Effect of oxygen mixing percentage on structural, optical and electrical properties of ZnTiO₃ thin films grown by RF magnetron sputtering

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ABSTRACT

Perovskites are important composites in the area of multidisciplinary applications. The enhancement in properties of the composite can be achieved by carefully choosing and tuning the properties of the thin film at the deposition. In this paper, ZnTiO₃ thin films were deposited on quartz and N-Si substrates at various oxygen mixing percentages (OMP) from 0 to 100% using RF magnetron sputtering technique. The deposited thin films were annealed at 600 °C for 1h and confirmed the cubic perovskite structure of ZnTiO₃. The roughness value of the thin film is (0.25–0.74 nm) < 1 nm and it is identified from the atomic force microscope. The optical properties of ZnTiO₃ thin film indicated the highest refractive index of 2.46, at 633 nm with optical bandgap values of 3.57 eV, with a thickness of 145 nm and 25 OMP. Electrical characteristics of ZnTiO₃ thin film measured from the conventional thermionic emission technique are: reverse saturation current $I_0$ is $5.83 \times 10^{-11}$ A, Barrier efficiency $\phi_{B, eff}$ is 0.87 eV, and Ideality factor $\eta$ is 2.35.

1 Introduction

Perovskites are one of the crucial composites in the field of multidisciplinary applications. For several decades, metal oxide semiconductor (MOS) thin films have played a significant role in interdisciplinary research and in their applications. In the present scenario, researchers are working on MOS composites. Generally, metal oxide composites form ABX₃ perovskites. Here ‘X’ is anions such as O, F, I, N, or halogens. ‘B’ is transition metal elements such as Ti, Mg, Pb, Fe, Cu, Ta, Zr, Al, Cr, Mn. ‘A’ is metal cations such as Ca, Zn, Ag, Cs, K, Na, Cd, Pb, Ba, La [1]. Fuel cells, non-linear optics, memory devices, gas sensors, photocatalysis, solar energy conversion, water splitting, decomposition are some of the important applications of perovskite [2–5]. The metal oxides such as ZnO, TiO₂, SnO₂, MnO₂, CuO, WO₃ are
known as wideband semiconductors. ZnO and TiO2 thin films have extensive applications among these metal oxides due to their intrinsic properties, mixed oxides formations, and transition metal doping. Incorporation of ZnO with TiO2 leads to Zn–Ti–O ternary oxides, which ensure the separation of electron–hole pairs efficiently [6]. Under the light, illumination contributes to optoelectronic device applications such as photovoltaic and dye-sensitized solar cells, light-emitting diodes, sensors, flat panel displays, and photodetectors. ZnO–TiO2 composite exists in zinc Orthotitanate (Zn2TiO4 in cubic spinel crystal structure), zinc titanate (ZnTiO3 in either cubic spinel or hexagonal perovskite structure), and zinc poly titanate (Zn2Ti3O8 in cubic spinel structure) [7]. The ideal cubic crystal structure of ZnTiO3 is rare and often distorted with reduced symmetry [8].

However, to obtain good quality stoichiometric and crystalline thin films: dopants, chemical composition, substrate temperatures, annealing temperatures, minimum thickness, critical phase, and suitable oxygen atmosphere are very important. A small weight percentage (1 wt%) of SnO2 has doped to ZnTiO3 stoichiometric composition [9]. It improves the properties of ZnTiO3 thin film because a minimal quantity of SnO2 can enhance the intensity of the cubic nature of ZnTiO3 thin film and increase the surface adatom mobility of the charges leads to the coalition of smaller grains [10, 11]. Several researchers studied the effect of oxygen mean pressures and concluded the impact of OMP on the thin films structural, electrical, and optical properties. The phase composition, crystal structure, and optical behaviour of the metal oxide thin films can be controlled by adjusting the oxygen flow rate in the sputtering process [12–16].

