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Transparent Conducting Oxides Thin Film Dosimetry: Present and the Future

M.M. Idris[1,2*], *I.O. Olarinoye*[1], *M.T. Kolo*[1] *and S.O. Ibrahim*[1]

[1]Department of Physics, Federal University of Technology, Minna Nigeria.
[2]Department of Phyiscs, Nasarawa State University, Keffi Nigeria.

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Abstract: Transparent Conducting Oxides (TCOs) are widely used in numerous new devices including solar cells, flat panel display, gamma sensor and many optoelectronic applications. Nowadays, the high demand for flexible optoelectronic devices requires the development of efficient and non-costly TCOs deposited on substrates. Over the past decades, several new materials and manufacturing techniques have been developed to satisfy the technological requirements. This article reviewed recent researches and advancements on application of TCO (such as ZnO, TeO_2, CuO, In_2O_3, SnO_2) thin film in the detection and measurement of gamma radiation and others. A comprehensive analysis of TCO thin film in the recent technological application is performed. Furthermore, critical evaluation and comparison of their benefits and limitations as dosimeters is done based on the available studies. Finally, the potentials of these devices and the challenges of realizing their applications as quintessential dosimeters are highlighted for future research and improvements.
Keywords: Transparent Conducting Oxide (TCO), Thin Film, and dosimetry.

1 Introduction

Transparent conducting oxide (TCO) films can be traced back to 1907 when K. Badeker first fabricated Cadmium Oxide (CdO) films by thermal oxidation of sputtered Cadmium [1, 2]. After that, there has been tremendous interest in TCO films due to their unique properties [3]. Combining high optical transmittance in visible light range, high infrared reflectance, and good electrical conducting, the potential of TCO was firstly noted. Over the past decades, several new materials and manufacturing techniques have been developed to satisfy the technological requirements [2, 4 – 6].

Transparent conducting oxide a compromise between high transmittance and low resistivity [1, 7]. Tin-doped indium oxide, ITO, is the most commonly used TCO, together with fluorine-doped tin oxide (FTO) [8]. However, the cost of In, and the high temperature needed for FTO deposition are limiting steps for the development of commercially available TCOs on plastic substrates [9, 10]. Doped ZnO thin films offer a promising alternative in particular for low temperature deposition [6]. Zinc oxide is cheap, abundant and non-toxic. Its wide band gap (E_g = 3.30 eV) is correlated with transparency in visible range. The substitutional doping of ZnO with group III metals such as Al, B and Ga via, for example, chemical vapor deposition (CVD), magnetron sputtering and pulsed laser deposition was already reported [6, 7, 11, 12].

Numerous instruments such as ionization chambers, hand-held and pocket dosimeters of various types, film badges, thermoluminescent dosimeters (TLDs), and optically stimulated luminescence dosimeters (OSLDs) are used to measure and monitor radiation in many areas of radiation applications [13–16]. Of recent, thin films of some TCO such as In_2O_3, TeO, MnO, etc have been adopted and studied for possible application [17–20]. TCOs are a special class of materials that exhibit high optical transparency as well as good electrical conductivity, two properties usually in contradiction with each other [2]. In recent years, portable devices and larger display are the trend of the market, resulting in considerable interest in TCOs due to their unique characteristics and essential role in the technology of thin film dosimetry [21, 22].

Studies has reported the radiation-induced changes in the optical, structural and electrical properties of TCO thin film of different compounds when exposed to gamma radiation [23, 24]. These provide evidence of thin films dosimeter for real-time and post-exposure gamma radiation measurement

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

application [25]. Gamma-ray photons strongly interact with solid material properties by creating structural defects (called colour centers or oxygen vacancies in oxides) and other disorders. The defect creation and annihilation take place simultaneously inside the material, having strong dependence upon the dose and dose rate. The defect creation is more at high doses and the defect annihilation is more at low doses. The fact now is that the degradation is much more severe for the higher radiation doses and thinner films [26, 27].

Mixing different TCOS in various proportions can control the properties of semiconductor thin films. Gamma-ray photons provide enough energy to move the electron from the valence band to the conduction band which leads to the creation of electron-hole pairs that increase the conductivity of the film. The interaction of high-energy gamma radiation with material generates electrons as well as a defect caused by the displacement of atoms in the lattice [28, 29]. The defect originated from this phenomenon changes the optical, mechanical, microstructural, and electrical properties of a material [10].

