

The procedure of growth of CdTe single crystals from the gas phase by means of the sublimation in vacuum with the use of the vertical configuration of a growth system is described. The low temperature photoluminescence (PL) spectra for the nominally undoped and chlorine-doped single crystals, grown by this method, are investigated and compared with the spectra for the corresponding crystals, obtained by the Bridgman growth method. It is shown that the crystals grown from the gas phase have a sufficiently high degree of structural perfection, though they contain a larger quantity of uncontrolled impurities . This conclusion is based on the fact that the PL spectra contain the clearly pronounced lines of the free exciton transitions.

1. Introduction

Cadmium telluride CdTe displays the properties which make this material suitable for the fabrication of detectors of high-energy radiation. In particular, the great atomic weight (nearly 50) and the density (5.68 g/ cm^3) allow the achievement of high values of the quantum efficiency coefficient for the X-ray and γ -radiation. Although the transport parameters of cadmium telluride are worse than those characteristic of the widely used silicon and germanium detectors, the high values of resistivity achievable in CdTe (up to $10^{10}\Omega \times \text{cm}$) make it possible to reduce a leakage current to a minimum, especially at room temperature. This allows a utilization of the detectors made from this material without an additional cooling, which is important from the viewpoint of a simplification and miniaturization of measurement circuits. To date, the substantial progress has been achieved in the production of the detectors of ionizing radiation on the basis of cadmium telluride and its solid solution CdZnTe [1], and not least this is connected with the improvement of growth methods for the single crystals of the compounds under consideration.

Since CdTe has the lowest melting temperature (1092 °C) among all $A^{II}B^{VI}$ compounds, it is grown predominantly from the liquid phase: by a vertical or horizontal modification of the Bridgman method [2, 3], by the methods of gradient crystallization [4] or moving heater (floating zone recrystallization) [5, 6]. As regards the last method, the growth is most often carried out from a solution that is enriched with tellurium (the Te weight fraction in a zone achieves 70 %), which enables one to reduce the growth temperature. The necessary semiinsulating state is usually achieved by means of a doping with elements of the III and VI groups of the Periodic table, mostly by chlorine.

The use of the liquid phase methods for the growth of cadmium telluride makes it possible to obtain the single crystals of this compound which are large in size and suitable for the creation of the radioactive radiation sensors of the spectrometric quality. However, the high temperatures necessary for the process of growth from a melt lead to the creation of a great deal of structural imperfections - dislocations, twins, low-angle block boundaries, cracks, and blisters [7, 8]. It is making use of a solution that brings about an increase in the concentration and the total area of precipitations and tellurium inclusions [9]. A contact of the liquid phase with the walls of a growth container leads to a rise in the level of background impurities. The disadvantages described lead to a reduction in the yield of the material with the necessary parameters.

The gas phase methods of the crystal growth can be more promising from this point of view. That is why, the quantity of publications devoted to the growth of the CdTe single crystals by means of the sublimation in closed and semiclosed growth systems [10-12], as well as by the solid phase recrystallization method [13], has been greatly increased in recent years. When halogens are added to cadmium telluride, the phenomenon of self-

compensation [14] occurs and the equilibrium between the concentrations of the donor and acceptor levels is achieved. What is more, as a result of the high chemical activity of chlorine, the deep self-purification of a crystal occurs [15] by means of the deactivation of electrically active centers in the process of their association with Cl in electrically non-active complexes. To date, a few models of the self-compensation mechanism in CdTe have been known [16], but neither of them is able to completely explain the whole body of experimental data. It is this fact that makes it especially urgent to study the impurity-defect structure of cadmium telluride single crystals depending on the conditions of their fabrication, which will show a way to correctly adjust the growth parameters. Thanks to the high values of sensitivity and resolving power, the method of lowtemperature PL makes it possible to investigate the specific features of exciton transitions, the parameters of donor and acceptor centers, as well as structural defects in CdTe which participate in the radiative recombination processes.

