ABSTRACT

Co$_x$Zn$_{1-x}$O ($x = 0.00, 0.04, 0.08$, and $0.10$) thin films were sprayed pyrolysis onto ordinary glass substrates. The micro-Raman spectroscopy revealed the presence of wurtzite structure in all films. The UV–Vis investigation showed good optical transmittance in the visible region with the increase in the absorption bands related to internal Co$^{+2}$ $d$–$d$ transitions over Co concentration. The optical gap energy decreased by 0.34 eV as Co doping increased, contrary to Urbach energy which increased by 230 meV. The SEM observation indicated grain shape modification of the surface morphology of the films in addition to slight decrease in the grain size. M-lines spectroscopy measured the ordinary refractive index which was found to increase by 0.0156 as the Co doping increased. Cobalt doping provoked the extinction of light coupling and propagation in the films manifested as an increase in full width at the half maximum of the guided peaks and a decrease in the reflected intensity. This was due to the increase in the extinction coefficient measured by UV–Vis spectroscopy.

1 Introduction

The developments of all forms of optical waveguides led to huge development in numerous fields like integrated optics, lasers, and photonics. Optical fibers are relatively flexible and immune to electromagnetic interference so they found use in communications. Transparent thin films waveguides are of high quality, controllable, and efficient and by that, they had been employed as bio and chemical sensors [1–3],
integrated optical amplifier [4], a guided layer in total internal reflection fluorescence microscope [5], and strain sensor [6] to name a few. A dielectric waveguide can be defined as any structure used to control the flow of electromagnetic waves in a certain direction. This guiding is possible by confining the electromagnetic wave within its surfaces. In order to understand the propagation of light in a waveguide, it is essential to characterize the refractive index and the extinction coefficient of the waveguide as the refractive index is a measure of the phase difference between the source wave and oscillating charges in the media and the extinction coefficient is a direct measure of the attenuation of the wave inside the media [7].

Dilute magnetic semiconductors (DMS) are materials that integrate new properties based on magnetic effects to a semiconductor host due to transition metals (TM) dopant such as V, Co, Cr, Mn, and Fe. DMS proved to be very unique devices in the microelectronics industry due to the fact that they exhibit spin-dependent magneto-electro-optical properties [8]. Therefore, a broad range of semiconductor devices can be conceptualized, including spin-polarized light-emitting diodes [9], spin-transistor logic devices [10], and lasers [11]. TM element doing offer control over both ferromagnetic and optical properties of wide gap semiconductors [12]. The incorporation of transition elements such as Co occupying substitutional sites give rise to crystal field splitting in the 3d levels of Co$^{2+}$. These transition are manifested in optical measurements [13, 14]. In addition, hybridization between the Co$^{2+}$ d level and ZnO electronic states resulting in the contribution of $s_{Co^{2+}}$ to the conduction band minimum and $d_{Co^{2+}}$ to valence band maximum. The spin dependency transport via the $sp - d$ exchange interaction (coupling) between Co and ZnO constitutes the main characteristics of Co-doped ZnO DMS [15].

The CdMnTe DMS on GaAs substrate was demonstrated as successful waveguide to achieve integrated optics [16] opening new path of investigating and applying DMSs as waveguides.

In the last decade, Zinc oxide (ZnO) related researches grew largely because of new or improved types of electronic and photonic devices [17]. Waveguide structures based on ZnO have been demonstrated, suggesting that ZnO thin films bears a potential use in optoelectronics and integrated optics [18–21].

Co-doped ZnO DMS where elaborated and tested for several applications such as mono modal waveguide [22] and tunneling magnetoresistance device [23]. For a better understanding and control over ZnO thin film waveguide, it is necessary to perform an accurate and direct characterization of its optical properties especially the refractive index. For that, several techniques are used such as ellipsometry, which can reveal the refractive index, thickness, and extinction coefficient [24]. Prism coupler based method alternatively called m-lines spectroscopy has been developed since the ’70s to characterize thin films. It measures the refractive index with $2 \times 10^{-4}$ accuracy and the thickness with 0.5% [25].

The effect of dopants on the refractive index of ZnO is not very obvious and is still a subject of interest. The root of the optical properties of a semiconductor is intimately related to both intrinsic and extrinsic effects. Intrinsic ones are manifested via the transitions taking place between the electrons and holes in the conduction and in the valence band, respectively, in addition to excitonic effects due to the Coulomb interaction. Extrinsic properties are directly related to dopants, which usually create electronic states in the band gap, and hence influence both optical absorption and emission processes [17]. Control over the optical gap energy of ZnO was possible by variety of dopants [26–28]. The investigation concerning the application of DMS as waveguides are very scarce and prism coupler technique proves to be a very adequate tool for that.

