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CHEMICAL COMPOSITION, STRUCTURAL AND ELECTRICAL PROPERTIES OF CdZnTeSe THICK POLYCRYSTALLINE FILMS

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Abstract. *Thick polycrystalline $Cd_{1-x}Zn_xTe_{1-y}Se_y$ (CZTS) films were synthesized via the close-spaced vacuum sublimation (CSVS) technique. Comprehensive investigations of their structural, compositional, and electrical properties were performed to assess their suitability as base layers for X-ray detector applications. The films were characterized using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). Morphological and structural analyses revealed uniform composition, dense microstructure, and high crystalline quality of the films deposited on glass substrates. Electrical and photosensitivity measurements demonstrated that detector prototypes incorporating CZTS films exhibit pronounced photoresponse under light illumination, confirming their potential for use in next-generation X-ray detection devices.*

Keywords: CdZnTeSe, thick films, close-spaced vacuum sublimation, crystal structure, photosensitivity, X-ray detector

SKŁAD CHEMICZNY, STRUKTURA I WŁAŚCIWOŚCI ELEKTRYCZNE GRUBYCH POLIKRYSTALICZNYCH WARSTW CdZnTeSe

Streszczenie. *Grube polikrystaliczne warstwy $Cd_{1-x}Zn_xTe_{1-y}Se_y$ (CZTS) zsyntetyzowano techniką sublimacji próżniowej w małych przestrzeniach (CSVS). Przeprowadzono kompleksowe badania ich właściwości strukturalnych, kompozycyjnych i elektrycznych, aby ocenić ich przydatność jako warstw bazowych do zastosowań w detektorach promieniowania rentgenowskiego. Warstwy scharakteryzowano za pomocą skaningowej mikroskopii elektronowej (SEM), spektroskopii rentgenowskiej z dyspersją energii (EDS) oraz dyfrakcji rentgenowskiej (XRD). Analizy morfologiczne i strukturalne wykazały jednorodny skład, gęstą mikrostrukturę i wysoką jakość krystaliczną warstw osadzonych na podłożach szklanych. Pomiary elektryczne i światłoczułości wykazały, że prototypy detektorów zawierające warstwy CZTS wykazują wyraźną fotoreakcję pod wpływem światła, co potwierdza ich potencjał do zastosowania w urządzeniach do detekcji promieniowania rentgenowskiego nowej generacji.*

Słowa kluczowe: CdZnTeSe, grube warstwy, sublimacja próżniowa w małej odległości, struktura krystaliczna, czułość na światło, detektor promieniowania rentgenowskiego

Introduction and literature review

For a long time, single crystals of high-ohmic chlorine-doped cadmium telluride CdTe:Cl were used as the base material for fabricating various types of hard radiation detectors [13, 18]. However, over the past two decades, a tendency to replace CdTe:Cl with three-component solid solutions, in particular containing Zn and Mn, has been observed [23]. The reason for this shift is the numerous advantages of $Cd_{1-x}Zn_xTe$ (CZT) and $Cd_{1-x}Mn_xTe$ (CMT) over the two-component compound: high resistivity, high charge carrier mobility and lifetime, tunable band gap depending on chemical composition, increased stability due to higher band gap, and stronger atomic bonds [6, 33]. As a result, these solid solutions are considered among the most important semiconductor materials for the development of room-temperature gamma-ray detectors [6, 8, 28]. Radiation detectors based on CZT and CMT are widely used for medical applications, X-ray and gamma-ray astronomy, non-destructive testing in industry, security applications, and others [16, 28, 29].

However, these materials have long-standing technological challenges. Despite significant advancements in growth technology over the past decades, single crystals of these compounds still suffer from axial and radial compositional inhomogeneity and the formation of numerous harmful defects in the material, such as ingot deformations, tellurium inclusions, grain boundary networks, twins, and even cracks, all of which negatively affect the efficiency of detectors made from these crystals [11, 35].