The aim of the given paper is the detailed investigation of the low temperature PL for both the nominally undoped and chlorine doped single crystals of cadmium telluride grown by a method which can be considered as a gas-phase analogy of the floating zone method. By means of a comparison of the PL spectra for these specimens (in what follows, we will refer to the specimens obtained by the sublimation method as Sspecimens) with the spectra of the crystals grown by the Bridgman method (B-specimens), a conclusion is drawn about an influence of a growth method on the impurity content and the degree of structure perfection of CdTe single crystals.

2. Methods of Crystal Growth

The method of crystal growth that we developed makes it possible to obtain the single crystals of CdTe [17] and its solid solution $Cd_{1-x}Zn_xTe$ [18]. The essence of the method is the following. The first stage of the technological process consists in the synthesis of a corresponding chemical compound in quartz ampoules pumped out to $p = 10^{-5}$ Torr. Extra pure (6N grade) Cd and Te are used as starting materials. To obtain chlorine-doped crystals, CdCl₂ salt preliminary dehydrated in a vacuum is added to the basic material. The corresponding weights are calculated proceeding from the assumption that, in the CdTe matrix, chlorine atoms occupy the places of tellurium ones. A sealed off ampoule is placed in a horizontal two-section furnace



Fig. 1. Growth ampoule and the temperature profile for the furnace for the growth of cadmium telluride single crystals: 1 – a charge, 2 – a CdTe crystal

and smoothly heated to ≈ 1100 °C in a non-gradient mode. Under these conditions, the ampoule is kept for 12 hours with a simultaneous rotation with a velocity of 10 min⁻¹ to ensure the complete synthesis of the compound and the homogenization of the mixture.

The second stage of the CdTe growth consists in the immediate formation of a single crystal from the mixture, preliminary ground into powder, by means of its sublimation in a quartz ampoule which is pumped out to $p = 10^{-5}$ Torr. The shape of the ampoule and the temperature profile for a vertical growth furnace are shown in Fig. 1. During the whole growth process, the mixture is sublimated at a constant temperature, and a CdTe crystal grows in the top part of the ampoule. Such a configuration enables one to avoid the utilization of a pedestal or a glass which would be necessary if a crystal was formed in the bottom part of the growth container. During its vertical motion upwards, the ampoule with the material goes through a temperature maximum which divides the isothermal zone from the source zone having a substantial temperature gradient. Thus, the method proposed can be considered as a gas phase analogy of the floating zone method. In the given case, the movement velocity presets a growth rate and equals 0.5mm/h, which is the optimal value for the temperature conditions used.

The reference specimens used for the comparison of the PL study results were obtained by the widely used





Fig. 2. PL spectra for the B- (a) and S-crystals (b) of the undoped CdTe

Fig. 3. The same as in Fig. 2, for the chlorine-doped CdTe crystals $(N_{\rm Cl}=10^{17}~{\rm cm}^{-3})$

Bridgman method. It is worth noting that the resistivities of the CdTe:Cl specimens under study grown either by the Bridgman method or by the sublimation one (with an equal concentration of the chlorine impurity) are almost the same and equal to $10^8 - 10^9\Omega \times \text{ cm}$.

3. Photoluminescence Studies

The PL spectra were studied at T = 5 K on the split areas of as-prepared single crystals with the (110) orientation with the use of an Ar⁺ laser (the excitation power density is approximately equal to 100 mW/ cm²), a MDR-23 monochromator, and a FEU-62 cooled photomultiplier. For all the experiments, the energy resolution was not worse than 0.5 m eV.

Figures 2–4 show the PL spectra for the undoped (Fig. 2) and chlorine-doped CdTe single crystals. The concentrations of the introduced chlorine were $N_{\rm Cl} = 10^{17}$ cm⁻³ (Fig. 3) and $N_{\rm Cl} = 5 \times 10^{19}$ cm⁻³ (Fig. 4). It is worth noting that these values refer to the concentrations of Cl in the starting mixture, not in the grown crystal. To make a comparison more demonstrative, the top PL spectra in all the figures concern the B-specimens, while the bottom ones refer to the S-specimens.