This paper reports a systematic study on structural, optical, morphological, and electrical properties of ZnTiO3 thin films deposited at oxygen mean pressures (OMP) variant by Radio Frequency sputtering. A small concentration of SnO2 was doped to the ZnTiO3 sputtering target. The crystallinity and structure are determined with XRD. The thin film optical constants, thickness, and excitation coefficients of ZnTiO3 thin films were measured using the Swanepoel envelope technique. Roughness and morphology were observed from AFM, the best and optimized conditions were used to determine I–V, R–V characteristics of ZnTiO3 thin film deposited on N-Si substrate with Ag electrodes. As per the author’s knowledge, very few literatures are available for I–V characteristics of ZnTiO3 thin film.

2 Experimental procedure

The ZnTiO3 thin films were deposited on quartz and N-Si substrates using the RF magnetron sputtering method. The stoichiometric ZnTiO3 with a small weight percentage (1 wt%) of SnO2 produced a sputtering target using the conventional solid-state reaction method. Elementary powders such as Zinc Oxide (ZnO, ~ 30 nm, 99.8% pure, Zincite phase), Titanium Dioxide (TiO2, ~ 35 nm, 99.9% pure, Anatase phase), Tin Oxide (SnO2, ~ 80 nm, 99.9% pure, cassiterite phase) were mixed using a planetary ball mill (Fritsch GmbH, Germany) with prescribed stoichiometry. The mixed powders were dried to room temperature. The powders were uni-axially pressed to produces a ZnTiO3 target of 60 mm diameter and sintered at 450 °C for 4 h. Before deposition, the sputter chamber has been evacuated up to 1.0 × 10−6 mbar base pressure. To obtain 3.0 × 10−2 mbar pressure, the chamber is pumped with argon (Ar) and oxygen (O) gases. The sputtering power is fixed to 50 W. The ZnTiO3 thin films were deposited at room temperature and annealed at 600 °C. For the uniform deposition rate, and the same thickness, deposition time was varied. To vary oxygen mixing percentage, different percentages of oxygen (O) and Argon (Ar) gases were applied to the chamber (Oxygen-Argon percentages: 0:100, 25:75, 50:50, 75:25, 100:0%) [17]. The thickness of the films and deposition rate were optimized using UV–VIS Spectroscopy (Veeco-Dektak 6 M). The thin films’ purity of phase and crystal structure was obtained using an X-ray diffractometer (Rigaku, TTRAX III 18 kW) with Cu-Ka radiation (λ = 1.5406 Å). Atomic force microscope (Agilent, 5500 series) is employed for roughness and surface morphology analysis thin films. ZnTiO3 (N-Si, Quartz) thin film was fabricated, and a top electrode (Ag) was deposited by thermal evaporation. UV–VIS–NIR Spectrophotometer (UV 3101PC, SHIMADZU) is employed for the spectral transmission characteristics in the 200–2500 nm wavelength range. To study the vibrational modes and FWHM of the thin film reviewed from Raman spectroscopy (LABRAM HR800, JOBIN YVON). I–V and R–V characteristics of the thin film were obtained from a 4-point probe station and Keithley (4200 SCS).
Table 1 represents the sputtering conditions of the ZnTiO₃ thin film.

### 3 Results and discussion

#### 3.1 X-ray diffraction

The X-ray diffraction (XRD) patterns of the ZnTiO₃ thin films produced at room temperature under various oxygen atmosphere conditions (0–100%) are shown in Fig. 1a. It is seen that the thin film deposited at room temperature is purely amorphous, which indicates that no crystallization occurred. At 600 °C, the ZnTiO₃ phase was found, and all peaks are confined to a cubic perovskite structure (ICDD: 00-039-0190). No secondary phases were found in the composite [18, 19]. Main reflections are obtained at (2 2 0), (3 3 1), (4 2 2), (5 1 1), (4 4 0) planes. The plane (3 1 1) at 2θ = 35.58° is the predominant peak. The highest intensity of peak at 2θ = 51.75° is Si substrate, which indicates the orientation of ZnTiO₃ thin film grown on N-type Si substrate. Crystallite size (D) is calculated from Scherrer approximation, which is defined as

\[ D = \frac{k \lambda}{\beta \cos \theta} \]

where D is the average crystallite size, \( \lambda \) is the X-ray wavelength, \( \beta \) is the width of the X-ray peak on the 2θ axis, normally measured as the full width at half maximum (FWHM), \( \theta \) is the Bragg angle, and k is Scherrer constant. Since k is not known for the present material system, k = 0.9 was used, making all D calculations estimates.

