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Effect of thermal neutron irradiation on the electrophysical and photoelectric properties of $Hg_{0.8}Cd_{0.2}Te$ crystals

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Abstract. We have studied experimentally the effect of thermal neutron irradiation on the electrophysical and photoelectric parameters of $Hg_{1-x}Cd_xTe$ crystals. The irradiation was shown to produce both donor- and acceptor-type radiation defects. In this case the majority charge carrier mobility decreases significantly. An analysis is given of a model for radiation defect production. The photoconduction processes are explained from the standpoint of clusterization of such radiation defects.

Keywords: $Hg_{1-x}Cd_xTe$, thermal neutrons, radiation defects, clusters.

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1. Introduction

The radiation treatment of $Hg_{1-x}Cd_xTe$ crystals and epitaxial films attracts attention as a promising technological technique to control their main electrophysical and photoelectric properties. This primarily concerns irradiation with X-rays, γ-quanta and electrons of various energies [1-4].

Neutrons are an interesting factor of radiation action on semiconductors, involving $Hg_{1-x}Cd_xTe$ solid solutions. They produce a wide spectrum of radiation defects. A limited number of papers [5,6] deal with the problem of $Hg_{1-x}Cd_xTe$ single crystals irradiation with fast or slow neutrons. The radiation defects in these crystals may be as follows: (i) substitutional ones appearing due to kinetic energy of fast neutrons, and (ii) impurity ones appearing due to transmutations when thermal neutrons are captured. In semiconductors containing Cd as one of components, thermal neutrons may produce individual point defects due to recoil atoms that result from the (n,γ) reaction involving ^{113}Cd isotope. The latter is characterized by anomalously high neutron capture probability (capture cross section of $2\cdot10^4$ *b*). The effect of transmutation doping of $Hg_{1-x}Cd_xTe$ crystals has been comprehensively studied in [5]. To obtain considerable transmutation doping level (especialy with impurities from the first group of the periodic table), the thermal neutron fluences $\Phi = 5\cdot10^{16} - 10^{18}$ cm^{-2} were required. At lower fluences irradiation with fast neutrons was used in [6], although at small fluences thermal neutrons may also make predominant contribution to the production of intrinsic point defects in crystal lattice. In particular, it was pointed in the above paper at an increase of electron concentration (as well as a drop of electron mobility) in *n*- $Hg_{0.8}Cd_{0.2}Te$ crystals exposed to fast neutron irradiation.

Bearing this in mind, we have performed experimental investigations of the effect of thermal neutrons (fluences $\Phi = 10^{13} - 10^{14}$ cm^{-2}) on the electrophysical and photoelectric properties of both *n*- and *p*- $Hg_{0.8}Cd_{0.2}Te$ single crystals.

2. Experimental procedures

In our investigations, we used crystals with initial concentration of electrons (holes) $(1\div10)\cdot10^{14}$ cm^{-3}(10^{16} cm^{-3}). Exposition to thermal neutrons was performed in the horizontal channel of a water-moderated nuclear reactor at room temperature. The maximum fluence was $\Phi = 3\cdot10^{14}$cm^{-2}. The ratio between the fast and slow neutron flows was 1/3. After irradiation the samples have been kept for 30 days. The Hall measurements were carried out in magnetic fields from 0.1 to 20 kOe; the temperature range was 300-77 K. The photoelectric measurements were performed using a pulse CO_2 laser (λ = 10.6 μm, bulk excitation) and spectrometer IKS-21.

3. Experimental results

We have registered an increase of electron concentration n in n-type crystals and a slight growth of hole concentration p in p-type crystals after neutron irradiation. Both electron and hole concentrations were found from the low-temperature plateau of the Hall coefficient: $n = 1/eR_h$, $p = 1/eR_h$. The temperature dependencies of the Hall coefficient R_h (Fig. 1) and electron mobility μ (Fig. 2), as well as magnetic field dependence of the Hall coefficient, $R_h(H)$ (Fig. 3) for n- type samples have shown that, from the «electrical» point of view, the samples remained macrouniform. This means that defects are produced almost uniformly over the crystal. In this case the electron mobility slightly drops. In the p-type crystals, along with a Hall coefficient decrease in the impurity conduction region, the point where it changes its sign ($R_{inv} = \mu_p(n/p)^{1/2}$) shifts to lower values of magnetic field (Fig. 4). At a pronounced asymmetry of electron and hole mobilities, this effect may also result from an increase in hole concentration. Obviously neutron irradiation of $Hg_{0.8}Cd_{0.2}Te$ produces defects of both types (donor as well as acceptor) in n- and p- crystals [5].

