

Dose-Response Characterization Of $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ Thin Films for High-Dose X-Ray Applications

Idris M. Mustapha^{1*}, Suleiman Babani², Akpanowo Mbet³, Ubong Effiong³, and Atef El-Taher⁴

¹Department of Physics, Nasarawa State University, Keffi, P.M.B. 1022, Keffi, Nasarawa State, Nigeria.

²Department of Electrical Engineering, Bayero University Kano, PMB 3011 Kano, Kano State, Nigeria

³Nigerian Nuclear Regulatory Authority, P.M.B. 558, Garki., Abuja, Nigeria.

⁴Department of Physics, Faculty of Science, Al Azhar University, Assuit- Egypt.

Received: 15 August. 2025, Revised: 21 August. 2025, Accepted: 30 August. 2025.

Published online: 1 September 2025.

Abstract: This study explores the structural properties and X-ray dosimetric performance of $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ thin films fabricated using the spray pyrolysis method. Aqueous solutions containing zinc acetate dihydrate and tellurium dioxide were deposited onto glass substrates to form both pure and doped ZnO-TeO₂ thin films. Interdigitated graphite electrodes were applied to the films to serve as electrical contacts. Current-voltage (I-V) measurements were conducted under X-ray irradiation from a linear accelerator (Linac). At all applied voltages, the measured current increased linearly with increasing X-ray dose. The thin films demonstrated sensitivity values ranging from 0.37 to 0.94 mA/cm²/Gy, corresponding to minimum detectable doses between 1.064 and 2.703 mGy. The linear regression analysis of the I-V characteristics produced correlation coefficients ranging from 0.966 to 0.998, with regression errors between 0.0006 and 0.0025. These findings suggest that $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ thin films are promising candidates for high-dose X-ray detection, particularly in clinical radiotherapy using Linac systems.

Keywords: I-V characteristics, X-ray radiation, thin film sensor, and spray pyrolysis.

1 Introduction

In recent years, there has been growing interest in developing advanced materials for the precise detection of ionizing radiation, particularly in healthcare, industry, and environmental protection. One of the critical needs in medical imaging and radiotherapy is the ability to accurately monitor X-ray doses, ensure effective treatment outcomes, and promote patient safety. [1-4]. Compared to conventional radiation detectors, thin-film-based dosimeters offer significant advantages such as flexibility, affordability, and suitability for integration into miniaturized systems [2, 5-8].

Zinc oxide (ZnO) and tellurium dioxide (TeO₂) are two promising compounds that have been widely explored for their complementary optical and electrical characteristics. Among these, zinc oxide (ZnO), a wide-bandgap semiconductor (~3.4 eV), is known for strong radiation responsiveness, which provides excellent electrical performance [2, 9-13]. TeO₂, on the other hand, enhances

the material's optical and structural qualities, making it suitable for dosimetric applications [14-16]. By combining these two oxides in specific proportions, it becomes possible to engineer thin films with improved sensitivity and dose response behavior under X-ray exposure.

Semiconducting thin films have emerged as promising candidates for radiation detection due to their tunable electrical properties, ease of fabrication, and compatibility with low-cost deposition techniques. Among these, zinc oxide (ZnO), a wide-bandgap semiconductor (~3.4 eV), is known for its high radiation sensitivity, chemical stability, and nontoxicity [17-19]. Tellurium dioxide (TeO₂), with a relatively lower bandgap (~2.8 eV), complements ZnO by enhancing the optical and electronic response of the composite material. When combined, ZnO and TeO₂ can form a hybrid thin film with improved electrical conductivity, enhanced sensitivity, and stable response under ionizing radiation. The performance of such a composite material depends significantly on the ratio of its components and the method of deposition [[7, 20-25].

*Corresponding author e-mail: idrismustapham@nsuk.edu.ng

Spray pyrolysis, a simple, cost-effective, and scalable technique, offers several advantages for thin-film fabrication, including uniform coating, controllable thickness, and suitability for large-area applications. It ensures uniform film deposition across substrates and is particularly effective for preparing multi-component oxide films with consistent stoichiometry [26-29].

This work investigates $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ thin films produced using the spray pyrolysis method. The study is aimed at evaluating the electrical response of the films to high-energy X-ray radiation, such as that encountered in medical linear accelerators (Linacs). Key performance metrics—including sensitivity, linear dose response, and minimum detectable dose—are analyzed to assess the feasibility of using these films in practical radiation sensing environments.