The effect of gamma radiation on TCOs have been investigated and reported in recent years by many researchers [30, 31]. However, the gamma radiation effect on various potential compound semiconductors including TCO thin film for radiation dosimetry application is scarce. Therefore, recent research has been focused on the investigation of the influence of gamma radiation on metal oxide semiconductors of different compounds. Thin films of In_2O_3, TeO_2, SiO, ZnO, CuO, MnO, etc, and their mixture which have versatile wide bandgap semiconductor material seem to be among the promising materials [27, 32]. The present work reports a review study on TCO thin film dosimetry with emphasis on the present and the future technology for a portable, cost-effective, and high sensitive gamma radiation dosimetry system.

2 Transparent Conducting Oxide (TCO)

Transparent conductive oxides (TCO) are materials with high electrical conductivity and are optically transparent. TCO's has transmittance of 80% and above in the visible spectrum characterized by having a bandgap of 3.1 eV and above, and electrical resistivity of less than 10-3Ω cm [2, 33]. The electrical conductivity is a consequence of the number of available charge carriers which are about 10^{20} cm^{-3} and above, and their mobility. The combination of these properties in one material has made TCOs essential in the production of optoelectronic devices such as flat-screen displays, photovoltaic cells, gas sensors, gamma sensors, and light-emitting diodes [7].
Thin film of CdO was the first TCO and was reported by Badekar in 1907 but developing it into practical use experienced very little progress probably because of its low transparency due to a bandgap of 2.3 eV [34]. Since then, other TCO materials have been discovered such as ZnO, In_2O_3, TeO, CuO, SnO_2 etc. The most successful films have been made using indium or tin-based oxides. However, indium and tin are in limited supply and relatively expensive to a lesser extent [35]. Thus, the need to find alternative materials that can be employed in devices such as gamma sensor is of paramount importance.

2.1 Optical Properties of TCOs

It could be contradictory for a material to be transparent and conductive since transparency requires a wide bandgap, which would otherwise hinder the formation of charge carriers. It would be possible for TCO to have 100% transmission only if there were no free electrons that could be excited from the conduction band minimum (CBM) to higher conduction band states [36]. However, transparency is not the only property that is desired of a TCO. Therefore, there is a need for compromise in which the concentration of charge carriers and the transparency are as high as possible. The transmittance of TCOs can be grouped into three regions: ultraviolet (UV) (10-400 nm), visible (400-700 nm) and near-infrared (>700 nm) (Figure 1) [37]. An increase in charge carrier concentration would increase the near-infrared absorption. In the conduction band, a high electron density would increase the reflection and absorption by the free electron gas (plasma) and hence reducing transmittance for higher wavelengths than the plasma wavelength. This type of optical profile is seen generally in thin films consisting of FTO and is a heat mirror requirement [38]. The blue shifting of the plasma band onset of an increase in reflectance is also dependent on the dielectric constant (a measure of capacitance) and the mean free relaxation time of the material (which is directly proportional to conductivity) i.e. the higher the electron density and lower the effective electron mass, the lower the free relaxation time [10]. However, the optically transparent property of TCO thin films remain in the visible region since the conduction band remains unchanged. The number of interference fringes depth is a function of film thickness which is a consequence of the variation of thickness across a film. Interference fringes can also be present as a result of multiple reflections that occur at the interfaces between the thin film and the air, the substrate and the thin film, and the barrier coating and a glass of the substrate.

2.2 Band Gaps

The bandgap arises from the splitting and overlapping of energy levels when atoms come close together forming the valence and conduction bands. The bandgap energy, Eg, is the energy needed for electrons to flow from the valence band maximum (VBM) to the conduction band minimum (CBM). Typical values for different materials are given in Table 3. Several factors affect the band gap of semiconductors [39]. A large bandgap is a feature of small interatomic spacing and large differences of

electronegativity [40]. The hybridization of orbitals and most notably, doping, also have measurable effects on the bandgap.