The average crystallite size estimated with Eq. (1) is increased from 3.5 to 6.2 nm, with an increase of OMP from 0 to 25. Crystallite size decreases from 6.2 to 4.2 nm with an increase of OMP from 25 to 100%, which is confined to the nanocrystalline nature of ZnTiO₃. It can be correlated that the sputtered atoms react with oxygen molecules which generates redistribution of energy and heat on the substrate’s surface. This process concurrently promotes sputtered species migration and crystallization. For ZnTiO₃ thin films initially, O₂ helps the crystalline growth up to 25 OMP, then the growth gradually decayed up to 100 OMP. The trends in lattice volume, D spacing, crystallite size, lattice strain, and lattice constant with respect to OMP were calculated and presented in Fig. 1b. The thin film deposited at 12.5–25% OMP is better for ZnTiO₃ thin film fabrication.

#### 3.2 Atomic force microscope

The microstructural properties of the thin film are made with an atomic force microscope. The surface morphology, holographic roughness (internal), and typical 3-D representation of ZnTiO₃ thin films deposited with different OMP’s is shown in Fig. 2a. The average roughness to be an increase from 0.25 to 0.74 nm with the increase of OMP from 0 to 25% and roughness decreases from 0.74 to 0.48 nm with the rise of OMP from 25 to 100%. AFM micrographs follow the same trend observed from XRD. But the films deposited in 100% oxygen and 0% oxygen atmosphere exhibited a uniform and homogeneous but low dense microstructure regarding surface topology and thickness. The grain growth enhancement may be optimized at 25% OMP for ZnTiO₃ thin film to improve the films crystallization in oxygen and argon mixed atmosphere. The roughness value is < 1 nm is depicted in ultra-fine thin films deposited by the sputtering technique. The small roughness peaks can act as nanostructured absorption sites for
sensing applications [20]. Figure 2b represents the RMS roughness of the deposited thin films.

3.3 Optical properties (UV–visible spectroscopy)

Figure 3a depicts the transmittance spectra of ZnTiO$_3$ thin films fabricated on the quartz substrates. It is computed on a scale of 200–2500 nm wavelength. In the visible range, thin films were transparent (>75%), and Fabry–Pérot interference behavior was perceived. Because of the thin film’s fundamental absorption, the transmittance was decreased to zero in the 235–265 nm wavelength range. The absorption edges show a bathochromic shift with increasing the OMP. The optical constants were determined using the Swanepoel envelope technique [21, 22]. The refractive index computed from the following equation:

$$n = \left[ N + (N^2 - n_s^2)^{1/2} \right]^{1/2}$$  \hspace{1cm} (2)

Fig. 1  a XRD patterns of ZnTiO$_3$ thin film at different oxygen mean pressures (OMP) (Ar = 100–0%, O$_2$ = 0–100%). b Lattice volume, d spacing, crystallite size, lattice strain of ZnTiO$_3$ thin film with respective to OMP (Ar = 100–0%, O$_2$ = 0–100%)
Fig. 2  a The AFM surface micrographs of the ZnTiO$_3$ thin films deposited at A 0% (Ar = 100%, O$_2$ = 0%), B 12.5% (Ar = 87.5%, O$_2$ = 12.5%), C 25% (Ar = 75%, O$_2$ = 25%), D 50% (Ar = 50%, O$_2$ = 50%), E 75% (Ar = 25%, O$_2$ = 75%), F 100% (Ar = 0%, O$_2$ = 100%) Oxygen mixing percentages. b Roughness of ZnTiO$_3$ thin film with respective to oxygen mixing percentage (OMP) (Ar = 100–0%, O$_2$ = 0–100%)
\[ N = 2n_s^2 \left( \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}} \times T_{\text{min}}} \right) + \frac{n_s^2 + 1}{2} \]  

