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Electrophysical properties of $Hg_2MnInTe_6$ single crystals for X- and γ-radiation detectors

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ABSTRACT. The electrophysical properties of $Hg_2MnInTe_6$ single crystals, grown by the modified zone melting method, were studied. In order to expand the band gap, a multiple part of Hg in 3(HgTe)-In_2Te_3 was replaced by an isovalent metal with a smaller ionic radius - Mn. The single crystals had an n-type conductivity and a resistivity of ~ $5\cdot10^6$ Ω×cm (293 K), which was determined from the linear region of the I-V curve for the In/$Hg_2MnInTe_6$/In structure with two ohmic contacts. The degree of compensation (~ 0.99) of the semiconductor material and the energy position of the deep level E_d (~ 0.37-0.4 eV) responsible for the dark conductivity were determined from the measurements of the temperature dependence of the resistivity and space charge limited current. The width of the band gap of single crystals, which is equal to E_g = 1.15 eV (293 K), was determined from optical measurements. Au/$Hg_2MnInTe_6$/In structures with rectifying contacts were made.

I-V curve for Au/*n*-$Hg_2MnInTe_6$/In structure and the dependence of resistivity vs. temperature for In/n-$Hg_2MnInTe_6$/In structure

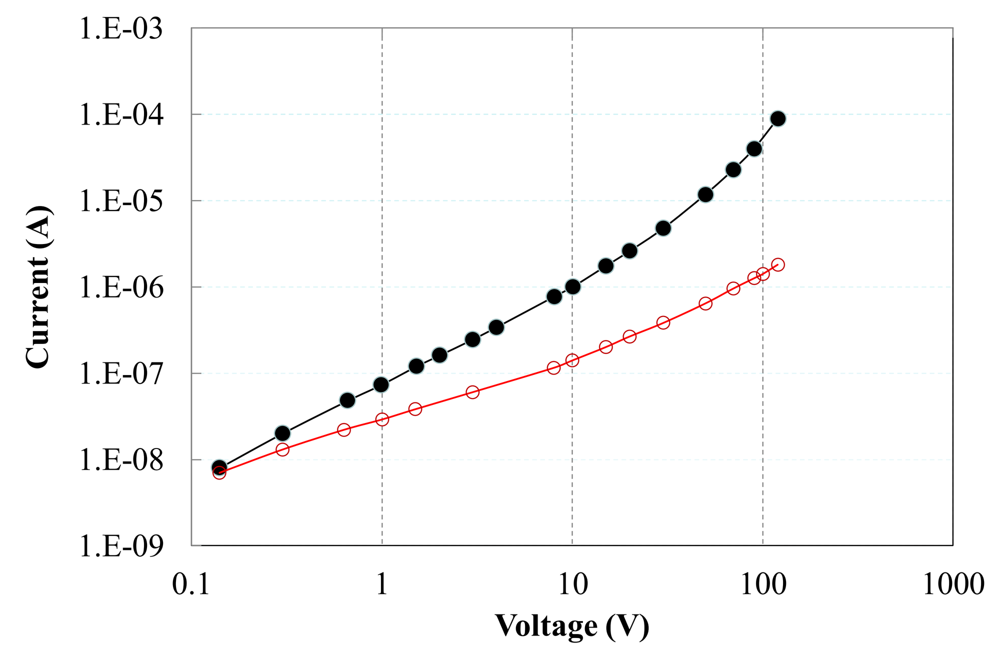

Fig. 1. I-V curve for the Au/n-$Hg_2MnInTe_6$ /In structure. Full circles – direct, open circles – inverted offset (300 K).