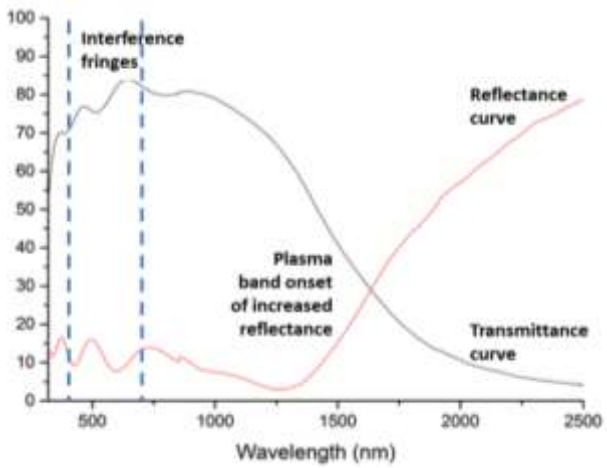

Fig.1: A Uv- vis spectra showing some characteristics seen in thin films.

Table 3: The band gap energies for different materials.

Type of material	Band gap energy /eV
Metal	<0.3
Semiconductor	<4
LInsulator	4-12

Semiconductors can be one of two types: indirect bandgap or direct bandgap (Figure 2). In a direct band gap semiconductor, the VBM and the CBM has the same momenta (the highest and the lowest energy points of the valence and conduction bands respectively line up vertically) but this is not true for indirect bandgap semiconductors, such as silicon. However, conservation of momentum is a requirement because the electrons from the conduction band must recombine with the holes in the valence band. This recombination could be radiative or nonradiative. The former is required for the material to have optical properties. In indirect bandgap semiconductors, the recombination requires phonons, vibrations of the crystal lattice [41, 42]. However, indirect semiconductors have poor optical properties because the probability of interaction between electrons and phonons is low resulting in a lower rate of radiative emission.

2.3 Doping

Other factors can also cause light absorptions in the TCO, such as defects in the bandgap which arise from imperfections in the structure [11]. Figure 3 shows the different forms of defects commonly found in the crystal lattice: vacancies (sometimes referred to as the Schottky defect) are created by the absence of an ion in the ordered lattice; interstitials are atoms that reside within the normal crystal structure where an atom is not usually found; a Frenkel pair arises when an ion moves from its usual position within the lattice to an interstitial space close by thus creating a vacancy and substitutional defects (also known as impurities) arise when an ion or atom (larger, smaller, or the same size and isovalent or aliovalent), replaces an ion or atom normally found in the lattice. Doping aims to improve conductivity and increase the bandgap.

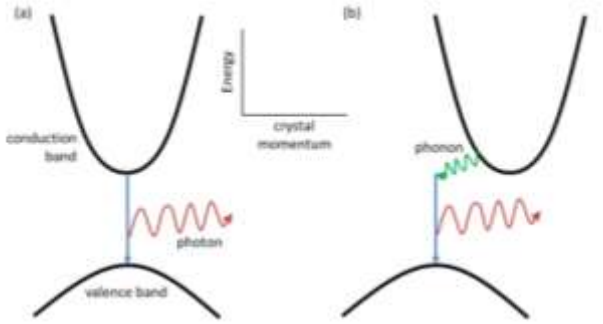

Fig. 2: The electronic band structure of (a) direct band gap and (b) indirect band gap semiconductors. Crystal momentum is a momentum-like vector that refers to the electrons in the lattice.

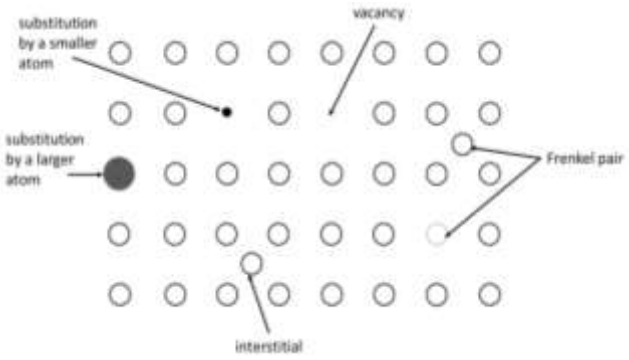

Fig. 3: The types of defects found in a crystal lattice.