One way to improve the structural quality of CdTe single crystals and CZT, CMT solid solutions is the introduction of Se atoms into the material, which has a segregation coefficient of $k = 1.0$ [20]. It has been observed that adding Se makes it possible to obtain samples with stable lattice parameter values and stable electrical characteristics throughout the ingot volume, as well as to reduce the number of defects in the crystals [21, 32]. However, the obtained $CdTe_xSe_{1-x}$ solid solution was not suitable for detectors, due to its higher leakage current. Although the band gap E_g of CdSe is higher than that of CdTe, the band gap of $CdTe_xSe_{1-x}$ solid solution is smaller than the E_g of cadmium telluride due to the crystal lattice disordering effect in the material [10]. As a result, the high resistivity of $CdTe_xSe_{1-x}$ required for the effective detector operation at room temperature could not be achieved. An increase in the band gap is required to enhance the material's resistivity. In $Cd_{1-x}Zn_xTe_{1-y}Se_y$, this effect was achieved by adding selenium to the $Cd_{0.9}Zn_{0.1}Te$ compound. Consequently, the development of methods for obtaining high-quality single crystals of $Cd_{1-x}Zn_xTe_{1-y}Se_y$ (CZTS) solid solution was initiated [22]. Subsequently, it was established that the obtained CZTS single crystals have high through-volume uniformity. They have virtually none of the defects that are commonly observed in CdTe, CZT, and CMT single crystals [7, 20, 21].

To reduce the cost of radiation detectors, structurally perfect monocrystalline and polycrystalline thick (up to 100 μm) films of cadmium telluride and other detector materials are being considered as detector materials instead of bulk single crystals [24]. For this purpose, both CdTe films and CZT, CMT solid solutions can be used [27]. In particular, CZT films with high crystalline quality, controllable chemical composition, and uniform distribution of components throughout the volume and on the surface were obtained using the close-spaced vacuum sublimation method in our previous works. However, only few works [4] are dedicated to the study of properties of CZTS films, and the possibility of using thick films of the CZTS solid solution as a base layer for hard radiation detectors has not been investigated at all. This determines the purpose of this work: deposition of thick polycrystalline CZTS films with high crystalline quality, the study of their chemical composition and structural and electrical properties, and evaluation of the photosensitivity of detector structures based on these films for further their investigation as a material for X-ray and gamma-ray detectors.

1. Researches methodology

The CZTS films were deposited by the close-spaced vacuum sublimation (CSVS) technique [9, 17] on glass substrates and ITO-coated glass substrates. A mixture of CdTe, ZnTe, and CdSe powders was used as a source material for evaporation; the total mass of the evaporated powder was 100 mg. Zn and Se concentrations in CZTS films were controlled by varying the mass ratio between cadmium telluride, zinc telluride, and cadmium selenide powders (see Table 1). The growth conditions were as follows: the substrate temperature T_S was in the range of 400°C to 450°C and the evaporator temperature T_E was 650°C. The distance between the evaporator and the substrate was 20 mm. The film thickness was controlled by the mass of source powder and the time of deposition. The diameter of the deposited films was 15 mm. Au electrodes were deposited using the vacuum thermal evaporation method at the substrate temperature of 200°C.

Table 1. Deposition conditions of CZTS polycrystalline films and source powder composition

Sample	Source powder proportions	Substrate	Substrate temperature, T_S, °C	Evaporator temperature, T_E, °C
CZTS.A5	CdTe: 1000 mg; ZnTe: 50 mg; CdSe: 7 mg	glass	400	650
CZTS.A7	CdTe: 1000 mg; ZnTe: 50 mg; CdSe: 7 mg	glass	400	650
CZTS.B6	CdTe: 1000 mg; ZnTe: 80 mg; CdSe: 15 mg	ITO	400	650
CZTS.B7	CdTe: 1000 mg; ZnTe: 80 mg; CdSe: 15 mg	ITO	400	650
CZTS.D3	CdTe: 1000 mg; ZnTe: 100 mg; CdSe: 70 mg	ITO	400	650
CZTS.D4	CdTe: 1000 mg; ZnTe: 100 mg; CdSe: 70 mg	ITO	450	650

The surface morphology of the films was investigated by SEO-SEM Inspect S50-B scanning electron microscope (SEM). Energy-dispersive spectroscopy (EDS) was used to study chemical composition of the films. EDS measurements were carried out by Oxford AZtecOne spectrometer equipped with X-MaxN20 detector on the surface area of 100 µm×100 µm.

The structural properties of the samples were studied by the X-ray diffraction (XRD) method. XRD pattern measurements were performed using DRON-3M diffractometer. The samples were analyzed in the 2θ angle range of 20° to 80°. The microstructural properties, including coherent scattering domain (CSD) size, were calculated using the full width at half maximum (FWHM) of the main (111) diffraction peak [3, 31].

