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Kinetic Effects in Cadmium Antimonide Crystals Before and After Gamma-Irradiation

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The influence of large doses of ^{60}Co gamma-rays on the electrical properties of cadmium antimonide crystals with different electrical conductivity has been investigated. It is revealed that radiation defects of both donor and acceptor types are introduced into the lattice of the material with gamma-irradiation. Their influence depends on the level of doping and the type of conductivity of the starting material. The effectiveness of removal of carriers is a consequence of the involvement of impurity atoms in the formation of corresponding radiation defects with deep levels.

Keywords: cadmium antimonide, gamma-irradiation, radiation dose, radiation defects, carrier concentration.

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Introduction

The existence of the multilateral influence of nuclear radiation on the properties of semiconductors reveals the great applied importance of radiation physics. The most important problem is the radiation resistance of semiconductors and semiconductor devices [1-3]. This determines the reliability of electronic systems in the context of nuclear radiation, in the nuclear industry and others. By selecting the type of radiation, dose, and irradiation conditions, one can achieve a direct change in the properties of the irradiated semiconductor devices. Thus, new effective methods of radiation technology are emerging [4-7].

Transformations of primary radiation defects into more complex disturbances begin only with their concentration and are conditioned by the number of existing defects, the rate of formation of new ones, and the temperature at which the crystal is irradiated [8]. As a result of irradiation, steady changes in the resistivity gradients result from changes in the carrier concentration and mobility caused by secondary radiation defects [9]. The change in the carrier concentration due to irradiation occurs differently in crystals with different impurity content and conductivity type and is a function of the initial impurity concentration [10-11].

I. Experimental results and their discussion

This paper investigates cadmium antimonide crystals grown by band melting, specially non-doped, and indium doped before and after γ-irradiation. Non-doped CdSb crystals had p-type conductivity due to small acceptors with $E_1 = 3.65$ meV and $E_2 = 6.2$ meV before irradiation. These acceptors are associated with cadmium (V_{Cd}) vacancies. The atoms of In predominantly enter the Cd lattice, leading to an increase in the concentration of free electrons. Impurities of In are widely used in doping to obtain n-CdSb with different free electron concentrations [12]. The samples were irradiated from a source of ^{60}Co at doses of $10^{18} \div 10^{19}$ cm^{-2}. At high doses of radiation, the concentration of radiation defects exceeds the concentration of uncontrolled impurities and the role of intrinsic radiation defects in determining the physical properties of a semiconductor is dominant. The exposure temperature did not exceed 340 K. To reduce the radioactivity to a safe level, the samples were kept in hot cells for $5 \div 8$ months.

According to the measurements of the specific

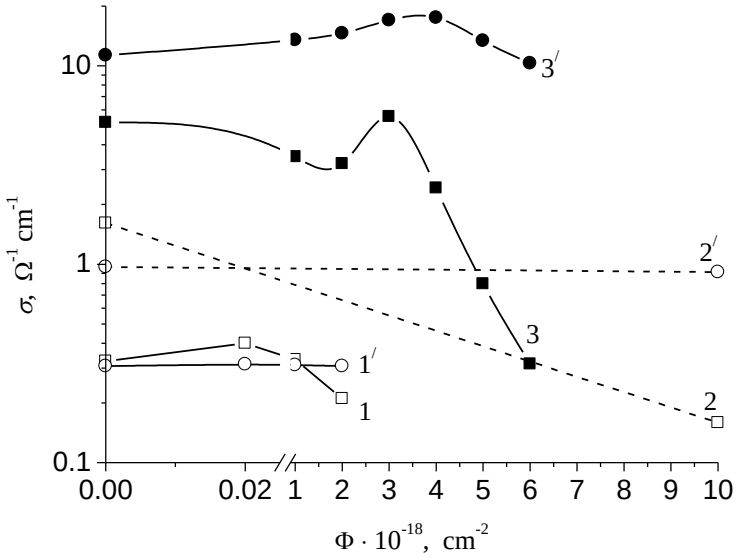

Fig. 1. Dose dependences of specific conductivity $\sigma = f(\Phi)$ for CdSb (1-2') and CdSb<In> (3, 3') crystals at temperatures T, K: 1-3 – 77; 1'-3' – 295.

