Semiconductor Physics, Quantum Electronics & Optoelectronics, 2012. V. 15, N 4. P. 358-359.

PACS 71.20.Nr, 72.15.Cz, 72.20.Jv, 72.80.Jc

X-ray dosimetry of copper-doped $CdGa_2S_4$ single crystals

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Abstract. Comparative analysis of the X-ray dosimetric characteristics of $CdGa_2S_4$ and $CdGa_2S_4\langle Cu\rangle$ single crystals demonstrates that after copper-doping the persistence of the crystal characteristics completely disappears. The current-dose characteristics $I_r \sim E^{\alpha}$ tend to linearity ($\alpha = 1$) at low dose rates of X-rays. At high dose rates, α tends to 0.5, which testifies to the mechanism of quadratic recombination of charge carriers generated by X-rays in $CdGa_2S_4\langle Cu\rangle$.

Keywords: copper-doped $CdGa_2S_4$ single crystals, X-ray sensitivity, effective hardness of X-rays, current-dose characteristics, radiation dose, X-ray detector.

Manuscript received 08.02.12; revised version received 14.08.12; accepted for publication 17.10.12; published online 12.12.12.

1. Introduction

$CdGa_2S_4$ belongs to the family of $A^{II}B_2^{III}C_4^{VI}$ (A^{II} = Zn, Cd, Hg; B^{III} = Al, Ga, In; C^{VI} = S, Se, Te) ternary diamond-like semiconductors. These materials have a large (up to 4.0 eV) direct bandgap and are attractive for UV optoelectronic applications [1-3]. Earlier [4], we reported the X-ray dosimetric properties of $CdGa_2S_4$ single crystals.

The purpose of this work was to investigate X-ray dosimetric characteristics of $CdGa_2S_4$ single crystals doped with Cu.

2. Experimental techniques

The copper-doped (3 mol.%) $CdGa_2S_4$ compound was prepared using the method of high-temperature synthesis by alloying high-purity (no lower than 99.999%) components in an evacuated silica ampoule. $CdGa_2S_4\langle Cu\rangle$ single crystals were grown from the synthesized pellets by chemical transport reactions in a closed volume with iodine as a carrier gas.

Electrical (Ohmic) contacts to the $CdGa_2S_4\langle Cu\rangle$ crystals were made using indium solder on their lateral faces. Separation between contacts was 0.25 cm. The area between these contacts was exposed to X-rays.

The X-ray dosimetric performance of $CdGa_2S_4\langle Cu\rangle$ single crystals was studied using a URS-55a X-ray generator and a Cu target BSV-2 X-ray tube. The X-ray intensity was controlled by varying the tube electric current at a given accelerating voltage (V_a). The X-ray dose was measured using DRGZ-02 X-ray dosimeter. The X-ray–induced current through the sample was measured using the U5-9 electrometric amplifier at a low-load resistance ($R_l << R_{cr}$). All the measurements were performed at T = 300 K. These $CdGa_2S_4\langle Cu\rangle$ single crystals showed high X-ray sensitivity.

3. Results and discussion

The X-ray conductivity coefficient characterizing the X-ray sensitivity of $CdGa_2S_4\langle Cu\rangle$ single crystals is defined as a relative X-ray–induced change in the conductivity per unit dose rate,

$$K_\sigma = \frac{\Delta\sigma_{E,0}}{\sigma_0 \cdot E}, \quad (1)$$

where $\Delta\sigma_{E,0} = \sigma_E - \sigma_0$, σ_E is the conductivity of single crystals subjected to X-ray radiation, and σ_0 is the dark conductivity at 300 K.

Fig. 1 plots X-ray conductivity coefficient K_σ calculated using the formula (1) versus the X-ray dose rate for $CdGa_2S_4\langle Cu\rangle$ single crystals at 300 K and applied voltage U = 150 V. It is seen that K_σ of $CdGa_2S_4\langle Cu\rangle$ single crystal varies between 0.064 and 0.49 min/R. From the experimental data, it follows that $K_\sigma(E)$ dependence for $CdGa_2S_4\langle Cu\rangle$ at low dose rates is an increasing function. This function has the largest slope in a narrow range of dose rates E: from 0.75 to 2.73 R/min for V_a = 25 keV (Fig. 1, curve 1). The curves 2 to 6 first slightly increase with the dose rate and then decrease starting from a certain E. For dose rates lower than 20 R/min, the coefficient K_σ for $CdGa_2S_4\langle Cu\rangle$ single crystal decreases with effective hardness (V_a) of X-ray radiation; at $E >$ 20 R/min, it becomes independent of V_a.

