Time-resolved photoelectric spectroscopy of photorefractive CdTe:V crystals

Time-resolved photoelectric spectroscopy of photorefractive CdTe:V crystals

Yu P Gnatenko[1,3]**, Yu P Piryatinski**[1]**, P M Bukivskij**[1]**,
D D Kolendryckyj**[1]**, O A Shigiltchoff**[1] **and R V Gamernyk**[2]

[1] Institute of Physics of NASU, 46 Prospekt Nauky, 03028 Kyiv, Ukraine
[2] Lviv National University, 8 Kyrylo and Mefodiy Street, 29005 Lviv, Ukraine

E-mail: gnatenko@iop.kiev.ua

Abstract

The time-resolved photoelectric spectroscopy technique was used for the characterization of semi-insulating CdTe:V crystals using a short light pulse with 9 ns duration from a nitrogen laser (337.1 nm). The stationary monochromatic illumination of crystals let us measure the time-resolved photocurrent caused by the detrapping of the electrons photogenerated by the pulse laser excitation. The dependence of the intensity of pulse photocurrent on the energy of additional monochromatic illumination in the photorefractive CdTe:V crystals with the delay time $t_d = 5$ ns, which corresponds to its maximum value, was investigated. The spectral dependence of pulse photocurrent produced by the detrapping process of electrons in CdTe:V crystals was measured under different intensities of the applied electric field. It is shown that the additional illumination at $\hbar\omega < E_g$ leads to the increase of the photocurrent intensity caused by the detrapping processes of electrons from impurity centres and intrinsic defects. The nature of the electron traps in CdTe:V was determined.

1. Introduction

At present, one of the most urgent tasks of modern optoelectronics is the development of novel fast photorefractive materials for the near-infrared (near-IR) range. Among the semiconductors crystals, taking into account their physical parameters, CdTe doped with 3d elements are very promising for applications in the areas of optical communication, optical storage, image recognition, optical computing and optoelectronics [1]. Previous studies of such materials have mainly concentrated on the analysis of the photorefractive properties [2–4] as well as of electron paramagnetic resonance (EPR), photo-EPR and optical spectra [5–8]. It should be noted that

---

[3] Author to whom any correspondence should be addressed.

the incorporation of 3d elements in CdTe crystals leads to the formation of deep impurity levels. The presence of the impurity ions in the two- and three-charged states in CdTe crystals, where the former are the source of the free electrons photogenerated during the laser excitation, is important for the photorefractive recording of information. Photoionization of these impurity centres results in the formation of free carriers whose diffusion creates a space-charge field and therefore changes the refractive index as a result of the electro-optic effect. At the same time, ionized deep impurity centres may function as traps for photoexcited carriers. Hence, the impurity states of 3d elements play a decisive role in the appearance of the photorefractive properties of semiconductor materials. The modern state of investigations of photorefractive semiconductor materials indicates that it is important to perform detailed studies of the carrier trapping and detrapping processes in these crystals. It would help us determine what has to be done to receive fast photorefractive semiconductor materials. It should be noted that even in the most studied case, CdTe:V crystals, the mechanisms of the influence of the impurity centres on the transport properties of such materials are at the first stage of understanding. Therefore it seems to be extremely important to make advances in this area.

It is also important to study the energy structure of intrinsic defects, which are responsible for creation of shallow levels. These defects may act as traps for carriers, including the photoinduced ones, and thus affect the transport properties of crystals. It should be noted that the intrinsic defects play an important role in the appearance of the semi-insulating properties of doped crystals, since they participate in charge compensation of such crystals. It should also be noted that further studies are required to determine the nature of the traps of electrons photoinduced by the laser excitation. It is important to obtain direct proof of the high speed of electronic processes with the participation of impurity centres and intrinsic defects using pulse laser excitation.

In this work, the studies of the processes of trapping and detrapping of the electrons photogenerated in CdTe:V at $T = 300$ K by the pulse N_2 laser were carried out using a novel technique of time-resolved photoelectric spectroscopy. In order to characterize CdTe:V crystals more completely, both absorption and photodiffusion current data are presented. These studies let us establish the nature and role of the impurity centres and intrinsic defects participating in the trapping and detrapping processes of the electrons in the investigated crystals.

2. Experimental procedures

The vanadium-doped CdTe semi-insulating crystals were grown by the vertical Bridgman technique. Doping was achieved by incorporation of vanadium into the melt. The initial concentration of the impurity atoms was about 10^{19} cm^{-3}. Prior to the synthesis of the CdTe:V crystals, single elements Cd and Te were purified by vacuum sublimation. Quartz ampoules of doubled melting were used for synthesis and growth of the single crystals. The process of CdTe synthesis took place in the sloping furnace. When the melting point (1365 K) was reached, the synthesis furnace was brought into oscillatory movement. After 4–6 h oscillation movement, the furnace was placed vertically and the synthesized material was cooled. The crystal bars obtained were more than 60–80 mm long, with diameter 14–18 mm. All investigated samples had n-type conductivity with resistance 10^7–10^8 Ω cm.