This work investigates the complex refractive index, i.e., the refractive index and the extinction coefficient via the correlation between m-lines and UV–Vis spectroscopy of bi-modal Co-doped ZnO thin films elaborated by spray pyrolysis.

2 Experimental

The sprayed solution for the undoped ZnO thin films was prepared by dissolving dihydrate zinc acetate $[\text{Zn(CH}_3\text{CO}_2]_2 \cdot 2\text{H}_2\text{O}]$ (Zinc acetate dihydrate $\geq 99.0\%$, AnalaR NORMAPUR) in 99.98% pure methanol to obtain 0.1 M solution that went a constant stirring at 60 °C for 45 min on a magnetic stirrer. The sprayed solutions of the Co-doped ZnO thin films were prepared under the same conditions and by using cobalt acetate $[\text{Co(CH}_3\text{CO}_2]_2 \cdot 4\text{H}_2\text{O}]$ as a Co precursor (Cobalt(II) acetate tetrahydrate ACS.
reagent, ≥ 98.0% Sigma-Aldrich). Each time the proper amount was added to 0.1 M [Zn(CH₃CO₂)₂ · 2H₂O] dissolved in methanol to produce the following contents of zinc and cobalt: CoₓZn₁₋ₓO with x equals 0.04, 0.08, and 0.10 (Fig. 1).

Ordinary glass substrates were ultra-sonically cleaned in a 1:1 mixture of acetone and ethanol for 15 min and left to dry in air. The films were deposited using spray pyrolysis at a deposition temperature of 450 °C.

In order to characterize our thin films, multiple techniques were used. For the structural properties micro-Raman was employed (Horiba Jobin Yvon HR800) at excitation wavelength of 473 nm. Scanning Electron Microscope (SEM) JEOL JSM-7001F model for surface morphology. Finally for the optical measurements, Metricon 2010/M Prism coupler with rutile TiO₂ prism: nₑ = 2.8639 and nₒ = 2.5822 at 632.8 nm with an apical angle of 44.60 ° was used to couple 632.8 nm He–Ne laser light into air/CoₓZn₁₋ₓO/glass waveguide in addition to Shimadzu UV-3101PC UV–Vis-NIR Scanning Spectrophotometer with wavelength resolution of 1 nm.

3 Results and discussion

3.1 Micro-Raman spectroscopy

Micro-Raman spectroscopy was used to study the impact of cobalt impurities on the crystal structure of ZnO thin films. This method permitted to detect disorder and defect due to dopant incorporation. Figure 2 showed the micro-Raman spectra of pure and Co-doped ZnO thin films in the range of 70–700 cm⁻¹. The ZnO has wurtzite structure so it possess 6mm (6₉₀°) crystal symmetry. There are 4 atoms per unit cell which leads to 12 phonon, 9 of them are optical and 3 are acoustic. These phonons dispersion at the center of Brillouin’s zone is written as: \( \Gamma = 2A₁ + 2B₁ + 2E₁ + 2E₂ \) [29, 30]. The undoped ZnO sample exhibited two clearly Raman-active peaks appeared around 102 and 441 cm⁻¹ in addition to a very weak hump around 570 cm⁻¹. The peaks at 102 and 440 cm⁻¹ were associated with \( E₂ \) (low) of non-polar vibration for heavier Zn atom and \( E₂ \) (high) of oxygen displacement, respectively [29, 31, 32]. In fact, the weak hump was the result of two overlapped peaks localized at 537 and 577 cm⁻¹ and were ascribed to \( A₁ \) (low)/\( E₁ \) (low) [33, 34]. Co-doped ZnO thin films showed similar peaks of the undoped sample with decrease in intensity of the oxygen displacement peak (\( E₂ \) (high)) and the enhancement of the mixed \( A₁ \) (Low)/\( E₁ \) (low) peaks. In the work of Thongam et al. [35] about ZnO thin films, it had been reported that the mixed \( A₁ \) (Low)/\( E₁ \) (low) peaks were due to the crystal imperfection and defects such as zinc interstitials and oxygen vacancies. Also, Ponnusamy et al. [36] reported that these peaks arose possibly because of defects. In any case, the Raman behavior of our thin films can be ascribed to the substituted...
cobalt anions which induced structural defects and therefore energetic defects in ZnO lattice.

