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Integrated detectors of ionizing radiation based on ZnSe(Te)/*p*ZnTe–*n*CdSe structures

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A new type of solid state integrated detector of ionizing radiation has been proposed. It has been shown that the properties of ZnSe(Te) crystals make it possible to develop integrated detectors with photoreceivers of a photosensitive heterostructure type arranged directly on the scintillator surface. A preparation method of ZnSe(Te)/*p*ZnTe–*n*CdSe detectors has been described and the output characteristics thereof have been obtained.

Предложен новый тип твердотельного интегрального детектора ионизирующего излечения. Показано, что свойства кристаллов ZnSe(Te) позволяют создавать интегральные детекторы с фотоприемниками типа фоточувствительной гетероструктуры, размещенные непосредственно на поверхности сцинтиллятора. Описан метод получения интегральных детекторов типа ZnSe(Te)/*p*ZnTe–*n*CdSe и получены их выходные характеристики.

Broad possibilities of purposeful variation of photoelectric, luminescence and electrophysical properties in $A^{II}B^{VI}$ semiconductor compounds and solid solutions based thereon stimulate continuous scientific and practical interest. One of the recent important steps in this direction is development of a new type scintillator based on isovalently doped zinc selenide [1–3]. This type of scintillation crystals shows the conversion efficiency 4–7 % higher and radiation stability 10^3–10^4 times higher as compared to CsI(Tl) crystals. Development of ZnSe(Te) scintillator has allowed to effectively fill the gap in the "scintillator-photodiode" detector series for modern radiation introscopy [4].

It is also known [5, 6] that certain complex structures based on wide-band AIIBVI compounds (e.g., *p*ZnTe–*n*CdSe heterostructures) exhibit a high photosensitivity in the visible spectral range corresponding to the luminescence maximum (λ_{max} = 620–640 nm).

A unique combination of semiconductor and scintillation properties in ZnSe(Te) crystals should make it possible to develop photoreceivers based on heterostructures formed directly on the surface of this scintillator. Compactness, small overall dimensions, the design simplicity and high performance characteristics are the advantages of the solid state integrated detectors (ID) of ionizing radiation consisting of a scintillator and a barrier-layer photocell over other types of detectors. Besides, such ID detectors do not require any power sources. In this paper, we describe preparation methods and parameters of a "photosensitive heterostructure — semiconductor scintillator" type ID, namely, ZnSe(Te)/*p*ZnTe–*n*CdSe.

The ZnSe(Te) crystals were grown by vertical Bridgman method in graphite crucibles under inert gas (Ar) pressure of $5 \cdot 10^6$ Pa. The temperature in the melting zone was 1860 K. As raw material, fine ZnSe and

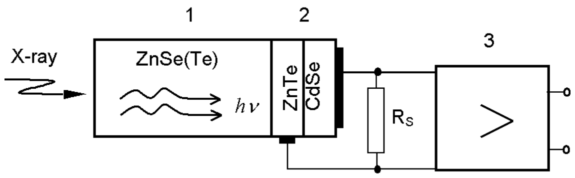

Fig. 1. Test structure of ZnSe(Te)/*p*ZnTe-*n*CdSe ID of ionizing radiation in integral construction design: *1*, ZnSe(Te) scintillator; *2*, *p*ZnTe-*n*CdSe photoreceiver; *3*, recording system.

ZnTe powders of ELMA type (class 6N) were used, which had been preliminarily treated in oxygen atmosphere [3]. The content of activator (Te) in ZnSe crystals was 0.5 mass %. At the final stage of scintillation properties formation, the ZnSe(Te) samples of (2–5)×5×5 mm^3 size were annealed in Zn vapor at T = 1300 K for 24 h [2]. The integrated detectors were obtained by successive epitaxial growth of ZnTe and CdSe layers onto Te doped ZnSe scintillator crystals oriented in the [110] direction. The ZnSe substrates were mechanically polished and etched in bromomethanol prior to deposition of ZnTe and CdSe layers. We used an epitaxial method involving a transport reaction and resublimation in an open system under reduction atmosphere. The CdSe and ZnTe polycrystals were used as the evaporating materials. The epitaxial growth of CdSe layers was accomplished in a short time after reloading of the reactor with the evaporating material. Doping of ZnTe with As and of CdSe with In was carried out during their growth.