The absorption and photodiffusion current (PDC) spectra were measured with a KSVU-23 device at $T = 78$ K. The PDC measurement technique was presented in detail in [9]. The time dependence of the shape of the laser pulse and the spectral distribution of pulse photocurrent (PPC) were measured using the stroboscopic system of registration with the time window equal to about 0.1 ns. Figure 1 shows the set-up of such measurements. For the excitation of the CdTe:V crystal a pulse nitrogen laser was used. The excitation wavelength was equal
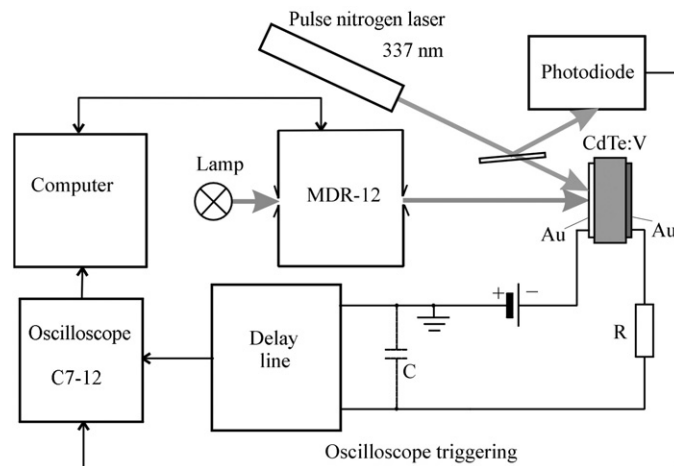
Figure 1. Time-resolved photoelectric spectroscopy set-up.

to 337.1 nm. The pulse frequency corresponded to 100 Hz. The pulse duration was 9 ns, and the pulse power of laser emission was 5 kW. Part of the light incident on the crystal was reflected from the quartz plate and fell on the photodiode, which was used for the starting of the oscilloscope. The PPC signal was supplied to the oscilloscope through the delay line. The final result was represented in the form of a series of points on the screen of the computer. PPC with sub-nanosecond time resolution was recorded with a load resistance of 50 Ω.

We used the same equipment to carry out the stationary illumination of the surface of the crystal with different wavelengths using a high-aperture MDR-12 monochromator. A tungsten lamp was used for illumination of the crystal. The different t_d times (where t_d is the delay time of the registration of signal) relative to the trigger pulse can be established. Changing the wavelength using the monochromator, we performed recording of the time-resolved photocurrent spectrum caused by the change in PPC under the influence of the stationary illumination. It should be noted that the stationary illumination makes it possible to measure the photocurrent spectra caused by an increase in the pulse component as a result of detrapping of the charge carriers from the traps. A change in the polarity and value of the voltage applied to the sample lets us determine the main type of the charge carriers participating in the photoconductivity. This process depends on the intensity of the external electric field. It is known that for pure and doped CdTe crystals the mobility for electrons is one order higher than that for holes. Therefore if the illuminated electrode has negative polarity, mostly electrons move through the crystal. In this work the electronic conductivity of CdTe:V crystals is investigated.

As a result of the excitation of CdTe:V crystal by the pulse laser, some of the free electrons photogenerated in the near-surface layer reach the opposite electrode; the others are trapped near the illuminated surface or in the bulk of the crystal. For CdTe:V crystals, these traps are both the intrinsic defects and the V^{3+} impurity ions. A cross section of the trapping of electrons by V^{3+} impurity ions depends both on the monochromatic illumination and on the value of the applied electric field. Additional stationary monochromatic illumination of the CdTe:V crystal and applied electric field contribute to the detrapping of carriers from the traps. This causes the PPC to increase. Measuring the PPC with stationary illumination makes it possible to investigate the dynamics of the filling of the traps for the different t_d times after the excitation of the crystal by a laser pulse. Besides, it also lets us find their energy position.
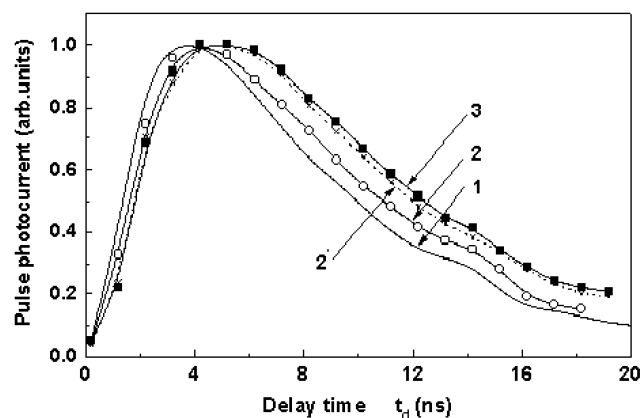
Figure 2. The shape of pulse photocurrent normalized to the maximum of pulse amplitude for CdTe:V, $N_V = 10^{19}$ cm^{-3} at 300 K. Curve 1 and curve 3 correspond to the electric field with intensities of 3.3 and 6.7 kV cm^{-1}, respectively. Curve 2′ and curve 2 correspond to the electric field with intensity of 5.3 kV cm^{-1} in the case of the presence the additional Nd:YAlG laser illumination and its absence, respectively.

