J. Rad. Nucl. Appl. **11**, No. 2, 147-151 (2026)

Journal of Radiation and Nuclear Applications
An International Journal

http://dx.doi.org/10.18576/jrna/110204

Development of $(TeO_2)_{0.4}(ZnO)_{0.6}$ Thin Film Sensors for Real-Time X-Ray Dosimetric Applications

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Received: 25 Dec. 2025, Revised: 15 Feb. 2026, Accepted: 1 Mar. 2026

Abstract: The growing demand for compact and real-time radiation monitoring systems has intensified interest in metal-oxide thin film sensors for X-ray dosimetry. In this study, $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films were developed and evaluated as potential real-time X-ray dosimetric sensors. The films were fabricated on soda-lime glass substrates using ultrasonic spray pyrolysis from co-doped precursor solutions and subsequently characterized for their structural, morphological, compositional, electrical, and dosimetric properties. X-ray diffraction analysis confirmed the polycrystalline nature of the films, with the coexistence of tetragonal α-TeO_2 and hexagonal wurtzite ZnO phases. FESEM images revealed a clustered gel-like morphology with agglomerated nanoparticles, while EDX spectra verified the presence of Te, Zn, and O as the dominant constituent elements with negligible contamination. Electrical characterization showed linear current–voltage behavior**,** indicating ohmic conduction and good charge transport characteristics. Under X-ray irradiation, the induced current increased linearly with absorbed dose, demonstrating a stable and reproducible real-time dosimetric response. The films exhibited a sensitivity in the range of 61–228 mA cm^{-2} Gy^{-1}**,** a minimum measurable dose (MMD) of 0.439–1.639 mGy**,** and linearity coefficients **(**R^2**)** between 0.869 and 0.913**.** The enhanced performance is attributed to the synergistic interaction between the high photon interaction capability of TeO_2 and the superior electronic transport properties of ZnO, which together promote efficient electron–hole pair generation and charge collection under irradiation. These findings demonstrate that $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films are promising candidates for real-time X-ray dosimetric applications in medical, industrial, and radiation safety environments.

Keywords: Thin film, spray pyrolysis, dosimetry, and gamma radiation.

1 Introduction

The increasing utilization of ionizing radiation in medical imaging, industrial inspection, security screening, and radiation therapy has heightened the demand for reliable, real-time dosimetric sensors. Accurate measurement of X-ray dose is critical not only for diagnostic quality and patient safety in healthcare but also for monitoring radiation exposure in industrial and environmental settings [1-3]. Traditional dosimeters, such as thermoluminescent detectors and ionization chambers, while effective, often suffer limitations including delayed readout, bulky instrumentation, and complex signal processing requirements. These constraints have driven the exploration of solid-state sensors that offer rapid response, compactness, and high sensitivity [4-6].

Among the emerging materials for direct radiation detection, tellurium dioxide (TeO_2) and zinc oxide (ZnO) have attracted significant attention due to their complementary physical and electronic properties. TeO_2 is a high-Z metal oxide with superior optical transparency, chemical stability, and significant interaction cross-section with high-energy photons, making it a promising candidate for optical and radiation sensing applications [2]. When doped with ZnO, a wide-bandgap semiconductor known for its high exciton binding energy and radiation-induced current response, the composite thin films exhibit enhanced photoelectric and electrical behaviours suitable for dosimetric sensing [5,7]. These synergetic effects are attributed to improved charge transport and optimized structural features arising from the interaction of TeO_2 and ZnO phases at specific compositions.

Recent studies have demonstrated the feasibility of TeO_2-based thin films as radiation sensors. Arshak and Korostynska [8] showed that TeO_2 thin films exhibited a linear increase in electrical current with increasing γ-radiation dose, suggesting potential for real-time dosimetry. More recent work by Idris et al. [1] reported the

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use of $(ZnO)_{0.2}(TeO_2)_{0.8}$ thin films as X-ray dosimeters, indicating that ZnO doping enhances radiation response in composite films. In a related study, Mustapha and colleagues [2] investigated $(ZnO)_x(TeO_2)_{1-x}$ thin films with varying ZnO content, finding that 40 wt% ZnO doping produced films with improved physicochemical and electrical properties, high transparency in the visible region, and significant dosimetric sensitivity. These films also displayed increased current under X-ray irradiation, demonstrating their applicability in real-time detection across a range of doses.