conductivity and the Hall effect, the dose dependences of specific conductivity $\sigma = f(\Phi)$ for p-CdSb crystals were constructed (Fig. 1). The appearance of radiation disturbances in antimony cadmium alters its electrical properties. However, this change does not increase in proportion to the integral dose, but in a complex way. These changes are especially noticeable at $T = 77$ K. The irradiation leads to an increase in the specific conductivity of the crystal from 0.325 to 0.4 $Ohm^{-1}cm^{-1}$ at $\Phi = 0 \div 1.9 \times 10^{16}$ cm^{-2} ($0 \div 10^7$ P), and at a further increase in the radiation dose $\Phi > 1.9 \times 10^{16}$ $см^{-2}$ ($> 10^7$ P) to its decrease (0.210 $Ohm^{-1}cm^{-1}$) below the initial value (curve 1 Fig. 1). When irradiated with doses of $\approx 10^{19}$ cm^{-2} of lower-resistance p-CdSb crystals (line 2 Fig. 1), the specific conductivity decreases by an order of 1.61 to 0.16 $Ohm^{-1}cm^{-1}$. The complex nature of $\sigma = f(\Phi)$ dependence was observed (curves 3, 3' Fig. 1) also in indium doped cadmium antimonide crystals CdSb <In>, by irradiation with their γ-quanta ^{60}Co [11].

When exposed to doses of $\Phi = 0 \div 1.9 \times 10^{16}$ cm^{-2} ($0 \div 10^7$ P) p-CdSb, additional impurity centers arise that have the same nature as the impurities in the original crystal. The appearance of additional acceptors and the number of holes in the valence band leads to an increase in nitrogen temperatures [8]. The decrease in conductivity with increasing dose γ-irradiation of more than 1.9×10^{16} cm^{-2} ($> 10^7$ P) is explained by the decrease in the number of centers providing hole conduction [10].

Creating structural disturbances in p-CdSb γ-irradiation with doses up to 1.9×10^{16} cm^{-2} (10^7 P) leads to an increase in the conductivity, carrier concentration and mobility [8]. With a further increase in dose, the nature of the change in these values becomes reversible, although the number of disturbances continues to increase. Probably, the emerging primary radiation disturbances are transformed at their concentration into centers, which release the previously captured valence electrons. This causes them to grow in the valence band and reduce the number of major carriers (holes). The decrease in the number of holes (less than in the original crystal) after doses of $> 1.9 \times 10^{16}$ cm^{-2} ($> 10^7$ P) indicates that there is an additional carrier scattering mechanism caused by irradiation. All this indicates the emergence of additional interaction between emerging violations.

According to measurements [13] of specific conductivity and Hall effect in the dose range $\Phi = (1 \div 6) \times 10^{18}$ cm^{-2} dose dependences of carrier concentration $n = f(\Phi)$ (Fig. 2) for CdSb<In> are

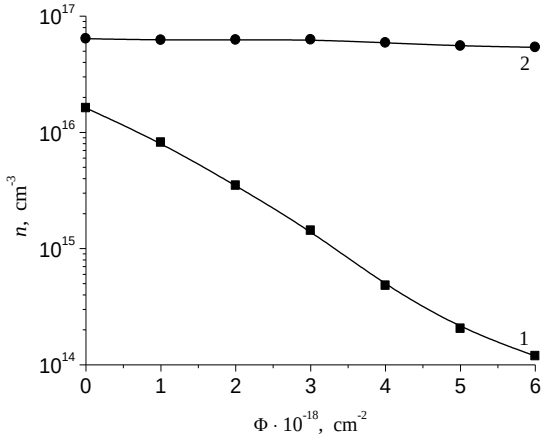

Fig. 2. Dose dependences of carrier concentration $n = f(\Phi)$ for CdSb<In> crystals at temperatures T, K: 1 – 77; 2 – 295.