3. Experimental results and discussion

3.1. Absorption and photodiffusion current spectra

The absorption spectra of CdTe crystal doped with vanadium atoms and those of pure CdTe were investigated at 78 K in [9]. The spectrum of CdTe:V reveals absorption bands in the transparency region of pure CdTe. It was shown that the positions of the bands correspond to the intracentre absorption of the V impurity ions having different charge states as well as photoionization absorption. According to [10] the absorption band in the long-wavelength region near 0.83 eV corresponds to the intracentre absorption between the $^4T_1(F)$ and $^4A_2(F)$ states of the V^{2+} impurity ions. Additional absorption bands with energies at 0.91 and 0.97 eV are also revealed. This absorption was observed [2] for CdTe:V crystals additionally doped with As acceptor impurity atoms. Studies of magnetic circular dichroism of absorption and photoconductivity spectra of CdTe:V:As crystals [2] showed that these additional absorption bands correspond to the intracentre absorption of the V^{3+} impurity ions and they can overlap with the photoionization absorption. The presence of V^{3+} ions in CdTe:V crystals was also detected in [8] by measuring the impurity photoluminescence spectra of CdTe:V at $T = 4.2$ K. The wide absorption band near 1.20 eV is due to both the intracentre transitions between the $^4T_1(F)$ states of V^{2+} impurity ions in CdTe and its overlap with the photoionizing absorption. It was established [9] that the excited $^4T_1(P)$ state of V^{2+} impurity ions in CdTe crystals is in resonance with the conduction band.

Information on the energy position levels of deep impurity centres and intrinsic defects relative to the crystal energy bands was obtained as a result of the photodiffusion current (PDC) measurements [9]. It should be noted that the PDC measurements allow us to determine not only the energy but also the type of phototransition [11]. It was shown that the PDC spectrum of the CdTe:V crystals at $T = 77$ K (figure 2, curve 3 in [9]) shows a broad structural band in the spectral range of 0.95–1.50 eV caused by photoionization transitions of both the impurity centres and intrinsic defects. In this case, the band gap of CdTe:V crystal is equal to 1.60 eV. The long-wavelength wing of the PDC band is extended to 0.95 eV. Therefore this value of the
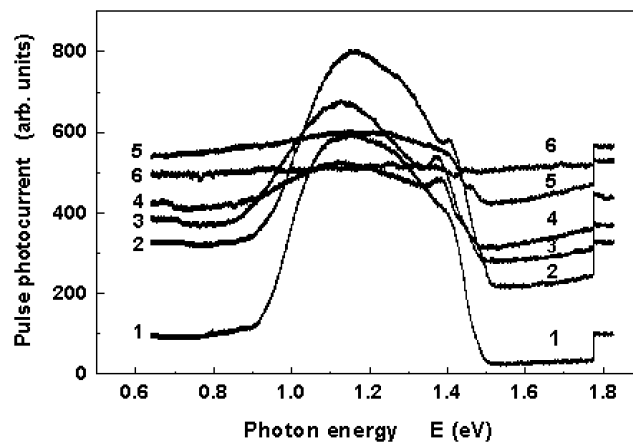
Figure 3. Spectral dependence of the intensity of pulse photocurrent at $t_d = 5$ ns under additional stationary monochromatic illumination for CdTe:V crystal, $N_V = 10^{19}$ cm^{-3} at 300 K. Curves 1–6 correspond to the electric field intensity of 3.3, 4.7, 5.3, 6.0, 6.7 and 7.3 kV cm^{-1}, respectively.

energy in fact determines the minimum value of photoionization energy of V^{2+} centres and, as a result, the V^{3+} centres are formed.

The observed maximums of the PDC bands at 1.16 and 1.23 eV coincide with the energy position of wide absorption band in CdTe:V. This suggests that the PDC bands are caused by the excitation of V^{2+} ions to the $^4T_1(P)$ state, which is in resonance with the conduction band. As a result of the interaction of a discrete impurity state with the continuum of the conduction band the auto-ionization of electrons from an excited impurity level to the conduction band occurs [9]. The PDC bands shown in the short-wavelength region are caused by the presence of intrinsic defects in CdTe:V crystals. The bands with energies 1.50 and 1.45 eV correspond to the photoionization of the acceptor $(V_{Cd}^{2-} + D^+)^-$ complex and the singly charged cadmium vacancy V_{Cd}^-.