First, consider the PL spectra for the undoped CdTe. For the B-crystal (see Fig. 2, *a*), the most intense line in the exciton spectra region (1.585 - 1.600 eV) is the (A^0, X) one with the energy maximum $E_{(A^0, X)} =$ $(1.589 \div 1.590)$ eV. In a vicinity of the energy values $E \approx 1.593$ eV, the weakly intense lines (D^0, X) from the excitons localized on neutral donors become evident at the signal amplification by 10. On the contrary, the PL lines from the free excitons in the region $(1.596 \div$ 1.597) eV are hardly visible.

According to the literature data, the (A^0, X) band dominates in the spectra of the undoped CdTe crystals and is present even in the purest material, where all other PL lines are absent [19, 20]. Upon studying the influence of the annealing in vacuum on the shape and the intensity of this line, as well as on the electrical properties of crystals, the authors of [21] concluded that it is the complex containing both a cadmium vacancy and a donor that is responsible for the appearance of this line. Such an origin of the band under consideration is also confirmed by the results of work [22], where the studies of the polarized PL were carried out in the epitaxial layers of CdTe. The relation of this band to the impurity-defect complex of $(V_{\rm Cd} - 2D)$ kind, where D is a non-identified donor, was founded in a more recent paper [23]. On the other hand, it is stated in the

fundamental paper on the investigation of the PL associated with the acceptor states in CdTe [24] that the line with a maximum at 1.5896 eV is a result of the radiative recombination of the excitons localized on neutral copper atoms, with the copper being a usual uncontrolled impurity in the compounds of such a kind. The recent studies of the PL and reflection spectra carried out on the ultrapure CdTe single crystals [25, 26] enabled the authors to refine the complex structure of the luminescence spectra in the vicinity of 1.590 eV and to associate it with the presence of $V_{\rm Cd}$ and $Cu_{\rm Cd}$. Returning to our case, it is the presence of an inflection on the short-wave side of the line under consideration that confirms its complex character (see Fig. 2, a).

The exciton PL spectrum for the S-crystal of CdTe contains the strongly pronounced bands (D^0, X) , W, and J, in addition to the (A^0, X) one (see Fig. 2,b). The authors of [27] carried out a detailed analysis of the PL spectra of CdTe crystals and revealed that, in a narrow spectral range (1.5928 - 1.5934 eV), there are 6 lines of the (D^0, X) type, and that they are associated with the hydrogen-like donor impurity centers. It was also shown that it is the elements of the III group located at Cd sites and the elements of the VII group, located at Te sites, that serve as donors. The $G (\approx 1.586 \text{ eV})$ and W (≈ 1.591 eV) bands are characteristic of the spectra of the exciton luminescence of cadmium telluride doped with chlorine [28, 29]. With an increase in the Cl concentration, the intensity of these lines increases, along with a simultaneous increase in both the intensity of the (D^0, X) band and the material resistivity [29]. Basing on these facts and the data on the results of the annealing in a cadmium atmosphere, the G and W bands were identified as those resulting from the radiative recombination of the excitons which are bound with the $(V_{\rm Cd} - 2{\rm Cl})$ and $(V_{\rm Cd} - {\rm Cl})$ complexes, respectively. The exciton band of $(V_{\rm Cd} - 2D)$ type also is manifested at the doping of CdTe with the elements of the III group. But in this case, its maximum is placed at approximately 1.584 eV [30, 31].

The FE free exciton lines from the upper and lower polariton branches of the PL spectra are much more intense for the S-crystal of the undoped CdTe, than for the B-one. The maximum of the ground state of a free exciton is observed at 1.5955 eV. After adding the free exciton bonding energy (10.5 meV) to this value, we obtain a value of the band gap for this material. It equals 1.606 eV, which coincides with the data of the majority of recent papers [32]. A maximum of the band which corresponds to the upper polariton branch is pronounced weaker and placed at approximately 1.597 eV.