3.2 UV–Vis measurements

The optical transmission spectra of undoped and Co-doped ZnO thin films in the range of 350–800 nm were depicted in Fig. 3. All films exhibited good optical transmittance. In the region ranging from 500 to 750 nm we can clearly observe a decrease in the average transmittance from 84 to 57 % with the increase of cobalt concentration. The observed spectra were very similar to those obtained in the literature for Co-doped ZnO thin films [37–41]. Due to the similar ionic radii of Zn$^{+2}$ (0.60 Å) and Co$^{+2}$ (0.58 Å) [13, 42] the substitution of Zn$^{+2}$ by Co$^{+2}$ ions in the tetrahedral coordinated structure was apparent as absorption bands at 568, 613, and 658 nm. These bands were attributed to electronic transitions in 3d levels of Co$^{+2}$ ($d$–$d$ transitions) [43–45]. Furthermore, the sharp absorption edge experienced a red shift upon Co doping indicating the decrease in the optical band gap. The optical band gap $E_g$ was calculated using the Tauc relation [46, 47]:

$$a h v = B (h v - E_g)^m$$

(1)

where $a$ is the absorption coefficient, $hv$ is the photon energy, $B$ is a constant, and the exponent $m$ depends on the nature of electronic transition ($m = 1/2$ for allowed direct transition of ZnO optical band). The optical band gap energy of all films was calculated by linear interpolation of $(ahv)^2$ versus $hv$ (Fig. 3). The values decreased from 3.15 to 2.81 eV as Co doping increased from 0 to 10 at.% (Fig. 4) due to crystal field splitting of Co$^{+2}$ 3d levels by the wurtzite structure. These new electronic states give rise to new donor electronic states just below the conduction band, in other words, the decrease in the optical band gap was the result of hybridization between Co$^{+2}$ and ZnO electronic states, mainly the contribution of s$_{Co^{+2}}$ to the conduction band minimum of ZnO [14, 48–52].

The Urbach energy is a characteristic parameter of energetic disorder in the band edge. It was calculated based on the next equation [53]:

$$\ln(a) = \ln(a_0) + \frac{hv}{E_U}$$

(2)

where $a_0$ is a constant, $hv$ is the photon energy and $E_U$ is the Urbach energy. Figure 4 depicted the evolution of the Urbach energy as a function of Co at.% dopant. It had been found to increase over Co content. This was a positive indication for the increase in the energetic disorder present in the films which is directly related to structural defects. This was in good correlation with the increase in the intensity of $A_1$(low)/$E_1$(low) peaks as a function of Co doping according to Raman spectra.
3.3 SEM observation

SEM images and the grains size distribution of undoped and 8 at.% Co-doped ZnO thin films were shown in Fig. 5. The undoped film showed grains of a mean diameter of around 280 nm formed by many crystallite aggregates with few pores surrounding them. For the 8 at.% Co-doped sample, it showed a dense bi-modal size distribution with bigger plated grains of a mean diameter close to 200 nm and finer plated grains with a mean diameter in the vicinity of 130 nm. Similar observations were reported by Salah et al. [54] for sprayed pyrolysis Co-doped ZnO thin films. In any case, the homogeneity across large-scale makes our thin films suitable for waveguiding applications.

3.4 M-lines measurements

In order to understand the effect of Co doping on the waveguiding properties of ZnO thin films, we used prism coupler technique to measure the thickness and the ordinary refractive index in the Transverse Electric (TE) polarization. The dispersion curves for the TE polarization is given by the following equation:

\[
k_0d \sqrt{n^2 - n_{eff}^2} = \arctan \left( \frac{n_{eff}^2 - n_s^2}{n^2 - n_{eff}^2} \right) + \arctan \left( \frac{n_{eff}^2 - n_s^2}{n^2 - n_{eff}^2} \right) + mn
\]

where \(n, n_s\) and \(n_{eff}\) are the refraction indices of the film, superstrate, substrate, respectively. \(m\) is the mode number. \(n_{eff}\) is the effective index of the mode \(m\) and \(k_0 = \frac{2\pi}{\lambda}\) is the wavevector in vacuum. For at least two propagation modes \((m = 0 \text{ and } m = 1)\) [55], we can calculate the refractive index and the thickness by simultaneously solving the resulting equations [56, 46].