Metallographic and X-ray studies of ZnTe and CdSe layer growth processes show that the optimal epitaxy conditions are as follows: ZnTe source temperature 820°C, ZnSe substrate temperature 555–565°C; for CdSe, these values are 760°C and 600–640°C, respectively. Thickness of ZnTe and CdSe layers was 6–8 and 18–20 μm, respectively. Electron concentration N_e and mobility μ_n in CdSe layers depend on the substrate temperature. Under the above conditions, the N_e and μ_n values are $(1.2–2.6)\cdot 10^{17}$ cm^{-3} and 570–590 $cm^2/(V\cdot s)$, respectively. For ZnTe layers, the hole concentration N_h is $3.7\cdot 10^{17}$ cm^{-3} and the hole mobility u_p = 60 $cm^2/(V\cdot s)$. Au and In were deposited by vacuum evaporation to make ohmic contacts for ZnTe and CdSe, respectively. A schematic diagram of the combined detector of ionizing radiation obtained as described above is presented in Fig. 1. It is seen that the heterostructure-photoreceiver (HP) is deposited directly on the scintillator surface and thus the reflection losses are minimized.

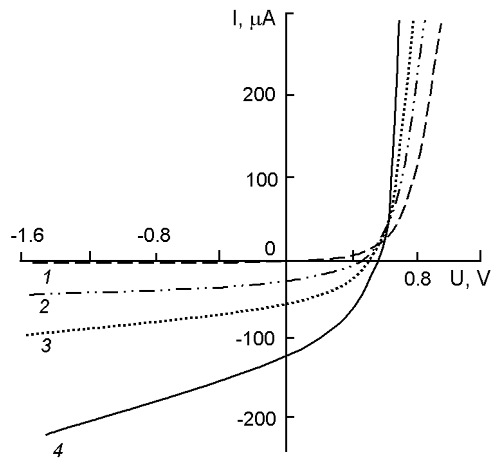

Fig. 2. Current-voltage characteristics of heterostructure-photoreceiver *p*ZnTe-*n*CdSe at different illumination levels: dark (*1*); $3\cdot 10^3$ lx (*2*); $6\cdot 10^3$ lx (*3*); $1\cdot 10^4$ lx (*4*).

For ID heterostructure-photoreceiver *p*ZnTe–*n*CdSe obtained by epitaxy from vapor phase as described above, the current vs voltage characteristics (IVC) have been measured at different illumination levels (Fig. 2). In contrast to *p–n* homojunctions, intersection of "light" and "dark" IVC is observed in the heterostructure case. The IVC intersection is decrease of the heterostructure series resistance due to photoconductivity of the material layers forming it. The dependence of open-circuit voltage U_{OC} and short-circuit current I_{SC} on the illumination intensity of HP *p*ZnTe–*n*CdSe is presented in Fig. 3. It is seen that I_{SC} rises linearly when the illumination is increased, while U_{OC} tends to saturation. Such a behavior is in good agreement with the sharp heterojunction theory. The efficiency of the *p*ZnTe–*n*CdSe heterostructure, calculated using experimental I_{SC} and U_{OC} values, is 6–8 % and is limited by rather high series resistance of a photoreceiver of such type.