3.2. Time-resolved photoelectric measurements

As noted above, studies of the PPC with negative polarity on the illuminated electrode were carried out. In this case the PPC is caused by the electronic conductivity of the charge carriers photogenerated by the laser pulse in the surface layer. PPC with positive polarity on the illuminated electrode was two orders weaker than that with negative polarity. Figure 2 represents the shape of the PPC measured with the sub-nanosecond time resolution and shows the time dependence of pulse photocurrent $I_{PPC}(t)$ (where $t = 0$–20 ns) during the action of the laser pulse. Curves were normalized on the maximum and measured with the different values of applied electric field. In the case of a small field and the absence of additional illumination, $I_{PPC}(t)$ has the same shape as the laser pulse. With an increase of the intensity of electric field (E) from 3.3 to 6.7 kV cm^{-1}, the amplitude of $I_{PPC}(t)$ increases linearly, and its half-width also increases. In this case the half-width of the photocurrent is 2.3 ns greater. This difference occurs on the descending part of the shape of the photocurrent whereas the ascending part remains the same. It can be seen from figure 2 (curve 2′) that the shape of the PPC is very sensitive to illumination by infrared light with wavelength equal to 1.06 μm.

Figure 3 shows the dependence of the intensity of the pulse photocurrent, which corresponds to the laser pulse maximum for the delay time $t_d = 5$ ns, on the energy of

stationary monochromatic illumination. The spectral dependence with the different values of intensity electric field ($E = (3.3$–$7.3)$ kV cm^{-1}) was measured. It can be seen that the monochromatic illumination with the energy $\hbar\omega > E_g$ (where E_g—the band gap of crystal) leads to the specific decrease of I_{PPC}, which is caused by the increase of the recombination of carriers near the crystal surface. In the case $\hbar\omega < E_g$ (1.5 eV at $T = 300$ K) we observed an increase in the intensity of the PPC due to detrapping of electrons from the defect levels in the CdTe:V crystals. Thus, the measurement of spectral dependence of the PPC makes it possible to obtain information about the energy levels of traps. The maximum of the broad band with energy 1.17 eV is caused by the photoionization transitions of V^{2+} ions as a result of the auto-ionization of electrons from the $^4T_1(P)$ excited state to the conduction band. It is determined by the following relation:

$$V^{2+} + \hbar\omega(1.17\,\text{eV}) \rightarrow V^{3+} + e_{cb}. \tag{1}$$

It is evident that the auto-ionization of electrons from the $^4T_1(P)$ state of V^{2+} ions is the main mechanism of their photorelease from the traps of impurity centres. Direct photoionization is less effective.
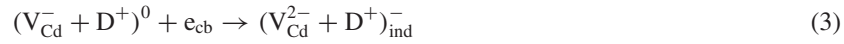
It should be noted that when the laser pulse was off, the PPC was equal to zero, as the stationary photocurrent itself was not registered. This indicates that only the electrons photogenerated during the laser excitation and captured by the traps contribute to the PPC. These captured electrons then can be released under the monochromatic illumination. As can be seen from figure 3, the increase of the applied electric field to 7.3 kV cm^{-1} leads to independence of the PPC on the monochromatic illumination. In this case it may be caused by the absence of the processes of capture of the photogenerated electrons.