For a plane wave traveling inside a lossy media in the form of a slob waveguide in the \(z\) direction,
\( \phi = \phi_0 \exp(-\gamma z + i\omega t) \), the propagation constant of the mode \( m \) is of the form [57]:

\[ \gamma_m = \alpha + i\beta_m \]  

(4)

where \( \alpha \) is the absorption coefficient, \( \beta \) is the phase constant and they are given by:

\[ \alpha = 2k_0 \cdot k; \quad \beta_m = k_0 \cdot n_{\text{eff}} \]  

(5)

where \( k \) is the extinction coefficient.

The extinction coefficient \( k \) was evaluated using UV–Vis measurement as it is directly related to the absorption coefficient and can be calculated using the transmittance \( T \) and the thickness \( d \) of the films as indicated by the following relation [58]:

\[ \alpha = \frac{\ln(T)}{d} \]  

(6)

The effective index was evaluated by m-lines spectroscopy using the Snell-Decartes equation of refraction [59]:

\[ n_{\text{eff}} = n_p \sin\left( \arcsin\left( \frac{n_a \sin(\theta)}{n_p} \right) + \theta_p \right) \]  

(7)

where \( n_p, n_a \) and \( \theta_p \) are the refractive index of the prism, the superstrate, and the base angle of the prism, respectively. By varying the incident angle on the prism’s side \( \theta \), we can excite many modes.

Figure 6 presented the reflected intensity vs. the angle of incidence in the TE polarization. All films experienced two guiding modes. The curves exhibited extinction behavior with Co doping through the diminishing intensity and broadening of the peaks indicating the degradation of the light coupling and propagation in the films.

In order to explain the behavior of the refractive index with the optical band gap evolution, we adopted the single-oscillator approximation [60, 61]. The refractive index is expressed in term of the energy of the incoming light \( E \) by the following expression:

\[ n^2 = \frac{E_o E_d}{E_o^2 - E^2 + 1} \]  

(8)

where \( E_d \) is a measure of the strength of inter-band optical transitions, \( E_o \) is the single-oscillator energy. According to Wemple-DiDomenico model, the single-oscillator energy can be approximated in terms of the optical gap energy as:

\[ E_g \approx E_o \frac{E_d}{2} \]  

The value of \( E_d \) for \( \text{Zn}^{+2} \) is close to that of \( \text{Co}^{+2} \) [62] and it was supposed to be unchanged.

The ordinary refractive index, the extinction coefficient, and the Full Width at Half Maxima (FWHM) of the m-lines peaks were plotted in Fig. 7. The ordinary refractive index experienced a slight increase upon cobalt content. In fact, the introduction of Co into ZnO had a decreasing effect on the optical gap which increased the refractive index according to the previous equation of the single-oscillator approximation. The decrease in the optical gap energy lowered the energy for electrons to be able to oscillate and contribute to the phase difference measured as an increase in the refractive index [7, 63]. In other words, the electronic polarizability which originates from the electronic cloud deformation was facilitated by the decrease in the optical gap energy. The extinction coefficient had a similar behavior. The introduction of Co in the films rendered the films to be more absorbent at 632.8 nm due to Co\(^{+2} \ d-d \) transitions in the visible region as previously discussed in the UV–Vis section. The propagation of the coupled light was less efficient as the attenuation of light increased with Co dopant in the thin films. This effect was confirmed by the width broadening and diminishing in intensity of m-lines peaks with their angular position remained virtually the same [25, 64].

Fig. 6 The reflected intensity of the TE polarization for two guided modes as a function of the incidence angle for undoped and Co-doped ZnO thin films
4 Conclusion

In this work we had reported the successful deposition of Co-doped ZnO thin films by spray pyrolysis. All films had a wurtzite structure according to micro-Raman spectroscopy. A decrease in the intensity of oxygen displacement peak ($E_2$ (high)) and an increase in intensity of structural defects peaks ($A_1$(Low)/$E_1$(low)) were observed over Co doping. According to UV–Vis measurements, the introduction of Co in ZnO had also induced the creation of new intrinsic and extrinsic electronic states. Optical band gap was found to decrease with Co doping due to electronic states hybridization between Co$^{2+}$ and ZnO. The energetical defects evolution had been confirmed by the Urbach energy calculation. M-lines spectroscopy allowed for the measurements of the ordinary refractive index and it increased as the Co doping increased which was attributed to the decrease in the gap energy based on the single-oscillator approximation. Furthermore, ZnO thin films developed absorbing behavior with Co which was obvious in the increase in both the full width at half maximum of the guiding peaks and the extinction coefficient in addition to the decrease in the reflected intensity. This was related to internal $d$–$d$ transitions which affected light coupling and propagation. The correlation between m-lines and UV–Vis measurements seems to be very reliable method to measure the complex refractive index of relatively high refractive index transparent waveguide. It is simple and inexpensive in comparison to other optical techniques. This paper acts as a guidance in optimization of Co-doped ZnO as a wave guide since the introduction of Co in the films promotes magnetic effects in ZnO yet the same dopent deteriorates its waveguiding properties. Therefore an optimal Co dopent percentage must be considered when designing Co-doped ZnO DMS waveguide.