(3)

where \( T_{\text{max}} \) is the transmittance maxima and \( T_{\text{min}} \) is the transmittance minima at a specific wavelength \( \lambda_s \), and \( n_s \) is the substrate’s refractive index. The following equation can calculate the thin films thickness \( (d) \),

\[ d = \frac{\lambda_1 \times \lambda_2}{2(\lambda_1 \times n_2 - \lambda_2 \times n_1)} \]  

(4)

\( n_1 \) and \( n_2 \) are the refractive indices of two adjacent maxima or minima at wavelengths \( \lambda_1 \) and \( \lambda_2 \).

The films’ thicknesses were in the range of 160–177 nm is almost constant. The refractive index \( (n) \) of the thin films was found to be 2.35–2.46. It follows the same trend as XRD and AFM. Usually, the refractive index depends on the thin films
crystallinity, electronic structure, and oxygen deficiencies.

The optical bandgap energy \( (E_g) \) of the thin films are acquired from the extrapolated linear portion of \( \alpha \) versus \( h\nu \) curve, where \( h\nu \) is the photon energy, \( \alpha \) is the absorption coefficient. The measure of crystalline order \( \beta \) related to the bandgap energy is \( (\alpha h\nu) = \beta (h\nu - E_g) \). The bandgap energy \( (E_g) \) is calculated by considering an allowed direct \( (m = 2) \) transition of electron between the highest occupied state of the valence band and the lowest unoccupied state of the conduction band. The thin films absorption edges at different OMP are shown in Fig. 3b. It is observed that the optical bandgap energy values are in the range of 3.4–3.6 eV. The bandgap variations might be due to reduced oxygen vacancies, variations in crystallinity, and improved grain size [23–25].

3.4 Energy dispersive spectra

The Energy dispersive spectrum technique confirmed the elemental distribution of the ZnTiO3 composite. Figure 4a shows the typical microstructure, elemental mapping, and Fig. 4b depicts the energy-dispersive spectra of ZnTiO3 films concerning different OMP’s.

3.5 Raman spectra

Figure 5a–f exhibit the Raman spectra of ZnTiO3 composite recorded in the wavenumber range from 50 to 1000 cm\(^{-1}\) and their spectral de-convolution, the spectrum was fitted with Gaussian function using origin pro software. Seven to eight active Raman modes were identified for deposited ZnTiO3 thin film at different OMP. Table 2 represents the Raman modes and full width at half maxima. The bands persist cubic phase of ZnTiO3, which displays two large and broad bands at 310.46, 433 cm\(^{-1}\) and all the spectral features are of the first order. The result can be explained based on the order–disorder model of the central Ti ion. According to group theory ZnTiO3 has ten Raman active modes 5 \( A_g \) + 5 \( E_g \). The bands at 102, 153, 433, 583 cm\(^{-1}\) are the \( E_g \) modes and 310, 489, 795 cm\(^{-1}\) are related to \( A_g \) modes of the ZnTiO3 Raman spectra [26, 27].
Fig. 5 The Raman spectra of the ZnTiO₃ thin films deposited at a 0 OMP, b 12.5 OMP, c 25 OMP, d 50 OMP, e 75 OMP, f 100 OMPs
3.6 I–V and R–V characteristics

Figure 6a shows the I–V characteristics of ZnTiO$_3$ thin film on N-type Silicon substrate which was deposited at 25 oxygen mixing percentage. The Ag electrodes were deposited on a thin film with thermal evaporation sputtering unit. The characteristics showed that the thin film has a non-linear and symmetrical response for both forward and reverse bias. The high resistivity of the film is also observed. In general, chemically deposited films have high resistance. It is due to low donor defect density and a large number of chemisorbed oxygen species. A large number of oxygen molecules are chemisorbed at the grain boundaries and on the surface of the thin film. The surface resistance of the thin film measured from the four-probe station is $R_S = 5.6 \times 10^9 \Omega$.