In addition to composite TeO_2-ZnO systems, nanostructured ZnO has been widely explored for radiation detection. Nanostructured ZnO materials have shown fast response times and high detection efficiency for X-rays and γ-rays due to their favourable electronic properties and radiation-induced signal generation mechanisms. Such studies underline the broader interest in oxide semiconductor thin films for radiation detection applications, motivating continued research into material optimization and device fabrication [9-12].

Despite these advances, there remains a need for systematic investigation of optimized composite thin films specifically tailored for direct, real-time X-ray dosimetry. In particular, the $(TeO_2)_{0.4}(ZnO)_{0.6}$ composition has been identified in preliminary reports as a promising balance between TeO_2's dense interaction potential and ZnO's electronic activity, but detailed studies on its fabrication, structural characteristics, and real-time dosimetric performance are limited. Therefore, this study focuses on the development of $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin film sensors and evaluates their potential as real-time dosimeters for X-ray applications.

2 Materials and Methods

The $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin film dosimetric sensors were fabricated following a structured procedure involving precursor preparation, co-doping, thin film deposition, characterization, electrical measurements, X-ray irradiation, and dosimetric analysis. The zinc acetate dihydrate precursor (0.863 g) was dissolved in a mixture of 2 mL acetylacetone and 58 mL methanol and stirred vigorously at room temperature for 15 minutes to obtain a homogeneous ZnO solution. Tellurium dioxide (0.638 g, MW = 159.6 g/mol) was dissolved in 40 mL of hydrochloric acid (43 mol%) and 20 mL of methanol, heated to 60 °C, and stirred for 15 minutes to form a TeO_2 solution. Additional methanol was added to prevent precipitation. Furthermore, a sol-gel solution of TeO_2 was prepared using titanium isopropoxide ($Te(OC_3H_7)_4$) dissolved in isopropanol, followed by the addition of acetic acid and methanol with continuous stirring for 2 hours to ensure solution stability. The ZnO and TeO_2 precursor solutions were co-doped to achieve the desired $(TeO_2)_{0.4}(ZnO)_{0.6}$ composition, and the mixture was allowed to equilibrate at room temperature for 24–48 hours before deposition.

Soda-lime glass substrates were cleaned thoroughly to remove dirt, grease, and hydrocarbons. The cleaning procedure involved sequential washing with soapy foam, distilled water, dilute hydrochloric acid, acetone, and methanol, followed by a final rinse in distilled water. The substrates were then dried in a dust-free environment to prevent contamination. Thin films were deposited on the prepared substrates using ultrasonic spray pyrolysis (U-Spray USP 1500). The atomized co-doped precursor solution was sprayed onto glass substrates maintained at 300 °C using a solution flow rate of 0.15 mL/min, carrier air pressure of 0.2 kg/cm², and a nozzle-substrate distance of 3.0 cm. A thin film of approximately 375 nm thickness was achieved using 1.2 mL of the precursor solution. Interdigitated graphite electrodes with 0.3 mm spacing and copper foils placed 10 mm apart were printed onto the film for electrical measurements.

Structural and phase analyses were carried out using X-ray diffraction (XRD) with Cu-Kα radiation ($\lambda = 1.54$ Å) at grazing incidence to minimize substrate contributions. Surface morphology was examined using scanning electron microscopy (SEM), providing detailed information about film topography and grain structure. Elemental composition and homogeneity of the films were verified through energy dispersive X-ray (EDX) analysis using a 20 keV electron beam [13-15].

The electrical properties of the films were evaluated by recording current-voltage (I–V) characteristics using an electrometer. For each X-ray dose, the mean I–V curve was obtained, from which current vs. dose (I–D) plots were constructed for applied voltages ranging from 0 to 4.8 V. Sensor sensitivity was calculated as the change in current per unit radiation dose, and the minimum measurable dose (MMD) corresponded to the dose producing a current change of 1 μA. For dosimetric testing, the thin films were irradiated individually using an Elekta Linear Accelerator at doses of 0, 100, and 200 cGy. The irradiation area of the films was 5 cm², and samples were mounted perpendicular to the beam in a holder with a diameter of 50 mm. All irradiation parameters were carefully controlled to ensure reproducibility and uniform exposure.