Fig. 4. The same as in Fig. 3, for the chlorine concentration $N_{\rm Cl}=5\times 10^{19}~{\rm cm}^{-3}$

In the region 1.50 - 1.57 eV, the PL spectrum of the undoped CdTe contains a series of the lines of the edge luminescence which consists of the main line and its two phonon replications (see Fig. 2). Even in early works, it was established that these lines are associated with two types of transitions: the high-energy component (e - A) corresponds to the electron transitions from the conductivity band to shallow acceptor centers, and the low-energy one does to the donor-acceptor transitions (D - A) [33, 34]. A comparison of the spectra of the edge PL for B- and S-specimens of the undoped CdTe shows that, in the latter case, the relative acceptor concentration is far greater.

Almost all researchers agree that the shallow hydrogen-like centers, which are responsible for the (D^0, X) line in the exciton region of the spectrum, manifest themselves also in the edge luminescence. The complicated complexes of the $(V_{\rm Cd} - 2D)$ type, with which excitons are also bound, are thought to serve as acceptor centers [23]. The edge radiation transitions become clearly apparent upon the doping of CdTe with chlorine, aluminum, indium [29, 31, 35].

For both kinds of cadmium telluride crystals, in the PL spectral region (1.3 - 1.5) eV, the highly structured band, brought about by the radiative recombination of donor-acceptor pairs (DAP) with the participation of longitudinal optical phonons, is evident (see Fig. 2). In

this case, the radiation intensity is far greater for the S-crystals (see Fig. 2, b).

The luminescence in the vicinity of 1.4 eV is typical of the CdTe compound, and it can contain a few constituents. Most pronounced is the band with the zero-phonon line at 1.455eV. As was shown in paper [36], where the single crystalline CdTe:Cl specimens were studied by the method of optically detected magnetic resonance, the above band is associated with the transitions from shallow donors (isolated chlorine atoms) to the so-called A-center containing a cadmium vacancy and the nearest substitution atom Cl_{Te} . These acceptor centers are induced upon the doping of the material by halogens [37] or the elements of the III group [30, 31]. The latter substitute for cadmium at the corresponding lattice sites, and a donor at the second nearest site forms a part of the $(V_{\rm Cd} - D)$ complex [38]. As the ionization energy for the acceptor centers of copper is 145 meV [24], it is clear that the phononless line for the corresponding donor-acceptor transition is also located at approximately 1.455 eV.

The third band Y with the phononless transition at 1.477 eV is usually accompanied by weakly intense phonon replications. This band is also observed in the PL spectra of the S-crystals of the purest CdTe, the characteristic of which is the absence of other constituents within this spectral region [19, 39]. It is shown that there exists a correlation between the density of dislocations and the line intensity and that the irradiation by γ -quanta, the action of non-axial stress [40], or high-power laser irradiation [41] lead to a line intensification. All these facts allow us to make conclusion that the Y-band is associated with the radiative recombination of the excitons trapped by the field of extensive defects. It is seen from Fig. 2 that the line under consideration is observed only in the Sspecimens of CdTe.

Let us compare the PL spectra for the S- and B-specimens of the chlorine-doped CdTe ($N_{\rm Cl} = 10^{17} {\rm ~cm^{-3}}$). As is seen from Fig. 3, the exciton spectra for the cases *a* and *b* are qualitatively similar. However, the line *W* in the case *b* is much more intense. This result correlates with a high intensity of the edge PL in the case *b*: a greater concentration of the ($V_{\rm Cd} - 2D$) acceptor centers, which form both the line *W* and the edge PL, makes the intensity of the corresponding PL bands increase. In the region 1.50 - 1.57 eV, the PL intensity is far less in the B-specimens, which is a result of a lower concentration of donor-acceptor pairs. For these crystals, as also for the case of the undoped CdTe, the *Y*-band is absent (see Fig. 3,*a*). A peculiarity of the PL spectra for the specimens with a chlorine concentration of $N_{\rm Cl} = 10^{17}$ cm⁻³ is the clear splitting of the (D^0, X) band into two peaks with the maxima shifted by about 0.5 meV. These peaks are brought about by the recombination of the excitons, which, being bound with the donors, are either in the ground or excited state. In the spectra of other specimens, only the peak with a longer wavelength is visible. However, such facts as a considerable width of the corresponding bands and the presence of a shortwave kink provide a foundation for the claim that the visible peak consists of two constituents.