As follows from figure 3 (curve 3), the maximum of the impurity band shifts to the long-wavelength range and its energy position at $E = 5.3$ kV cm^{-1} corresponds to 1.13 eV. It should be noted that the position of the maximum of this band at $E < 5.3$ kV cm^{-1} is practically constant and corresponds to an energy of 1.17 eV. Such shift of the maximum of the impurity band may be caused by the influence of the applied electric field on the impurity states of photoinduced $(V^{2+})_{ind}$ ions. As a result of such an effect the main $^4T_1(F)$ state can be split by the applied electric field into some components. In this case the energy of the main state of V^{2+} ions decreases. A similar effect takes place for the excited $^4T_1(P)$ state which is in resonance with the conduction band. Since the impurity band maximum is shifted to the long-wavelength range it is evident that the splitting of the excited $^4T_1(P)$ state is greater than that for the main $^4T_1(F)$ state. This may be caused by the resonance of the $^4T_1(P)$ state with the conduction band, since it is known [12] that the interaction of a discrete impurity state with the conduction band continuum leads to the broadening of the excited impurity level.
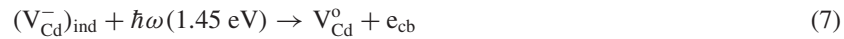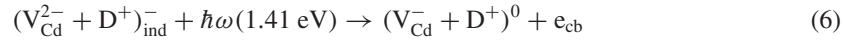
Analysis of the PPC spectrum (figure 3, curve 2) shows that there is a structure on its short-wavelength wing at 1.41 eV, caused by the photoionization transitions of electrons from the acceptor level with the energy of $E_v + 0.09$ eV to the conduction band. This level corresponds to the singly charged acceptor $(V^{2-} + D^+)^-$ complex. It should be noted that such acceptor complexes were also revealed earlier [9] in the PDC spectrum of CdTe:V crystals. It can be seen from figure 3 (curve 3) that the position of the PPC band on the short-wavelength wing corresponds to the energy of 1.38 eV at $E = 5.3$ kV cm^{-1}. For $E < 6.0$ kV cm^{-1} the position of this band corresponds to the energy 1.41 eV. It is known [13, 14] that the singly charged acceptor $(V_{Cd}^{2-} + D^+)^-$ complexes can have different energies in the range $E_v + (0.10$–$0.15)$ eV. This is caused by the presence in the complexes of different donor atoms. Therefore we suppose that the PPC bands at 1.41 and 1.38 eV correspond to the different acceptor complexes. This indicates that the acceptor complexes with the smaller binding energies do not capture free electrons from the conduction band at $E \geqslant 6.0$ kV cm^{-1}.

In our opinion this may be caused by the dissociation of these complexes under such applied electric field. As shown in figure 3 (curve 5), the shoulder at 1.45 eV is revealed. We think that it is caused by the photoionization transitions from the singly charged vacancy cadmium V_{Cd}^- to the conduction band. It is interesting to note that this band at $E < 6.0$ kV cm^{-1} does not appear in the PPC spectra (figure 3, curves 1 and 2). It is possible that this PPC band at $E < 5.3$ kV cm^{-1} has considerably smaller intensity than the PPC bands caused by the acceptor complexes. Therefore such a band does not appear on the steep short-wavelength wing of PPC spectra.

Thus the analysis of the obtained results indicates the presence in the CdTe:V crystal of V^{3+} ions, neutral cadmium vacancies V_{Cd}^o and neutral acceptor $(V_{Cd}^- + D^+)^0$ complexes, which are the traps for the photogenerated electrons. Furthermore, impurity V^{2+} ions, singly charged acceptor $(V_{Cd}^{2-} + D^+)^-$ complexes and singly charged cadmium vacancies V_{Cd}^- are available in the crystal. It should be noted that auto-compensation of charge in CdTe:V is caused by the presence of V^{3+} ions as well as acceptor centres of types $(V_{Cd}^{2-} + D^+)^-$ and V_{Cd}^-. The processes of trapping of the electrons photogenerated by laser pulse may be represented by the following relations:

$$V^{3+} + e_{cb} \rightarrow V_{ind}^{2+} \tag{2}$$

$$(V_{Cd}^- + D^+)^0 + e_{cb} \rightarrow (V_{Cd}^{2-} + D^+)_{ind}^- \tag{3}$$

$$V_{Cd}^o + e_{cb} \rightarrow (V_{Cd}^-)_{ind}. \tag{4}$$

The processes of the photorelease of electrons from the traps under the influence of stationary monochromatic illumination can be represented by the following relations:

$$V_{ind}^{2+} + \hbar\omega(0.90\text{--}1.35 \text{ eV}) \rightarrow V^{3+} + e_{cb} \tag{5}$$

$$(V_{Cd}^{2-} + D^+)_{ind}^- + \hbar\omega(1.41 \text{ eV}) \rightarrow (V_{Cd}^- + D^+)^0 + e_{cb} \tag{6}$$

$$(V_{Cd}^-)_{ind} + \hbar\omega(1.45 \text{ eV}) \rightarrow V_{Cd}^o + e_{cb} \tag{7}$$

Analysis of the shape, intensity, and the energy position of the PPC bands corresponding to the different intensity of electric field indicates that the efficiency of electron trapping by the deep impurity centres, i.e. V^{3+} ions and the intrinsic defects (neutral V_{Cd}^o and $(V_{Cd}^- + D^+)^0$ acceptors), depends on the increase of the electric field intensity. As follows from figure 3, the decrease of the electron trapping efficiency occurs predominantly for the deep impurity traps, i.e. V^{3+} ions. The broad impurity PPC band decreases strongly at $E = 6.0$ kV cm^{-1}. For an intensity of electric field of 6.7 kV cm^{-1} this PPC band (figure 3, curve 5) practically disappears. At the same time the short-wavelength wing of the PPC spectrum still exists. In this case, the intensity of PPC bands at 1.41 eV and at 1.38 eV decreases more quickly than the intensity of the PPC band at 1.45 eV. Therefore the electron trapping efficiency for the neutral acceptor $(V_{Cd}^- + D^+)^0$ complexes decreases more quickly in comparison with the neutral cadmium vacancies V_{Cd}^o.

