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# Temperature rise in crystals subjected to ultrasonic influence

R.K. Savkina *, A.B. Smirnov

*V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Pr. Nauki 45, 03028 Kiev, Ukraine*

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**Abstract**

The nonuniform temperature distribution in the surface of $Hg_{1-x}Cd_xTe$ semiconductor crystals during ultrasonic excitation was detected. This phenomenon was associated with a sonic-stimulated temperature rise around dislocations and a macroscopic heating of nonperfect regions. The dislocation moving in an ultrasonic field was considered as a linear thermal source and the temperature distribution around the dislocation was calculated. The discrete distribution of thermal sources is realised for $Hg_{1-x}Cd_xTe$ solid solutions at the average dislocation density $\sim 10^{10}\,m^{-2}$. The model of the sonic-stimulated activation of internal sources of the infrared radiation was proposed.


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## 1. Introduction

It is known that dislocation motion during the deformation process is damped by the electron and phonon systems of the crystal. As a consequence, the dislocation kinetic energy is dissipated into heat. For the first time the heating around moving dislocations was discussed in [1,2]. There are a number of works in which this phenomenon is investigated for metals [3], for semi-crystalline materials [4], etc. in the frame of traditional methods of material deformation. In this paper the result of investigations of the ultrasonically stimulated phenomenon of the temperature rise around dislocations in semiconductor mercury–cadmium telluride (MCT) crystals is presented. The possibility of such effect applications is discussed.

The physical origin of the ultrasonic (US) effects on a crystal with extended defects is connected with interaction between acoustic waves and dislocations in the frame of the vibrating string model of Granato and Luecke [5]. Such interaction results in an effective transformation of the absorbed

* Corresponding author. Tel.: +380 44 5704544; fax: +380 44 2658342.
*E-mail address:* r.savkina@lycos.com (R.K. Savkina).

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US energy into the internal vibration states of the crystal stimulating numerous defect reactions [6–10].

Previous study of the ultrasonically induced transformation of the crystal defect structure and the modification of charge-carrier scattering conditions in MCT crystals has shown a sensitivity of this material to sonic vibrations [9]. The correlation between the value of the sonic-stimulated effect and the state of the defect system of this material was also determined [10]. The result of investigations has allowed us to formulate the general systematics of sonic-stimulated processes and to propose an effective procedure for the direct influence of US treatment on MCT-based device performance. In this investigation the heating effect of ultrasound on MCT crystals is considered.

## 2. Experimental procedure and results

*N*-type $Hg_{1-x}Cd_xTe$ alloys with $x = 0.2$ and electron concentration $n_0 = (3–5) \times 10^{20}$ m$^{-3}$ at 78 K were the subject of the investigation. Samples were cut from single-crystal ingots grown by the Bridgman method. The linear dimensions of samples after polishing and chemical etching were $8 \times 2\,\mathrm{mm}^2$ and their thickness was about 1 mm. The dislocation density was measured by an optical microscope NV2E (Carl Zeiss Jena), and varies from $10^8\,\mathrm{m}^{-2}$ to $10^{11}\,\mathrm{m}^{-2}$.

Longitudinal US vibrations with frequency $f_{US}$ = 5–7 MHz and intensity $W_{US} \leqslant 0.5\,\mathrm{W/cm}^2$ were generated by a $LiNbO_3$ transducer (35° *Y*-cut). It was used an in situ pre-threshold intensity regime of US influence, i.e. switching off the ultrasound led to a relaxation of all sample parameters to their original values.

Several thermocouples were placed along the samples investigated and the nonuniform macroscopic temperature distribution in their surface during in situ US loading was detected. The value of the sonic-stimulated deviation of the temperature from the average value in the crystal was within $\Delta T \cong$ 10–20 K at US intensity $W_{US} \leqslant 0.5\,\mathrm{W/cm}^2$. We performed chemical selective etching of samples and observed with the optical microscope an inhomogeneous distribution of extended defects such as dislocations. It was determined that the sonic-stimulated heating of imperfect regions takes place.