For both the chlorine-doped CdTe specimens with $N_{\rm Cl} = 5 \times 10^{19} {\rm ~cm^{-3}}$, the spectra are almost the same (see Fig. 4). Within the regions 1.3 - 1.5 eV and 1.50 - 1.57 eV, the PL bands are identical: in both the cases, the Y-band is evident, and the intensity of the edge PL is far weaker than that of the donor-acceptor pairs and the exciton PL. Contrary to the undoped and weakly doped crystals, the zero-phonon line and the first replication of the edge luminescence don't split into the (e - A) and (D - A) components. What is more, the maximum of their phononless bands is shifted to the short-wave side by about 10 meV. The latter fact is often noted in the literature and explained by a growth of the Coulomb interaction between the donors and acceptors, as the distance between them decreases [42, 43]. For the B- and S-specimens, small differences in the spectra can only concern the exciton PL: the relative intensity of the exciton PL is noticeably greater in the case b compared to the case a.

It is known [44] that, for the series of lines which appear as a result of the electron interaction with the longitudinal optical phonons, the energy distribution of the line intensities can be presented as a sum of the Gauss functions:

$$I(w) = Aw^{2} \sum_{p=0} \frac{S^{p}}{p!} e^{-S} \times \\ \times \exp\left[-\frac{1}{2} \left(\frac{\hbar(w_{0} - pw_{\text{LO}} - w)}{\Gamma}\right)^{2}\right],$$
(1)

where $\hbar\omega_0$ presets the energy location of the phononless line, Γ determines the width of a corresponding line, and S is a Huang—Rhys factor, which serves as a measure of the value of the electron-phonon interaction and is equal to the average number of the phonons radiated in the transition. The sum is taken over all possible phonon transitions (p = 0, 1, ...).



Fig. 5. Decomposition (see Eq. (1)) of the edge PL spectra into two bands -(D-A) and (e-A), for the B- (a) and S-crystals (b) of CdTe:Cl $(N_{\text{Cl}} = 10^{17} \text{ cm}^{-3})$

Let us apply this formula to the decomposition of the edge luminescence bands for the crystals with $N_{\rm Cl} = 10^{17}$ cm⁻³. In our case, the PL spectrum measured experimentally is described by a sum of two series: $I(\omega)/I_{\text{max}} = \alpha I_{D-A}(\omega) + (1 - \omega)$ $\alpha)I_{e-A}(\omega)$, where α and $(1 - \alpha)$ are the weight coefficients which determine the relative contributions of either the donor-acceptor luminescence $I_{D-A}(\omega)$ or that corresponding to the conductivity band-acceptor transition $I_{e-A}(\omega)$, respectively. The best agreement between the experimental and theoretically calculated curves was achieved for the following values of the parameters: $\hbar\omega_{\rm LO} = 21.6 \text{ meV}, S_{D-A} = 0.26, \hbar\omega^{D-A} =$ 1.547 eV, $\Gamma_{D-A} = 2.4 \text{ meV}$, $S_{e-A} = 0.38$, $\hbar \omega^{e-A} =$ 1.555 eV, $\Gamma_{e-A} = 4$ meV, $\alpha = 0.64$ for the B-specimens (Fig. 5,b), and $\hbar\omega_{\rm LO} = 21.6$ meV, $S_{D-A} = 0.29$, $\hbar\omega^{D-A} = 1.543$ eV, $\Gamma_{D-A} = 1.6$ meV, $S_{e-A} = 0.25$, $\hbar\omega^{e-A}~=~1.548$ eV, $\Gamma_{e-A}~=~5.6$ meV, $\alpha~=~0.21$ for the B-specimens. It is seen that, for the latter case, the contribution responsible for the transition from the conductivity band to an acceptor is dominant.

Similar calculations were carried out for the PL spectra in the 1.3 - 1.5 eV region. In this case, for the



Fig. 6. The same as in Fig. 5, for the energy region near 1.4 eV

B-specimens of CdTe:Cl, the calculations were carried out for the DAP band with its LO-phonon replications (Fig. 6,*a*), whereas the PL band for the S-specimens was decomposed into two constituents: DAP and *Y* with their phonon replications (Fig. 6,*a*). A value of the Huang—Rhys factor is greater for the former case ($S_{\text{DAP}} = 1.9$) than for the latter one ($S_{\text{DAP}} = 1.6$), see Fig. 6.

