ISSN 1560-8034, 1605-6582 (On-line), SPQEO, 2020. V. 23, N 1. P. 102-109.

Dependence of the melting threshold of CdTe on the wavelength and pulse duration of laser radiation

V.P. Veleschuk[1*], O.I. Vlasenko[1], Z.K. Vlasenko[1], S.N. Levytskyi[1], D.V. Gnatyuk[2], A.V. Shefer[3], V.V. Borshch[3] and O.B. Borshch[3]

[1]*V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, 41, prospect Nauky, 03680 Kyiv, Ukraine*
[2]*Graduate School of Science and Technology, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu 432-8011, Japan*
[3]*National University "Poltava Yuri Kondratyuk Polytechnic" 24, prospect Pershotravnevyi, 36011 Poltava, Ukraine*
[*]*E-mail: vvvit@ukr.net*

Abstract. The melting threshold of CdTe I_{th} depending on the laser radiation wavelength (λ = 300…800 nm) and pulse duration (τ_p = 7 ns…1 ms) have been calculated. Three fractions of the energy released during thermalization of excess carriers were considered: immediately after excitation (i), during non-radiative bulk (ii) and non-radiative surface (iii) recombination, which together determine the depth of heat penetration into the crystal and, therefore, the melting threshold of the CdTe surface region. It has been shown that in the range of laser pulse durations from 7 ns up to 1 μs, the CdTe melting threshold mainly depends on the absorption coefficient $\alpha(\lambda)$. For pulse durations longer than 1 μs, it started to depend also on the spectra of the reflectivity coefficient $R(\lambda)$. It has been found that changes in the non-equilibrium excess carriers parameters – surface recombination velocity, lifetime and diffusion depth – can vary the CdTe melting threshold at least by 25 percent.

Keywords: CdTe, melting threshold, pulsed laser irradiation.

https://doi.org/10.15407/spqeo23.01.102
PACS 81.15.Fg, 81.65.Cf, 61.82.Fk

Manuscript received 17.01.19; revised version received 24.02.20; accepted for publication 18.03.20; published online 23.03.20.

1. Introduction

Cadmium telluride is a basic material for creation of detectors sensitive to X- and γ-ray radiation [1–10]. One of the effective methods to treat the semiconductor crystal surface under formation of barrier structures for CdTe-based diode-type nuclear radiation detectors is application of nanosecond laser irradiation. In some cases, it allows to form and optimize the required parameters of the CdTe surface, for instance, sheet charge carrier concentration, surface states, surface recombination velocity, *etc*., before contact metal (In, Au, Ag, Ni, Cr, *etc*.) deposition or under creation of a high barrier *p-n* junction in the semiconductor surface region [2–8]. Pulsed laser irradiation (PLI) of semiconductors can provide unique conditions for cleaning of crystal surfaces, annealing of morphological and structure imperfections, modification of the surface component composition and other changes necessary to form device structures that are particularly promising in development of CdTe-based diode-type high energy radiation detectors. An actual problem also concerns formation of ordered nanostructures on the CdTe surface under pulsed laser irradiation [9].

Irradiation with short laser pulses is effective for various technological procedures of semiconductor surface treatment including cleaning, polishing etching, oxide film removal and stress relieving, local annealing and epitaxial recrystallization. For PLI of semiconductors and metal-semiconductor structures, lasers with various pulse durations (τ_p) and radiation wavelengths (λ) are used: ruby (694 nm) and YAG:Nd (1^{st} to 3^{rd} harmonics: 1064, 532, and 355 nm) lasers, as well as the excimer KrF (248 nm), XeCl (308 nm) and XeF (351 nm) ones, which are mainly applied to semiconductor surface modification. Most commonly used laser pulse durations are as follows: 7, 15, 20, 80, 120 ns, 1 μs and 1 ms. Therefore, in this work, we are interested first of all in the wide range τ_p = 7…120 ns.

The literature sources reporting both experimental and numerical calculations contain information about CdTe melting threshold I_{th} just for few values of λ and τ_p.

Also, some mismatches concerning the values of CdTe melting threshold and, accordingly, various interpretations of changes in the photoelectric properties under nanosecond laser irradiation are observed. For example, in the works [11, 12], the melting threshold for CdTe(111) crystals under pulsed ruby laser irradiation with τ_p = 20 ns was found equal to 2 MW/cm^2 as based on the experiments and calculations. Under the same conditions for CdTe(111), there are the following values: I_{th} = 8 MW/cm^2 in our work [13], 4 MW/cm^2 in [14], and 10…12 MW/cm^2 in [15]. It has been experimentally and theoretically obtained that under irradiation with an excimer KrF laser (λ = 248 nm, τ_p = = 20 ns), I_{th} = 2.5 MW/cm^2 [3, 4, 17]. I_{th} for CdTe with Al film deposited on the back side is equal to 15 MW/cm^2 when irradiating by the neodymium laser (λ = 1064 nm, τ_p = 20 ns) [16].

Thus, there are many unresolved and unclear issues related to PLI of CdTe, for development of CdTe-based device structures, it is often required to know the melting threshold of a surface layer of the semiconductor, which depends on the laser pulse duration τ_p, radiation wavelength (optical absorption coefficient $\alpha(\lambda)$) as well as parameters of the CdTe crystal surface, in particular the surface recombination velocity S and lifetime of non-equilibrium excess carriers (NEC). These parameters depend on surface processing procedures and characteristics of the semiconductors, including the concentration of impurities and dopants [5, 10]. Relevant experimental researches are very labor- and time-consuming. Therefore, the calculations of I_{th} for CdTe as the functions of λ and τ_p of lasers and semiconductor parameters become very useful and interesting from both fundamental and practical viewpoints. The corresponding results have been presented in this study.