The fluence dependencies of electron and hole concentrations in the crystals studied may be presented as $n = n_0 \exp(K_1\Phi)$, $p = p_0 \exp(K_2\Phi)$. The empirical coefficients K_1 and K_2 are $\approx 2\cdot10^{-15}$ and $\approx 3\cdot10^{-16}$ cm^2, respectively (Fig. 5). The appearance of donor- and acceptor-

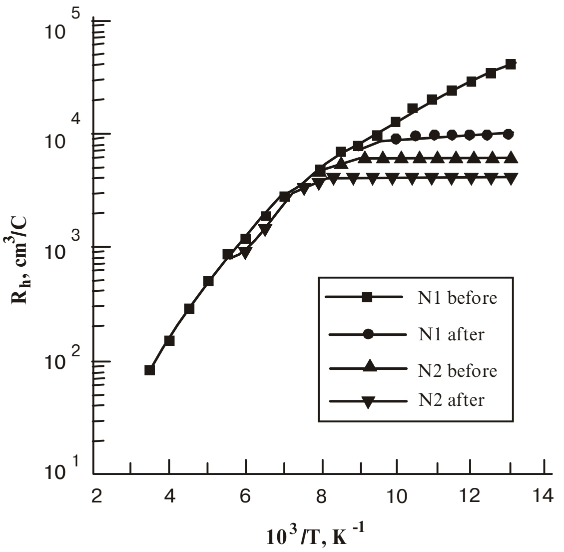

Fig. 1. Hall coefficient versus temperature curves for two n- $Hg_{0.8}Cd_{0.2}Te$ crystals with different electron concentrations taken before and after neutron irradiation (fluence of 10^{14} cm^{-2}).

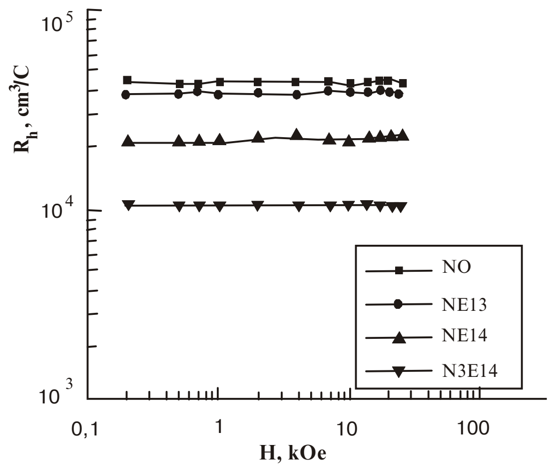

Fig. 3. Hall coefficient versus magnetic fiield curves taken at T = 77 K for n- $Hg_{0.8}Cd_{0.2}Te$ crystal at different neutron fluences.

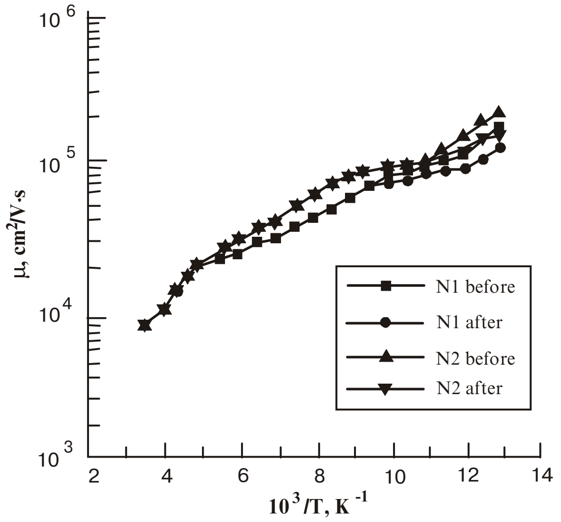

Fig. 2. Electron mobility versus temperature curves for two n- $Hg_{0.8}Cd_{0.2}Te$ crystals taken before and after neutron irradiation (fluence of 10^{14} cm^{-2}).