3 Results and Discussion

The $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin film was successfully fabricated using zinc acetate dihydrate dissolved in methanol as the precursor via spray pyrolysis. The deposition process produced uniform, highly transparent films, with a measured thickness of 10.84 µm, confirmed by cross-sectional FESEM imaging.

XRD analysis (Figure 1) revealed that the $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films are polycrystalline, exhibiting characteristic peaks corresponding to tetragonal α-TeO_2 at 20.60° (JCPDS 78-1713) along the (101) plane and hexagonal wurtzite ZnO at 66.20° (JCPDS 043-0002) along the (103) plane [15]. A minor peak at 31.65° originates from the silicon substrate. These results confirm the coexistence of both TeO_2 and ZnO phases in the composite films, consistent with previous studies on oxide thin film composites for dosimetry applications [2, 17].

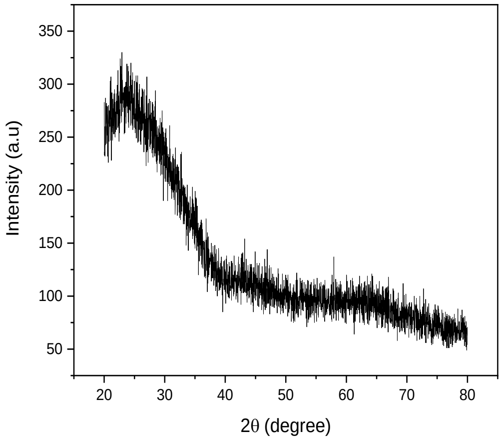

Fig. 1: XRD pattern of $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin film at room temperature.

FESEM imaging (Figure 4) revealed a clustered, gel-like morphology with non-uniform, agglomerated nanoparticles. ZnO doping improved the TeO_2 film structure, enhancing surface homogeneity.

EDX spectra confirmed the presence of Te, Zn, and O as major elements, with negligible contamination from the substrate or Pt buffer layer (Table 1). The high purity of the films ensures reliable electrical and dosimetric measurements.

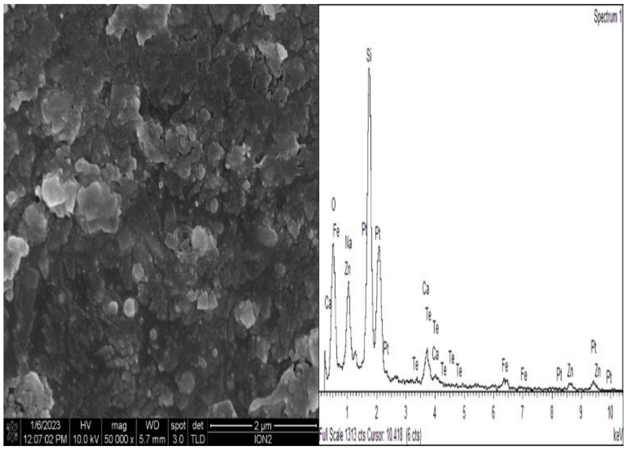

Fig. 2: FESEM image and EDX spectra of $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin film.

The I–V characteristics of the thin films were measured in the voltage range 0–6 V. The induced current increased linearly with applied voltage, indicative of ohmic behavior. The linear response reflects microstructural modifications resulting from co-doping, which influences electrical, optical, and structural properties of the films [16-18]

The dosimetric response of the thin films was evaluated under X-ray irradiation by varying absorbed dose, dose rate, and exposure time (Table 1). The induced current increased linearly with X-ray dose, demonstrating the suitability of the films for real-time X-ray detection. The sensitivity ranged from 0.61 to 2.28 mA/cm²/Gy, and the minimum measurable dose (MMD) ranged from 0.439 to 1.639 mGy. The linearity index (R^2) was 0.882–0.913, with minimal uncertainty, confirming high reproducibility and reliability.