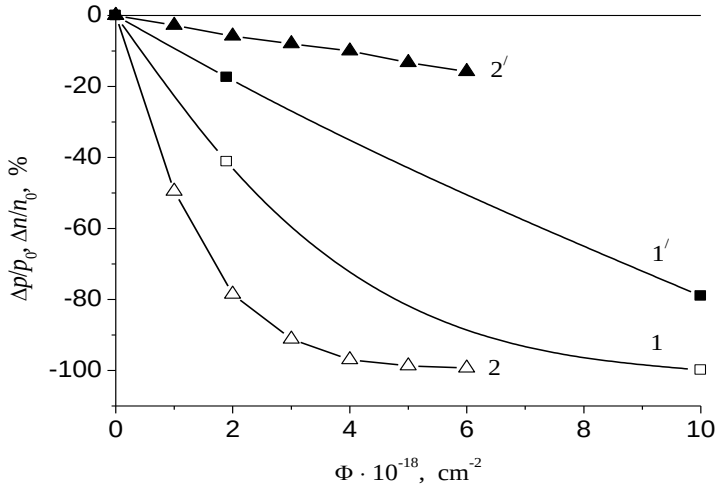

Fig. 3. Dose dependences of relative change of carrier concentration $\frac{\Delta p}{p_0} = f(\Phi)$, $\frac{\Delta n}{n_0} = f(\Phi)$ for CdSb crystals at $T = 77$ K (1-2) and 295 K (1'-2') temperatures: 1, 1' – p-CdSb; 2, 2' – n-CdSb<In>.

Table 1

Removal efficiency of current carriers in the γ -irradiated cadmium antimonide

	p-CdSb, cm^{-1}		n-CdSb<In>, cm^{-1}
p_0, n_0, cm^{-3}	3.3×10^{15}	8.1×10^{16}	6.4×10^{16}
$T \approx 77$ K	2.43×10^{-4}	1.40×10^{-3}	$2.68\times10^{-3} \div 8.02\times10^{-3}$
$T \approx 295$ K	3.00×10^{-4}	6.40×10^{-3}	$1.61\times10^{-3} \div 1.86\times10^{-3}$

constructed.

There are practically no changes in the carrier concentration from the dose at room temperature (curve 2 Fig. 2). However, at nitrogen temperatures (curve 1 Fig. 2) the carrier concentration with increasing radiation dose has a more pronounced character. The decrease in the concentration in CdSb<In> is explained by the removal of electrons from the conduction band, which is likely to cause, according to [9], the formation of radiation defects with deep levels in the bandgap of the crystal. In addition, the CdSb crystals are characterized by the existence of heterogeneities in the distribution of impurities along the growth axis, which in turn can significantly affect the value of kinetic coefficients [14].

The change in the carrier concentration after irradiation of $\Phi > 10^{18}$ cm^{-2} occurs differently for different samples at $T = 77$ K and 295 K (Fig. 3). To reduce the carrier concentration as at $T = 77$ K (from 1.1×10^{15} to 6.6×10^{14}, from 1.4×10^{16} to 1.2×10^{13} cm^{-3}), and 295 K (from 3.3×10^{15} to 2.7×10^{15}, 8.1×10^{16} to 1.7×10^{16} cm^{-3}) γ -irradiation of CdSb, CdSb<In> leads. Much more significant changes are observed at lower temperatures. For p-CdSb at both $T = 77$ K and $T = 295$ K temperatures, samples with a lower (curves 1, 1') initial carrier concentration were found to be more sensitive to radiation. With slight changes with increasing dose of ^{60}Co γ -quanta at $T \approx 295$ K (curve 2), CdSb<In> at $T \approx 77$ K becomes very sensitive to irradiation and at $\Phi \approx 5\times10^{18}$ cm^{-2} the dependence 2' is saturated.

The removal efficiency (rate) of current carriers $\Delta p/\Phi$, $\Delta n/\Phi$ emphasizes the difference in the behavior of these materials during irradiation (Table 1).