4. Discussion of Results

The analysis of the PL spectra for the cadmium telluride crystals grown by the method developed by us and the comparison of them with the spectra for the analogous crystals grown by the Bridgman method has revealed the following principal differences:

1. For the undoped and weakly doped $(N_{\rm Cl} = 10^{17} \text{ cm}^{-3})$ crystals, the intensities of the edge PL bands (1.50 - 1.57 eV) and PL in the vicinity of 1.4 eV are noticeably higher in the S-specimens. For these specimens, the lines originated from the excitons located on a shallow donor (the (D^0, X) line) and on the acceptor complexes of $(V_{\rm Cd} - 2D)$ and $(V_{\rm Cd} - D)$

types (the G and W lines) are much more pronounced too.

2. For the crystals grown from a gas phase both nominally undoped and doped with chlorine, the free exciton bands are clearly pronounced. The total luminescence intensity in the exciton region of the spectrum is also slightly greater in these crystals compared to the B-counterparts.

3. For the PL spectra of the undoped and weakly doped crystals, the Y band in the vicinity 1.4 eV is present in the S-specimens and absent in the B-specimens.

The first difference can apparently be explained by a higher level of uncontrolled impurities in the Sspecimens, namely the shallow substitutional donors which can also form the complexes with anion vacancies. What also testifies in favour of this argument is the smaller value of the Huang-Rhys factor in the Sspecimens, which can be a result the influence of the shielding effect of the uncontrolled impurities on the processes of electron-phonon interaction and the greater concentration of donor-acceptor pairs. Since the energy position of the (D^0, X) , G, and W peaks is the same for all the specimens under study, both the undoped and the chlorine doped ones, it is likely that it is chlorine that is the main impurity in the nominally undoped crystal.

In our opinion, this fact results not only from the insufficient purity of the starting materials, but also from the technological peculiarities of the process of CdTe crystal growth from the gas phase. The direct analyses carried out by other researchers [45, 46] revealed a high enough content of uncontrolled impurities in 6N Cd and in the CdTe crystals grown from it. In particular, the chlorine concentration reached 10^{17} cm⁻³. When the growth method described above is used, a singlestage sublimation of CdTe occurs. In consequence, the content of background impurities in a material should decrease as a result of the purification by means of the vacuum distillation method. However, this purification method is not efficient at a reduction of the content of volatile elements with a high vapour pressure, to which Cl belongs as well. On the contrary, the use of the liquid-phase methods results in the displacement of chlorine into the ingot end, which is unusable in practice [9, 47]. This occurs owing to the fact that the segregation coefficient for chlorine is far less than 1 (0.37, or even 0.005, according to various data [48]). The results presented in [49] confirm this fact by showing that the Cl content is more than one order higher in the material grown by the method of transport through the gase phase, than in that obtained by the Bridgman method, when the same starting components are used.

We consider that, basing on the above facts, it is reasonable to claim that the content of Cl and other non-identified shallow donors in the nominally undoped and weakly doped specimens obtained by the method proposed by us are almost the same. It is this fact that makes it possible to explain the similarity of their luminescence spectra, contrary to the case of the crystals grown by the Bridgman method.

Another feature of the S-crystals of CdTe consists in the sufficiently high degree of their perfection, the evidence of which is the presence of the clearly pronounced PL lines originated from free excitons, with the line intensity being slightly higher than that in the corresponding B-specimens. On the other hand, however, the presence of the Y band in the PL spectra of these crystals implies that they contain a number of extensive defects. The preliminary investigations showed that, in the crystals grown from the gas phase, the concentration of dislocations doesn't exceed 10^5 cm^{-2} , but there is sufficiently high quantity of twins and lowangle grain boundaries. The reason for their creation is supposed to be the stresses which appear in a crystal after its passing through the considerable axial temperature gradient in the outgoing zone of the growth furnace. At present, we are carrying out the detailed studies of both the degree of structural perfection of the material obtained and its correlation with the conditions of the material growth within the growth method proposed by us.