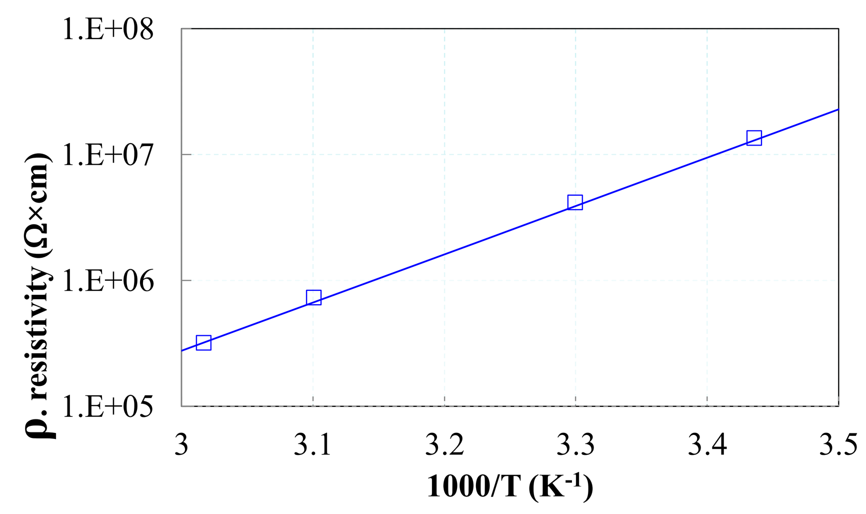

Fig. 2. The dependence of resistivity vs. temperature. Activation energy ≈ 0.76 eV.

Dependence of differential resistance on voltage

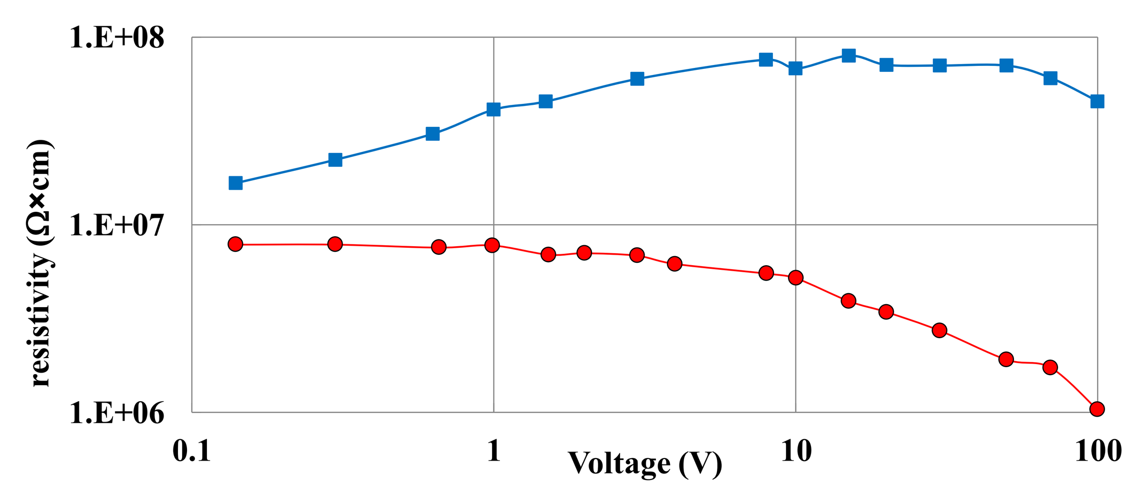

Fig. 3. Dependence of differential resistance on voltage for Au/n-$Hg_2MnInTe_6$ /In structure. Full circles – direct, squares – inverted offset (300 K). "Minus" was applied to Au-electrode. Crystal thickness was 0.74 mm.

Calculation of compensation compensation for n-$Hg_2MnInTe_6$ single crystals

$$p + N^{+}_{d} = n + N^{-}_{a} \qquad (1)$$

$$p + \frac{N_d}{1+\exp\left(\frac{\Delta\mu - E_d}{kT}\right)} = n + \frac{N_a}{1+\exp\left(\frac{E_a-\Delta\mu}{kT}\right)} \qquad (2)$$

$$n = \frac{N_c}{1+\exp\left(\frac{E_g-\Delta\mu}{kT}\right)} \qquad (3)$$

$$p = N_v \frac{N_v}{1+\exp\left(\frac{\Delta\mu}{kT}\right)} \qquad (4)$$

$$\rho(T) = \frac{1}{q(n\mu_n + p\mu_p)}, \qquad (5)$$

$$\Delta\mu(T) = E_g + kT\ln\left(\frac{1 \pm \sqrt{1-4q^2\rho^2\mu_n\mu_p N_v N_c \exp\left(-\frac{E_g}{kT}\right)}}{2q\rho\mu_n N_c}\right) \qquad (6)$$