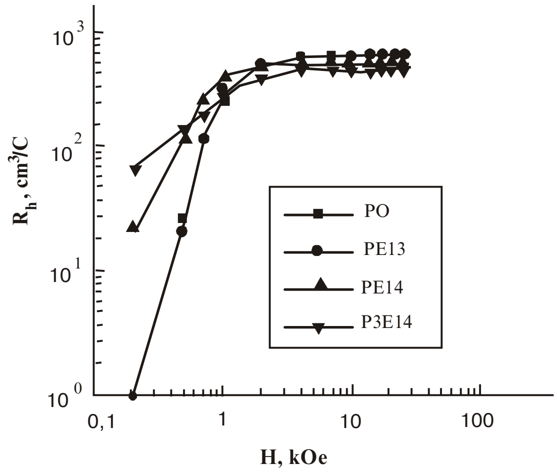

Fig. 4. The same as in Fig. 3 but for p- $Hg_{0.8}Cd_{0.2}Te$ crystal.

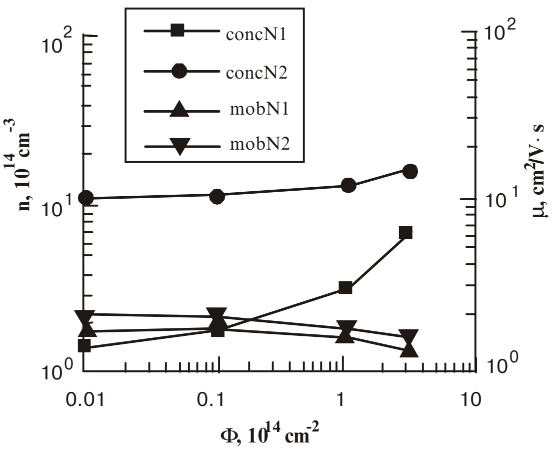

Fig. 5. Electron concentration and mobility versus neutron fluence curves taken for two *n*- $Hg_{0.8}Cd_{0.2}Te$ crystals.

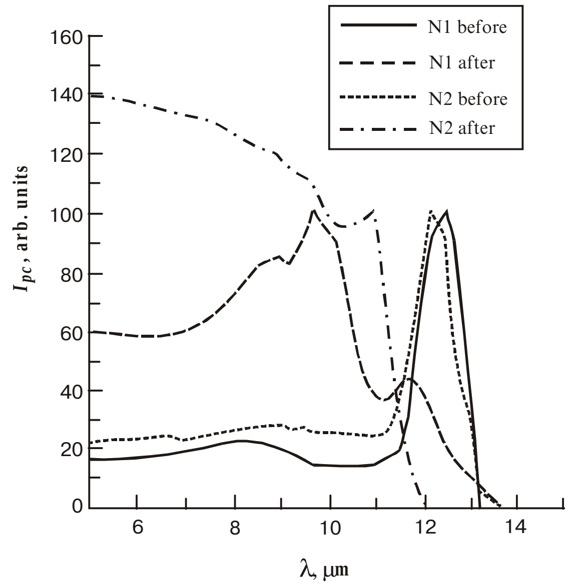

Fig. 7. Photocurrent spectral curves taken for two *n*- $Hg_{0.8}Cd_{0.2}Te$ crystals before and after neutron irradiation (fluence of $10^{14}cm^{-2}$).

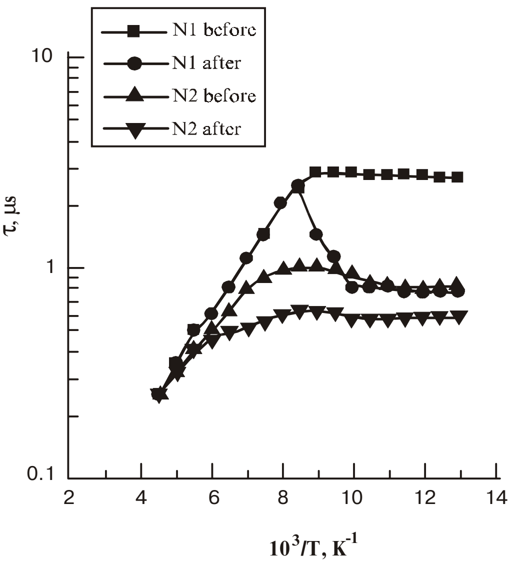

Fig. 6. Lifetime of nonequilibrium charge carriers versus temperature curves (for notation see Fig.1).

type defects is corroborated by the fact that the nonequilibrium charge carrier lifetime decreasses after neutron irradiation.