## 3. The dislocation as a linear thermal source in the crystal

It is thought that the sonic-stimulated nonuniform heating of the crystal is connected with a selective absorption of the US energy at dislocations. In conformity with the Granato-Luecke model the dislocation moves in an ultrasonically loaded crystal as a vibrating string. Through the damping of the dislocation motion by electrons and phonons its kinetic energy is dissipated into the heat. A vast amount of acoustic energy is put into the material during period of the ultrasonic wave $t_{US}$ which is $\sim 10^{-7}$ s in our experiment. Since $t_{US}$ is less than the time of the heating relaxation, the heat may not have sufficient time to dissipate throughout the sample or to radiate into the environment during one period of the external influence. Thus, the temperature around dislocations may become considerably raised.

The dislocation moving under the US action was considered as a linear thermal source. According to [11] the temperature distribution around the dislocation line $L$ can be written as

$$T(R,t) = T_0 + \frac{W_0}{\rho c} \int_t \mathrm{d}t' \times \int_L G(R - R_l - v(t-t'), t-t')\,\mathrm{d}l. \qquad (1)$$

In the above expression, $G(R,t)$ is Green's function of a point thermal source, $R_l$ is a dislocation line coordinate, $W_0$ is the energy dissipated by a dislocation per unit time and length, $\rho$ is a crystal density, $C$ is a crystal specific heat, and $T_0$ is an average equilibrium temperature in a crystal. We assume that the dislocation line is placed along the OY direction ($R_l = \{0, y, 0\}$), is normal to plane $xz$ and is the infinity.

The temperature rises around the dislocation until an equilibrium temperature distribution is reached during a time which can be determined as $t \sim \max\{t_{US}, t_1, t_2\}$, where $t_1$ is a characteristic time for thermal equilibrium attainment between individual dislocations, and $t_2$ is a characteristic time of the thermal equilibrium attainment between the sample and the environment. In addition, the temperature increases in direct proportion to the time for an adiabatic condition $t < t_{US}$ and as a square root of the time for $t > t_{US}$. Values of $t_1$ and $t_2$ can be easily estimated [12]. They are $\sim 10^{-5}$ s and ~5–6 min, respectively. Thus, the temperature field around a dislocation becomes saturated during $t \sim t_2$. In fact, the equilibrium temperature distribution in the crystal was observed experimentally in a few minutes after switching on the ultrasound.

The stationary temperature field $(t \to \infty)$ around a dislocation moving with velocity $v$ along the $x$-direction is

$$T(x,z) = T_0 + \frac{W_0}{2\pi\chi} \exp\left(\frac{|x|}{R_0}\right) K_0\left(\frac{r}{R_0}\right), \tag{2}$$

where $r = (x^2 + z^2)^{1/2}$, $\chi$ is a thermal conductivity, $K_0$ is a zeroth order modified Bessel function, and $R_0 = 2\ \chi/\rho C v$. The regularity of the temperature distribution around dislocation for cases $r \ll R_0$ and $r \gg R_0$ can be written as

$$T = T_0 + \frac{W_0}{2\pi\chi} \ln\frac{R_0}{r} \tag{3}$$

and

$$T = T_0 + \frac{W_0}{2\pi\chi} \left(\frac{\pi R_0}{2r}\right)^{1/2} \exp\left(\frac{x-r}{R_0}\right), \tag{4}$$

respectively. For $r > R_0$ the temperature decreases exponentially and as a consequence $R_0$ can be considered as a stationary heating radius of the dislocation. In Fig. 1 the temperature distribution around the dislocation line calculated according to Eq. (3) is shown. The calculated value of the temperature rise (~25 K) is in a good agreement with the measured value ($\Delta T \cong$ 10–20 K).

If the average distance between dislocations $d$ exceeds twice the heating radius $R_0$ a discrete distribution of thermal sources is realised. Otherwise, the thermal source distribution is continuous. Fig. 2 shows regions of discrete (1) and continuous (2) distribution of thermal sources separated by $d = 2R_0$ uniformly and allows us to determine the limiting value of the average dislocation density. It was determined that the heating radius of the linear thermal source estimated by expression $R_0 = 2\chi/\rho C v$ is ~0.5 μm for MCT crystals if the dislocation velocity $v$ is 0.01 $v_{aw}$ [13], where $v_{aw}$ is velocity of the acoustic wave. Thus, the discrete character of the thermal source distribution may be realised for MCT solid solutions up to dislocation density $N_{DIS} < 10^{11}\ m^{-2}$. It is worth emphasis-