2. Calculation formulas for the melting threshold

Certainly, the rapid (tens or hundreds of nanoseconds) process of heating-cooling of the CdTe surface under nanosecond laser irradiation is rather complicated for mathematical description with regard for the temperature dependences of the thermal and optical parameters as well as the concentration of photoexcited NEC. The threshold value for the laser-induced melting of the semiconductor crystal surface is determined first of all by the thermal diffusion depth $L_T = \sqrt{k\tau_p}$ and the light absorption depth $d \sim \alpha^{-1}$, where α is the absorption coefficient, and k – thermal diffusion coefficient. The melting threshold for the semiconductor surface subjected to PLI is theoretically determined, as a rule, by solving a non-stationary equation of thermal conductivity with corresponding boundary conditions across the phase interface (the Stefan problem).

The mathematical modeling of phase transitions initiated in cadmium telluride by PLI on the basis of the heat conductivity equation [4, 14, 17–21] is complicated due to the necessity of taking into account those fractions of the radiation energy that are spent on the instant thermalization ($\tau \approx 10^{-12}$ s) and excitation of the electron-hole plasma followed by its diffusion and recombination. In the work [19], it has been done by making allowance for the energy fractions that are released during thermalization of excess carriers immediately after their excitation and at the non-radiative bulk and surface recombinations. Taken together, these fractions define the depth of heat penetration into the crystal and, accordingly, the melting threshold. In other words, it is the "semiconductor" crystal parameters taken into consideration.

Therefore, the mathematical calculation of the laser-induced heating process should provide a detailed account for the diffusion and parameters of NEC as well as the temperature dependences of the optical and thermophysical characteristics. In the case of uniform irradiation of the surface of a semi-infinite crystal, the laser power density I required to heat the semiconductor surface from an initial temperature T_0 to a final temperature T_f is given by the following well-known formula [19, 21]:

$$I_0 = \frac{\rho c(T_0)\Delta T L_H}{[1-R(T_0)]\tau_p} \qquad (1)$$

where ρ is the density, c – specific heat, R – reflectivity, τ_p – laser pulse duration, and $\Delta T = T_f - T_0$. Unlike the simple expression $\sqrt{k\tau_p}$, the depth of heat penetration into material in Eq. (1) is given by the following expression, in which the NEC parameters have already been taken into account [19]:

$$L_H = \frac{1-R(T_0)}{c(T_0)\Delta T}\int_{T_0}^{T_f}\frac{dTc}{(1-R)\alpha}\times$$

$$\times\left[\chi_T/(L_T\alpha+1)+\chi_B^{NR}/(L_T\alpha+L_D\alpha+1)+\chi_S^{NR}/L_T\alpha\right]^{-1}, \qquad (2)$$

where $\alpha = \alpha_1 + \alpha_2 + \alpha_{FC}$ is the total optical absorption coefficient, α_1 and α_2 are the one- and two-photon band-to-band absorption coefficients, α_{FC} is the free-carrier absorption, $L_D = \sqrt{D\tau_B}$ – free carrier diffusion depth, $D = \frac{k_B T}{e}\frac{\mu_n\mu_p}{\mu_n+\mu_p}$ – ambipolar carrier diffusion coefficient, k_B – Boltzmann constant, τ_B – bulk carrier recombination lifetime, μ_n and μ_p are the electron and hole mobilities, respectively.

There the thermal diffusion depth $L_T(T) \approx \pi^{1/2}\left[k(T)\tau_p\right]^{1/2}(T-T_0)/\Delta T$.

The parameters χ_T, χ_B^{NR}, and χ_S^{NR} are the fractions of the laser energy entering into the crystal, which is spent, respectively, for thermalization of excess carriers immediately after excitation, non-radiative bulk recombination and non-radiative surface recombination, and are given by the following expressions:

$$\chi_T = \left\{ \left[1 - \frac{\eta_Q E_R}{h\nu} \right] \alpha_1 + \left[1 - \frac{E_R}{2h\nu} \right] \alpha_2 + \alpha_{FC} \right\} \Big/ \alpha , \qquad (3)$$

$$\chi_B^{NR} = \left(\tau / \tau_B^{NR}\right)\left(1 - \chi_T\right), \qquad (4)$$

$$\chi_S^{NR} = \left(\tau / \tau_S^{NR}\right)\left(1 - \chi_T\right) L_D \alpha / \left(L_D \alpha + 1\right), \qquad (5)$$

where η_Q is the dimensionless parameter and this quantity affects the fraction of the photon energy that thermalizes at the absorption depth, oppositely to the fraction that eventually appears as the recombination energy at the diffusion depth. For some semiconductors, for a certain λ, η_Q is about unity [19].

Here, $h\nu$ is the photon energy, E_R – recombination energy, $\tau = \left(\tau_B^{-1} + \tau_S^{-1}\right)^{-1}$ – effective carrier recombination lifetime, $\tau_S = L_D/S$ – effective surface lifetime, S – surface recombination velocity, τ_B^{NR} and τ_S^{NR} are the non-radiative components of two NEC lifetimes.

