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Dislocations as internal sources of infrared radiation in crystals subjected to ultrasonic influence

R.K. Savkina, A.B. Smirnov, F.F. Sizov
V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine
41, prospect Nauky, 03028 Kyiv, Ukraine
Phone: (044) 525-1813; fax: (044) 525 1810
E-mails: r_savkina@rambler.ru, alex_tenet@isp.kiev.ua, sizov@isp.kiev.ua

Abstract. We have carried out a systematic study of mercury cadmium telluride crystals subjected to the high-frequency and high-intensity ultrasonic influence. The charge carrier transport parameters were determined from the Hall coefficient and conductivity measurements. Temperature dependences of the electron concentration without and during the ultrasonic load were calculated. A good agreement between the experimental and theoretical data was obtained. A model of internal source of the infrared radiation associated with a dislocation is proposed for the explanation of sonically stimulated effects in the semiconductor system. We have considered a possibility of the thermooptical excitation in $Hg_{1-x}Cd_xTe$ alloys during sonication, which can result in the nonequilibrium charge carrier generation and changes in electrical parameters of the material.

Keywords: $Hg_{1-x}Cd_xTe$, ultrasound, dislocation.

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1. Introduction

Intensive ultrasound-dislocation interaction in the frame of the vibrating-string model of Granato-Lucke has resulted in numerous phenomena observed in ultrasonically loaded crystals [1]. We demonstrated previously that the action of an acoustic wave excited in a $Hg_{1-x}Cd_xTe$ (MCT) crystal, which remains the most widely used variable gap semiconductor for IR photodetectors, results in an essential change of the carrier concentration up to the change of the conduction type [2]. Study of characteristics of MCT alloys subjected to the influence of ultrasound (US) allowed us to detect the nonuniform temperature distribution in the surface of this material during ultrasonic excitation associated with an US-stimulated temperature rise around dislocations [3]. It is possible to use this effect as the basis of a non-destructive technique for the structural perfection control of semiconductors.

US is widely used for the characterization of materials. Thus, acoustic thermography is one of the forms of nondestructive examination which is exploited in different fields (aeronautics, architecture and building, medicine, science) for the characterization of metals, plastics, composites, *etc.* [4]. But, as we see for MCT crystals, the acoustic thermography of semiconductor crystals can meet difficulties related to the possibility of a change of crystal properties during the examination.

In this study, our efforts will be focused on a detailed analysis of the US-stimulated processes in MCT crystals. In particular, we will consider a possibility of the thermooptical excitation in this material during ultrasonic influence which can result in the nonequilibrium charge carrier generation and changes in electrical parameters of the crystal.

2. Methodology and results

All experiments have been performed on MCT crystals with $x \sim 0.22$ grown by the Bridgman method. The linear dimensions of samples after polishing and chemical etching were 8×2 mm, and their thickness was about 1 mm. The dislocation density was measured by an optical microscope NV2E (Carl Zeiss, Jena) and varied from 10^4 to $10^6 cm^{-2}$.

We set the subthreshold-intensity conditions of sonication described in detail elsewhere [2, 5], which results in a transformation of the already existing structural defects and does not cause the generation of new defects [6]. Samples were mounted on piezoelectric transducers from $LiNbO_3$ (35 *Y*-cut) operating in the resonance vibration mode. The basic resonance frequency was varied from 5 to 8 MHz, and the acoustic power W_{US} did not exceed 0.5 W/cm^2.

The temperature dependences of the Hall coefficient and the conductivity were studied. The classical configuration of the Hall method was used to obtain the value of electron concentration. All parameters have been measured during sonication. Their change had a reversible character with a relaxation time of 10^2-10^3 s after switching off US. We also investigated the dependence of the carrier concentration on the effective US stress amplitude σ_{US} ($\sigma_{US} = (2\rho\, v_{US} W_{US})^{1/2}$, where ρ = 7.6 g/cm^3 is the density of a MCT crystal, and v_{US} = $3.4 \cdot 10^5$ cm/s is the velocity of a longitudinal acoustic wave).

The initial value of electron concentration varies from $3 \cdot 10^{14}$ to $5 \cdot 10^{14}$ cm^{-3} at T = 80 K for all samples with the *n*-type of conductivity. The Hall mobility varies from 53000 to 140000 cm^2/V·s under the same conditions. The effect of ultrasonic loading manifests itself as an increase in the electron concentration in the impurity-conductivity temperature range (T < 120 K) and correlates with the extended defect density in the samples under study. The ratio of the carrier concentration measured during sonication to its initial value, Δ, varies from 1.2 to 2.5 depending on the density of dislocations N_{DIS} (see Table). Really, as we have shown previously, the US-stimulated phenomena in MCT single crystals correlate with a degree of their structural perfection [5].