2.4 Electrical Conductivity

Electrical conductivity is one of many properties that depends on the thermal excitation of electrons from the ground state. The Boltzmann distribution describes the number of particles in the excited state at a particular temperature, according to equation (1).

$$N_i \propto e^{-\frac{E_i}{KT}} \quad (1)$$

Where Ni is the number of particles in a given state, i; E is the energy of a state, k is the Boltzmann constant and T is the temperature. However, the Boltzmann distribution is not appropriate for electrons in a solid as it does not account for the fact that electrons are indistinguishable and that they obey Pauli's exclusion principle that two electrons occupying an orbital must have opposite spins. Hence, the Fermi-Dirac distribution gives a better representation, as

given in equation (2).

$$f(E) = \frac{1}{1+e^{\left[\frac{E-E_f}{KT}\right]}} \quad (2)$$

The function, *f*(E), is the fraction of the allowed levels with energy E which are occupied. The Fermi level or Fermi energy, E_f, is the cut-off between completely filled levels below E_f and completely empty levels above it. It can also be defined as the maximum energy level an electron can occupy at zero K. For a metal, the Fermi level is within a band which is why they are such good conductors.

In a semiconductor the electrons have to move from the valence band to the conduction band, i.e. the electrons need to gain sufficient energy to overcome the band gap, E_g (Figure 4).

If this is achieved in a pure semiconductor at room temperature, then the semiconductor is called an intrinsic semiconductor (Figure 4b). In a pure semiconductor, at any given temperature, the number of electrons excited into the conduction band would be equal to the number of holes left behind in the valence band. Hence, the Fermi level is placed half-way in the bandgap. However, the conduction of semiconductors can be increased by doping in which case the semiconductor is called extrinsic, and can be n- or p-type if the doped atom is of greater or lower valency than the host atom, respectively. The Fermi level in extrinsic semiconductors moves away from its ideal mid band gap position: it is closer to the conduction band in n-type and moves down to the valence band in p-type.

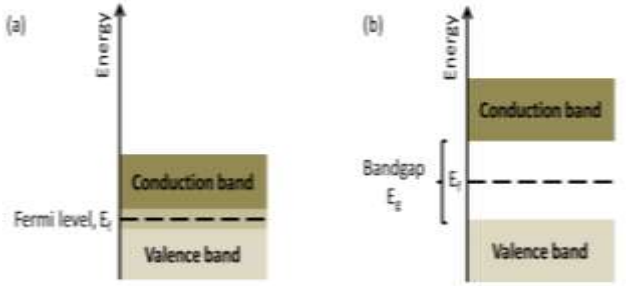

Fig. 4: Energy band gaps and the Fermi level in a (a) metal and (b) pure semiconductor.

In intrinsic semiconductors, conduction has long been attributed to the presence of unintentionally introduced donor centers (native defects) due to metallic interstitials or oxygen vacancies that produce donor levels below the conduction band. The premise behind this is based on the fact that the oxide ion is smaller than the cations, however, to consider oxygen vacancies as the primary cause of conductivity is still very much contentious [45].

2.5 n- and p- Type Semiconductors

Doping produces extrinsic semiconductors. The objective of doping is to increase the carrier concentration to achieve greater conductivity. Extrinsic semiconductors can be n- or p-type depending on whether the majority charge carrier is negative or positive, respectively; these semiconductors are produced by doping the TCO with an atom with a greater valency (donor impurity) or lower valency (acceptor impurity), respectively, than the atoms in the lattice (Figure 5).

Tin doped indium oxide (ITO) produces an n-type semiconductor because indium, a group III element, is doped with Sn, a group IV element. In n-type semiconductors, the electrons are the majority charge carriers because visible photons can excite electrons from the high lying donor level to the conduction band. In p-type semiconductors a group IV element, for example, would be doped with a Group III element resulting in holes. These holes are the majority charge carriers since the visible photons have enough energy to excite holes from the low-lying acceptor band to the valence band [42].

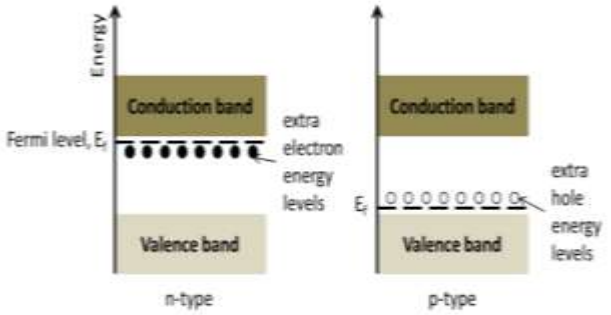

Fig. 5: Energy band gaps in n- and p-type semiconductors.