3. Results and discussion

In Eqs. (1) to (5), the NEC parameters and temperature dependences of the thermophysical characteristics have to be taken into account, the corresponding data for CdTe are presented in Table 1, and the dependences α(λ), R(λ) are shown in Fig. 1. The temperature dependence of the optical absorption coefficient, due to the bandgap shift and change of NEC concentration, is described rather well by the approximation formula $\alpha(\lambda) = \alpha_0 + A(\lambda) T m^{-1}$ [14, 18]. But it should be noticed that variations of the absorption and reflectivity R coefficients of CdTe under heating are weak [4]. α_{FC} for semi-insulating CdTe is much less than α_1, and the two-photon absorption α_2 for the fundamental absorption region λ = 300…800 nm is negligible.

It is important to know the NEC lifetime at the surface and in the bulk of CdTe under PLI. In a general case, the NEC lifetime in the CdTe bulk is given by the expression:

$$1/\tau_B = 1/\tau_{SR} + 1/\tau_{Rad} + 1/\tau_{Auger} ,$$

where τ_{SR}, τ_{Rad}, τ_{Auger} are the carrier recombination lifetimes according to the Shockley–Read–Hall, radiative, and Auger mechanisms, respectively. At high levels of NEC excitation, which takes place at our laser power densities, the Auger recombination [4, 19] dominates. Accordingly, the carriers lifetime $\tau_B \approx \tau_{Auger} = 1/\tau_{Auger} \cdot n^2$, where n is the NEC concentration. On the other hand, the lifetime can be divided into the radiative and non-radiative components, as in the expressions (3) to (5): $1/\tau_{B(S)} = 1/\tau_{B(S)}^{Rad} + 1/\tau_{Auger(S)}^{NR}$.

Since radiative recombination is low and does not contribute to the lattice heating, the first term can be neglected. As a result, $\tau_B = \tau_B^{NR}$ and $\tau_S = \tau_S^{NR}$. Hence, under PLI conditions, the NEC lifetime in the CdTe bulk is mainly governed by the Auger recombination, whereas the NEC lifetime at the CdTe surface is defined by the recombination velocity S.

In our calculations, we used the typical parameters of detector-grade semi-insulating p-CdTe (Acrorad Co. Ltd), which were used for fabrication of M-p-n structured X/γ-ray diode detectors [1–7]. Under laser irradiation of CdTe, the measured NEC lifetime reaches $3 \cdot 10^{-8}$ s [8].

Fig. 1b demonstrates the results of calculations for the CdTe melting threshold under PLI within the wavelength region 300…800 nm for various pulse durations τ_p. For clarity, in Fig. 1a, the data for R(λ) (measured by Gentsar P.O. [24]) and α(λ) in logarithmic scale are presented. The calculation was performed using Eqs (1) and (2) and taking into account the data from Table 1.

From Fig. 1b, one can see that the increase in pulse duration τ_p leads to a decrease in the sensitivity of the melting threshold I_{th} to the excitation wavelength λ. For instance, at τ_p = 7 ns the threshold laser intensity changes by ΔI_{th} = 5.6 MW/cm^2, *i.e.*, from 4.7 up to 10.3 MW/cm^2 with wavelength variation from 300 up to 800 nm. While at τ_p = 1 μs, the meting threshold of CdTe changes (increased) only by ΔI_{th} = 0.045 MW/cm^2, *i.e.*, from 0.4 to 0.355 MW/cm^2. Table 2 shows the absolute ΔI_{th} and relative $\Delta I_{th}/I_{th}$ values for different laser pulse durations.

This decrease in the value of ΔI_{th} with increasing τ_p can be explained by the fact that the thermal diffusion depth L_T increases with rising τ_p and becomes much larger than 1/α, and therefore the melting threshold I_{th} becomes less dependent on the optical absorption coefficient α(λ).

From Fig. 1a, one can see that, when λ changes from 380 to 800 nm, the reflection coefficient R changes from 0.4 to 0.29, *i.e.*, it increases by the factor 1.38. At the same time, the absorption coefficient α changes from $4.4 \cdot 10^5$ cm^{-1} to $2.1 \cdot 10^4$ cm^{-1}, *i.e.*, it decreases by more than one order of magnitude. It is evident that, if only the reflectivity decreases, the melting threshold I_{th} decreases according to Eq. (1); but if only α decreases, I_{th} increases, because a larger volume of the CdTe surface layer is heated up. Therefore, the dependence α(λ) determines the dependence I_{th}(λ) (Fig. 1b).

Within the region 300…420 nm, the curves R(λ) and α(λ) have two peaks, which are associated with the electron transitions into minimum L of the conduction band ($L_{4.5V} - L_{6C}$ and $L_{6V} - L_{6C}$ transitions). This characteristic behavior of the curves R(λ) and α(λ) in the indicated region reveals itself in the dependence I_{th}(λ), where the maximum and minimum are observed (Fig. 1b).

For λ > 800 nm, especially in the range of transparency (from 850 nm), two-photon absorption and, accordingly, the doping impurity and defect concentrations (which strongly affect I_{th}) have to be taken into account. Usually, the coefficient of two-photon absorption of CdTe β = 0.1…0.2 cm/MW (at λ = 1.064 μm).

Table 1. Parameters of CdTe.