2 Experimental Procedure

2.1 Chemical Synthesis

To prepare the precursor solutions for ZnO and TeO_2 , 0.863 g of zinc acetate di-hydrate was dissolved in 60 ml of methanol, and 0.638 g of tellurium dioxide powder was dissolved in 40 ml of hydrochloric acid (concentration to 43% w). The ZnO solution was stirred with a magnetic stirrer until a clear, homogeneous solution was obtained. For the TeO_2 solution, stirring was carried out under mild heating conditions (67°C) for 12 minutes, until transparency was achieved. 20 ml of methanol was added to the TeO_2 solution to prevent precipitation and enhance solubility. Before film deposition, the ZnO and TeO_2 solutions were combined in an 8:2 volumetric ratio. The resulting mixture was stored at ambient temperature for about 36 hours to allow chemical stabilization before deposition.

2.2 Thin Film Deposition

The (ZnO) and (TeO_2) were mixed in a 2:8 volumetric ratio, and the thin films were fabricated using an ultrasonic spray pyrolysis approach. A benchtop automated spray system (U-spray USP 1500) was employed to atomize and spray the ZnO- TeO_2 composite solution onto pre-heated soda-lime glass substrates. Compressed air acted as the carrier gas. For each deposition cycle, 10 ml of the mixed precursor solution was loaded into the system's dispensing tank, and the substrate temperature was held constant at 300°C . The flow parameters included a solution feed rate of 0.15 ml/min, air pressure of 0.2 kg/cm², and a nozzle-to-substrate distance of 3.0 cm. The spray nozzle consisted of a coaxial design with an inner solution tube and an outer airflow channel, enabling effective atomization by air suction. Spraying continued until 1.2 ml of the precursor

was deposited onto 10 mm × 10 mm glass substrates for clarity. After deposition, the coated substrate was removed and allowed to cool naturally at room temperature. A thick graphite-based interdigitated electrode (IDE) pattern with 0.3 mm spacing was printed onto the film surface. Copper contacts, spaced 10 mm apart, were also attached at both edges of the graphite layer to serve as electrical terminals.

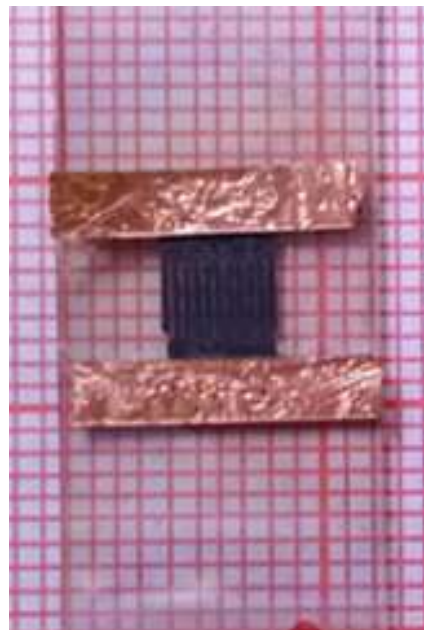


Fig. 1: Fabricated $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ thin film sensor.

2.3 Current–Voltage Characteristics During X-ray Irradiation

The $(\text{ZnO})_{0.2}(\text{TeO}_2)_{0.8}$ thin film's X-ray dose response was evaluated using a linear accelerator delivering 6 MV X-ray photon beams at doses of 0, 50, 100, 150, 200, and 250 cGy, all delivered at a constant dose rate of 400 cGy/min. During exposure, the thin film sensor was positioned perpendicular to the beam to ensure uniform irradiation. The setup featured a beam field size of $5 \times 5 \text{ cm}^2$ and a source-to-surface distance (SSD) of 100 cm. To achieve build-up region compensation and maximize surface dose deposition, a 10 mm thick bolus was placed directly on top of the sample.

As the irradiation proceeded, the resulting electrical current induced in the sensor was monitored in real-time using an electrometer connected to the sample. The readings were simultaneously transmitted and displayed on a computer screen located in the control room, using CCTV footage from inside the treatment bunker. The current–voltage (I–V) characteristics were recorded at each radiation dose for applied bias voltages of 0 to 6 V in 1 V increments. A schematic diagram illustrating the entire experimental setup

for measuring the I–V response of the thin films during irradiation is shown in Figure 2.