One of the possible reasons for this behavior of the X-ray conductivity coefficient $K_\sigma(E,V_a)$ is as follows. At relatively low accelerating voltages, X-ray conduction is predominantly caused by X-ray absorption in a surface layer of the crystal. In this case, as the X-ray intensity increases, the mechanism of quadratic surface recombination becomes dominant, which leads to the observed decrease in the X-ray conductivity. An increase in the accelerating voltage leads to an increase in the effective X-ray hardness. As a result, the depth of X-ray penetration into the crystal increases; i.e., X-ray absorption and generation of respective free carriers occur predominantly in the bulk, and the fraction of X-rays penetrating through the crystal increases. Consequently, as the accelerating voltage increases, the X-ray conductivity coefficient decreases and becomes less dependent on the dose rate.

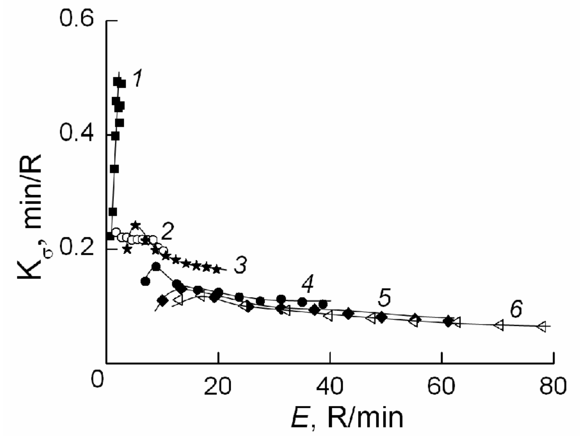

Fig. 1. X-ray conductivity coefficient as a function of X-ray dose rate for a $CdGa_2S_4\langle Cu\rangle$ single crystal (U = 150 V) at X-ray tube voltages V_a = 25 (*1*), 30 (*2*), 35 (*3*), 40 (*4*), 45 (*5*) and 50 keV (*6*). T = 300 K.

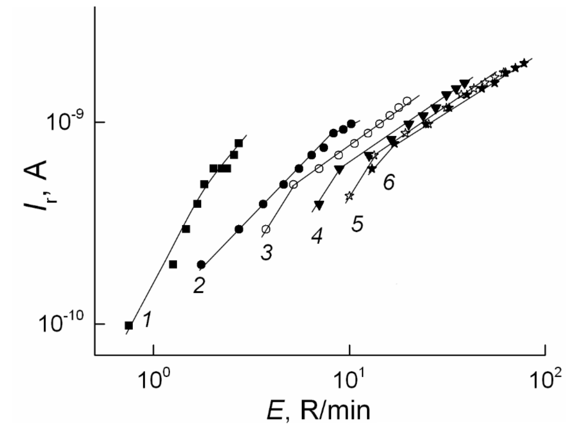

Fig. 2. Photocurrent-dose curves of $CdGa_2S_4\langle Cu\rangle$ single crystal for tube voltages V_a = 25 (*1*), 30 (*2*), 35 (*3*), 40 (*4*), 45 (*5*) and 50 keV (*6*).

From analyzing the current-dose characteristics of $CdGa_2S_4\langle Cu\rangle$ single crystals (Fig. 2), it follows that the dependence of the steady-state X-ray current on the dose rate can be adequately described by a power law: $I_r = I_E - I_0 \sim E^\alpha$, where I_0 is the dark current, and I_E is the current under exposure to X-rays at a dose rate E (R/min).

It is follows from Fig. 2 that the current-dose characteristics tend to linearity (α = 1) at low dose rates of X-rays. At relatively high dose rates of hard X-rays (at high voltages V_a), the exponent α tends to 0.5. $I_r \sim E^{1/2}$ dependence is characteristic for the mechanism of quadratic recombination of charge carriers generated by X-rays in $CdGa_2S_4\langle Cu\rangle$ single crystals.

Earlier [4], when studying the X-ray dosimetric characteristics of undoped $CdGa_2S_4$ single crystals, we found that, when X-ray radiation is switched off, the dark current reaches a steady-state value within 2-3 min rather than at once. Doped $CdGa_2S_4\langle Cu\rangle$ single crystals compare favorably current in them does not relax with time. When X-ray radiation is switched off, the dark current value is reached almost at once.

4. Conclusions

The obtained results have demonstrated that copper-doped (3 mol.%) $CdGa_2S_4$ single crystals are characterized with a high X-ray sensitivity and can be used for designing the non-cooled fast-response X-ray detectors.

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