- Korbutyak D.V., Venger E.F., Krylyuk S.G. et al. // Optoelektron. Polupr. Tekhn. – 2001. – 34. – P.5–34.
- Rudolph P. // Progr. Cryst. Growth Charact. Mat. 1994. - 29. - P.275-381.
- Cheuvart P., El-Hanani U., Schneider D., Triboulet R. // J. Cryst. Growth. – 1990. – 101. – P.270–274.
- Matveev O.A., Terent'ev A.I. // Fiz. Tekhn. Polupr. 1995.
 29, N2. P.378-383.
- Ohmori M., Iwase Y., Ohno R. // Mater. Sci. and Eng. B. 1993. – 16. – P.283–290.
- 6. Funaki M., Ozaki T., Satoh K., Ohno R. // Nucl. Instrum. and Method. A. 1999- ${\bf 436}.$ P.120–126.
- 7. Milenov T.I., Gospodinov M.M. // Ibid. 1992. **322**. P.363—367.
- Milenov T.I., Gospodinov M.M. // Mater. Sci. and Eng. B. – 2001. – 84. – P.189–194.
- Rudolph P., Engel A., Schentke I., Grochoski A. // J. Cryst. Growth. - 1995. - 147. - P.297-304.
- Boone J.L., Cantwell G., Harsch W.C. et al. // Ibid. 1994. - 139. - P.27-36.

- Klinkova L.A., Erofeeva S.A. // Izv. AN SSSR, Neorg. Mater. - 1988. - 24, N2. - P.223-225.
- Laash M., Kunz T., Eiche C. et al. // J. Cryst. Growth. 1997. – 174. – P. 596 – 707.
- Hassani S., Lusson A., Tromson-Carli A., Triboulet R. // Ibid. - 2003. - 249. - P.121-127.
- 14. Mandel G. // Phys. Rev. A. 1964. 134. P.1073-1079.
- Matveev O.A., Arkad'eva E.N., Goncharov L.A. // Dokl. AN SSSR. - 1975. - 221, N2. - P.325-328.
- Korbutyak D.V., Mel'nychuk S.V., Tkachuk P.M. // Ukr. Fiz. Zh. - 1999. - 44, N6. - P.730-737.
- Popovich V.D., Grigorovich G.M., Peleschak R.M., Tkachuk P.N. // Fiz. Tekhn. Polupr. - 2002. - 36, N6. - P.674-678.
- Britan V.B., Pigur O.N., Popovich V.D., Tsyutsyura D.I. // Izv. RAN, Neorg. Mater. - 2005. - 41, N7. - P.680-682.
- Kvit A.V., Klevkov Yu.V., Medvedev S.A. et al. // Fiz. Tekhn. Polupr. - 2000. - 36, N6. - P.674-678.
- Wang J.F., Song S. H., Ishikawa Y., Isshiki M. // Mater. Sci. and Eng. B. - 2005. - 117. - P.271-275.
- Seto S., Tanaka A., Masa Y.et al. // Appl. Phys. Lett. 1988. – 53, N16. – P.1524–1526.
- Kuhn T.A., Ossau W., Bicknell-Tassius R.N., Landwehr G. // Ibid. - 1989. - 55, N25. - P.2637-12639.
- Shin H.-Y., Sun C.-Y. // Mater. Sci. and Eng. B.— 1998. —
 52. P.78—83.
- Molva E., Pautrat J.L., Saminadayar K. et al. // Phys. Rev. B. - 1984. - 30, N6. - P.3344-3353.
- Song S.H., Wang J.F., Lalev G.M. et al. // J. Cryst. Growth. – 2003. – 252. – P.102–106.
- 26. Yang B., Ishikawa Y., Miki T. et al. // Ibid. 1996. 159. - P.171-174.
- Francou J.M., Saminadayar K., Pautrat J.L. // Phys. Rev. B. - 1990. - 41, N17. - P.12035-12046.
- Saminadayar K., Francou J.M., Pautrat J.L. // J. Cryst. Growth. - 1985. - 72. - P.236-241.
- 29. Shin H.-Y., Sun C.-Y. // Ibid. 1998. 186. P.354-361.
- Seto S., Suzuki K., Abastillas V.N., Inabe K. //Ibid. 2000. - 214/215. - P.974-978.
- Song S. H., Wang J., Ishikawa Y. et al. // Ibid. 2002. 237 239. P. 1726-1730.
- Fonthal G., Tirado-Mejía L., Marín-Hurtado J.I. et al. // J. Phys. Chem. Solids. - 2000. - P.579-583.
- Halsted R.E., Segall B. // Phys. Rev. Lett. 1963. 10, N2. - P.392-395.
- 34. Panosyan Zh.R. // Trudy FIAN SSSR. 1973 68. P.147-202.
- Figueroa J.M., Sánchez-Sinencio F., Mendoza-Alvarez J.G. et al. // J. Appl. Phys. - 1986. - 60. - P.452-454.