3 Results and Discussion

The I–V characteristics of the fabricated thin film sensors are presented in Figure 4. The plots display clear evidence of semiconducting behavior across all tested samples. The observed variations in electrical sensitivity suggest that an appropriate compositional balance of ZnO to TeO₂ significantly improves the overall conductivity of the

composite film, as previously reported [28, 29]. Among the tested films, D5, fabricated with a higher ZnO ratio than the standard (ZnO)_{0.2}(TeO₂)_{0.8}, demonstrated the poorest charge transport characteristics. This reduced conductivity is likely due to defect states, film morphology, crystallinity, and the relatively wide bandgap of ZnO, approximately 3.4 eV, in contrast to the narrower 2.8 eV bandgap of TeO₂. The enhanced conductivity observed in TeO₂-rich compositions likely results from improved charge transport facilitated by increased density of available energy states and reduced recombination losses.

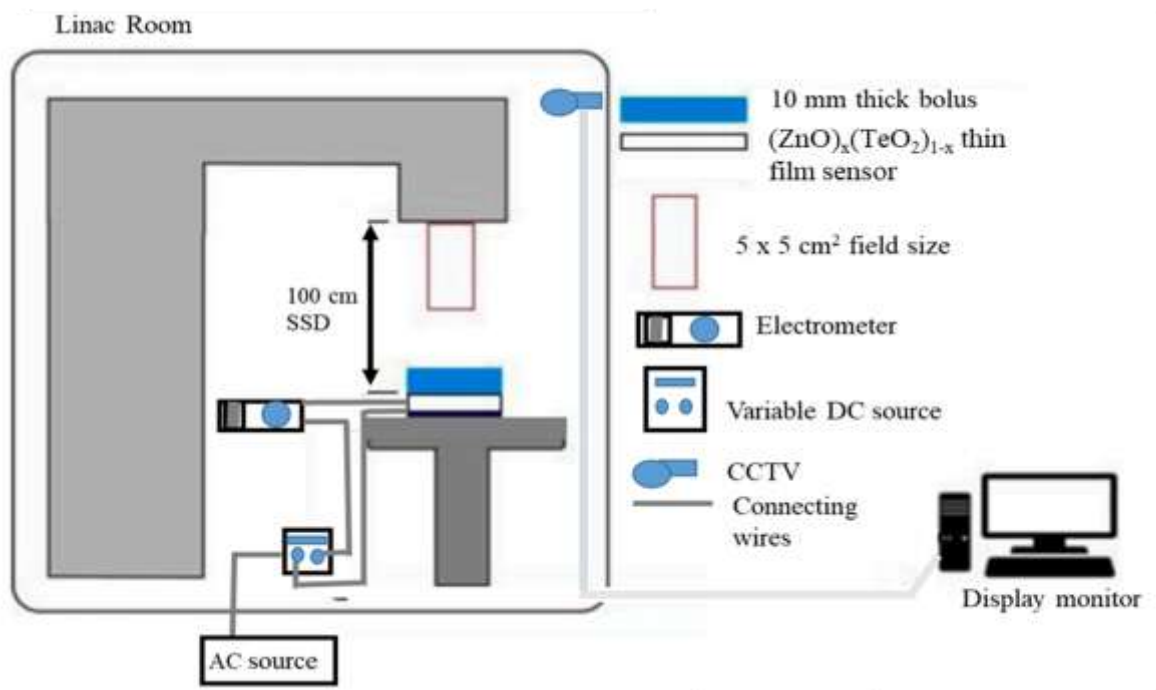


Fig.2: Schematic view of the experimental setup.

Table 1: Summary of the sensitivity, minimum measurable dose, regression linearity, and regression error of the thin film devices.

Absorbed Dose (cGy)	Sensitivity (mA/(cm ² .Gy)) x 10 ⁻²	Minimum Measurable Dose (mGy)	Regression Linearity (%)
0.00	NA	NA	99.8
50.00	94.000	1.064	98.7
100.00	53.000	1.887	97.8
150.00	41.000	2.439	97.7
200.00	42.000	2.381	96.9
250.00	37.000	2.703	96.6

NA=Not Applicable

Figure 3 presents the current–voltage (I–V) characteristics of the (ZnO)_{0.2}(TeO₂)_{0.8} thin film sensors under varying X-ray doses from 0.0 to 2.5 Gy. Current was measured at each applied voltage within the 0–6 V range, corresponding to the different radiation dose levels. Linear regression was applied to the I–V data, and key performance parameters—including sensitivity, correlation coefficient (R²), and regression error—are summarized in Table 1. The R² values, which reflect the linearity of the response, were found to range between 0.966 and 0.998, confirming a strong linear relationship between induced current and X-ray dose at all applied voltages. The data show a proportional increase in current with radiation dose. This linear trend aligns with findings reported by Maity et al. [28], Shamma et al. [29], Amal et al. [25], and Gryzinski et al. [30], in comparable oxide-based thin-film sensors. The

sensitivity of the thin film devices to X-ray dose was found to vary between 0.37 and 0.94 mA/cm²/Gy across the measured voltage range. Additionally, regression error values remained low, falling between 0.0006 and 0.0025, further confirming the reliability of the measurements. Notably, these sensitivity values compare favorably with those of some existing commercial dosimeters [22, 31, 32], supporting the potential of the (ZnO)_{0.2}(TeO₂)_{0.8} thin film sensors for practical radiation sensing applications.