In an intrinsic semiconductor, the concentration of electrons and holes is equal to the intrinsic concentration, i.e., $n = p = n_i$, making the material electrically neutral. n and p can be changed by adding an n-type or p-type impurity, respectively. However, the product of n and p is a constant independent of the doping type and the doping level, as shown in equation (3):

$$np = n_i^2 \quad (3)$$

This relationship is called the mass-action law. To illustrate this, without the involvement of thermodynamic analyses, let's consider increasing the number of donors by a large factor, N. This would mean that the number of free electrons will increase by a factor N to $N\mathrm{n}_i$ and the recombination rate with holes will also increase by a factor of N. Hence, the density of holes will decrease from ni to n_i/N and the number of electrons will decrease from $N\mathrm{n}_i$ to $N\mathrm{n}_i - \mathrm{n}_i/N$. The product of electron concentration and hole concentration is given in equation (4):

$$\left(N_{n_i} - \frac{n_i}{N}\right)\left(\frac{n_i}{N}\right) = n_i^2\left(1 - \frac{1}{N^2}\right) \approx n_i^2 \quad (4)$$

There are three general considerations of doping:

i. the dopant is soluble in the lattice structure;
ii. the shallowness of the dopant level since deep donor levels require more energy to generate the charge carriers;

iii. the dopant should not act as a compensatory acceptor (a low energy electron killing defect) [43].

Furthermore, this has to be achieved without impairing the transparent properties of the film. Adding a dopant to the oxide can widen or narrow the band gap particularly at higher doping concentrations [6, 44]. The increase in the bandgap is called the Moss-Burstein effect and is due to the Fermi level moving into the conduction band caused by an increase in the carrier concentration. The electrons can only be excited to levels above the Fermi level because all the states below this are occupied [45]. Although, in some cases increasing dopant concentration can increase the bandgap there is a limit after which conductivity becomes compromised due to a deterioration in film structure resulting in the reduced mobility of the free electrons [46]. Conversely, band gap narrowing has also been observed after doping accompanied by significant increases in conductivity and mobility of charge carriers [37]. Bandgap narrowing is still poorly understood [47]. However, in heavily doped films, the most likely cause is the creation of energy levels near the conduction band and the valance band by shallow level donor impurities and shallow acceptor level impurities, respectively. This phenomenon is called bandgap renormalization. Several attempts have been made to model the narrowing, more recently, from data on doped ZnO films [11].

2.6 n-type TCOs

The majority of TCOs in use are n-type semiconductors. Most have been based on the binary oxides of Sn, In, Zn, and Cd but two-binary system oxides (e.g., $ZnO\text{-}SnO_2$) and ternary (e.g., $ZnSnO_3$) or quaternary oxides (e.g., Cu_2ZnGeO_4) have also been made. All types have also then been doped with a diverse range of elements or compounds [41]. Highly conducting and transparent films, with free-electron concentrations of 10^{20} cm^{-3} or greater, can be made without doping but such films are not stable at high temperature (Table 4)[11].

Table 4: Band structures of n-type binary oxides [48].

Oxide	Lattice structure	minimum band gap /eV
CdO	rock-salt	0.8 indirect; 2.3 direct
$In2O_3$	Bixbyite	2.9 direct
ZnO	Wurzite	3.3 direct
SnO_2	Rutile	3.6 direct
Ga_2O_3	Complex	4.5-4.9 direct

Metal cation doping has been successful in increasing electrical conductivity particularly using dopants with an electronic configuration of $(n\text{-}1)d_{10}$ $(n)s_0$ (where n, the quantum number, is ≥ 5)[1]. The doping of In_2O_3 with Sn to form ITO significantly reduced the resistivity from the order of 10^{-3} Ωcm to 10^{-5} Ωcm . Doping of binary compounds using metallic dopants can increase the density of conducting electrons because the dopants act as electron donors. In terms of carrier concentrations, compare 2.22×10^{19} cm^{-3} measured in In_2O_3 with 2.5×10^{21} cm^{-3} in ITO. Fluorine has been widely used as a non-metallic dopant with oxides of Sn, Zn, and In because it increases the conductivity of the film by acting as a donor since F- replaces the O_2^- ion.