Parameter	**Value**
Density ρ_0 (kg/m^3)	5860
Melting temperature (°C)	1092
Specific heat c (J/kg·K)	209 [22]
Thermal diffusion coefficient k (m^2/s)	7.1 (5.8)·10^{-6} [22]
Temperature dependence of density ρ (kg/m^3)	5887–0.1165·T [17, 18]
Temperature dependence of specific heat c (J/kg·K)	205+3.6·10^{-2}·T [17, 18, 22]
Temperature dependence of thermal diffusion k (m^2/s)	2.16·10^{-3}/T [22]
Temperature dependence of thermal conductivity (J/m·s·K)	1507/T [17, 18, 22]
Ambipolar diffusion coefficient D (m^2/s)	3.9·10^{-4} (300 K); 5.7·10^{-4} (1000 K) [23]
Bulk carrier recombination lifetime τ_B (for p-CdTe), s	(10–30)·10^{-9} [8, 23]
Surface carrier lifetime τ_S (s)	(0.5–1)·10^{-9} [8, 23]
Auger recombination coefficient γ_{Auger} (cm^6/s)	1.7·10^{-30} [22, 23]
Surface recombination velocity S (m/s)	10^3–10^5 [8, 10, 23]
Recombination energy E_R (eV)	1.5
Electron mobility μ_n (cm^2/V·s)	1000–1100 (300 K) [22-24]
Hole mobility μ_p (cm^2/V·s)	80–100 (300 K) [22-24]
Electron diffusion depth L_D (m)	(0.4–2)·10^{-6} [23]

Table 2. Absolute and relative values of the I_{th} under variation of λ from 300 up to 800 nm, according to Fig. 1b.

τ_p (ns)	7	20	80	120	1000
$\Delta I_{th} = I_{th}$(800 nm) – I_{th}(300 nm)	5.60	2.15	0.68	0.46	0.045
$\Delta I_{th}/I_{th}$ (800 nm)	0.54	0.45	0.34	0.3	0.11

Below λ = 300 nm, the absorption coefficient of CdTe is very high, and light is absorbed at the depth of about 10 nm. For example, for excimer KrF laser (λ = = 248 nm, τ_p = 20 ns, α = 1.1·10^6 cm^{-1}) I_{th} = 2.5 MW/cm^2 [3, 4, 17], while according to our calculations I_{th} = 2.71 MW/cm^2, which is quite a reasonable value, because the reflectivity R has a rather high value close to 0.46 at λ = 248 nm [22, 24].

Also, the dependence of the melting threshold on the laser pulse duration is important (see Fig. 2). The melting threshold falls drastically with an increase in τ_p in accordance with Eqs (1) and (2), because the heated-up layer volume increases. If the pulse duration becomes shorter, the rate of laser energy delivery becomes higher or, in other words, the process of heat transfer into deeper layers becomes slower owing to the thermal conductivity.

The dependence in Fig. 2a provides information about the melting threshold change at the variation of the pulse duration from 7 up to 120 ns, because typical lasers operating in the Q-switching mode have pulse duration of 7, 15, 20, 80 or 120 ns. The plot in Fig. 2b demonstrates the dependence concerned in a wide interval of τ_p, *i.e.*, from 5 ns to 1 ms in the log-log scale. With increasing τ_p by six orders of magnitude, I_{th} decreases by three orders of magnitude, for example, from 8.7 MW/cm^2 to 10 kW/cm^2 for λ = 532 nm.

From Fig. 2b, one can see that at the pulse duration close to τ_p = 1 μs, the curves intersect. The explanation is as follows: initially I_{th} is defined by α, and it is obvious that the rise of α leads to a decrease of I_{th}. With increasing the pulse duration, the thermal diffusion depth becomes much larger in comparison with the radiation depth penetration d, *i.e.*, $L_T >> 1/\alpha$. Therefore, the factor $L_T\alpha$ is defined by τ_p. And, at $\tau_p \approx 1$ μs, the ratio d/L_T equals 0.01, whereas the relative difference between the reflection coefficients, for example $\Delta R/R = (R_{308\ nm} - R_{694\ nm})/R_{308\ nm}$ = 0.15. At τ_p = 1 ms, the ratio d/L_T is only 0.0033. Accordingly, the value ΔR begins to affect the melting threshold significantly after 1 μs.