The spectral characteristics of the ID were studied under illumination through the ZnSe scintillator crystal with band gap E_g = 2.67 eV. Therefore, photons with energy lower than 2.67 eV pass through ZnSe crystal practically without absorption and are absorbed in the HP. The generated electron-hole pairs are separated by the heterojunction, thus creating a current in the external circuit. The photosensitivity region is situ-

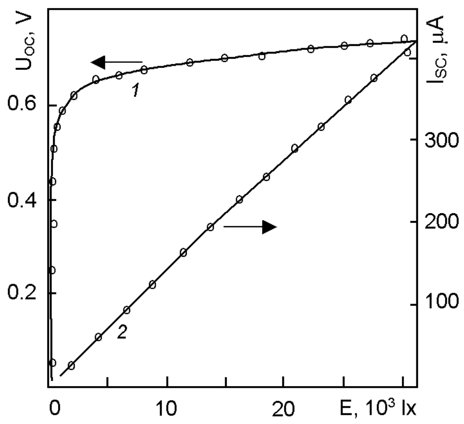

Fig. 3. Dependences of open-circuit voltage U_{oc} (*1*) and short-circuit current I_{sc} (*2*) on illumination intensity E for pZnTe-nCdSe heterostructure.

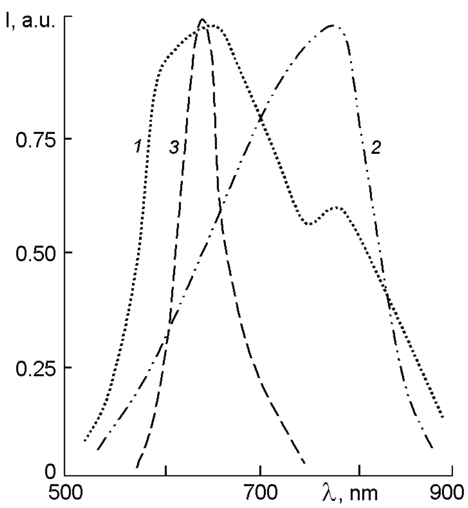

Fig. 4. Spectral sensitivity distribution of a pZnTe-nCdSe photoreceiver at different electrons concentration in CdSe layers of ZnSe(Te)/pZnTe-nCdSe ID (*1*, $2.4\cdot10^{17}$ cm^{-3}; *2*, $3.6\cdot10^{15}$ cm^{-3}) and luminescence spectrum of ZnSe(Te) crystal scintillator (*3*).

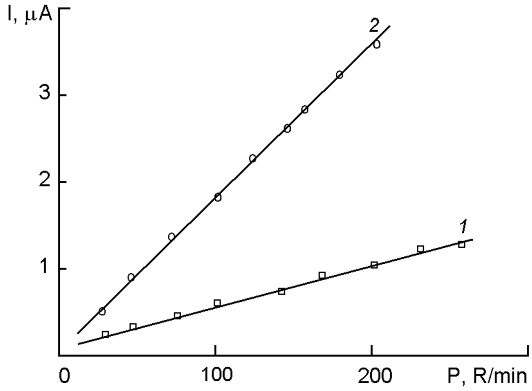

Fig. 5. Dosimetric characteristics of the ZnSe(Te)/pZnTe-nCdSe integrated detectors of ionizing radiation; *1*, illumination through photoreceiver; *2*, illumination through scintillator crystal.

ated between wavelengths λ of 560 and 850 nm that corresponds to photon energies close to the band gap of ZnTe (E_g = 2.26 eV) at 300 K) and CdSe (E_g = 1.71 eV), respectively. The quantum efficiency in the spectral characteristic maximum amounts 0.61 to 0.68. The absolute monochromatic sensibility at λ = 630 nm reaches the values of 0.32–0.35 A/W. Time constant of the ZnTe–CdSe heterojunction is $3.2\cdot10^{-4}$ to $1.6\cdot10^{-5}$ s what is acceptable for the operation of photodetector.