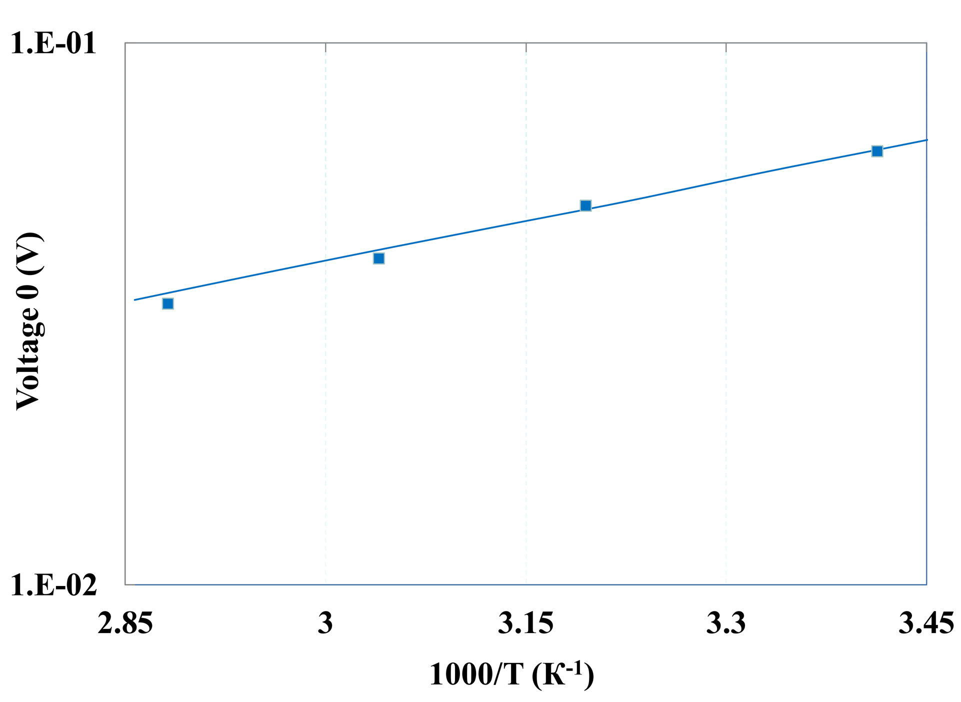

Fig. 4. Dependence of the transition voltage from the I–V section, where Ohm's law is fulfilled, to SCLC part vs. temperature. Activation energy ≈ 0.1 eV.

Experimental dependence of ρ(T) (Equation 6), obtained from Fig. 2.

Match of the calculation and experiment is obtained when E_d ~ 0.37-0.4 eV and N_d/N_a = 0,99.

$E_g(T) = E_{go} - \gamma\cdot T$, E_{go} = 1.27 eV, $\gamma = 4.0\times10^{-4}$ eV K^{-1}

μ_n =200 cm²/(V·s)
μ_p = 70 cm²/(V·s)