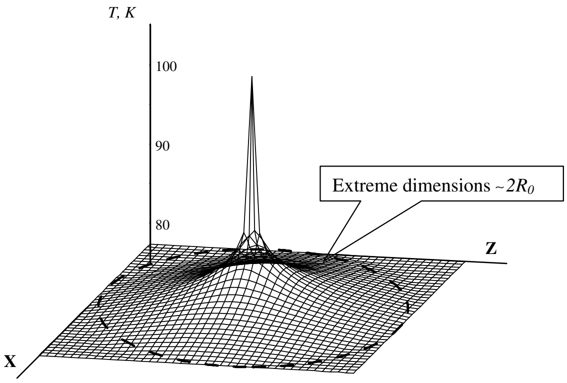


Fig. 1. Sonic-stimulated temperature distribution around dislocation line calculated by Eq. (3): equilibrium crystal temperature is $T_0 = 78$ K, sonic-stimulated temperature increase is $\Delta T = T - T_0 = 25$ K, intensity of the ultrasonic loading is $W_{US} = 0.4\ W/cm^2$.

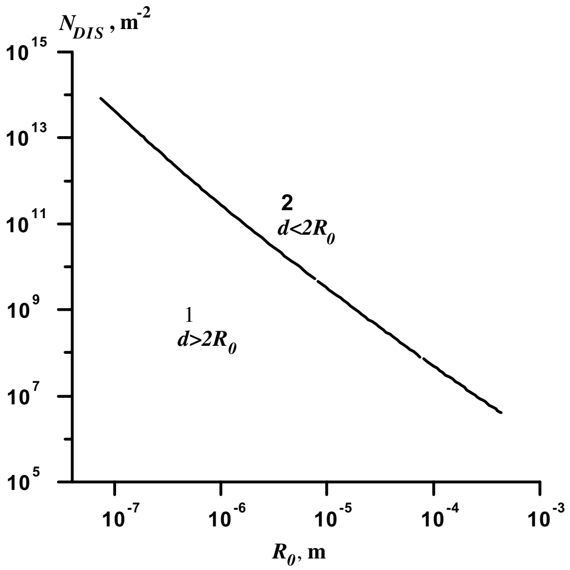


Fig. 2. The region of the discrete (1) and continuous (2) character of thermal source distribution.

ing that the US power density used caused no permanent change in the crystal. In this connection the amplitude of the forced motion of the dislocation is equal to a few Burgers vectors [13] and far less than the heating radius $R_0$.

Mercury–cadmium telluride is widely used material for infrared (8–14 μm) detector technology. The quality and reliability of MCT-based devices can be dramatically changed by extended defects such as dislocations and low angle boundaries. It is proposed that the investigation of the ultrasonically stimulated heating can be used for control of the structural perfection of MCT solid solutions.

In practice, the attempt to investigate MCT crystals which differ in extended defect density was undertaken and it was shown that the phenomenon of ultrasonically stimulated heating manifests itself in the following way. As we see from Fig. 2 for samples with uniform distribution of dislocations and $N_{\mathrm{DIS}} \leqslant 10^8\,\mathrm{m}^{-2}$ sonic-stimulated temperature distribution has a discrete character. Macroscopic heating was not detected. We observed the sonic-stimulated macro-heating for MCT crystals with a nonuniform dislocation distribution. For such samples the average value of the dislocation density varied from $10^9\,\mathrm{m}^{-2}$ to $10^{10}\,\mathrm{m}^{-2}$ and some "hot" regions with $N_{\mathrm{DIS}} \geqslant 10^{11}\,\mathrm{m}^{-2}$ were found. Finally, samples with a mechanically produced damage layer and $N_{\mathrm{DIS}} \sim 10^{12}\,\mathrm{m}^{-2}$ were investigated. The total heating of such samples during US loading took place.

## 4. The dislocation as an internal source of the infrared radiation in the crystal

It was demonstrated previously that crystal regions with a substantial density of extended defects may become heated during ultrasonic loading in consequence of the intense absorption of the acoustic wave energy around the dislocations. As is well known any substance with temperature $T > 0\,\mathrm{K}$ irradiates some energy to the environment. The spectral distribution of such irradiation is described by Planck equation and its maximum lies in the region of $\lambda \cong 10$–$40\,\mu\mathrm{m}$ for $T = 300$–$77\,\mathrm{K}$:

$$r_\lambda = \frac{2\pi hc^2}{\lambda^5}\left(\mathrm{e}^{\frac{hc}{\lambda kT}} - 1\right)^{-1}, \tag{5}$$

where $c$ is a light velocity in the vacuum, $h$ is Planck's constant, $k$ is Boltzmann's constant. Thus, the hot region around the dislocation can be considered as an internal source of the infrared radiation (IR).