Current-voltage characteristic measurements of the films were conducted under dark conditions and under white LED illumination with a power density of approximately 0.2 W/cm^2.

2. Results

2.1. Chemical composition and surface morphology

The estimation of atomic concentrations of chemical elements in CZTS films was carried out using EDS. A typical EDS spectrum of a CZTS sample is shown in the inset of Fig. 1. The results of the chemical composition studies are presented in Table 1. As seen in Table 1, the investigated films have a low concentration of Zn and Se atoms. In particular, the Zn concentration varies from 0.72 at.% to 3.1 at.%, while the Se concentration varies from 0.07 at.% to 1.61 at.%. Concentrations of Zn and Se in CZTS films increase with an increase in the mass proportions of ZnTe and CdSe in the source powder.

Table 2. Chemical composition, structural properties of CZTS polycrystalline films

Sample	Cd, at. %	Te, at. %	Zn, at. %	Se, at. %	*a*, nm	FWHM (111), degrees	CSD size, L, nm
CZTS.A5	50.63	48.57	0.72	0.08	0.64703	0.593	15.5
CZTS.A7	50.13	48.65	1.15	0.07	0.64827	0.574	16.0
CZTS.B6	49.50	48.31	1.94	0.24	0.64015	0.550	16.8
CZTS.B7	48.45	48.17	3.10	0.28	0.64544	0.652	14.1
CZTS.D3	50.37	47.49	1.18	0.96	-	-	-
CZTS.D4	49.46	46.77	2.16	1.61	-	-	-

The SEM images of CZTS film surfaces are shown in Fig. 1 (a-c). The effect of substrate type on the surface morphology was observed. The surface of the CZTS.A5 sample obtained on a glass substrate consists of uniform grains with average grain size of ~14 µm. In contrast, the surfaces of the CZTS.B6 and CZTS.D4 samples, obtained on ITO-coated glass substrates, consist of grains with non-uniform size and shape, average grain size is ~9 µm in the CZTS.B6 sample and ~7 µm in the CZTS.D4 sample. The modification of the film surface could be caused by the effect of substrate type on the growth mechanism of the film [1, 12].

As seen in the SEM image in Fig. 1(d), showing the film cross-section, grains have a columnar-like structure similar to CdZnTe films, and the film thicknesses range from 27 µm to 32 µm. The substrate type exhibited no measurable influence on the resulting film thickness.

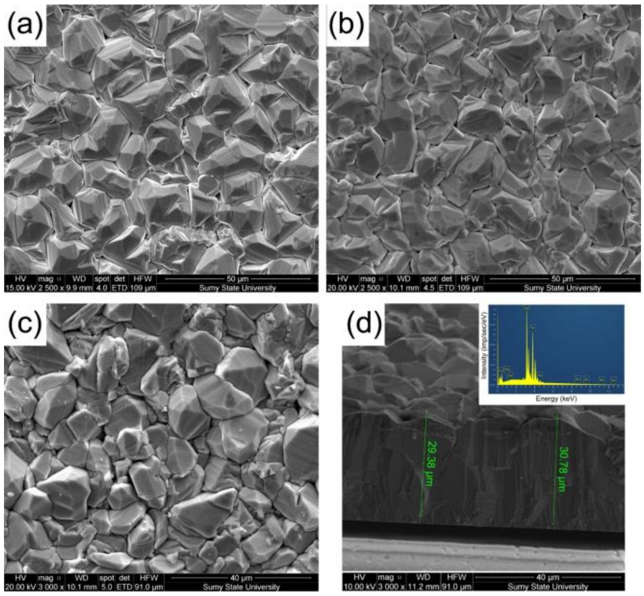

Fig. 1. SEM images of CZTS.A5 (a), CZTS.B6 (b), CZTS.D4 (c), sample surface, and CZTS.A5 sample cross-section (d), EDS spectrum of CZTS.A5 sample (on the inset)

2.2. XRD analysis

The XRD patterns from CZTS.A5, CZTS.A7, CZTS.B6, and CZTS.B7 samples are shown in Fig. 2. The patterns of CZTS.A5 and CZTS.A7 samples on glass substrates include reflections from the (111), (220), (311), (400), (331), (422), and (511) planes of the cubic zinc-blende phase [34]. The dominant (111) peak corresponds to a preferential orientation in the [111] direction. The peaks from the hexagonal phase of CZT, as well as from CdTe, ZnTe, CdSe, ZnSe, and Te secondary phases, were not detected. The diffraction peaks are sharp and symmetrical, which indicates composition uniformity and high crystal quality.