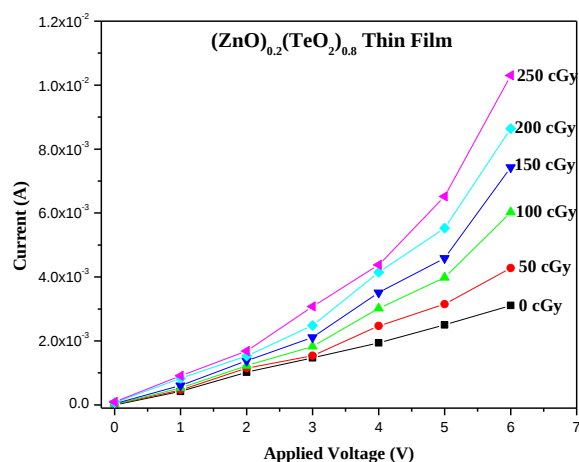


Fig. 3: Typical I-V characteristics plot at different X-ray doses for (ZnO)_{0.2}(TeO₂)_{0.8} thin film device.

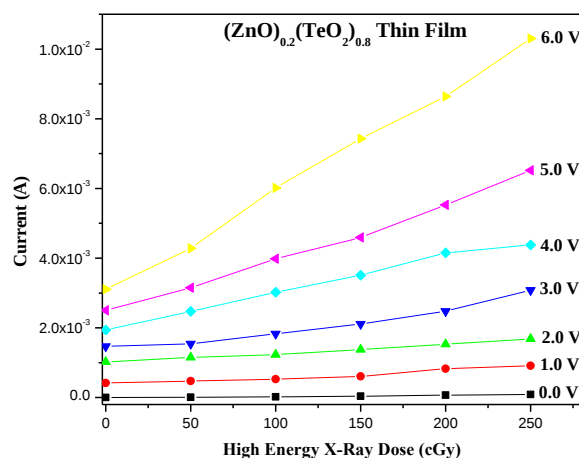


Fig. 4: Current versus X-ray Dose (I-D) plot at different applied Voltages for (ZnO)_{0.2}(TeO₂)_{0.8} thin film sensor.

The operational range for employing the (ZnO)_{0.2}(TeO₂)_{0.8} thin film sensor in real-time X-ray dosimetry is defined by the region in which the measured current exhibits a consistent linear increase with radiation dose, demonstrated

up to 2.5 Gy (250 cGy). Integrated into a dosimetric system comprising the thin film sensor, a 6 MV medical linear accelerator delivering doses between 0.5 and 2.5 Gy, and an electrometer with a detection threshold of 0.1 μA, the device is capable of detecting minimum measurable X-ray doses ranging from 1.064 to 2.703 mGy at an applied bias of 1.0 V.

These results highlight the sensor's suitability for high-dose X-ray monitoring in clinical radiotherapy environments, where precise dose measurement is critical for patient safety and treatment efficacy [33-39].

4 Conclusions

This study demonstrated that (ZnO)_{0.2}(TeO₂)_{0.8} thin films, fabricated via spray pyrolysis, are promising for high-dose X-ray monitoring. The thin films, prepared via spray pyrolysis, exhibited clear semiconducting behavior and a strong linear relationship between induced current and X-ray radiation dose across the tested range of 0 to 250 cGy. The I-V measurements revealed that the electrical response of the sensors was dose-dependent, with sensitivity values ranging from 0.37 to 0.94 mA/cm²/Gy and high regression linearity (R^2 between 0.966 and 0.998). The minimum detectable dose was estimated to fall between 1.064 and 2.703 mGy at an applied voltage of 1.0 V, indicating potential for low-dose X-ray detection.

These results indicate that the (ZnO)_{0.2}(TeO₂)_{0.8} thin film sensor possesses the essential qualities required for real-time X-ray dosimetry, including high sensitivity, linear response, and low measurement error. Its compatibility with 6 MV photon beams from a medical linear accelerator further supports its relevance for radiotherapy applications. Therefore, this material system offers a promising and cost-effective alternative for developing reliable dosimeters for clinical and industrial use.

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