Figure 4 shows the calculated $\Delta n/\Phi$ dependences (1 and 2) of the removal efficiency of current carriers when

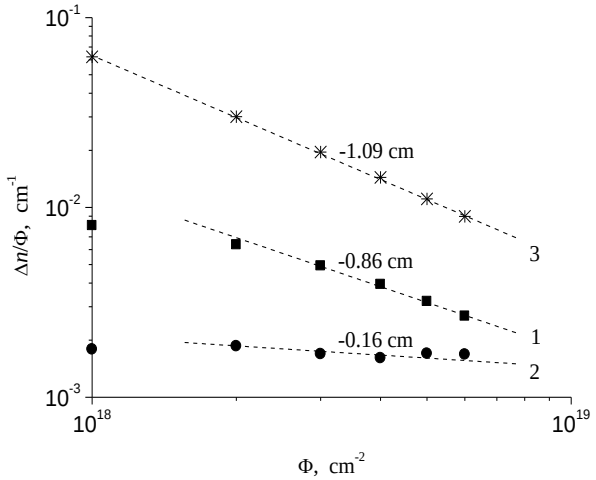

Fig. 4. Removal efficiency (rate) of current carriers (1, 2) and introduction of deep energy levels (3) as a function of dose ^{60}Co γ -quanta $\frac{\Delta n}{\Phi} = f(\Phi)$ for CdSb<In> crystals at temperatures T, K: 1 – 77; 2, 3 – 295.

changing the dose of ^{60}Co γ-quanta of CdSb<In> crystals at $T = 77$ and 295 K. The values $\Delta n/\Phi$ remain practically constant (curve 2) with increasing radiation dose at $T \approx 295$ K. More tangible changes are observed (curve 1) at $T \approx 77$ K, that is, CdSb<In> becomes sensitive to γ-irradiation. The change from Φ of the removal efficiency of current carriers calculated at $T = 77$ and 295 K is described accordingly:

$$\frac{\Delta n}{\Phi} \propto \Phi^{-0,86}, \quad \frac{\Delta n}{\Phi} \propto \Phi^{-0,16}.$$

These results show that the removal efficiency of current carriers is significantly dependent on the concentration of donors and acceptors in crystals. Apparently, impurity atoms are involved in the formation of corresponding radiation defects with deep levels. When ionization levels of radiation defects are fully ionized, the carrier concentration does not reach the initial value before irradiation. This indicates that irradiation causes defects with deeper levels. Analysis of the rates of formation of deep centers $\Delta n/\Phi$ (where Δn – the carrier concentration of in the ionization regions ($T \approx 295$ K) of these levels after irradiation) shows that the efficiency decreases with increasing dose of ^{60}Co γ-quanta (dependence 3 Fig. 4) by law:

$$\frac{\Delta n}{\Phi} \propto \Phi^{m}, \text{ or } \Delta n = C\Phi^{m+1},$$

where m calculated when $T = 295$ K is –1.09 cm.

The decline Δn with increasing dose of ^{60}Co γ-quanta is explained by the introduction of radiation defects N_D ($n_0 - N_D = \Delta n$). The concentration calculations N_D show that it is described by the radiation dose dependence $N_D = C\Phi^{0,09}$.

The authors of [9] investigated in detail the changes in the carrier concentration under n-Ge γ-irradiation with a wide concentration range of the donor impurity Sb and confirmed the assumption that these changes are a function of the initial impurity concentration. With regard to CdSb, with a small amount of experimental data, information about the nature of radiation defects and their effect on the change in electrophysical parameters is ambiguous, due to a number of reasons.

Changes in the carrier concentration when γ-irradiation from the impurity concentration is described by the dependence of the type

$$\Delta n = K n_0^m, \qquad (1)$$

where $\Delta n = n_0 - n$ (n_0 and n are the concentration of current carriers before and after γ-irradiation), K is depends on the irradiation dose, and the average value of the exponent m is a function of temperature.