Patterns from CZTS.B6 and CZTS.B7 samples on ITO-coated glass substrates include reflections from (111), (220), (311), (400), (331), (422), and (511) planes of the cubic phase of CZTS. Also, peaks which correspond to reflections from (222), (400), (440), (622) of ITO film were observed [30]. Similar to samples on glass substrates, the (111) peak was dominant over other cubic-phase peaks in the patterns of the CZTS.B6 and CZTS.B7 samples. In the XRD pattern of the CZTS.B6 sample, the peaks from the CZTS film have lower intensity than the peaks from the ITO film, indicating a deterioration in the texture quality of the CZTS film deposited on ITO-coated glass substrates. The splitting of the (111) diffraction peak observed in the XRD patterns of CZTS.B6 and CZTS.B7 samples is caused by the formation of several solid solutions with different Zn and Se concentrations. To identify these solid solutions, peak separation and simulation were carried out. In both cases, the (111) peak was separated into peak with higher intensity and peak with lower intensity. For calculations of substructural properties and lattice parameter, the peak with higher intensity was used. The diffraction peaks in the XRD patterns of the CZTS.B6 and CZTS.B7 samples are shifted toward higher angles relative to the peak positions in CZTS.A5 and CZTS.A7 due to an increase in Zn and Se content in the films.

The values of lattice parameter *a* calculated from the position of the (111) peak are presented in Table 2. As is known [25], in cadmium-zinc-telluride solid solution the lattice parameter value decreases with an increase in zinc content. The same behaviour of lattice parameter with Zn concentration change is expected for CZTS films with equal Se concentration (CZTS.A5 and CZTS.A7, CZTS.B6 and CZTS.B7). However, in the present study, we observed some disagreement between results obtained by EDS and XRD. As shown in Table 2, the CZTS.A5 sample, which has a lower Zn concentration, exhibits a higher lattice parameter value than CZTS.A7, and the same was observed for CZTS.B6 and CZTS.B7 samples.

There are two main reasons that could cause the mismatch between EDS and XRD results of determination of metals concentration in the films: 1) inhomogeneity in the distribution of elements within the CZTS films, Unlike the EDS method, which is limited by the X-ray probe's penetration depth (approximately a few micrometres), XRD provides integral data on the phase composition throughout the entire volume and 2) errors in EDS measurements. In the case of a rough surface, measurement errors could reach up to 5 mass% [2]. Therefore, in this study, EDS measurements can only be used for a rough estimation of the chemical element concentrations in the CZTS samples.

The study of microstructural parameters (Table 2) showed that CSD size in CZTS samples is in the range from 14.1 nm to 16.8 nm. It should be noted that the obtained CSD size values for CZTS films are approximately four times smaller than those reported for CdZnTe films in our previous work. This difference may be caused by the deformation of the CdZnTe crystal lattice due to the introduction of Se atoms, as the atomic radius of Se (120 pm) is smaller than that of Te (140 pm).

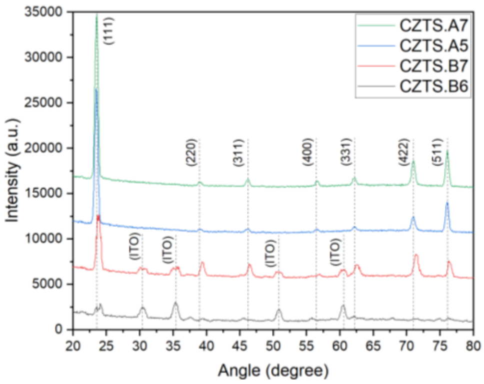

Fig. 2. XRD patterns of CZTS.A5, CZTS.A7, CZTS.B6, CZTS.B7 samples. Vertical dashed lines in the XRD data show the peak positions for cubic phase of CdTe

2.3. Current-voltage characteristics and photosensitivity

The top electrode material for CZTS film-based detector prototype was selected to obtain the Ohmic top contact. We used Au, which has a work function of 4.7 eV, larger than the electron affinity of p-type CZTS, which is approximately 4.6 eV [15, 19]. Similarly, a gold contact was used in a single-crystal CZTS detector prototype in [5].