Chemisorption is the process of trapping conduction electrons from the negatively charged oxygen species ($O^{2-}$, $O^-$). Due to this chemisorbed species, the resistivity of the oxide surface is high. For reducing gas molecules, the negatively charged chemisorbed species act as reaction centers. When reduction gases come in contact with the oxide surface, the trapped electrons release because of the reaction between gas molecules and the oxygen species. The electrons return to the conduction band, so the resistance is decreased. After the removal of the gas, the electrons are again trapped, and the resistance increases. Thus such high resistive films containing an enhanced density of chemisorbed species are particularly suitable for resistive mode gas sensor applications [28].

From the conventional thermionic emission (TE) theory, the forward I–V characteristics of the ZnTiO$_3$ thin film deposited on N-type Si substrate with Ag contacts can be delineated by

$$I = I_0 \exp \left( \frac{V - IR_S \eta}{\eta kT} \right)$$

(5)

where $I_0$ is the reverse saturation current, $V$ is the applied voltage, $R_S$ is the series resistance, $\eta$ is the ideality factor, $q$ is the charge, $K$ is the Boltzmann constant, and $T$ is the absolute temperature.

The reverse saturation current $I_0$ is given by

$$I_0 = A A^* T^2 \exp \left(- \frac{q \phi_{B, eff}}{kT} \right)$$

(6)

where $A$ is the contact area of ZnTiO$_3$ ($\sim 0.76 \times 10^{-2} \text{ cm}^{-2}$), $A^*$ is the effective Richardson constant of ZnTiO$_3$ ($\sim 37 \text{ A cm}^{-2} \text{ K}^{-2}$), and $\phi_{B, eff}$ is

| Modes | 0 OMP | 12.5 OMP | 25 OMP | 50 OMP | 75 OMP | 100 OMP |
|-------|-------|----------|--------|--------|--------|---------|
|       | Raman shift (cm$^{-1}$) | FWHM (cm$^{-1}$) | Raman shift (cm$^{-1}$) | FWHM (cm$^{-1}$) | Raman shift (cm$^{-1}$) | FWHM (cm$^{-1}$) |
| 1     | 102.36 | 51.98    | 99.05  | 56.25  | 98.99  | 57.42   |
| 2     | 152.52 | 94.75    | 145.03 | 97.56  | 145.20 | 99.41   |
| 3     | 310.46 | 206.13   | 307.61 | 225.15 | 304.26 | 221.82  |
| 4     | 432.60 | 123.57   | 435.78 | 127.45 | 442.91 | 144.33  |
| 5     | 488.94 | 64.12    | 493.75 | 67.43  | 492.52 | 54.85   |
| 6     | 582.57 | 161.05   | 589.37 | 122.00 | 599.36 | 85.58   |
| 7     | 795.39 | 133.46   | 785.34 | 147.05 | 701.78 | 79.37   |
| 8     | 795.39 | 133.46   | 785.34 | 147.05 | 796.67 | 113.22  |

Table 2: Raman shift and FWHM of the modes for ZnTiO$_3$ thin film at different oxygen mixing percentages
the effective barrier height at zero bias. It is described as

$$\phi_{B, eff} = -\frac{kT}{q} \ln\left(\frac{I_0}{AA'T^2}\right)$$  \hspace{1cm} (7)

Taking natural logarithm on both sides of Eq. (5), we obtain

$$\ln I = \ln I_0 + \frac{q(V - IR_s)}{\eta kT}$$  \hspace{1cm} (8)