Fig. 1 shows the temperature dependences of the carrier concentration that are typical of the *n*-MCT single crystals under study. The dependence of the carrier concentration on the effective US stress amplitude is plotted in Fig. 2 (curves 1-3).

The study of the dependence of the carrier concentration on the effective US stress amplitude for MCT bulk crystals, which demonstrate the *p*-type of conductivity in the impurity-conductivity temperature range (T < 100 K for the samples investigated in our experiment), has shown that the sonically stimulated *p*-to-*n* conductivity type conversion is observed (see Fig. 2, curves 4, 4′). It should be noted that the investigation of the magnetic field dependence of the Hall coefficient during sonication of *p*-MCT bulk crystals has also demonstrated the phenomenon of the sonically stimulated *p*-to-*n* conductivity type conversion in the region of low magnetic fields and at the liquid nitrogen temperature [7].

Thus, our study has demonstrated that the action of a high-frequency deformation excited in MCT bulk crystals by a piezotransducer results in an increase of the electron component of conductivity up to the conductivity type conversion.

Table. Some parameters of typical investigated *n*-$Hg_{1-x}Cd_xTe$ crystals, *T* = 80 K.

Sample	n_0, cm^{-3}	n_{US}, cm^{-3}	Δ, a.u.	N_{DIS}, cm^{-2}	ρ, Ohm·cm
1	$3.5 \cdot 10^{14}$	$4.1 \cdot 10^{14}$	1.17	10^5	0.14
2	$5 \cdot 10^{14}$	$6 \cdot 10^{14}$	1.2	$3 \cdot 10^5$	0.15
3	$3.2 \cdot 10^{14}$	$5.4 \cdot 10^{14}$	1.7	$7 \cdot 10^5$	0.3
4	$3 \cdot 10^{14}$	$7.5 \cdot 10^{14}$	2.5	$2 \cdot 10^6$	0.35

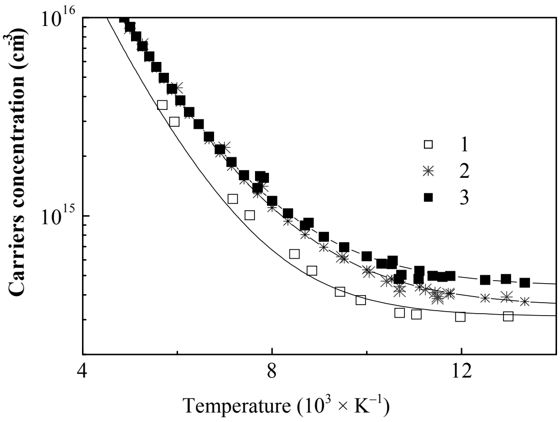

Fig. 1. Temperature dependences of the carrier concentration for the typical *n*-MCT single crystal, N_{DIS}~10^6 cm^{-2}. *1* – initial, *2*, *3* – during sonication with 0.4 and 0.5 W/cm^2, respectively. Solid lines present the results of the fitting procedure.

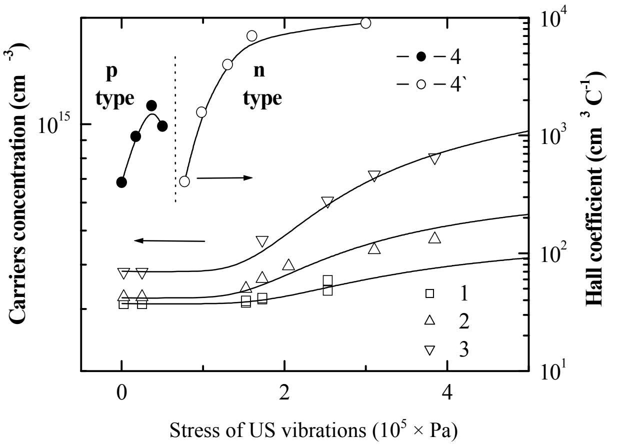

Fig. 2. Effective US stress amplitude dependences of the carrier concentration for the typical *n*-MCT single crystal (N_{DIS}~10^6 cm^{-2}) measured at: T = 80 K (curve *1*), 85 K (*2*), 95 K (*3*). Solid lines present the results of the fitting procedure. Curves 4, 4′ present the amplitude dependence of the Hall coefficient for the *p*-MCT single crystal at 80 K.