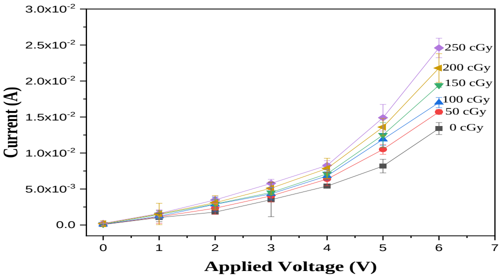

Fig. 3: I–V characteristics under different X-ray doses.

Table 1. X-ray irradiation parameters and dosimetric response of $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films.

Dose (cGy)	**Dose Rate (cGy/min)**	**Time (min)**	**Sensitivity (mA/cm²/Gy)**	**MMD (mGy)**	**R² (%)**	**Linearity Error (×10⁻³)**
50	200	0.25	228	0.439	91.1	4.2
100	250	0.40	122	0.820	91.3	4.5
150	300	0.50	97	1.031	88.8	5.2
200	350	0.57	80	1.250	86.9	6.5
250	400	0.63	61	1.639	88.2	5.8

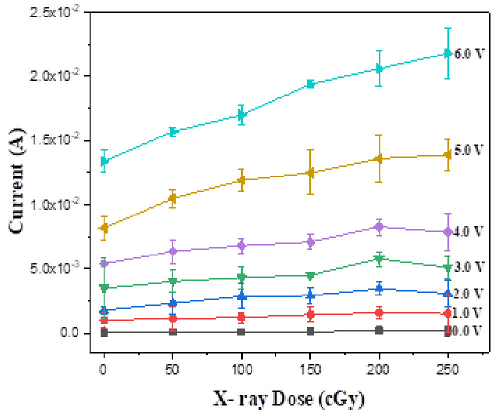

Fig. 4: Current vs. X-ray dose (I–D) plots at different applied voltages.

The linear increase in current with X-ray dose is attributed to electron-hole pair generation, defect formation, and partial healing of intrinsic defects. At low doses, fine homogeneous grains and recombination of intrinsic defects reduced resistivity, enhancing current density [19-20].

The $(TeO_2)_{0.4}(ZnO)_{0.6}$ films exhibit a uniform, transparent morphology with polycrystalline α-TeO_2 and wurtzite ZnO phases, consistent with the XRD and FESEM analyses. Co-doping with ZnO improved microstructure, electrical conductivity, and radiation sensitivity, corroborating previous reports on metal oxide composites [2, 6, 10].

X-ray irradiation enhanced conductivity through energy transfer from photons to electrons, promoting electron-hole pair formation and generating additional charge carriers. The observed linearity and high sensitivity confirm that $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films are suitable for real-time X-ray dosimetric applications, offering reproducible, high-fidelity responses over a wide dose range.

4 Conclusions

In conclusion, $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films were successfully developed by ultrasonic spray pyrolysis and demonstrated strong potential as real-time X-ray dosimetric sensors. Structural characterization confirmed the formation of a polycrystalline composite consisting of α-TeO_2 and wurtzite ZnO phases, while FESEM and EDX analyses revealed a uniform, highly transparent film with clustered nanoscale morphology and high elemental purity. The incorporation of ZnO into the TeO_2 matrix improved the microstructural and electrical properties of the films, resulting in linear ohmic I–V behavior and stable charge transport characteristics. Under X-ray irradiation, the films exhibited a clear linear increase in induced current with absorbed dose, confirming their suitability for direct and real-time dose detection. The sensors showed high sensitivity (61–228 mA cm^{-2} Gy^{-1}), low minimum measurable dose (0.439–1.639 mGy), and good linearity ($R^2 = 0.869$–0.913), indicating reliable and reproducible dosimetric performance across the investigated dose range. These enhanced properties are attributed to the synergistic combination of TeO_2's strong photon interaction capability and ZnO's favorable charge transport behavior, which together promote efficient electron–hole pair generation and collection under irradiation. Overall, the results suggest that $(TeO_2)_{0.4}(ZnO)_{0.6}$ thin films are a promising, low-cost, and effective material system for real-time X-ray dose monitoring in medical, industrial, and radiation protection applications, with further optimization and long-term stability studies expected to support future practical deployment.

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