For a low current region of the forward bias I–V characteristics, the forward bias current is in the order of $I_0$. The effect of $R_s$ is negligible due to the negligible value of $R_s$. Thus, the reverse saturation current value $I_0$ can be calculated from the intercept of $\ln I$ versus $V$ plot (shown in Fig. 6b) with the current ($I$) axis for $V = 0$, which gives $I_0 \sim 5.83 \times 10^{-11}$ A. The value of $I_0$ is then used in Eq. (7) to determine the value of $\phi_{B, eff}$ as 0.87 eV. This value may be deviated from the ideal value because of high surface states, generation-recombination, image force lowering effect in the depletion region, and the barrier inhomogeneities at the junction. Now, the ideality factor ($\eta$) is computed from the slope of the linear region of the forward bias $\ln I$ versus $V$ plot as

$$\frac{dV}{d\ln I} = \frac{\eta kT}{q}$$  \hspace{1cm} (9)

From Eq. (9), the ideality factor ($\eta$) is estimated as $\sim 2.35$, much larger than unity. The high $\eta$ values represent the interfacial thin oxide layer, a wide

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**Fig. 6** a I–V characteristics of ZnTiO$_3$ thin film on N-Si substrate deposited at 25 OMP. b $\ln (I)$–V characteristics of ZnTiO$_3$ thin film on N-Si substrate deposited at 25 OMP.

**Fig. 7** a The bias-dependent resistance $R_i = \frac{dV}{dI}$ versus $V$ characteristics of ZnTiO$_3$ thin film on N-Si substrate deposited at 25 OMP. b $V$–$\ln (I)$ characteristics of ZTO thin film on N-Si substrate deposited at 25 OMP.
distribution of barrier height, and the bias voltage dependence of the barrier height [29, 30].

To determine the value of the device’s series resistance, we have used the \( R_i = \frac{dV}{dI} \) versus \( V \) plot of the measured I–V data, as shown in Fig. 7a. where \( R_i \) is the bias-dependent resistance. The series resistance is almost negligible at lower values of current. At higher values of current \( R_s \) shows a significant effect so that it exhibits nonlinear characteristics. In the high current region, the voltage drop \( IR_s \) is much larger than the voltage appearing across the ZnTiO\(_3\) thin film and hence applied bias \( V = IR_s \). The input resistance \( R_i \sim 2.3 \times 10^9 \Omega \) is determined from Fig. 7b. Electrical parameters of ZnTiO\(_3\) thin film measured from thermionic emission (TE) theory is shown in Table 3.

4 Conclusions

The RF magnetron sputtering was used to deposit ZnTiO\(_3\) thin films on quartz and N-Si substrates. The influences of the OMP on structural, optical, morphological, and electrical properties were studied systematically. The deposited thin films annealed at 600 \(^\circ\)C were crystallized in pure ZnTiO\(_3\) phase without any secondary phases. As per AFM results, the roughness value of the deposited thin film is < 1 nm and hence it can be said that the films are ultra fine. As per the optical spectroscopy, it can be said that the thin films refractive index is high at 25 OMP is 2.46. The optical bandgap varies from 3.4 to 3.6 eV with varying OMP. The stoichiometry of the thin film meets the elemental composition. Eight to nine vibrational modes are observed from the Raman spectra, representing the cubic structure of ZnTiO\(_3\). The electrical parameters of the thin films are reverse saturation current \( I_0 \) is \( 5.8 \times 10^{-11} \) A, Barrier efficiency is \( \phi_{B, \text{eff}} \) is 0.87 eV, and ideality factor \( \eta \) is 2.35. Hence it can be concluded that the estimated thin film parameters are more suitable for optoelectronic, dielectric, and gas sensing applications.