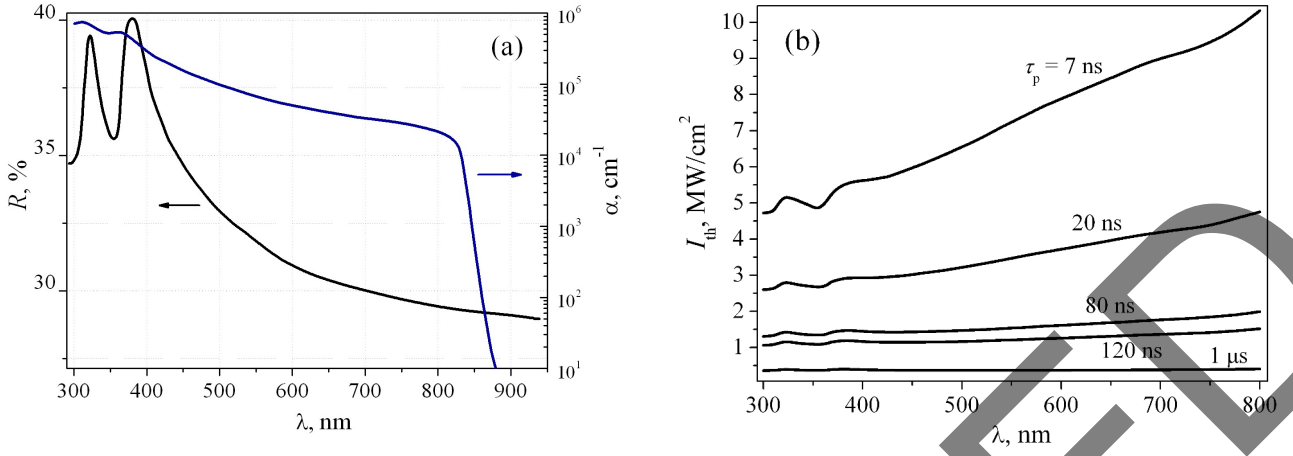


Fig. 1. (a) Experimental dependences $R(\lambda)$ and $\alpha(\lambda)$ for CdTe [22, 24] and (b) calculated dependence of the melting threshold on the laser wavelength $I_{th}(\lambda)$ for various τ_p.

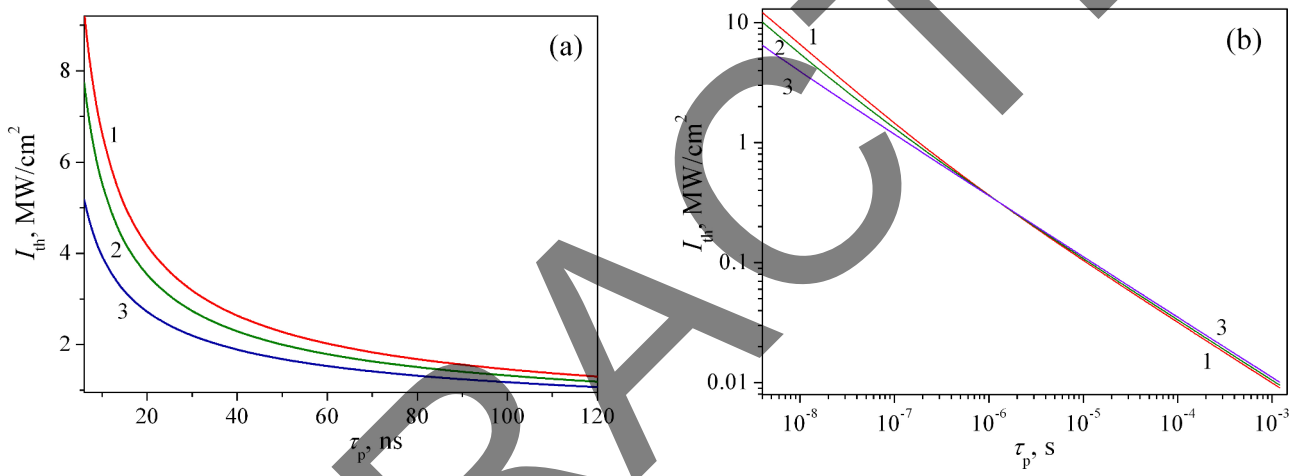


Fig. 2. Dependence of the CdTe melting threshold I_{th} on the pulse duration τ_p up to 120 ns (a) and up to 1.2 ms (b) at λ = 694 (*1*), 532 (*2*) and 308 nm (*3*).

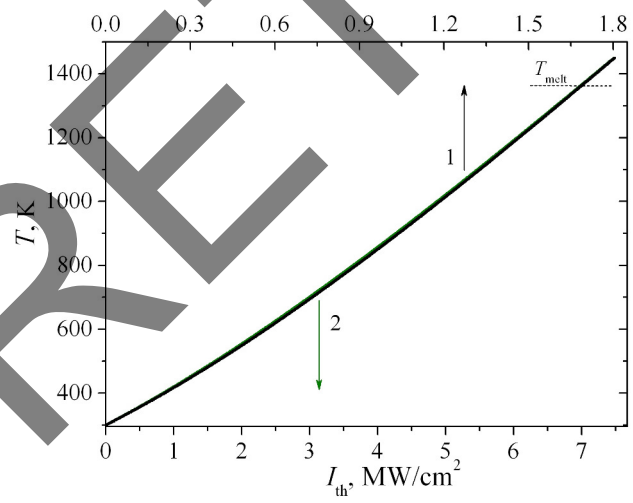


Fig. 3. Dependence of the CdTe surface temperature on the laser power density at τ_p = 120 ns, λ = 694 nm (*1*) and τ_p = 7 ns, λ = 532 nm (*2*).

And, since $R_{308\ nm} > R_{532\ nm} > R_{694\ nm}$, the melting threshold slightly increases, because with increasing R more light is reflected. Therefore, even though $\alpha_{308} > \alpha_{532} > \alpha_{694}$, after the intersection point in Fig. 2b, I_{th} becomes to be defined by the reflectivity $R(\lambda)$.