2.7 p-type TCOs

P-Type oxides are essential in the production of complementary metal-oxide semiconductors (CMOS). Nickel oxide, NiO, was the first reported p-type TCO but transmittance of the films was only 40%, the resistivity was 1.4×10^{-1} Ωcm and the films were stable for use at temperatures below 100°C [8]. A few years later, in 1997, the discovery of a highly transparent p-type TCO was announced. The thin film in question consisted of copper aluminum oxide, $CuAlO_2$, with a maximum transmittance in the visible range of 60%, however, the resistivity was about 1 Ωcm which was 3-4 orders of magnitude greater than the n-type ITO, one of the better TCOs used in industry [35]. Since then, several different methods have been used to produce Cu-Al-O p-type thin films, including sputtering, chemical vapour deposition, sol-gel deposition and chemical solution. It is worth noting that some studies have produced films but have not published a complete characterization [11].

3 Present Literatures

Many research has been carried out on transparent conducting oxide (TCO) thin films and their mixtures for dosimetry applications [49, 50, 51]. The demand for radiation dosimeters of different types and variety including miniaturized radiation dosimeters involving thin-film technology became necessary owing to the expanding use of ionizing radiation in different areas of endeavor [52]. TCO-based gamma radiation thin film dosimetry are of great interest due to ease in fabrication, compact in size, better sensitivity, low cost, etc. The induce changes upon exposure to ionizing radiation depends on the type of radiation, the radiation dose, and the parameters associated with the films.

Due to the limitation in supply and the demand for better performances TCO, many research works has focused on developing a new type of TCO or structure, but the physics behind TCO is still not well understood [2]. Arshak and Korostynska [53] reported changes in the optical properties of NiO and TeO_2 thin films under the gamma rays influence. Result indicates that the changes observed are due to the gamma ray's effect on the concentration of defects present already in the materials and play a vital role in determining the properties of the materials. Antanassova

[54] investigated the changes in thin films of TaO_2 due to the gamma irradiation and observed degradation in the characteristics of the thin films. The changes are found to be related to the thickness of the film. When the mixtures of two or more materials are prepared, the changes are observed to be different [22, 55, 56]. Riyadh et al. [57] reported the effect of gamma radiation on the absorption spectra and optical energy gap of SeO_2 thin film. The properties of In_2O_3 and SiO mixed thin films fabricated by the co-evaporation technique were reported Arshak et al [36]. Film of SiO has an open structure that contains a large number of dangling bond centers and the density of these centers decreases as the In_2O_3 content is increased in the complex SiO/In_2O_3.This gives rise to the porosity increase of the resulting film and a decrease in the optical energy gap decreases.

Compound oxide films of the $ZnO\text{-}In_2O_3$ system were deposited by simultaneous sputtering of ZnO and In_2O_3 targets [55]. The $Zn_3In_2O_6$ film in the homologous phase showed lower carrier mobility than that of $Zn_2In_2O_5$. Statements have been made that the carrier concentration increases with increasing Zn supply and that Zn atoms take oxygen away from In_2O_3 bulk through the formation of ZnO.

In_2O_3 and TeO_2 mixture thin film of thickness 600nm [25], 335nm [53] prepared by thermal evaporation technique have been studied in detail. The studies revealed that radiation induced current increases linearly with a gamma radiation dose up to 160 Gy and decreases thereafter [25]. Sudha et al. [50] prepared In_2O_3 thin film by thermal evaporation in the vacuum on a clean glass substrate and annealed at 400^{o}C for 1 hour after deposition. The I-V characteristics showed an enhancement in the current value under the forward biased condition with the increase up to 75 Gy and decrease thereafter.

TeO thin film has been investigated by different authors [47, 58, 59]. TeO thin film for a range of thickness from 300 to 1500nm was prepared on the glass substrate by thermal evaporation in a vacuum. The current density increases quite linearly with the gamma radiation dose up to a dose of 80 Gy and decreases thereafter at different applied voltages [47]. Arshak et al. [56] investigated MnO and TeO_2 thin film as gamma radiation sensors. A thermal coating system was used to deposit MnO/TeO_2 thin film of thickness 180 nm on a clean glass substrate. The values of current were observed to increase with the increased radiation dose up to a level of 1400 µSv and decline thereafter.

The quest to design and fabricate a practical dosimeter using thin film technology is not realistic yet due to the limitation placed on some properties of available TCO. However, research is ongoing to develop a better performing TCO that can address the problem which fading, stability, reproducibility, sensitivity and so on. ZnO doped TeO_2 mixture seems to give a promising result, but a lot still need to be done in other to fully realize its potential for dosimetry application.