References

1. R.J.D. Tilley, Perovskites Structure-Property Relationships, 1st edn. (Wiley, Hoboken, 2016)
2. S. Brittman, G. Widia, P. Adhyaksa, E.C. Garnett, The expanding world of hybrid perovskites: materials properties and emerging applications. MRS Commun. 5(1), 7–26 (2020). https://doi.org/10.1557/mrc.2015.6
3. V. Chellappan, S. Ramakrishna, Science direct perovskites: solar cells & engineering applications—materials and device developments. Sol. Energy 122, 678–699 (2015). https://doi.org/10.1016/j.solener.2015.09.041
4. Q. Chen, N. De Marco, Y. Michael, T. Song, C. Chen, H. Zhao, Under the spotlight: the organic–inorganic hybrid halide perovskite for optoelectronic applications. Nano Today 10, 355–396 (2015). https://doi.org/10.1016/j.nantod.2015.04.009
5. N.S. Kumar, R.P. Suvarna, K.C. Babu, Microwave heated lead cobalt titanate nanoparticles synthesized by sol-gel technique: structural, morphological, dielectric, impedance and ferroelectric properties. Mater. Sci. Eng. B 242, 23–30 (2017). https://doi.org/10.1016/j.mseb.2019.03.005
6. M. Yuste, R. Escobar-Galindo, N. Benito, C. Palacio, O. Martinez, J.M. Albella, O. Sanchez, Effect of the Incorporation of titanium on the optical properties of zno thin films: from doping to mixed oxide formation. Coatings 9(180), 1–12 (2019). https://doi.org/10.3390/coatings9030180
7. V. Kumar, P. Kumar, M. Kumar, P. Jain, D. Bhandari, Y.K. Vijay, Study of post annealing influence on structural, chemical and electrical properties of ZTO thin films. J. Alloys Compd. 509(8), 3541–3546 (2011). https://doi.org/10.1016/j.jallcom.2010.10.212
8. Y. Huang, Y. Lee, D. Tsai, F. Shieu, Effect of annealing on formation and microstructure of ZnTiO\(_3\) thin films by DC reactive magnetron co-sputtering. Mater. Sci. Forum 2011(687), 610–616 (2011)
9. H.S. Varaprasad, P.V. Sridevi, M.S. Anuradha, Optical, morphological, electrical properties of ZnO-TiO$_2$-SnO$_2$/CeO$_2$ semiconducting ternary nanocomposite. Adv. Powder Technol. 32(5), 1472–1480 (2021). https://doi.org/10.1016/j.apt.2021.02.042

10. F. Guo, X. Sun, B. Liu, Z. Yang, J. Wei, D. Xu, Enhanced lifetime and photostability with low-temperature mesoporous ZnTiO$_3$/compact SnO$_2$ electrodes in perovskite solar cells. Angew. Chem. Int. Ed. 58, 1–7 (2019). https://doi.org/10.1002/anie.201911796

11. P. Sutta, R. Medl, M. Netrvalov, P. Nov, Optical properties of zinc titanate perovskite prepared by reactive RF sputtering. J. Electr. Eng. 68, 10–16 (2017). https://doi.org/10.1515/jee-2017-0049

12. N. Aghilizadeh, A.H. Sari, D. Dorranian, Role of Ar/O$_2$ mixture on structural, compositional and optical properties of thin copper oxide films deposited by DC magnetron sputtering. J. Theor. Appl. Phys. 11(4), 285–290 (2017). https://doi.org/10.1007/s40094-017-0268-6

13. B. Abdallah, A.K. Jazmati, R. Refaai, A.E. Commission, Oxygen effect on structural and optical properties of ZnO thin films deposited by RF magnetron sputtering. Mater. Res. 20(3), 607–612 (2017). https://doi.org/10.1590/1980-5373-MR-2016-0478

14. P. Gogoi, P. Srinivas, P. Sharma, D. Pamu, Optical, dielectric characterization and impedance spectroscopy of Ni-substituted MgTiO$_3$ thin films. J. Electron. Mater. 45(2), 899–903 (2016). https://doi.org/10.1007/s11664-015-4209-3

15. N.S. Kumar, R.P. Suvarna, K. Chandra, B. Naidu, Multiferroic nature of microwave-processed and sol-gel synthesized nanoPb$_{1-x}$Co$_x$TiO$_3$ (x = 0.2 – 0.8) ceramics. Cryst. Res. Technol. 3(3), 1–7 (2018). https:// doi.org/10.1002/crat.201800139