In *n*-type crystals with low equilibrium electron concentration (n_0), the Auger mechanism of the nonequilibrium charge recombination changes for the Shockley-Reed one over some neutron fluence range (Fig. 6). The energy level E_a that corresponds to the appearing recombination centers lies ≈ 50 meV over the valence band top. Such levels appear also under other types of irradiation [8].

In crystals with rather high concentrations of equilibrium charge carriers the mechanism of nonequilibrium charge carrier recombination remains the same over the whole fluence range studied, and the lifetime of nonequilibrium charge carriers depends inversely on n_0^2. This is an evidence that the Auger mechanism of nonequilibrium charge carrier recombination prevails. On spectral curves of the steady-state photocurrent, $I_{pc}(\lambda)$, of irradiated crystals there are nonmonotonic sections in the intrinsic absorption region, while the latter shifts toward high frequencies (Fig. 7). This effect seems to be related to the appearance of regions that are slighly disordered by radiation. Their sizes are about diffusion length of nonequilibrium change carriers that is about 25 μm for *n*-type crystals.

4. Discussion of results

Let us evaluate a concentration of point defects (of the Frenkel type) that are initially produced in $Hg_{0.8}Cd_{0.2}Te$ crystals exposed to thermal and fast neutrons. The effect of thermal neutrons on $Hg_{0.8}Cd_{0.2}Te$ crystals at low fluences reduces to activation of nuclei of ^{113}Cd isotope accompanied by practically instant (~ 10^{-13}s) occurrence of (*n*, γ) reaction. As a result, γ- quanta are emitted, giving an atom the recoil energy. This energy is sufficient for an atom to be transferred to an interstitial, as well as to knock from their sites Hg and Cd atoms (in about the same numbers). If one takes that the energy of Frenkel pair formation is about 7eV for both sublattices [11], then the total energy that is released at capturing one neutron is sufficient to produce four Frenkel pairs. Since the number of Cd atoms in the lattice of crystals studied is one fourth (fifth) that of Hg(Te) atoms, the number of Cd- involving defects per captured neutron is 1-2. The concentration of excited $^{114}Cd^*$ atoms may by calculated from the following expression for fluence Φ [12]:

$$[^{114}Cd^*] = \Phi \rho a x \sigma_T N_A / A \qquad (1)$$

Here $\rho = 7.63$ g/cm^3 is the $Hg_{0.8}Cd_{0.2}Te$ density; $x = 0.2$ characterizes the composition; a is the ^{113}Cd fraction in the natural mixture of Cd isotopes; N_A is Avogadro's number; A is the $Hg_{0.8}Cd_{0.2}Te$ molecular weight; σ_T is the capture cross-section for a thermal neutron (in our case it equals to $2{\cdot}10^4\, b$) [13].

The estimation made using expression (1) gives $[^{114}Cd^*] \cong 7.3\ \Phi$ [cm^{-3}]. The concentration of Cd-involving Frenkel pairs is about the same, while that of Hg(Te) - involving Frenkel pairs is four times higher. Thus $N_{Cd} \cong 7.3\ \Phi$[cm^{-3}], $N_{Hg} \cong 29\ \Phi$[cm^{-3}] and $N_{Te} \cong 29\ \Phi$[cm^{-3}]. Therefore at the maximum fluence used the concentration of defects of each polarity is about 10^{16} cm^{-3}. If they are electrically active, then they can be detected experimentally.

Using the conclusions of [5] where the Hg_{80} $(n, \beta)\rightarrow Au_{79}$ nuclear transmutation was assumed, one may expect that at initial ($\Phi < 10^{15}$ cm^{-2}) irradiation stages clusterization of a semiconductor matrix [9] may grow. If the gap energy increases with pressure P (i.e., $dEg/dP > 0$), then the photoconduction long-wavelength edge shifts. This is also favored by some phenomena that accompany nuclear reactions induced by thermal neutron irradiation, such as γ-quanta and high-energy electrons production during nuclear transmutation. If, however, the above clusters are small and their properties differ from those of a crystal matrix but slightly, then they practically do not manifest themselves in electrophysical measurements. This agrees with the fact that changes in the majoirity charge carrier mobility are moderate.

Conclusions

Exposition of $Hg_{1-x}Cd_xTe$ single crystals to low fluences of thermal neutron irradiation leads to production of stable donor- and acceptor- type defects. This results from activation of ^{113}Cd isotope nuclei accompanied by the (n, γ) reaction. Recombination in the appearing nonuniform regions (clusters) is determined by the deeplying energy level, $E_a \approx 50$ meV.

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