4 Benefits, Limitations and Challenges as Potential Dosimeters

Unlike most dosimeters such as ionization chamber, film badges, thermoluminescent dosimeters (TLDs), optically stimulated luminescence dosimeters (OSLDs) and so on, transparent conducting oxide or metal oxide thin films are almost independent of exposure angle [1]. This implies that the TCO thin films will give more accurate dose measurements that are independent of the beam direction and will have a wide geometric applicability range [60, 61]. The application of TCO films in monitoring radiation levels in public and occupational exposure is feasible. TCO film can be applied to medical exposure in the area of radiotherapy where angles of the field are selected while ensuring maximum dose delivery to targets, and at the same time sparing the organs at risk [62]. Therefore, the ability to measure the absorbed dose efficiently at all angles doesn't require the alteration of radiation field angles to suit the measurable dosimetry angle of the thin film dosimeter. If beam alteration to suit the film's dosimetric range is done, there may be an increase in radiation exposure to the OARs. However, considering the geometrical shape of thin films, they are not symmetrical like the ionization chambers. Thus, there may be variation in results from different positions and angles of radiation exposure [61, 63].

The TCO thin film-based dosimeter's radiation-induced current is expected to vary within only a <5 percentage range, even after frequent consecutive radiation exposures giving rise to consistent results. Therefore, there is little or no need for TCO film recalibration; a procedure that is normally applicable to dosimeters in medical radiation field [60]. The fewer vacancies and interstitial may be the reason for this consistency [18, 64, 65] created in the lattice structure of TCO film – hence, insusceptibility to radiation-induced damages. The films 'accumulated-dose related errors are minimum, i.e., they produce consistent results.

TCO thin films are expected to have high spatial precision [60]. These films could be further developed for not only gamma and X-ray detection but possibly charged ionizing radiation. Since these films are relatively thinner and more flexible, they could also be easily applied in dosimetry applications that involve curved surfaces where normal dosimeters cannot easily be applied [61, 63].

The bandgap energy is proportional to the amount of energy of a photon released after recombination of an electron and a hole where TCO's bandgap is in the 3- 4 eV range, indicating that films can be operated at room temperature [66]. Therefore, TCO's thin film-based dosimeters will have less temperature dependence since the room temperature's heat energy may not excite electrons from the valence band to the conduction band which may consequently result in a photocurrent. Thus, a considerable huge amount of the induced current would be as a result of

the incident electromagnetic radiation on the detector window. This implies higher quantum efficiency levels and accuracy of the dosimeter. However, low energy radiation whose energy is below the bandgap will have less probability of being accurately detected. This may limit the TCO thin film dosimeters from measuring low energy radiations. Even though some studies have reported the detection of some photocurrents induced by radiations whose energy is below the bandgap [60, 61], the probability of occurrence is negligible.

TCO thin films are cost-effective [52] and are associated with a direct detection method–thus low noise effects [45]. TCO films also have a high sensitivity to noise ratio and they are nearly independent of the air kerma rate [61]. A direct signal is produced from a TCO film detector that was not processed using any configuration formula/measurements; hence, simpler and faster read-out compared to traditional detectors. TCO film sensors were observed to be reproducible [60].

5 Future Prospects

Thin-film dosimetry devices made of TCO are promising radiation detectors, but more research has to be carried out to resolve or alleviate grave flaws like lattice structure displacements that mainly hinder their reproducibility and repeatability dosimetric parameters. Execution of more successful studies addressing the various drawbacks highlighted in this review presents a potential for providing more resilient, reliable, and accurate thin-film dosimeters.

In general, these research/development trends could be focused on mainly improving the thin film device sensitivity to radiation. This is because the thin film devices are purposely fabricated for gamma and x-ray radiation applications. While enhancing the sensitivity of these devices, their measurable dose ranges could also be expanded. This would, hence, make the thin film devices applicable for both low and high radiation dose measurements.

6 Conclusions

TCO thin film are expected to have higher sensitivity, low cost, compact in size, higher spatial resolution, and so on when compared to the traditional dosimeter already in use such as ionization chamber, film badge, thermoluminescence dosimeter (TLD), optically stimulated luminescence dosimeter (OSLD), etc. The value of sensitivity is reasonably high in comparison to the commercially available gamma radiation dosimeters. TCO thin film has high scope for their use in the gamma radiation doses under a variety of practical situations involving a very low level of the gamma radiation doses such as those involved in the teaching and research laboratories.

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