The nature of the relative change in the carrier concentration after γ-irradiation from the impurity concentration for CdSb and CdSb<In> crystals is also different (Fig. 5). These changes are more pronounced for specimens with a higher initial impurity level. At $\Phi > 10^{18}$ cm^{-2} ($T = 295$ K) $\Delta p/p_0$ for CdSb increases from ≈ 17.4 % (at $p_0 \approx 3.3 \times 10^{15}$ cm^{-3}) to ≈ 79 % (at

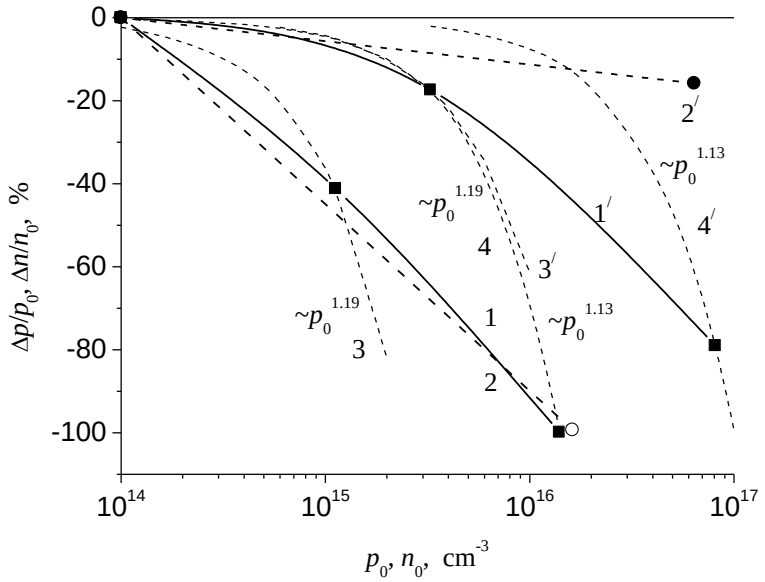

Fig. 5. Relative change of carrier concentration after γ-irradiation as a function of impurity concentration $\Delta p/p_0 = f(p_0)$, $\Delta n/n_0 = f(n_0)$ for CdSb at $T \approx 77$ (1-4) and 295 K (1'-4 '):
1, 1' – p-CdSb; 2, 2' – n-CdSb <In>; 3, 3', 4, 4' – the dependences described (2).

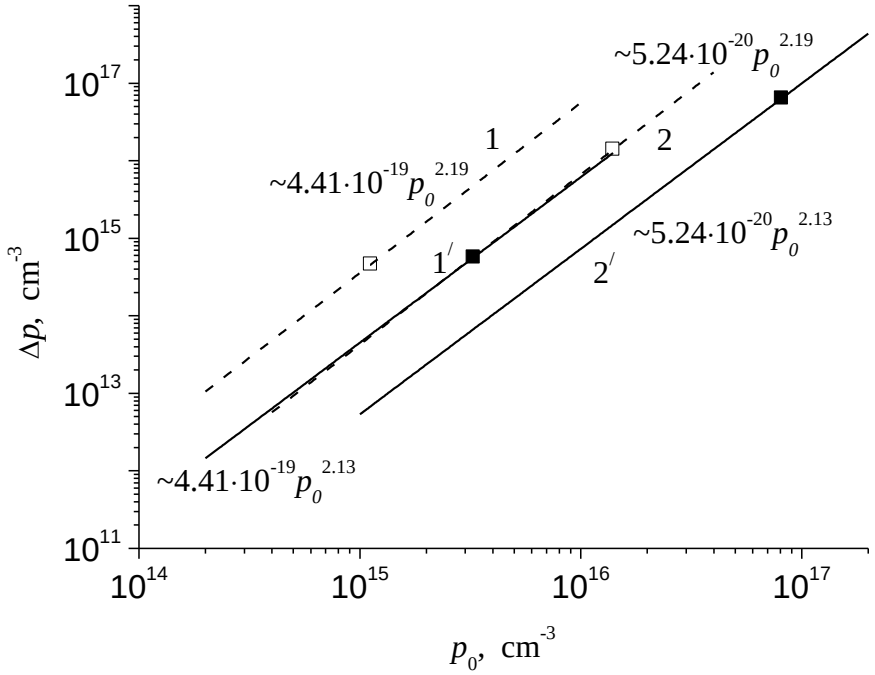

Fig. 6. Change of carrier concentration as a function of impurity concentration $\Delta p = f\left(p_0\right)$ after γ -irradiation p-CdSb at temperatures $T \approx 77$ (1, 2) та 295 K (1', 2'): 1, 1' – $\Phi = 1.9\times10^{18}$ см$^{-2}$; 2, 2' – $\Phi = 10^{19}$ см$^{-2}$.