As was found, the ultrasound effect manifests itself in an increase of the electron contribution to the conductivity of MCT crystals [9,10]. For example, the ultrasonically stimulated change of the electron concentration $\Delta$ ($\Delta$ is ratio of the carrier concentration measured during ultrasonic loading to the carrier concentration measured without ultrasonic loading) varies from 1.2 to 3 at $T = 78$ K for $n$-MCT samples [10]. It was shown that the absorption of the acoustic wave energy by dislocations during US influence has resulted in electrical activation of point defects "bounded" at extended defects [9]. At the same time, the ultrasonically stimulated heating can be considered as another factor stimulating electron processes in MCT crystals under US influence.

First of all, the temperature rise around dislocations can result in activation of the additional value of jogs which act as donors for the material investigated [14]. But the efficacy of this mechanism is insignificant [15]. On the other hand, an appearance in the crystal of internal sources of IR may results in nonequilibrium charge carriers (NCC) generation as a consequence of the intrinsic absorption of the MCT alloys. Let us estimate the significance of such a mechanism. The MCT ($x = 0.2$) typically investigated sample with dislocation density of $N_{\mathrm{DIS}} \leqslant 10^{10}\,\mathrm{m}^{-2}$ and electron concentration of $n_0 = 3 \times 10^{20}\,\mathrm{m}^{-3}$ will be considered. Its band gap at 78 K is 0.113 eV ($\lambda \approx 11\,\mu\mathrm{m}$) [16]. At a crystal temperature of 78 K the region around the dislocation warms up to $\sim$100 K under US influence. The irradiation intensity of the hot region can be estimated by integrating (5) in the interval $\Delta\lambda = 7$–$11.2\,\mu\mathrm{m}$, which overlaps the region of the MCT intrinsic absorption. This value is $\sim 3 \times 10^{23}$ quantum $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. We consider the spectral region of the MCT fundamental absorption. In this connection we neglected components of transmittance and reflectance of the surrounding

MCT and the emissivity of the internal IR source was set to unity.

The concentration of nonequilibrium carriers generated by internal IR sources increases according to [17]:

$$\Delta n(t) = \alpha\beta\tau_r I\left(1 - \exp\left(-\frac{t}{\tau_r}\right)\right), \tag{6}$$

where $\alpha$ is an absorption coefficient, $\beta$ is a quantum yield, $\tau_r$ is the NCC lifetime, $I$ is an intensity of thermal irradiation sources, $t$ is time. Fig. 3 shows the time dependence of the ultrasonically stimulated rise of the charge carrier concentration $n(t) = n_0 + \Delta n(t)$, where $n_0 = 3\times 10^{20}\,\mathrm{m}^{-3}$ is an equilibrium charge carrier concentration estimated experimentally at 78 K for real MCT sample, $\Delta n(t)$ is NCC concentration calculated by Eq. (6).

As can be seen from Fig. 3, the process of carrier generation is limited by the carrier recombination process with a characteristic time $\tau_r$. At $t \to \infty$ the concentration of nonequilibrium charge carriers reaches the stationary value $\Delta n_{\mathrm{st}} = \alpha\beta\tau_r I$ (see calculated values in the figure caption). The penetration of the acoustophotoexcited NCC to the inter-dislocation area is controlled by diffusion processes. Fig. 3 (curve 4) shows NCC concentration $\Delta n(x)$ as a function of distance from IR source $x$ calculated (taking into account diffusion and nonuniform absorption) by the equation [17]:

$$\Delta n(x) = \frac{\Delta n_{st}}{\alpha^2 L^2 - 1}\left(\alpha L e^{-\frac{x}{L}} - e^{-\alpha x}\right), \tag{7}$$

where $L = (D\tau_r)^{1/2}$ is a diffusion length, and $D$ is a bipolar diffusion coefficient. If $L \sim R_0$ and $d > 2R_0$, nonequilibrium charge carriers are localized inside the hot region and a macroscopic increase of the carrier concentration in the crystal is absent. If $L > R_0$, the diffusion of NCC outwards from the hot region is possible. But the macroscopic contribution of acoustophotoexcited charge carriers to the crystal conductivity takes place only if $\Delta n(x) \geqslant n_0$ at $x = 0.5\ (N_{\mathrm{DIS}}^{-0.5})$.