As shown above (figure 2), the shape and intensity of pulse photocurrent is very sensitive to the infrared light illumination. Therefore in this work we also investigated how the monochromatic infrared illumination affects the intensity of the PPC at $t_d = 5$ ns for different electric field intensities. The additional excitation of the CdTe:V crystal by the pulse Nd:YAlG laser was used. The excitation wavelength was 1.06 μm. The pulse frequency corresponded to 30 Hz. The pulse duration was 10 ns and the pulse power of laser emission was 500 kW. The results obtained are shown in figure 4. As follows from this figure, the intensity of the PPC in the case of the absence of the additional infrared illumination (curve 1) increases linearly with the electric field intensity up to $E = 5.3$ kV cm^{-1}. Then the increase weakens and at $E \geqslant 6.7$ kV cm^{-1} the intensity of the PPC does not depend any more on the applied electric field. It is evident that this dependence of the intensity of the PPC on the intensity of the electric
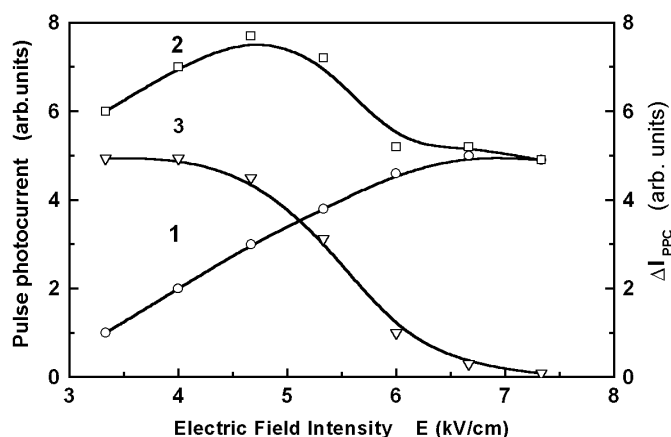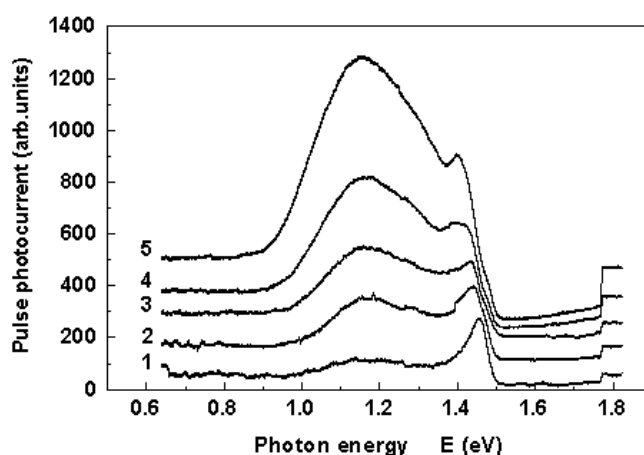
Figure 4. Dependence of the pulse photocurrent intensity at $t_d = 5$ ns on the intensity of the electric field for CdTe:V, $N_V = 10^{19}$ cm^{-3} at 300 K. Curve 1 and curve 2 correspond to the excitation by N$_2$ pulse laser only and the additional illumination by the Nd:YAlG laser, respectively. Curve 3 corresponds the difference between the PPC values (ΔI_{PPC}) presented by the curve 2 and curve 1.

field is due to the decrease of the electron capture efficiency of the different traps caused by the increasing intensity of the electric field. At the value of $E > 6.7$ kV cm^{-1} neither the deep impurity traps nor the intrinsic defect traps capture the electrons photogenerated by the N$_2$ pulse laser in CdTe:V.

It can be seen from figure 4 (curve 2) that the monochromatic illumination of the CdTe:V crystal with an energy of 1.17 eV (wavelength equals to 1.06 μm) leads to a strong increase of the intensity of the PPC in comparison with the absence of infrared illumination (curve 1). It should be noted that such an increase takes place at $E \leqslant 4.7$ kV cm^{-1}. For $E > 4.7$ kV cm^{-1} (curve 2) the intensity of the PPC is almost independent of the intensity of the electric field at $E \geqslant 6.7$ kV cm^{-1}.