The spectral sensitivity characteristic shape depends on electron concentration in CdSe layers which, in its turn, is defined by the ZnTe substrate temperature T_s (Fig. 4). It is seen from Fig. 4 that an increase of electron concentration in CdSe layers results in a shift of pZnTe–nCdSe HP spectral characteristics towards shorter wavelength. In this case, the compatibility of the detector photosensitivity spectrum with radiation spectrum of the ZnSe scintillator crystals (curve *3*, Fig. 4) is much better. The concordance factor a_c of the radiation and photosensitivity spectra represented in Fig. 4 was calculated using the numerical integration technique in accordance with the expression [5]:

$$a_c = \int_{\lambda_{min}}^{\lambda_{max}} S_{sc}(\lambda) S_{ph}(\lambda) d\lambda \;/\; \int_{\lambda_{min}}^{\lambda_{max}} S_{sc}(\lambda) d\lambda \quad , \qquad (1)$$

where S_{sc} and S_{ph} are spectral radiation intensities of the scintillator and the spectral sensitivity of the HP with respect to the maximum; λ_{max}, λ_{min} are spectrum boundaries; a_c is 0.98 in the case of the pZnTe–nCdSe spectrum represented by the curve *1* and 0.62 for the curve *2*.

The obtained dosimetric characteristics at constant potential on the X-ray tube are linear in the whole range of the dose rates (Fig. 5). Curve *1* was obtained under irradiation through the HP and curve *2*, through the scintillator crystal. Sensitivity of the detectors to X-ray irradiation with the 8.86 keV energy was calculated using the expression [6]:

$$\frac{I_{sc}}{P} = \quad (2)$$
$$= e\eta \cdot \frac{\mu_{MHz}}{\mu_{HMB}} \cdot \frac{1 - \exp(\mu_{MZ} d_{sc})}{\mu_{MZ} d_{sc}} \cdot V_{sc}\rho_{sc}\xi\gamma\beta,$$

where I_{sc} is the total photocurrent; μ_{MHZ}, mass absorption coefficient of the scintillator; μ_{HMB}, that of air; μ_{MZ}, mass attenuation coefficient of substance with mass number Z; ξ, efficiency of the scintillator light collection by the HP; β, quantum efficiency of the HP; γ, collection coefficient of charge carriers; d_{sc}, scintillator thickness; V_{sc}, scintillator volume; ρ_{sc}, scintillator density. The calculation has been performed for the short-circuit conditions. The obtained value of the X-ray sensibility of 316 nA·min/R·cm^2 is in a rather good agreement with the average experimental values of 180–220 nA·min/R·cm^2. The temperature dependence of the short-circuit current within the range of 20–100°C is negligible and does not exceed ±5 %. Testing of the ZnSe(Te)/*p*ZnTe–*n*CdSe integrated detectors carried out under real homographic conditions show that their sensitivity, inertia (decay time) and dynamical linearity range of dosimetric characteristic make it possible to use the ID in X-ray introscopic systems and medical homographs.

To conclude, the high radiation sensitivity of ZnSe(Te)/*p*ZnTe–*n*CdSe integrated detectors is due to the close contact of scintillator and HP, diminishing the reflection losses, and to high values of the spectral concordance factor (0.62–0.98). The short-circuit current in output circuit of the ID depends linearly on X-ray radiation dose rate in the range up to 280 R/min. The response time of the HP is of the same order as the scintillator flash duration, namely 10^{-5} s. The ID could be operated up to temperatures at least 100°C.

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Інтегральні детектори іонізуючої радіації на основі структури ZnSe(Te)/*p*ZnTe–*n*CdSe

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Запропоновано новий тип твердотільного інтегрального детектора іонізуючої радіації. Показано, що властивості кристалів ZnSe(Te) дозволяють утворювати інтегральні детектори з фотоприймачами типу фоточутливої гетероструктури, розташовані безпосередньо на поверхні сцинтилятора ZnSe(Te). Описано метод отримання інтегральних детекторів типу ZnSe(Te)/*p*ZnTe–*n*CdSe та одержано їх вихідні характеристики.