The current-voltage (I-V) characteristics of ITO/CZTS/Au sandwich structures, measured under dark conditions (filled circles) and white light illumination (open circles), are shown in Fig. 3. The observed nonlinear behaviour of the dark I-V characteristics can be explained by the presence of the electrical barrier between p-type CZTS film and n-type ITO coating [14, 26]. Logarithmic plots ln(I) vs. ln(V) of CZTS samples under illumination revealed a linear characteristic up to ~20 V, followed by another linear region with different slopes, which indicates the diode-like behaviour of the ITO/CZTS/Au structure.

The values of electric resistance *R* of CZTS films calculated at a bias voltage of 25 V in the linear region of dark I-V characteristic are presented in Table 2. The resistance varied in the range from 2.7×10^{6} to 1.2×10^{7} Ω. We assume that the differences in CZTS film resistance are caused by a combination of several factors: band-gap widening due to an increase in Zn and Se concentration in the material, film-to-film thickness variation, and diffusion of Au into grain boundaries.

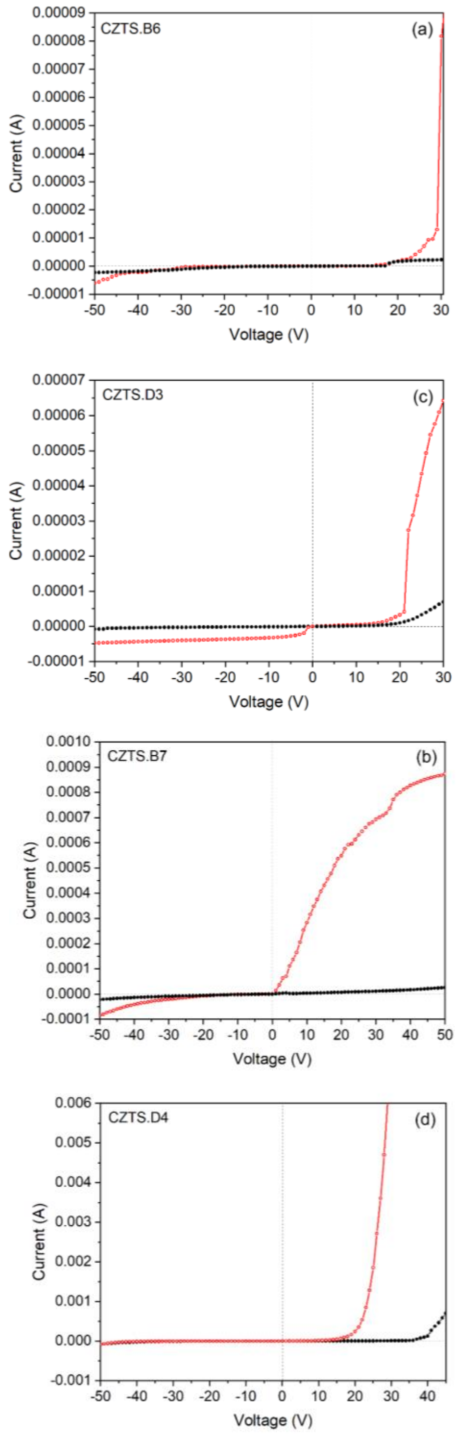

Fig. 3. Current-voltage characteristics of ITO/CZTS/Au sandwich-structures under dark conditions (filled circles) and white light illumination (open circles)

As seen in Fig. 3, the detector current under illumination at the same bias voltage is larger than the current under dark conditions. The ratio R_I of current under illumination I_{light} to dark current I_{dark} ($R_I = I_{light}/I_{dark}$) at a bias voltage of 20 V (CZTS.B7, CZTS.D3, CZTS.D4) and 25 V (CZTS.B6) for CZTS films is presented in Table 3. The change in current of the illuminated samples is attributed to increase in photogenerated carriers, which indicates the photosensitivity of CZTS films.

Table 3. Electrical properties and photosensitivity of CdZnTeSe polycrystalline films

Sample	I_{dark}, A	I_{light}, A	R, Ohm	$R_I=I_{light}$ / I_{dark}
CZTS.B6	2.07×10^{-6}	5.32×10^{-6}	1.2×10^{7}	2.6
CZTS.B7	7.23×10^{-6}	5.48×10^{-4}	2.7×10^{6}	75.8
CZTS.D3	1.02×10^{-6}	3.29×10^{-6}	7.6×10^{6}	3.2
CZTS.D4	2.79×10^{-6}	1.65×10^{-4}	5.4×10^{6}	59.1

3. Conclusion

Thick polycrystalline CdZnTeSe (CZTS) films were successfully deposited on glass and ITO-coated glass substrates via the close-spaced vacuum sublimation (CSVS) technique. Comprehensive analyses of their morphological, structural, compositional, and electrical properties were performed to evaluate their potential for detector applications. Surface morphology studies revealed smooth and compact film surfaces, with the substrate type exerting a notable influence on grain size and uniformity. Films deposited on ITO-coated glass exhibited smaller and less uniform grains compared to those on bare glass substrates.