$p_0 \approx 8.1\times10^{16}$ cm^{-3}), and for CdSb<In> $n_0 \approx 6.4\times10^{16}$ cm^{-3}, $\Delta n/n_0 \approx 15.8$ % (curves 1'-2' Fig. 5). At $T = 77$ K, these values are respectively: 41.2 %, 99.9 %, 99.3 % (curves 1-2 Fig. 5).

Considering that the change in the carrier concentration in a specially non-alloyed p-CdSb is described Equation 1, the $\Delta p = f\left(p_0\right)$ dependence was determined by irradiation with the ^{60}Co γ quanta ($\Phi = 1.9\times10^{18}$ cm^{-2} та 10^{19} cm^{-2}), solving the system of equations

$$\begin{cases} \Delta p_1^{77} = K_1\left(p_{01}^{77}\right)^{m77} \\ \Delta p_1^{295} = K_1\left(p_{01}^{295}\right)^{m295} \\ \Delta p_2^{77} = K_2\left(p_{02}^{77}\right)^{m77} \\ \Delta p_2^{295} = K_2\left(p_{02}^{295}\right)^{m295} \end{cases}, \qquad (2)$$

$\Delta p = p - p_0$ is change in concentration before (p_0) and after γ -irradiation (p) at $T = 77$ and 295 K (indices of the corresponding values "77" and "295"); indices "1" and "2" correspond to p-CdSb with different p_0; K_1, K_2 are coefficients that depend on the amount of Φ radiation dose. The solutions system of Equations 2 are $m_{77} = 2.19$; $m_{295} = 2.13$; $K_1 = 4.41\times10^{-19}$; $K_2 = 5.24\times10^{-20}$.

The relationship between Δp and p_0 at $T \approx 77$ and 295 K is given by $\Delta p^{77} = K\left(p_0^{77}\right)^{2.19}$ and $\Delta p^{295} = K\left(p_0^{295}\right)^{2.13}$.

Figure 6 shows $\Delta p = f\left(p_0\right)$ dependences on impurity concentration at $T = 77$ (curves 1, 2) and 295 K (curves 1', 2') and radiation doses $\Phi = 1.9\times10^{18}$ cm^{-2} (curves 1, 1'; $K_1 = 4.41\times10^{-19}$) and 10^{19} cm^{-2} (curves 2, 2'; $K_2 = 5.24\times10^{-20}$).

Conclusions

When gamma irradiation of cadmium antimonide occurs "purification" of the material. The reason for the removal of current carriers (electrons from the conduction band and holes from the valence band) is the formation of radiation defects with deep energy levels in the band gap. The revealed changes in the electrophysical parameters for n-CdSb<In> crystals can be explained by the prevailing formation in the material of acceptor-type radiation defects, the energy levels of which are in the lower half of the band gap, where as for p-CdSb crystals by the introduction of more donor-type radiation defects the number of radiation acceptors and the shift of the Fermi level under the influence of radiation into the permissible energy region.

Thus, when irradiated with CdSb, radiation defects of both donor and acceptor types are introduced into the lattice of the material, and their effect on the properties depends on the initial impurity concentration, the doping level, and the conductivity type of the starting material.

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Кінетичні ефекти у кристалах антимоніду кадмію до і після гамма-опромінення

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Проведено дослідження впливу великих доз гамма-квантів ^{60}Co на електричні властивості кристалів антимоніду кадмію з різною вихідною електропровідністю. Виявлено, що при гамма-опроміненні в ґратку матеріалу вводяться радіаційні дефекти як донорного, так і акцепторного типів. Їх вплив залежить від рівня легування та типу провідності вихідного матеріалу. Ефективність видалення носіїв є наслідком участі атомів домішки в утворенні відповідних радіаційних дефектів з глибокими енергетичними рівнями.

Ключові слова: антимонід кадмію, гамма-опромінення, доза опромінення, радіаційні дефекти, концентрація носіїв.