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TEMPERATURE DEPENDENCIES OF FERMI LEVEL IN SYNGLE CRYSTALS OF CADMIUM ANTIMONIDE WITH DEEP ENERGY LEVELS

The article calculates and analyzes the dependence of Fermi level for temperature 77 – 300 K in CdSb single crystals with deep energy levels E_c – 0.12 eV, E_c – 0.16 eV and E_c – 0.3 eV which are brought about, correspondingly: in the first case – by doping with tellurium, in the second case – by γ-irradiation a dose Φ ~·10^{18} γ-quant/cm^2 of doped with tellurium crystals by and in the third case – by γ-irradiation a dose Φ ~ 4·10^{18} γ-quant/cm^2 of doped with indium crystals by. It is shown at temperature rise Fermi level decreases in the direction from the conduction band to the middle of forbidden band on account of the fad that charge carriers concentration increases in conduction band and decreases on the deep levels, i.e., they become exhausted.

Keywords: *Fermi level, single crystal, CdSb, deep energy level, γ-irradiation, doping.*

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ТЕМПЕРАТУРНІ ЗАЛЕЖНОСТІ РІВНЯ ФЕРМІ В МОНОКРИСТАЛАХ АНТИМОНІДУ КАДМІЮ З ГЛИБОКИМИ ЕНЕРГЕТИЧНИМИ РІВНЯМИ

У статті розраховано і проаналізовано залежності рівня Фермі для температури 77 – 300 К в монокристалах CdSb з глибокими енергетичними рівнями E_c – 0,12 еВ, E_c – 0,16 еВ та E_c – 0,3 еВ, які отримані відповідно: у першому випадку – легуванням телуром, у другому випадку – γ-опроміненням дозою Φ ~·10^{18} γ-квант/см^2 легованих телуром кристалів і в третьому випадку – γ-опроміненням дозою Φ ~ 4·10^{18} γ-квант/см^2 легованих індієм кристалів. Показано, що при підвищенні температури рівень Фермі знижується в напрямку від зони провідності до середини забороненої зони внаслідок того, що концентрація носіїв заряду збільшується в зоні провідності і зменшується на глибоких рівнях, тобто вони виснажуються.

Ключові слова: *рівень Фермі, монокристал, CdSb, глибокий енергетичний рівень, γ-опромінення, легування.*

Statement of the problem. The presence of various defects which develop in semiconductor volume in consequence of doping with certain impurities in the process of crystal growing or on account of irradiation leads to the formation of deep energy levels in the forbidden band. Determination of Fermi level position in dependence on temperature is of interest when studying the band structure of semiconductors with deep levels so long as it gives useful information concerning the distribution of charge carriers in energy bands.

Analysis of the latest research and publications. The study of CdSb band structure has been carried out in works [1-4]. In particular, authors [4] investigated the position of Fermi level for crystal of cadmium antimonide doped with cooper at low temperatures (4.2 – 50 K). The article [5] 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 effect of radiation defects in specially non-doped and tellurium-, indium-doped cadmium antimonide crystals before and after high doses of ^{60}Co *γ*-quanta irradiation was studied on the basis of measurements and analysis of temperature dependences of electrical conductivity, Hall effect in the temperature range (78 – 295) K [6]. Gamma-irradiation with high doses leads to significant changes in electrophysical properties. The mechanisms responsible for these changes are established and a theoretical explanation of these effects is given.

Goals of the article. Investigate the temperature effect on the position of the Fermi level for the range 77 – 300 K in CdSb single crystals with deep energy levels.

Presentation of the main material. We have investigated dependencies of Fermi level for temperature interval 77 – 300 K in CdSb single crystals with deep energy levels E_c – 0.12 eV, E_c – 0.16 eV and E_c – 0.3 eV which are brought about, correspondingly: in the first case – by doping with tellurium, in the second case – tellurium-doped crystals are *γ*-irradiation with a dose Φ ~10^{18} *γ*-quant/cm^2 and in the third case – indium-doped crystals are *γ*-irradiation with a dose Φ ~ 4·10^{18} *γ*-quant/cm^2.