3. Dislocations as an agent of the ultrasonic wave energy accumulation and redistribution

In conformity with the Granato-Lucke model, dislocations move in an ultrasonically loaded crystal as a vibrating string and selectively absorb the US energy. Considering the prevalence of the mechanism of US-dislocation interaction in a crystal [8], we suggest that several factors determine US-stimulated processes in MCT alloys. The first factor is the so-called Cottrell atmospheres. The dislocation contribution to a change in MCT properties clearly appears [9-11]. Moreover, the electrical properties of dislocations are mainly determined by their extrinsic effects such as a change or a redistribution in the surrounding atmosphere of point defects, which has a donor-like character, rather than by the intrinsic ones due to their dangling bonds [12]. The absorption of acoustic energy by dislocations during the US influence has resulted in the electrical activation of donor-like point defects "bounded" at extended defects, that was discussed in detail elsewhere [2]. As a consequence, the increase of the electron component of conductivity occurs. The obtained values of relaxation time of the electron concentration for a bulk MCT sample after switching off the US loading confirm the ionic nature of the ultrasonically stimulated processes running in this material.

Another factor stimulating the electron processes in MCT crystals during sonication is the dissipation of the kinetic energy of moving dislocations through the damping by electrons and phonons. First of all, the temperature rise around dislocations can result in the activation of the additional number of jogs which work as donors for the material investigated [13]. The presence of jogs on a dislocation is the well-established aspect of defects in crystals. In ionic materials such as alkali-halide crystals, jogs are known to act as extrinsic sources for ionic defects. Since II-VI compounds are shown to have a degree of ionicity, hence, jogs in these materials also act as sources for vacancies and interstitials, i.e., as donors and acceptors. Therefore, they can significantly influence the electrical properties of these compounds [13]. The creation of additional nonequilibrium jogs by the dislocation interaction is possible due to the balance state disturbance in a crystal during sonication.

On the other hand, the US-stimulated warmed regions around extended defects, in fact "warmed dislocations", can be considered as the internal sources of infrared radiation (IR). We demonstrated previously that the crystal regions with a substantial density of extended defects may become heated during sonication [3]. We considered an MCT sample with a dislocation density of $N_{\mathrm{DIS}} \sim 10^6$ cm^{-2} and the electron concentration $n_0 = 3.1\cdot10^{14}$ cm^{-3}. Its band gap at 78 K was 0.113 eV ($\lambda \approx 11$ μm). The value of the US-stimulated deviation of the temperature from the average value in the crystal was within $\Delta T \cong 10\ldots20$ K at the US intensity $W_{\mathrm{US}} \le 0.5$ W/cm^2. The irradiation intensity of the hot region can be estimated by integrating the Planck equation in the interval $\Delta\lambda = 7\ldots11.2$ μm. This value is $\sim 10^{23}$ quantum·m^{-2}·s^{-1}. We neglected the components of transmittance and reflectance of the surrounding MCT, and the emissivity of the internal infrared source was set to unity since the spectral region of the MCT fundamental absorption was considered.

The appearance of internal sources of IR in the MCT crystal may result in the generation of nonequilibrium charge carriers (NCC) as a consequence of the intrinsic absorption. The concentration of nonequilibrium carriers generated by internal sources of IR increases according to [14] as

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

where α is the absorption coefficient, β is the quantum yield, τ_r is the NCC lifetime, I is the intensity of thermal irradiation sources, t is the time. As seen from Eq. (1), the carrier recombination process with a characteristic time τ_r limits the generation of carriers. At $t \to \infty$, the concentration of nonequilibrium charge carriers reaches the stationary value $\Delta n_{\mathrm{st}} = \alpha\beta\tau_r I$. Diffusion processes control the penetration of the acoustophotoexcited NCC to the inter-dislocation area. Taking diffusion and nonuniform absorption into account, the NCC concentration $\Delta n(d)$ as a function of the distance from the infrared source d can be calculated by the expression [14]

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

where $L = (D\,\tau_r)^{1/2}$ is the diffusion length, and D is the bipolar diffusion coefficient.