It is clear that the increase of the PPC intensity under pulse illumination with an energy of 1.17 eV is caused by the detrapping of electrons from the deep impurity V_{ind}^{2+} centres only. This energy corresponds to the auto-ionization of electrons from the excited $^4T_1(P)$ state as a result of the interaction of a discrete impurity level with the conduction band continuum. It should be noted that curve 2 in figure 4 corresponds to the pulse photocurrent originated from two sources. The first source is the excitation of free electrons from the valence band to the conduction band caused by the pulse N$_2$ laser. The second source is the excitation of the electrons from the main $^4T_1(F)$ state of V^{2+} ions to the excited $^4T_1(P)$ state and their auto-ionization to the conduction band. The analysis of the dependences mentioned above (figure 4, curve 1 and curve 2) indicates that the pulse photocurrent caused by the electron detrapping from the deep impurity centres decreases at $E > 4.0$ eV cm^{-1}. This is caused by the decrease of the efficiency of electron capturing by the deep impurity traps (V^{3+} ions) under such applied electric field. In this case the concentration of (V^{2+})$_{ind}$ centres decreases, which leads to the decrease of the PPC intensity caused by the detrapping of electrons from these centres. Free electrons practically are not being captured by V^{3+} ions at $E \geqslant 6.7$ kV cm^{-1} and the (V^{2+})$_{ind}$ centres are not formed. Figure 4 (curve 3) shows the difference between the PPC values (ΔI_{PPC}) presented by curve 2 and the curve 1. In our opinion, the $\Delta I_{PPC}(E)$ dependence presents to a certain degree the efficiency of electron capture by the deep impurity traps, i.e. V^{3+} ions, on the applied electric field intensity.

Figure 5. Spectral dependence of the intensity of pulse photocurrent at $t_d = 5$ ns under the different intensities of additional stationary monochromatic illumination for the CdTe:V crystal, $N_V = 10^{19}$ cm^{-3} at 300 K. Curves 1–5 correspond to the different light intensity values equal to $I_0, 2I_0, 8I_0, 16I_0$ and $40I_0$, respectively.

Figure 5 shows the spectral dependence of the intensity of the pulse photocurrent for the CdTe:V crystal at $t_d = 5$ ns under additional stationary monochromatic illumination in the case of different light intensities. The PPC spectra were measured at the constant value $E = 4.7$ kV cm^{-1}. Curves 1–5 correspond to the different intensity values equal to $I_0, 2I_0, 8I_0, 16I_0$ and $40I_0$, respectively. It should be noted, first of all, that at the lowest intensity (curve 1) the PPC band has a maximum at 1.45 eV. Here the intensity of the broad PPC band caused by the photoionization transitions of the deep impurity centres is very small. The increase of the light illumination intensity (curve 2) leads to the decrease of the PPC band at 1.45 eV which appears on the short-wavelength wing of the PPC band as a kink at different illumination light intensity (curves 2–5). At larger illumination intensity, the maximum of the PPC band appears at 1.44 eV (curve 2). It is evident that the broad band intensity noticeably increases relative to the 1.44 eV band, which becomes more intensive in the short-wavelength range at $I = 8I_0$ (curve 3). Then the 1.41 eV band increases in comparison with the 1.44 eV band. In this case the intensity of the broad impurity band becomes the most intensive in the PPC spectrum and at the larger light intensity (curve 4 and curve 5) the difference between the intensity of the 1.17 eV band and the intensity of the bands positioned on the short-wavelength wing increases. The intensities of the 1.44 eV band and the 1.41 eV band become almost identical (curve 4). As a result of their superposition the band on the short-wavelength wing broadens. Then the 1.41 eV band increases (curve 5) and becomes the most intensive in the short-wavelength range of the PPC spectrum.

These results indicate that the efficiency of the detrapping processes of electrons from traps with different energy depends on the illumination light intensity. At low intensity (curve 1 and curve 2) the traps with the energies of $E_v + 0.05$ eV and $E_v + 0.06$ eV are detrapped. These energies correspond to the singly charged cadmium vacancies and possibly to the charged acceptor centres caused by the presence in the CdTe:V crystal of residual atoms such as Na or Li [15], respectively. The increase of the light intensity (curve 5) leads to the effective detrapping of the electrons from the singly charged acceptor $(V_{Cd}^{2-} + D^+)_{ind}^-$ complexes with the energy of $E_v + 0.09$ eV. In this case the broad impurity band at 1.17 eV becomes the most intensive. This may be caused by the larger concentration of deep impurity traps, i.e. V^{3+}

ions, in comparison with the concentration of other electron traps, namely the neutral cadmium vacancies and the neutral acceptor complexes. The concentration of V^{3+} ions in CdTe:V crystals usually is about 10^{16} cm^{-3} [16]. Therefore it can happen that the concentration of the neutral V_{Cd}^o and $(V_{Cd}^- + D^+)^0$ acceptors in the CdTe:V crystals investigated is less than 10^{16} cm^{-3}.