It is necessary to point out the qualitative agreement between the value of the ultrasonically stimulated carrier concentration increase calculated according to the model of IR sources for real MCT crystal with typical charge carrier lifetime and experimentally obtained results reported in [10,15]. Thus, for sample with $n_0 = 3\times 10^{20}\ \mathrm{m}^{-3}$, $\tau_r \sim 10^{-7}\,\mathrm{s}$ and $N_{\mathrm{DIS}} \leqslant 10^{10}\,\mathrm{m}^{-2}$ the charge carrier concentration measured during ultrasonic loading by the Hall method is $n_{\mathrm{US}} = 7\times 10^{20}\,\mathrm{m}^{-3}$ whereas estimation in the frame of IR sources model shows $n(x) = n_0 + \Delta n(x) \sim 7.5\times 10^{20}\,\mathrm{m}^{-3}$ at $x = 5\,\mu\mathrm{m}$ (see Fig. 3, curve 4). However, more experiments are, clearly, necessary.

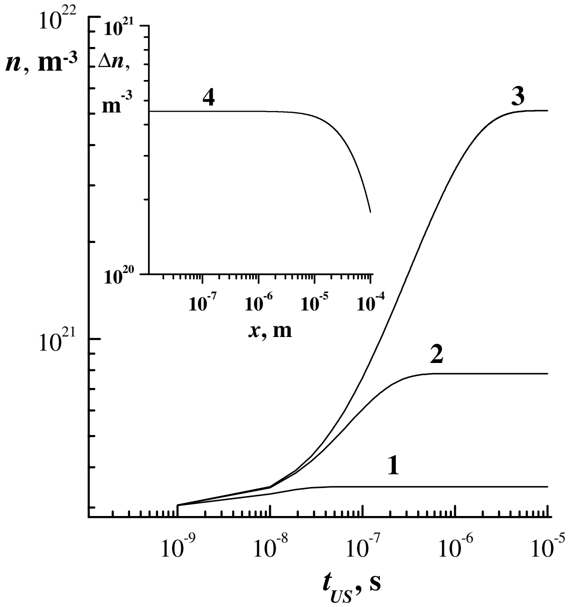


Fig. 3. The ultrasonically stimulated charge carrier concentration rise during functioning time of the internal source of infrared radiation $n(t) = n_0 + \Delta n(t)$: curve 1—$\tau_r = 10^{-8}\,\mathrm{s}$, $\Delta n_{\mathrm{st}} = 4.8\times 10^{19}\,\mathrm{m}^{-3}$, $L = 2\,\mu\mathrm{m}$; curve 2—$\tau_r = 10^{-7}\,\mathrm{s}$, $\Delta n_{\mathrm{st}} = 4.8\times 10^{20}\,\mathrm{m}^{-3}$, $L = 6\,\mu\mathrm{m}$; curve 3—$\tau_r = 10^{-6}\,\mathrm{s}$, $\Delta n_{\mathrm{st}} = 4.8\times 10^{21}\,\mathrm{m}^{-3}$, $L = 20\,\mu\mathrm{m}$. Curve 4 represents NCC concentration $\Delta n(x)$ as a function of distance from IR source for MCT sample with $\tau_r \sim 10^{-7}\,\mathrm{s}$.

## 5. Conclusions

In this paper the result of an experimental study of the nonuniform temperature distribution stimulated by ultrasound effect in $Hg_{0.8}Cd_{0.2}Te$ crystals is presented. This phenomenon was associated with a sonic-stimulated temperature rise around dislocation and heating of nonperfect regions of samples investigated. It is possible to use the effect investigated as the basis of a nondestructive technique for structural perfection control of $Hg_{1-x}Cd_xTe$ alloys.

We have considered regions around dislocations heated by ultrasound effect as sources of the infrared radiation, which can result in non-equilibrium charge carrier generation and changes in the electrical parameters of the material. We assume that an activation of the internal sources of infrared radiation under intense external influences including elastic waves, which are accompanied by dislocation motion, might become important and have to be taken into account for MCT based devices. The proposed model can serve also as an explanation of ultrasonically stimulated phenomena in wide-gap semiconductor (for example, a shallow level ionization).

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