According to [7], the equation expressing the condition of electroneutrality and enabling the determination of Fermi level position in semiconductors with deep levels may be written down in the form:

$$n + N_a + n_d = p + N_d, \qquad (1)$$

where n and p is, correspondingly, concentration of free electrons and holes; N_d is concentration of deep level centers; N_a is concentration of shallow acceptors which compensate deep level centers; n_d is concentration of unionized donors which is determined as follows:

$$n_d = \frac{N_d}{1 + g \cdot exp(\frac{E_f - E_d}{kT})}, \quad (2)$$

where g is spin degeneracy factor; E_f is Fermi level energy; E_d is energy of deep level activation.

Taking into account the relations $n_i^2=np$ (n_i is charge carriers own concentration) and $n = N_c\, exp(-\frac{E_f}{kT})$ we obtain cubic equation with respect to n:

$$n^3 + n^2(N_a + N'_c) - n\left(N'_c(N_d - N_a) + n_i^2\right) - n_i^2 N'_c = 0, \quad (3)$$

where $N'_c = \frac{1}{2} N_c\, exp(\frac{\alpha}{k}) exp(-\frac{E_d}{kT})$ and N_c is states effective density in conduction band; α is coefficient that takes into account the dependence of deep level activation energy on temperature.

The analysis of Eq. 3 shows that at low temperature, when $n << N_a < N_d$, its solution coincides with expression describing temperature dependency of free electrons concentration in case of partially compensated donor level:

$$n = gN_c(1/K - 1)\exp(\alpha / K)\exp(-E_d / kT), \quad (4)$$

where $K=N_a/N_d$.

Holes concentration at low temperatures is:

$$p = \frac{n_i^2}{n} \sim \exp(-E_d^* / kT), \quad (5)$$

where $E_d^* = E_g - E_d$; E_g is forbidden band with.

At high temperatures ($N_a << n << N_d$) smoothly come nearer to n_i and at further temperature rise a region of intrinsic semiconductor at which $n_i=n=p$ ensues.

It is known [7] that equilibrium concentration of electrons for non-degenerate semiconductor equals:

$$n = N_c\, exp\left(\frac{E_f - E_c}{kT}\right). \quad (6)$$

Taking into account that the solution of Eq. 3 at low temperatures ($n << N_a < N_d$) has the form Eq. 4 we shall obtain expression for determination of Fermi level position:

$$E_f = E_d + kT\, ln\left(\frac{N_d - N_a}{2N_a}\right). \quad (7)$$

Accordingly, at high temperatures:

$$E_f = E_c + kT\, ln\left(\frac{n}{N_c}\right). \quad (8)$$

Temperature dependencies of Fermi level position $E_f(T)$ for CdSb single crystals with deep energy levels in forbidden band have been determined with the use of experimentally obtained dependences of charge carriers concentration on temperature (Fig. 1).

As Figure 1 indicates, the obtained dependences $E_f(T)$ may be conditionally divided into low temperatures region, impurity exhaustion region and high temperatures region. At low temperatures average energy of lattice thermal vibrations cannot afford substantial excitation of valence band electrons and their transition to conduction band. However, it should be noted that this energy is sufficient enough for excitation the charge carriers from deep energy levels and their transition to conduction band. Therefore, only impurities charge carriers are practically exited at low temperatures.

Conclusions. At temperature rise the concentration of charge carriers increases in the conduction band and decreases on the deep levels. i.e., they are being exhausted. At full exhaustion of impurity the concentration of charge carriers in the conduction band becomes practically equal to donor impurity concentration. At further rise of temperature more intensive excitation of proper carriers begins and Fermi level moves in the direction to the middle of forbidden band. It should also be noted that after irradiation the lowering velocity of Fermi level for crystals with deeper radiation level E_c – 0.3 eV is greater (Figure 1, c) than that for crystals with shallower level E_c – 0.16 eV (Figure 1, b).

The obtained results are of practical value, in particular, for various calculations with the use of Fermi level value in dependence on temperature.

