{1-x}Cd_xTe$	KPT-61	0.740	0.61	$3.2*10^{16}$	$1.2*10^{16}$	p

Figure 3 registers the absorption spectra of $Hg_{1-x}Cd_xTe$ epitaxial layers measured at a temperature of 300 K in the absence of magnetic field. Using the above stated procedure we calculated $E_g=E_g(x, T)$. The obtained data for the studied layers are presented in Table 4.

Absorption spectra were also obtained for $Hg_{1-x}Mn_xTe$. Comparing the experimental results from Figs. 2 and 3 and from Tables 3 and 4, the following can be emphasized: continuous lines in spectra 2 and 3 are theoretic calculations realized in the Kane's concepts of the energy band model formulated for the narrow-gap semiconductors.

We can emphasize a sufficient agreement between the experimental data and theoretical calculations for the effective weights from the range relative to the alloy component concentration and the concentration of charge carriers: for the electrons – $m^k_e \sim (0.005 \div 0.106\ m_e)$, for heavy holes – $m^*_{hh} \sim (0.441 \div 0.50\ m_e)$, for light holes – $m^*_{lh} \sim (0.0115 \div 0.018\ m_e)$ and $\varepsilon_\infty = 16$. The form of rather abrupt absorption fundamental edge and the coincidence of the theoretic and experimental absorption spectra confirm that the studied $Hg_{1-x}Cd_xTe$, $Hg_{1-x}Mn_xTe$, and $Hg_{1-x-y}Cd_xMn_yTe$ layers have a high degree of homogeneity and a satisfactory technical-scientific level of the technological process used in this work.

For comparison, Figs. 2 and 3 present the absorption spectra of indium antimonide calculated in terms of the same theoretical conceptions; the absorption spectra of $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ SMSC and $Hg_{1-x}Cd_xTe$ nonmagnetic material have the same form at the temperature of 300 K; in the case of the $Hg_{1-x}Mn_xTe$ and $Hg_{1-x}Cd_xTe$ alloys with the increase in the manganese and tellurium concentration in the respective alloy the fundamental absorption border moves to the spectral pitch of great energies; for a $Hg_{1-x-y}Cd_xMn_yTe$ layer with the same content of cadmium with the increase of manganese concentration in the alloy the fundamental absorption edge also moves to the spectral range of great energy; in the $Hg_{1-x-y}Cd_xMn_yTe$ system varying the content of cadmium and manganese in certain concentration intervals, materials with the same energy band, but with different concentration of manganese can be obtained. This is a very important conclusion for the experimental study of the change interaction determined by the specific properties of manganese as the alloy component. In the $Hg_{1-x-y}Cd_xMn_yTe$ alloy with the same content of manganese and with the increase of cadmium content the fundamental absorption edge also moves to the spectral range of high energies.

Conclusions

In the present work we studied the main regularities of components distribution on the epitaxial layer geometry of $Hg_{1-x}Mn_xTe$, $Hg_{1-x}Cd_xTe$, and $Hg_{1-x-y}Cd_xMn_yTe$ using the micro-X-ray-structural method and the optic method. A curve of standardization was constructed, using the energy band from the experiment to determine the concentration of cadmium and manganese. Analyzing the absorption spectrum structure, it was determined that in the absence of external magnetic field the energy spectra of the charge carriers of the $Hg_{1-x}Mn_xTe$ and $Hg_{1-x-y}Cd_xMn_yTe$ semimagnetic materials and of the $Hg_{1-x}Cd_xTe$ nonmagnetic material with the same energy band have the same form. The theoretical calculations of absorption spectra were realized in terms of the Kane model with its non-parabolic perturbations specific for indium antimonide as a narrow-gap semiconductor. It was also studied how the energy band is modified in dependence on the respective component concentration.

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