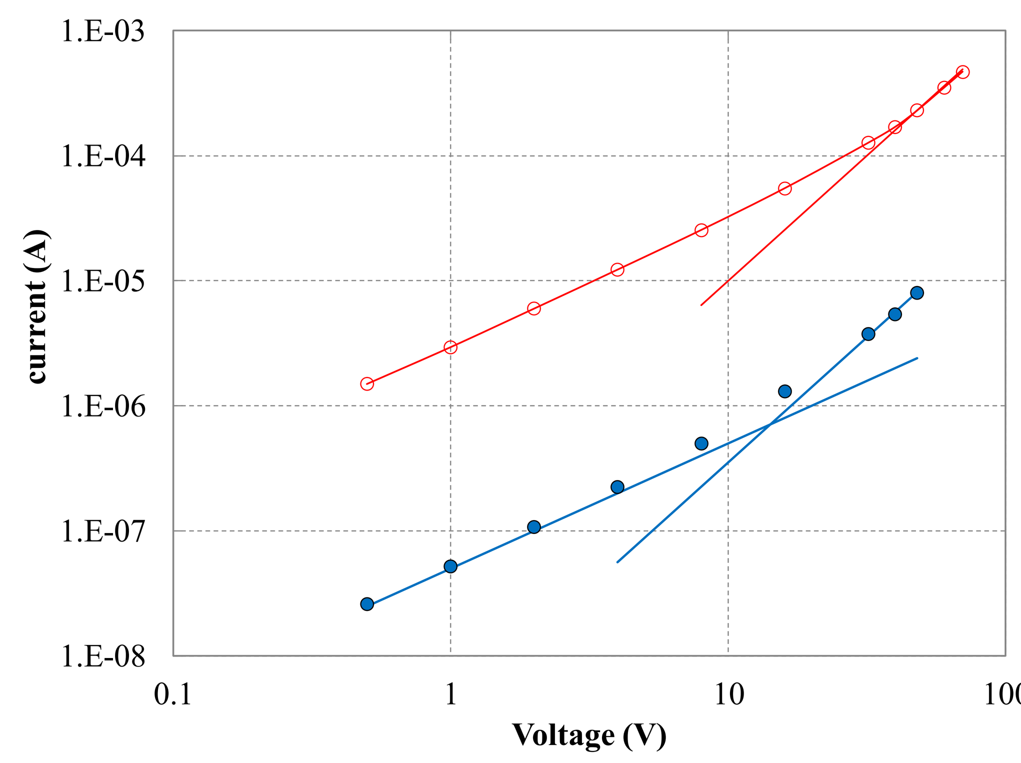

Fig. 5. I-V curve for In/n-$Hg_2MnInTe_6$/In: full circles - 293 K, open circles - 347 K. Crystal thickness - 0.74 mm.

Determination of the band gap, the product $(\mu\tau)_n$ and the amount of compensation of the In/n-$Hg_2MnInTe_6$ single crystals