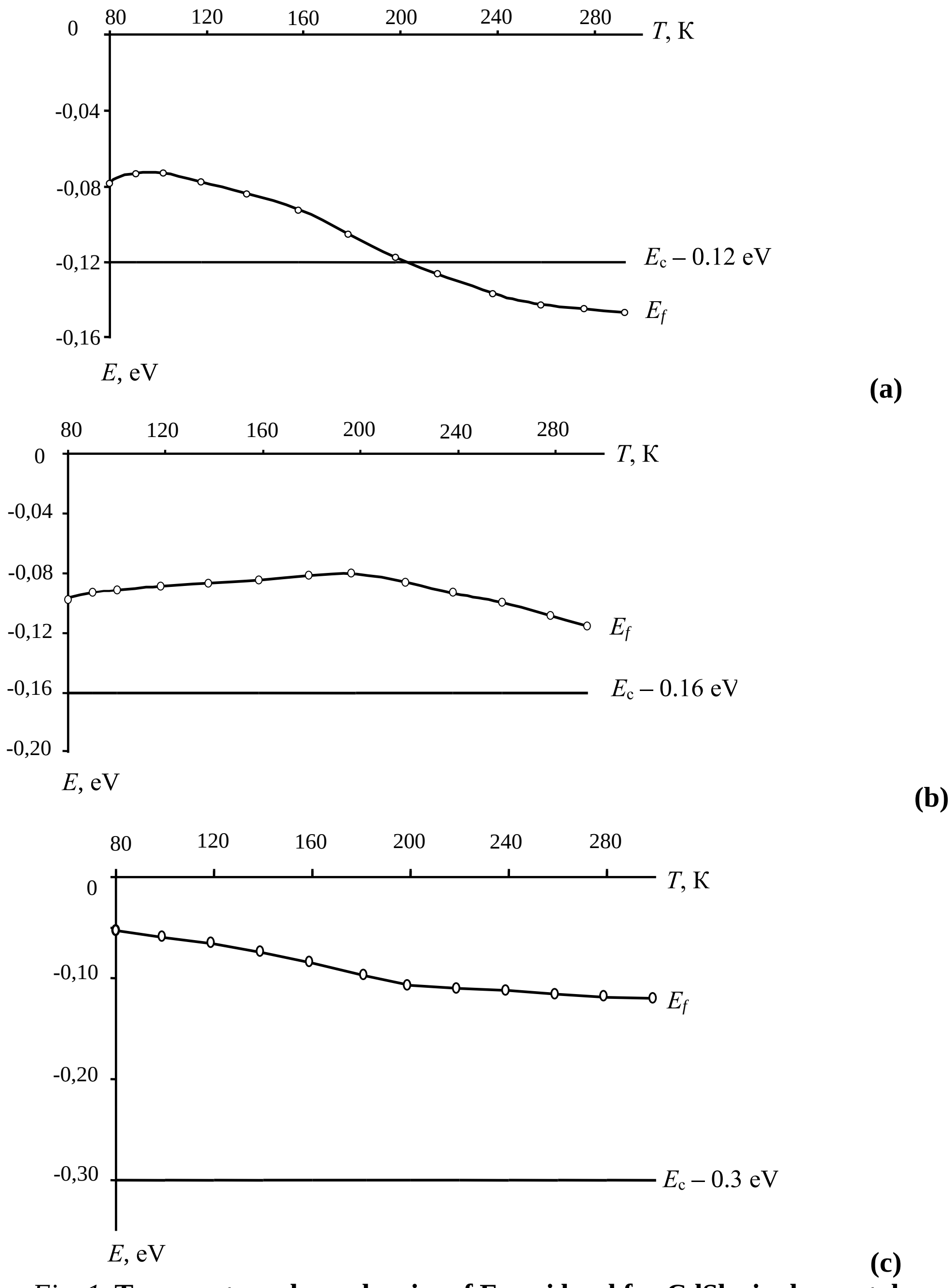

Fig. 1. **Temperature dependencies of Fermi level for CdSb single crystals:**
(a) doped with tellurium;
(b) doped with tellurium and γ-irradiated by a dose $\Phi \sim 10^{18}$ γ-quant/cm^2;
(c) doped with indium and γ-irradiated by a dose $\Phi \sim 4 \cdot 10^{18}$ γ-quant/cm^2

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