If $L \sim R_0$ and $(N_{\mathrm{DIS}})^{-0.5} > 2R_0$, nonequilibrium charge carriers are localized inside the hot region and a macroscopic increase of the carrier concentration in the crystal is absent. Here, R_0 is the stationary heating radius of a linear thermal source [3]. If $L > R_0$, the NCC diffusion outwards from the hot region is possible. But the macroscopic contribution of acoustophotoexcited charge carriers to the crystal conductivity takes place only if $\Delta n(d) \ge n_0$ at $d = 0.5\,(N_{\mathrm{DIS}})^{-0.5}$.

4. Discussion

Let us analyze the experimental dependence of the carrier concentration obtained for the typical *n*-MCT sample on temperature and the US stress (see Figs. 1, 2). The initial behavior of the electron concentration measured for *n*-MCT crystals (curve 1, Fig. 1) was satisfactorily described by the relation $n(T,x) = n_0 + n_i(T,x)$, where $n_0 = 3.1\cdot10^{14}$ cm^{-3} is the experimental value of the electron concentration measured without US load in the region of impurity conduction at $T = 80$ K. The intrinsic concentration and the band-gap were calculated by expressions [15]

$$n_i(T,x) = (1.093 - 0.296x + 4.42\cdot10^{-4}T + 1.25924\cdot10^{-2}xT)\times$$
$$\times 5\cdot10^{20} E_g(T,x)^{3/4} T^{3/2} \exp\left(-\frac{E_g(T,x)}{2kT}\right),$$

$$E_g(T,x) = -0.25 + 1.59x +$$
$$+ (1-2.08x)\cdot5.233\cdot10^{-4}T + 0.327x^3.$$

Taking into account the determining factors of sonic-stimulated processes in MCT alloys considered previously, the temperature dependence of the electron concentration under the US load can be written as

$$n_{\mathrm{US}}(T,x)=n_0+n_i(T,x)+\Delta n(T,\tau_r)+ \\ +\Delta n_j(T,N_{\mathrm{DIS}},2G_f)+\Delta n_b(T,W_b), \quad (3)$$

where $\Delta n\,(T,\tau_r)$ is an increase of the electron concentration due to the generation of nonequilibrium carriers by internal sources of infrared radiation; $\Delta n_j\,(T,N_{\mathrm{DIS}},2G_f) = N_0 \exp(-G_f/kT)$ [13] is an increase of the electron concentration due to the increase of the jog concentration under condition of the temperature rise, where N_0 is the number of the sites with jogs and G_f is a free energy of the jog formation; $\Delta n_b\,(T,W_b) = N \exp(-W_b/kT)$ is an increase of the electron concentration due to the electrical activation of the donor-like point defects "bounded" at extended defects, where W_b is their binding energy, N is the total defect concentration in the crystal [8].

The best agreement between the experimental and calculated $n_{\mathrm{US}}(T,x)$ dependences (points and solid lines in Fig. 1) was obtained in the frame of the supposition about the alloy composition decreasing up to $x \sim 0.21$. We used the following parameters in the calculations: the NCC lifetime $\sim 2\cdot 10^{-7}$ s, the dislocation density $N_{\mathrm{DIS}} \sim 10^6$ cm^{-2}, the free energy of a jog formation ~ 0.1 eV and the binding energy of point defects ~ 0.08 eV. We also satisfactorily theoretically described the US amplitude dependences of the carrier concentration for an *n*-MCT single crystal using the proposed model of the combined effect of analyzed factors (see Fig. 2).

The supposition about the alloy composition reduction allows us to describe the concentration change at higher temperatures. At the same time, the electron concentration increase due to the generation of nonequilibrium carriers by internal sources of infrared radiation is considerable in the region of the impurity conduction ($T \le 100$ K). This means that the activation of the internal sources of infrared radiation, which can be considered as the thermooptical excitation in MCT alloys in the region of the operating temperature, has to be taken into account for MCT-based devices.

5. Conclusions

In this paper, we have demonstrated that the action of acoustic waves excited in a MCT crystal by a piezo-transducer results in an essential change of the carrier concentration up to the change of the conduction type. The possible mechanism of sonically stimulated effects is discussed in the frame of the intensive ultrasound dislocation interaction model. As a consequence, the temperature dependences of the electron concentration without and during an US load are calculated. A good agreement between the experiment and theoretical fits is obtained. The possibility of the thermooptical excitation of the solid with the activation of internal sources of infrared radiation as a consequence of the acoustic wave energy absorption is determined. We assume that the activation of internal sources of infrared radiation might become important and has to be taken into account for MCT-based devices.

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