According to our calculations for CdTe at τ_p = 80 ns and λ = 694 nm, the value I_{th} = 1.7 MW/cm^2 (Fig. 2a), and the experimental value I_{th} = 1.5 MW/cm^2 [25], *i.e.*, an agreement takes place. Also, in the work [18], according to the results of numerical simulation at λ = 694 nm, τ_p = 80 ns, I_{th} = 1.25 MW/cm^2, and at τ_p = 20 ns, I_{th} = 3 MW/cm^2. Besides, in this work cadmium evaporation was taken into account, owing to which CdTe began to melt at a certain depth from its surface.

Furthermore, according to our calculations for the ruby laser pulse duration τ_p = 1.2 ms the CdTe melting threshold equals 9 kW/cm^2, which is close enough to the value 4.2 kW/cm^2 obtained theoretically and experimentally in [26]. In [5], for CdTe (111) at τ_p = 7 ns, λ = = 532 nm experimentally determined I_{th} = 8.6 MW/cm^2, while according to Fig. 2a I_{th} = 7 MW/cm^2.

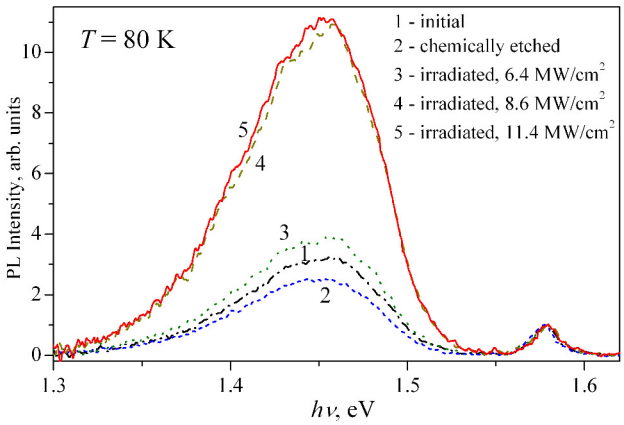


Fig. 4. Photoluminescence spectra of *p*-CdTe at 80 K: initial (*1*), etched (*2*) and after irradiation by the YAG:Nd laser (*1* to *3*), λ = 532 nm, τ_p = 7 ns. The curves are normalized by the intrinsic band intensity.

One can see that, within the pulse duration interval from 7 to 120 ns, I_{th} changes from 8.4 to 1.3 MW/cm^2 at λ = 694 nm (6.5 times), and from 4.8 to 1.07 MW/cm^2 at λ = 308 nm (4.5 times).

For the ruby laser at τ_p = 20 ns, we have I_{th} = = 4.17 MW/cm^2, while under changes of the pulse duration from 15 up to 25 ns, I_{th} changes from 5.05 to 3.6 MW/cm^2, or relative change of the power density $\Delta I_{th}/I_{th}$ = 0.35. This fact is important to be taken into consideration at laser treatment of CdTe.

It is worth to note that, if the pulse duration becomes shorter than 1…2 ns, the electric field strength increases strongly, so such processes as ablation, ionization, laser-induced breakdown of vapor over the surface start to play a significant role.

Fig. 3 shows the dependence of the CdTe surface temperature on the laser pulse power density for different values of τ_p and λ, which are often used for surface processing of CdTe [5–7, 9, 11–13, 16–18, 24–26]. Two curves are combined in the scale of laser power density. It is seen that the dependence of $T(I)$ is nonlinear due to the temperature dependence of the parameters c, χ, ρ and coefficient α. The power density melting threshold for constant parameters is somewhat greater than that for temperature-dependent parameters (for example, 9.5 MW/cm^2 for τ_p = 7 ns, λ = 532 nm).

Electronic and optical parameters of the CdTe surface will differ a little, depending on the specific kind of surface treatment: chemical polishing, annealing in a definite atmosphere, and so on [5, 10]. Accordingly, I_{th} will depend on the NEC parameters: S, τ and L_D. The rise of the surface recombination velocity S from 10^3 m/s to 10^5 m/s and the corresponding change of the surface lifetime τ_S^{NR} result in variation of I_{th} by 16%. The rise of L_D from 0.4 to 2 μm results in the 9% increase of I_{th}. In our case, $\tau_S^{NR} < \tau_B^{NR}$ by an order. Therefore, the CdTe melting threshold under the nanosecond laser irradiation slightly depends on the kind of surface treatment and doping concentration.

One of the non-destructive effective methods for controlling the state of the near-surface layer of CdTe is photoluminescence (PL) at T = 80 K. To monitor the melting threshold, the PL spectra of Cl-compensated *p*-CdTe(111) single crystals with the dimensions of 5×5×0.5 mm produced and polished by Acrorad Co. were investigated.

From Fig. 4, it is evident that a significant rise of defect region of the PL spectrum (peak at E = 1.45 eV) occurs after irradiation of the CdTe sample with I = 8.6 MW/cm^2, which corresponds to the melting of a thin (1/α) CdTe layer.

5. Conclusions

The melting threshold of CdTe depending both on the laser radiation wavelength (λ = 300…800 nm) and pulse duration (τ_p = 7 ns…1 ms) has been calculated. It was shown that within the range of laser pulse duration from 7 ns to 1 μs, the CdTe melting threshold depends mainly on the absorption coefficient α(λ). For pulse durations longer than 1 μs, it starts to depend also on the spectra of the reflectivity coefficient $R(\lambda)$, because the thermal diffusion depth becames much larger in comparison with the laser radiation penetration depth in CdTe. It has been demonstrated that, for shorter laser pulse durations τ_p, the melting threshold changes more, when radiation wavelength λ varies.