4. Summary

In this work, we have investigated the processes of trapping and detrapping of photoinduced electrons in photorefractive CdTe:V crystals at $T = 300$ K using the novel time-resolved photoelectric spectroscopy technique. The stationary monochromatic illumination of crystals let us measure the time-resolved photocurrent, which is caused by the detrapping of electrons photogenerated by the pulse nitrogen laser excitation. The dependence of the intensity of the pulse photocurrent on the energy of additional monochromatic illumination at the delay time $t_d = 5$ ns was investigated. In this case, the spectral dependence of pulse photocurrent caused by the detrapping processes of electrons in CdTe:V crystals has been measured under different intensities of the applied electric field. It was shown that the additional illumination at $\hbar\omega < E_g$ leads to an increase of the photocurrent intensity as a result of detrapping electrons from impurity centres and intrinsic defects. The studies carried out in this work indicate that the electronic processes with the participation of impurity ions of vanadium and acceptor complex centres are fast and occur in the nanosecond range. It should be noted that not only the impurity V^{3+} ions, but also the neutral acceptor complexes, can be traps for the free electrons, photogenerated by the laser pulse. Therefore, in this case the effective concentration of traps for the electrons during the photorefractive recording of information is defined by concentrations of both types of defect. From the point of view of the decrease of electron–hole competition during the appearance of a space-charge field, the relative increase of traps of another type in the CdTe:V crystal is very important. It should also be noted that the basic mechanism of the photogeneration of electrons from the impurity V^{2+} centres is their auto-ionization from the excited $^4T_1(P)$ state to the conduction band. This process takes place both in the case of the stationary excitation of the crystal (photodiffusion current and photoconductivity measurements), and also during the excitation by the pulsed nitrogen laser under stationary illumination. Finally, it should be noted that use of the time-resolved photoelectric spectroscopy technique makes it possible to study the carrier transport processes in the various photoconductive materials taking into account their real defect structure, which is of great scientific and technological interest.

References

[1] Günter P and Huignard J-P (ed) 1989 *Photorefractive Materials and their Applications I and II* (*Springer Topics in Applied Physics* vol 61 and 62) (Berlin: Springer)
[2] Montmorillon L A, Delaye Ph, Roosen G, Bou Rjeily H, Ramaz F, Briat B, Gies J G, Zeilinger J P, Tapiero M, Bardeleben H J, Arnoux T and Launay J C 1996 *J. Opt. Soc. Am.* B **13** 2341
[3] Marfaing Y 1999 *J. Cryst. Growth* **197** 707

[4] Schwartz R N, Wang C C, Trivedi S, Jagannnathan G V, Davidson F, Boyd P R and Lee U 1977 *Phys. Rev.* B **35** 15378
[5] Schwartz R N, Ziari M and Trivedi S 1994 *Phys. Rev.* B **49** 5274
[6] Bardeleben H J, Mazoyer V, Launay X and Launay J C 1995 *Semicond. Sci. Technol.* **10** 163
[7] Christmann P, Meyer B K, Kreissl J, Schwartz R and Benz K W 1996 *Phys. Rev.* B **53** 3634
[8] Peka P, Lehr M U, Shulz H-J, Schwarz R and Benz K W 1994 *Appl. Phys.* A **58** 447
[9] Gnatenko Y P, Faryna I O, Bukivskij P M, Shigiltchoff O A, Gamernyk R V, Paranchych S Y and Paranchych L D 2002 *J. Phys.: Condens. Matter* **14** 7027
[10] Gnatenko Y P, Gamernyk R V, Faryna I O, Blazhkiv V S and Krochuk A S 1996 *Fiz. Tekh. Poluprovodn* **30** 1975
     Gnatenko Y P, Gamernyk R V, Faryna I O, Blazhkiv V S and Krochuk A S 1996 *Semiconductors* **30** 1027 (Engl. Transl.)
[11] Gnatenko Y P, Faryna I O, Bukivskij P M, Shigiltchoff O A, Gamernyk R V and Paranchych S Y 2005 *Semicond. Sci. Technol.* **20** 378
[12] Ippolitova G K, Omelyanovskij E M and Perova A D 1975 *Fiz. Tekh. Poluprovodn* **9** 1308
[13] Gnatenko Yu P, Gamernyk R V, Farina I A and Babii P I 1998 *Fiz. Tverd. Tela* **40** 1216
     Gnatenko Yu P, Gamernyk R V, Farina I A and Babii P I 1998 *Sov. Phys.— Solid State* **40** 1107 (Engl. Transl.)
[14] Seto S, Tanaka A, Masa Y, Dairaku S and Kawashima M 1988 *Appl. Phys. Lett.* **53** 1526
[15] Chamonal J P, Molva E and Pautrat J L 1982 *Solid State Commun.* **43** 801
[16] von Bardeleben H J, Mazoyer V, Launay X and Launay J C 1995 *Semicond. Sci. Technol.* **10** 163