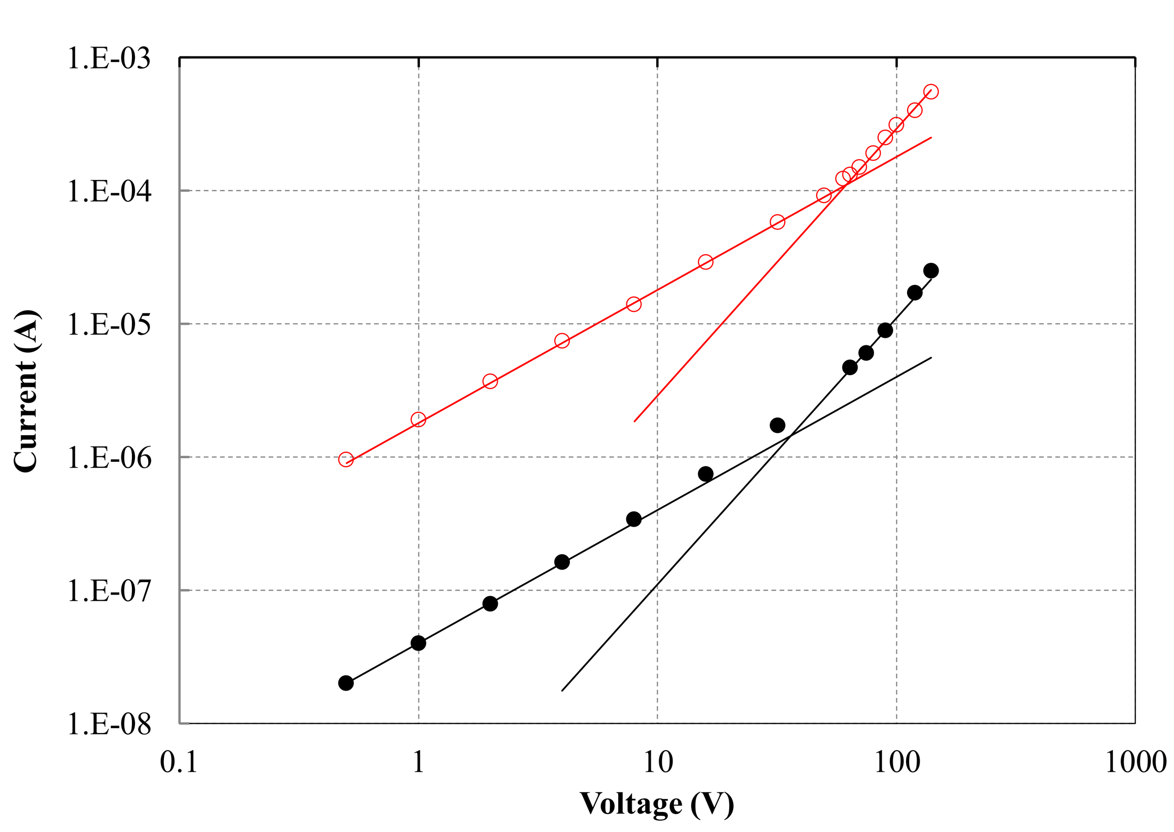

Fig. 6. I-V curve for In/n-$Hg_2MnInTe_6$/In: full circles - 293 K, open circles - 347 K. Crystal thickness was 1.0 mm.

For In/$Hg_2MnInTe_6$/In structures with two ohmic contacts from the I–V measurements in the current range, where the Ohm law applies and in the SCLC range, the product $(\mu\tau)_n$ was determined, which for different parts of the ingot was $(\tau\mu)_n \approx$ 0.015-0.031 V^{-1}cm^2.

$$(\mu\tau)_n = d^2/V_o \qquad (7)$$

where d is the thickness of the crystal, Vo is the transition voltage of the I–V curve, where Ohm's law (I~V) transforms to the quadratic ($I\sim V^2$) dependences, which is formed by the SCLC (the crystal thickness d=0.074 mm, Vo ≈ 16 V).

Based on the analysis of the measurement results presented in Fig. 2 and Figs. 4-6 and the numerical solution of the electroneutrality equation (1) using (5) and (6), we conclude that single crystals In/n-$Hg_2MnInTe_6$ are highly compensated.

To determine the width of the band gap, three plates with a size of 4x4 mm² and a thickness of d_1 =0.5 mm, d_2=0.25 mm and d_3 = 0.1 mm were prepared. For each plate the width of the band gap of single crystals Eg (d) from the optical transmission measurements was determined:

$$\alpha_\omega \sim (\hbar\omega - E_g)^{1/2} \qquad (8)$$

The value of Eg is determined by extrapolating the rectilinear sections of the dependences α_ω, built in the coordinates $\alpha_\omega^{-1/2}$–$\hbar\omega$, to the cross-section with the energy axis $\hbar\omega$. The desired value was determined according to

$$E_g = 1.5 - 0.06 \lg d \qquad (9)$$

Expression (9) in semi-logarithmic coordinates is approximated by a line that cuts off at d = 1 μm on the abscissa, the desired value of the band gap Eg = 1.15 eV (at 293 K).

CONCLUSION

$Hg_2MnInTe_6$ single crystal of n-type conductivity was grown by the modified method of band melting. The width of the band gap equal to Eg = 1.15 eV (293 K) was determined from optical measurements. The resistivity of single crystals ρ≈ $5\cdot10^6$ Ω·cm (293 K) was determined from the linear region of I-V curves for the In/n-$Hg_2MnInTe_6$/In structure. Using 1) the temperature dependence of the resistivity ρ and 2) the temperature dependence of the transition voltage Vo from the ohmic section of the I–V curves to the SCLC, and 3) solving of electroneutrality equation, the degree of compensation (~ 0.99) of the semiconductor material and the energy position of the deep Ed level (~0.37-0.4 eV) responsible for dark conductivity were determined. The equations of electroneutrality were solved numerically. Both structures with two ohmic contacts (In/n-$Hg_2MnInTe_6$/In) and structures with a rectifying contact - Au/n-$Hg_2MnInTe_6$/In were prepared. The value $(\mu\tau)_n \approx$ 0.015-0.031 V^{-1}cm^2 was defined. $Hg_2MnInTe_6$ semiconductor crystals were characterized by high radiation resistance of electrical and photoelectric parameters and can be used both for the manufacture of photodiodes in the optical range and for ionizing radiation detectors.