It has been found that changes in the non-equilibrium excess carriers parameters, such as the increase of surface recombination velocity S from 10^3 to 10^5 m/s, and also the diffusion depth L_D from 0.4 to 2 μm, can vary the CdTe melting threshold at least by 25%. Variation of the ruby laser pulse duration within the interval of 20 ± 5 ns induces the relative change of the melting threshold $\Delta I_{th}/I_{th}$ by 35%.

The calculated values of CdTe melting threshold agree well with the literature experimental data. The obtained results have been used to optimize the laser-assisted techniques of surface processing and stimulated doping of CdTe crystals.

Acknowledgements

This research was supported by the following research projects: “Laser pulsed photothermoacoustic formation of CdTe-based sensor structures with super-high resolution for radiation monitoring systems” (State Fund for Fundamental Research of Ukraine, grant number F85) and “Development of Cd(Zn)Te-based X/gamma-ray detectors with high resolution for security and diagnostics instruments” (2019 Cooperative Research at Research Center of Biomedical Engineering, Japan, grant number 2022).

References

1. Del Sordo S., Abbene L., Caroli E., Mancini A.M., Zappettini A., Ubertini P. Progress in the development of CdTe and CdZnTe semiconductor radiation detectors for astrophysical and medical

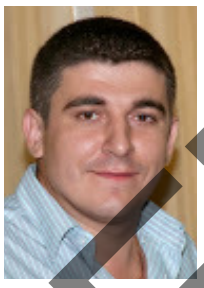
applications. *Sensors.* 2009. No 9. P. 3491–3526. https://doi.org/10.3390/s90503491.
2. Gnatyuk V.A., Aoki T., Hatanaka Y., Vlasenko O.I. Metal–semiconductor interfaces in CdTe crystals and modification of their properties by laser pulses. *Appl. Surf. Sci.* 2005. **244**, No 1-4. P. 528–532. https://doi.org/10.1016/j.apsusc.2004.10.113.
3. Gnatyuk V.A., Aoki T., Nakanishi Y., Hatanaka Y. Surface state of CdTe crystals irradiated by KrF excimer laser pulses near the melting threshold. *Surf. Sci.* 2003. **542**, No 1-2. P. 142–149. https://doi.org/10.1016/S0039-6028(03)00987-7.
4. Gnatyuk V.A., Aoki T., Gorodnychenko O.S., Hatanaka Y. Solid-liquid phase transitions in CdTe crystals under pulsed laser irradiation. *Appl. Phys. Lett*. 2003. **83**, Issue 18. P. 3704–3706. https://doi.org/10.1063/1.1625777.
5. Gnatyuk D.V., Poperenko L.V., Yurgelevych I.V., Dacenko O.I., Aoki T. Characterization of functional layers of CdTe crystals subjected to different surface treatments. *IEEE Trans. Nucl. Sci.* 2015. **62**, No 2. P. 428–232. https://doi.org/10.1109/TNS.2015.2394329.
6. Gnatyuk V.A., Levytskyi S.N., Vlasenko O.I., Aoki T. Laser-induced doping of CdTe crystals in different environments. *Adv. Mat. Res*. 2011. **222**. P. 32–35. https://doi.org/10.4028/ www.scientific.net/AMR.222.32.
7. Zelenska K., Gnatyuk D., Aoki T. Laser-based technique of formation of CdTe-metal diode structures for high energy radiation detectors. *IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop, NSS/MIC/RTSD*. 2016. P. 8069953(3). https://doi.org/10.1109/NSSMIC.2016.8069953.
8. Kosyachenko L.A., Aoki T., Lambropoulos C.P. *et al*. Optimal width of barrier region in X/γ-ray Schottky diode detectors based on CdTe and CdZnTe. *J. Appl. Phys.* 2013. **113**, P. 054504. https://doi.org/10.1063/1.4790358.
9. Vlasenko A.I., Baidullaeva A., Veleschuk V.P., Mozol P.E., Boiko N.I., Litvin O.S. On the formation of nanostructures on a CdTe surface, stimulated by surface acoustic waves under nanosecond laser irradiation. *Semiconductors.* 2015. **49**, No 2. P. 229–233. https://doi.org/10.1134/S1063782615020220.
10. Makhnii V.P., German I.I., Chernykh E.I. Influence of treatment on the surface parameters of singlecrystalline cadmium telluride substrates. *Poverkhn. Rentgen. Sinkhrotron. Neitron. Issled*. 2013. No 6. P. 65–67 (in Russian).
11. Golovan' L.A., Kashkarov P.K., Sosnovskikh Y.N., Timoshenko V.Yu., Chechenin N.G., Lakeenkov V.M. Investigation of laser-induced defect formation in CdTe crystals by Rutherford backscattering. *Phys. Solid State.* 1998. **40**, No 2. P. 187–189.
12. Golovan' L.A., Kashkarov P.K., Timoshenko V.Yu. Laser-induced melting and defect formation in cadmium telluride. *Laser Physics.* 1996. **6**, No 5. P. 925–927.
13. Baidullaeva A., Veleshchuk V.P., Vlasenko A.I., Dauletmuratov B.K., Lyashenko O.V., Mozol P.E. Effect of melting on the acoustic response of CdTe and GaAs subjected to the pulsed laser irradiation. *Semiconductors*. 2008. **42**, No 3. P. 281–285. https://doi.org/10.1134/S106378260803007X.
14. Bell R.O., Toulemonde M., Siffert P. Calculated temperature distribution during laser annealing in silicon and cadmium telluride. *J. Appl. Phys.* 1979. **19**, No 3. P. 313–319.
15. Blamires N.G., Totterdel D.H.J. Orientation dependent surface damage observed in laser irradiated cadmium telluride. *J. Phys. D: Appl. Phys*. 1983. **16**, No 12. P. 2361–2365.
16. Shul'pina I.L., Zelenina N.K., Matveev O.A. Heat effect of pulsed laser radiation on the real structure of CdTe single crystals. *Phys. Solid State*. 2000. **42**, No 3. P. 561–565.
17. Zhvavyi S.P., Zykov G.L. Numerical simulation of the dynamics of phase transitions in CdTe induced by irradiation with nanosecond pulses of an excimer laser. *Semiconductors.* 2006. **40**, No 6. P. 632–635. https://doi.org/10.1134/S1063782606060030.
18. Kovalev A.A., Zhvavyi S.P., Zykov G.L. Dynamics of laser-induced phase transitions in cadmium telluride. *Semiconductors.* 2005. **39**, No 11. P. 1299–1303.
19. Meyer J.R., Kruer M.R., Bartoli F.J. Optical heating in semiconductors: Laser damage in Ge, Si, InSb, and GaAs. *J. Appl. Phys.* 1980. **51**, No 10. P. 5513–5521. https://doi.org/10.1063/1.327469.
20. Dubyk K., Chepela L., Lishchuk P., Belarouci A., Lacroix D., and Isaiev M. Features of photothermal transformation in porous silicon based multilayered structures. *Appl. Phys. Lett.* 2019. **115**, No 2. P. 021902. https://doi.org/10.1063/1.5099010.
21. Koroteev N.I., Shumai I.L. *Physics of Power Laser Irradiation*. Nauka, Moscow, 1991 (in Russian).
22. Madelung O. *Semiconductors*: Data Handbook. 3rd ed. Springer, Berlin, 2004.
23. Triboulet R., Siffert P. *CdTe and Related Compounds; Physics, Defects, Hetero- and Nano-structures, Crystal Growth, Surfaces and Applications.* Elsevier, Oxford, 2010.
24. Vlasenko O.I., Gentsar P.O. *Optical Spectroscopy of the Functional Materials of Electronic Engineering.* Art-Ok, Kyiv, 2018.
25. Gatskevich E.I., Ivlev G.D., Prikryl P. *et al*. Pulsed laser-induced phase transformations in CdTe single crystals. *Appl. Surf. Sci*. 2005. **248**, No 1-4. P. 259–263. https://doi.org/10.1016/j.apsusc.2005.03.045.
26. Galochkin O.V., Zhykharevich V.M., Rarenko A.I. *et al*. Powerful monoimpulsive laser radiation influence on melting depth of CdTe and $Cd_{0.8}Mn_{0.2}Te$ crystals. *Phys. and Chem. of Solid State.* 2012. **13**, No 1. P. 224–229 (in Ukrainian).