- Hofmann D.M., Omling P., Grimmeis H.G. et al. // Phys. Rev. B. - 1992. - 45, N11. - P.6247-6250.
- Mochyzuki K. // J. Cryst. Growth. 2000. 214/215. -P.9-13.
- Brunthaler G., Jantsch W., Kaufmann U., Schneider J. // J. Phys: Cond. Matter. - 1989. - 1. - P.1925-1928.
- Halliday D.P., Potter M.D.G., Mullins J.T., Brinkman A.W. // J. Cryst. Growth. - 2000. - 220. - P.30-38.
- 40. Seto S., Tanaka A., Takeda F., Matsura K. // Ibid. 1994. — 138. — P.346—351.
- Medvid A., Litovchenko V.G., Korbutjak D.V. et al. // Rad. Measur. - 2001. - 33. - P.725-730.
- Savitskii A.V., Parfenyuk O.A., Ilashchuk M.I. et al. // Fiz. Tekhn. Polupr. - 2004. - 38, N5. - P.516-521.
- Agrinskaya N.V., Matveyev O.A., Nikitin A.V., Sladkova V.A. // Ibid. - 1987. - 21, N4. - P.676-679.
- Soltani M., Certier M., Evrard R., Kartheuser E. // J. Appl. Phys. - 1995. - 78, N9. - P.5626-5632.
- 45. Emziane M., Durose K., Romeo N. et al. // Semicond. Sci. and Techn. 2005. P.434–442.
- 46. Yang B., Ishikawa Y., Doumae Y. et al. // J. Cryst. Growth. - 1997. - 172. - P.370-375.
- Hage-Ali M. and Siffert P. // Nucl. Instrum. and Meth. A. 1992. – 322. – P.313–323.
- Kuchar L., Drápala J., Lunacek J. // J. Cryst. Growth. 1996. – 161. – P.94–103.
- Zappetini A., Bissoli F., Zha M., Zanotti L. // Phys. status solidi (c). - 1, N4. - P.739-742.

Received 29.09.05. Translated from Ukrainian by A.I. Tovstolytkin

ОСОБЛИВОСТІ ФОТОЛЮМІНЕСЦЕНЦІЇ МОНОКРИСТАЛІВ CdTe, ВИРОЩЕНИХ МЕТОДОМ СУБЛІМАЦІЇ

Д.В. Корбутяк, С.Г. Крилюк, Н.Д. Вахняк, В.Д. Попович, Д.І. Цюцюра

Резюме

Описано спосіб вирощування монокристалів CdTe з газової фази шляхом сублімації у вакуумі з використанням вертикальної конфігурації ростової системи. Досліджено спектри низькотемпературної фотолюмінесценції номінально нелегованих і легованих хлором монокристалів, отриманих цим методом, і проведено їх порівняння зі спектрами ФЛ відповідного матеріалу, одержаного методом Бріджмена. Встановлено, що вирощені із газової фази кристали містять більшу кількість неконтрольованих домішок, проте мають достатньо високу структурну досконалість, про що свідчить наявність в спектрах ФЛ чітко виражених ліній вільних екситонів.