16. N. Madaoui, L. Bait, K. Kheyar, N. Saoula, Effect of argon-oxygen mixing gas during magnetron sputtering on TiO$_2$ coatings. Adv. Mater. Sci. Eng. (2017). https://doi.org/10.1155/2017/4926543

17. S. Pattipaka, J.P. Goud, G. Prakash, B.K.C. James, R. Alikia, K.D. Pamu, Effect of oxygen partial pressure on nonlinear optical and electrical properties of BNT—KNNG composite thin films. J. Mater. Sci. 31(4), 2986–2996 (2020). https://doi.org/10.1007/s10854-019-02842-4

18. Z. Liu, S. Lei, H. Fan, X. Ren, J. Fang, L. Ma, Novel sintering and band gap engineering of ZnTiO$_3$ ceramics with excellent microwave dielectric properties. J. Mater. Chem. C 3(311), 4040 (2017)

19. L.G. Teoh, W. Lu, T.H. Lin, Y. Lee, The effect of Mg dopant and oxygen partial pressure on microstructure and phase transformation of ZnTiO$_3$ thin films. J. Nanomater. (2012). https://doi.org/10.1155/2012/539657

20. S.-C. Wu, W.-H. Yau, C.-H. Tsaid, C.-P. Chouas, Nanotechnology behavior of thermal treatment of zinc titanate thin films. Surf. Interface Anal. 44, 1314–1318 (2012). https://doi.org/10.1002/sia.5019

21. G.M. Gavrilov, D.A. Minkov, E. Marquez, S.M.F. Ruano, Advanced computer drawing envelopes of transmittance spectra of thin film specimens. IARJSET 3(9), 163–168 (2016). https://doi.org/10.17148/IARJSET.2016.3931

22. R. Swanepoel, Determination of the thickness and optical constants of amorphous silicon. J. Phys. E 16, 1214 (1983)

23. C. Ye, Y. Wang, Y. Ye, J. Zhang, G.H. Li, Preparation and photoluminescence of undoped thin films. J. Appl. Phys 106, 033520 (2009). https://doi.org/10.1063/1.3190820

24. E. Garcia-Ramirez, M. Mondragon-Chaparro, O. Zelaya-Angel, Band gap coupling in photocatalytic activity in ZnO—TiO$_2$ thinfilms. Appl. Phys. A 108, 291–297 (2012). https://doi.org/10.1007/s00339-012-689

25. N. Raghuram, T. Subba Rao, N. Suress Kumar, K. Chandra Babu Naidu, H. Manjunatha, B. Ramakrishna Rao, A. Khan, A.M. Asiri, BaSrLaFe$_{12}$O$_{19}$ nanorods: optical and magnetic properties. J. Mater. Sci. (2020). https://doi.org/10.1007/s10854-020-03342-6

26. T. Bernert, L. Bayarjargal, B. Winkler, Synthesis and high (pressure, temperature) stability of ZnTiO$_3$ polymorphs studied by Raman spectroscopy. Solid State Sci. 43, 53–58 (2015). https://doi.org/10.1016/j.solidstatesciences.2015.03.014

27. J.A. Baier-Saip, E. Ramos-Moor, A.L. Cabrera, Raman study of phase transitions in KNbO$_3$ Raman study of phase transitions in KNbO$_3$. Solid State Commun. 135, 367–372 (2005). https://doi.org/10.1016/j.ssc.2005.05.021

28. M. Erkovan, E. Fentürk, Y. Fahin, M. Okutan, I-V characteristics of Pt$_x$Co$_{1-x}$ (x = 0.2, 0.5, and 0.7) thin films. J. Nanomater. (2013). https://doi.org/10.1155/2013/579131

29. D. Somvanshi, S. Jit, Analysis of I–V characteristics of Pd/ ZnO thin film/N-Si Schottky diodes with series resistance. J. Nanoelectron. Optoelectron. 9(1), 1–6 (2014). https://doi.org/10.1166/jno.2014.1543

30. D.K. Schroder, Semiconductor Material and Device, 3rd edn. (Wiley, Hoboken, 2006)