Authors and CV

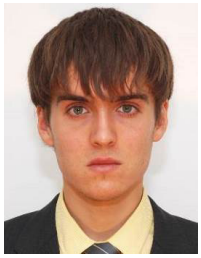
V.P. Veleschuk, Ph.D., Senior researcher at the V. Lashkaryov Institute of Semiconductor Physics. The area of scientific interests – solid state physics, CdTe radiation detectors, UV LEDs.

A.I. Vlasenko, Professor, Doctor of Sciences at the V. Lashkaryov Institute of Semiconductor Physics. The area of scientific interests – physics of defects and non-equilibrium processes in complex semiconductors.

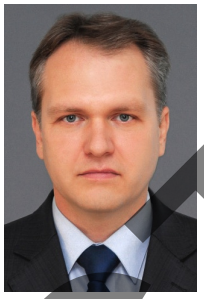
Z.K. Vlasenko, Ph.D., Senior researcher at the V. Lashkaryov Institute of Semiconductor Physics. The area of her scientific interests – solid state physics, recombination properties of CdTe, CdHgTe.



S.N. Levytskyi, Ph.D., Senior researcher at the V. Lashkaryov Institute of Semiconductor Physics. The area of scientific interests – physics of optoelectronic systems, technology of radiation detectors and laser systems.



D.V. Gnatyuk, Ph.D., Graduate School of Science and Technology, Shizuoka University, Japan. The area of scientific interests – optics, laser irradiation, CdTe-based radiation detectors.



O.V. Shefer, Doctor of Sciences. Head of department of automatics, electronics and telecommunications at the National University "Poltava Yuri Kondratyuk Polytechnic". The areas of scientific interests are solid semiconductors, plasma and electric devices.

V.V. Borshch, Ph.D., Associate Professor of department of automatics, electronics and telecommunications at the National University "Poltava Yuri Kondratyuk Polytechnic". The area of his scientific interests are electric motor for automatic systems, photo- and light emitting diodes, UV LEDs and radiation.

O.B. Borshch, Ph.D., Associate Professor of department of heat and gas supply, ventilation and heat power engineering at the National University "Poltava Yuri Kondratyuk Polytechnic". Scientific interests – processes of heat and mass exchange with variable physical parameters, controlled by the semiconductor sensors.