X-ray diffraction analysis confirmed that all CZTS films crystallize in the cubic zinc blende structure. The films grown on glass substrates demonstrated sharp and symmetrical diffraction peaks, indicative of high crystalline quality and compositional homogeneity. In contrast, films on ITO-coated glass displayed broader peaks and evidence of multiple solid-solution layers, suggesting a degradation in texture quality.

Electrical and photoresponse measurements conducted on ITO/CZTS/Au heterostructures revealed resistances in the range of 2.7×10^6–1.2×10^7 Ω. The current–voltage characteristics showed a pronounced increase in photocurrent under white LED illumination compared to dark conditions, confirming the inherent photosensitivity of the CZTS layers.

Overall, the results demonstrate that CZTS thick films synthesized by the CSVS method exhibit favourable structural quality and significant photoresponse, highlighting their promise as base materials for the development of next-generation X-ray detectors.

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References

[1] Arashti, M. G., Hasani, E., Kamalian, M., & Habashi, L. B. (2023). Effect of substrate type on the physical properties of thermally evaporated CdS thin films for CdTe/CdS solar cells applications. *Physica Scripta*, *98*(6), 065403. https://doi.org/10.1088/1402-4896/acd485

[2] Burany, S. (2003). *Scanning Electron Microscopy and X-Ray Microanalysis*. J. Goldstein, D. Newbury, D. Joy, C, Lyman, P. Echlin, E. Lifshin, L. Sawyer, and J. Michael. Kluwer Academic, Plenum Publishers, New York; 2003, 688 pages (Hardback, $75.00) ISBN 0-306-47292-9. *Microscopy and Microanalysis*, *9*(5), 484–484. https://doi.org/10.1017/S1431927603030617

[3] Bushroa, A. R., Rahbari, R. G., Masjuki, H. H., & Muhamad, M. R. (2012). Approximation of crystallite size and microstrain via XRD line broadening analysis in TiSiN thin films. *Vacuum*, *86*(8), 1107–1112. https://doi.org/10.1016/j.vacuum.2011.10.011

[4] Cao, M., Xu, Z., He, W., Zhang, Z., Wang, Z., Hu, Q., Huang, J., & Wang, L. (2025). Enhanced photoelectrochemistry properties of CdZnTeSe thin films. *Applied Surface Science*, *680*, 161372. https://doi.org/10.1016/j.apsusc.2024.161372

[5] Chaudhuri, S. K., Sajjad, M., Kleppinger, J. W., & Mandal, K. C. (2020). Charge transport properties in CdZnTeSe semiconductor room-temperature γ -ray detectors. *Journal of Applied Physics*, *127*(24), 245706. https://doi.org/10.1063/5.0006227

[6] Del Sordo, S., Abbene, L., Caroli, E., Mancini, A. M., Zappettini, A., & Ubertini, P. (2009). Progress in the Development of CdTe and CdZnTe Semiconductor Radiation Detectors for Astrophysical and Medical Applications. *Sensors*, *9*(5), 3491–3526. https://doi.org/10.3390/s90503491

[7] Egarievwe, S. U., Roy, U. N., Harrison, B. A., Goree, C. A., Savage, E. K., Jones, J., & James, R. B. (2019). Fabrication and Characterization of CdZnTeSe Nuclear Detectors. *2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, 1–3. https://doi.org/10.1109/NSS/MIC42101.2019.9059726

[8] Fiederle, M., Feltgen, T., Meinhardt, J., Rogalla, M., & Benz, K. W. (1999). State of the art of (Cd,Zn)Te as gamma detector. *Journal of Crystal Growth*, *197*(3), 635–640. https://doi.org/10.1016/S0022-0248(98)00761-1

[9] Gnatenko, Yu. P., Bukivskij, P. M., Faryna, I. O., Opanasyuk, A. S., & Ivashchenko, M. M. (2014). Photoluminescence of high optical quality CdSe thin films deposited by close-spaced vacuum sublimation. *Journal of Luminescence*, *146*, 174–177. https://doi.org/10.1016/j.jlumin.2013.09.070

[10] Hannachi, L., & Bouarissa, N. (2008). Electronic structure and optical properties of CdSexTe1−x mixed crystals. *Superlattices and Microstructures*, *44*(6), 794–801. https://doi.org/10.1016/j.spmi.2008.09.013

[11] Hossain, A., Bolotnikov, A. E., Camarda, G. S., Cui, Y., Gul, R., Roy, U. N., Yang, G., & James, R. B. (2017). Direct observation of influence of secondary-phase defects on CZT detector response. *Journal of Crystal Growth*, *470*, 99–103. https://doi.org/10.1016/j.jcrysgro.2017.04.002

[12] Huang, J., Gu, Q., Yang, F., Tang, K., Gou, S., Zhang, Z., Shen, Y., Zhang, J., Wang, L., & Lu, Y. (2019). Growth and properties of CdZnTe films on different substrates. *Surface and Coatings Technology*, *364*, 444–448. https://doi.org/10.1016/j.surfcoat.2018.10.083

[13] Johns, P. M., & Nino, J. C. (2019). Room temperature semiconductor detectors for nuclear security. *Journal of Applied Physics*, *126*(4), 040902. https://doi.org/10.1063/1.5091805

[14] Kang, S., Jung, B., Noh, S., Cho, C., Yoon, I., & Park, J. (2012). Feasibility study of direct-conversion x-ray detection using cadmium zinc telluride films. *Journal of Instrumentation*, *7*(01), C01010–C01010. https://doi.org/10.1088/1748-0221/7/01/C01010

[15] Liang, X. Y., Min, J. H., Chen, J., Wang, D., Li, H., Wang, Y., Wang, L. J., & Zhang, J. J. (2012). Metal/Semiconductor Contacts for Schottky and Photoconductive CdZnTe Detector. *Physics Procedia*, *32*, 545–550. https://doi.org/10.1016/j.phpro.2012.03.599

[16] Mathy, F., Gliere, A., d'Aillon, E. G., Masse, P., Picone, M., Tabary, J., & Verger, L. (2004). A three-dimensional model of CdZnTe gamma-ray detector and its experimental validation. *IEEE Transactions on Nuclear Science*, *51*(5), 2419–2426. https://doi.org/10.1109/TNS.2004.835906

[17] Opanasyuk, A., Kurbatov, D., Znamenshchykov, Ya., Diachenko, O., & Ivashchenko, M. (2023). CdTe-/CdZnTe-Based Radiation Detectors. In G. Korotcenkov (Ed.), *Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors* (pp. 35–73). Springer International Publishing. https://doi.org/10.1007/978-3-031-24000-3_2

[18] Opanasyuk, A. S., Kurbatov, D. I., Kosyak, V. V., Kshniakina, S. I., & Danilchenko, S. N. (2012). Characteristics of structure formation in zinc and cadmium chalcogenide films deposited on nonorienting substrates. *Crystallography Reports*, *57*(7), 927–933. https://doi.org/10.1134/S1063774512070206

[19] Prabakar, K., Venkatachalam, S., Jeyachandran, Y. L., Narayandass, Sa. K., & Mangalaraj, D. (2004). Microstructure, Raman and optical studies on Cd0.6Zn0.4Te thin films. *Materials Science and Engineering: B*, *107*(1), 99–105. https://doi.org/10.1016/j.mseb.2003.10.017

[20] Roy, U. N., Camarda, G. S., Cui, Y., Gul, R., Hossain, A., Yang, G., Zazvorka, J., Dedic, V., Franc, J., & James, R. B. (2019). Role of selenium addition to CdZnTe matrix for room-temperature radiation detector applications. *Scientific Reports*, *9*(1), 1620. https://doi.org/10.1038/s41598-018-38188-w

[21] Roy, U. N., Camarda, G. S., Cui, Y., & James, R. B. (2020). X-ray topographic study of Bridgman-grown CdZnTeSe. *Journal of Crystal Growth*, *546*, 125753. https://doi.org/10.1016/j.jcrysgro.2020.125753

[22] Roy, U. N., Camarda, G. S., Cui, Y., & James, R. B. (2023). Growth interface study of CdTeSe crystals grown by the THM technique. *Journal of Crystal Growth*, *616*, 127261. https://doi.org/10.1016/j.jcrysgro.2023.127261

[23] Schlesinger, T. E., Toney, J. E., Yoon, H., Lee, E. Y., Brunett, B. A., Franks, L., & James, R. B. (2001). Cadmium zinc telluride and its use as a nuclear radiation detector material. *Materials Science and Engineering: R: Reports*, *32*(4–5), 103–189. https://doi.org/10.1016/S0927-796X(01)00027-4

[24] Sellin, P. J. (2006). Thick film compound semiconductors for X-ray imaging applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 563(1), 1–8. https://doi.org/10.1016/j.nima.2006.01.110

[25] Stolyarova, S., Edelman, F., Chack, A., Berner, A., Werner, P., Zakharov, N., Vytrykhivsky, M., Beserman, R., Weil, R., & Nemirovsky, Y. (2008). Structure of CdZnTe films on glass. *Journal of Physics D: Applied Physics*, *41*(6), 065402. https://doi.org/10.1088/0022-3727/41/6/065402

[26] Takahashi, J., Mochizuki, K., Hitomi, K., & Shoji, T. (2004). Growth of $Cd_{1-x}Zn_xTe$(x~0.04) films by hot-wall method and its evaluation. *Journal of Crystal Growth*, *269*(2–4), 419–424. https://doi.org/10.1016/j.jcrysgro.2004.05.054

[27] Tokuda, S., Kishihara, H., Adachi, S., & Sato, T. (2004). Preparation and characterization of polycrystalline CdZnTe films for large-area, high-sensitivity X-ray detectors. *Journal of Materials Science: Materials in Electronics*, *15*(1), 1–8. https://doi.org/10.1023/A:1026297416093

[28] Triboulet, R., & Siffert, P. (2010). Foreword. In *CdTe and Related Compounds; Physics, Defects, Hetero- and Nano-structures, Crystal Growth, Surfaces and Applications* (p. xi). Elsevier. https://doi.org/10.1016/B978-0-08-046409-1.00012-5
[29] Verger, L., Bonnefoy, J. P., Glasser, F., & Ouvrier-Buffet, P. (1997). New developments in CdTe and CdZnTe detectors for X and γ-ray applications. *Journal of Electronic Materials*, *26*(6), 738–744. https://doi.org/10.1007/s11664-997-0225-2
[30] Vieira, N. C. S., Fernandes, E. G. R., Queiroz, A. A. A. D., Guimarães, F. E. G., & Zucolotto, V. (2013). Indium tin oxide synthesized by a low cost route as SEGFET pH sensor. *Materials Research*, *16*(5), 1156–1160. https://doi.org/10.1590/S1516-14392013005000101
[31] Warren, B. E. (2012). *X-Ray Diffraction*. Dover Publications, Inc.
[32] Yang, G., Bolotnikov, A. E., Cui, Y., Camarda, G. S., Hossain, A., Kim, K. H., Franc, J., Belas, E., & James, R. B. (2013). Low-Temperature Photoluminescence Study of CdTe:In Crystals Annealed in Molten Bismuth. *Journal of Electronic Materials*, *42*(11), 3138–3141. https://doi.org/10.1007/s11664-013-2683-z
[33] Yang, G., & James, R. B. (2010). Applications of CdTe, CdZnTe, and CdMnTe Radiation Detectors. In R. Triboulet, P. Siffert (Eds.), *CdTe and Related Compounds; Physics, Defects, Hetero- and Nano-structures, Crystal Growth, Surfaces and Applications* (pp. 214–238). Elsevier. https://doi.org/10.1016/B978-0-08-096513-0.00002-9
[34] Zhang, Y., Wang, L., Xu, R., Huang, J., Tao, J., Meng, H., Zhang, J., & Min, J. (2016). A novel intermediate layer for Au/CdZnTe/FTO photoconductive structure. *Applied Surface Science*, *388*, 589–592. https://doi.org/10.1016/j.apsusc.2015.09.194
[35] Zou, J., Fauler, A., Senchenkov, A. S., Kolesnikov, N. N., Kirste, L., Kabukcuoglu, M. Pinar., Hamann, E., Cecilia, A., & Fiederle, M. (2021). Characterization of Structural Defects in (Cd,Zn)Te Crystals Grown by the Travelling Heater Method. *Crystals*, *11*(11), 1402. https://doi.org/10.3390/cryst11111402

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