Author contributions

YB conceived the idea of the articles and m-lines measurements. The elaboration of the films in addition to UV–Vis and micro-Raman measurements were carried out by HD scanning electron microscope images were performed by IS. All others contributed to the interpretation of the results and provided critical feedback and helped shape the research, analysis, and manuscript.

Funding

The authors have not disclosed any funding.

Data availability

The datasets generated during and/or analyzed during the current study are included in the manuscript and available from the corresponding author on reasonable request.

Declarations

Conflict of interest There are no conflicts of interest between the authors.
References

1. J.-N. Yih, Y.-M. Chu, Y.-C. Mao, W.-H. Wang, F.-C. Chien, C.-Y. Lin, K.-L. Lee, P.-K. Wei, S.-J. Chen, Optical waveguide biosensors constructed with subwavelength gratings. Appl. Opt. 45(9), 1938–1942 (2006)

2. H. Mukundan, A. Anderson, W. Grace, K. Grace, N. Hartman, J. Martinez, B. Swanson, Waveguide-based biosensors for pathogen detection. Sensors (Basel, Switzerland) 9, 5783–809 (2009)

3. F. Arcadio, L. Zeni, A. Minardo, C. Eramo, S. Ronza, C. Perri, G. D’Agostino, G. Chiaretti, G. Porto, N. Cennamo, A nanoplasmic-based biosensing approach for wide-range and highly sensitive detection of chemicals. Nanomaterials 11, 1961 (2021)

4. J. Ben Naceur, M. Gaidi, F. Bousbih, R. Mechiakh, R. Chtourou, Annealing effects on microstructural and optical properties of nanostructured-TiO2 thin films prepared by sol-gel technique. Curr. Appl. Phys. 12(2), 422–428 (2012)

5. A. Priyadarshi, F.T. Dullo, D.L. Wolfson, A. Ahmad, N. Jayakumar, V. Dubey, J.-C. Tinguely, B.S. Ahsulwalia, G.S. Murugan, A transparent waveguide chip for versatile total internal reflection fluorescence-based microscopy and nano-scopy. Commun. Mater. 2(1), 1–11 (2021)

6. A. Alidoust Ghatar, D. Jahnani, O. Akhavan, Strain effects on optical properties of linearly polarized resonant modes in the presence of monolayer graphene. Mater. Sci. Eng. B 277, 115584 (2022)

7. Richard, P.F., Robert, B.L., Matthew, S.: The Feynman Lectures on Physics, New Millennium (ed.). Basic Books, New York (2010) (Originally published 1963–1965)

8. H. Ohno, D. Chiba, F. Matsukura, T. Omiiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani, Electric-field control of ferromagnetism. Phys. Rev. Lett. 84(6), 076601 (1995)

9. V.G. Truong, P.-H. Binh, P. Renucci, M. Tran, Y. Lu, H. Jaffrès, J.-M. George, C. Deranlot, A. Lemaître, T. Amand, X. Marie, High speed pulsed electrical spin injection in spin-light emitting diode. Appl. Phys. Lett. 94(14), 141109 (2009)

10. S. Sugahara, M. Tanaka, A spin metal-oxide-semiconductor field-effect transistor using half-metallic-ferromagnet contacts for the source and drain. Appl. Phys. Lett. 84(13), 2307–2309 (2004)

11. S. Datta, B. Das, Electronic analog of the electro-optic modulator. Appl. Phys. Lett. 56(7), 665–667 (1990)

12. G. Korotcenkov, S. Thomas, A.T. Sunny, V. Prajitha, Colloidal Metal Oxide Nanoparticles: Synthesis, Characterization and Applications (Elsevier, Amsterdam, 2019)

13. H. Ji, C. Cai, S. Zhou, W. Liu, Structure, photoluminescence, and magnetic properties of co-doped ZnO nanoparticles. J. Mater. Sci. 29(15), 12917–12926 (2018)

14. A. Ciechan, P. Boguslawski, Calculated optical properties of Co in ZnO: internal and ionization transitions. J. Phys. 31, 255501 (2019)

15. A. Ciechan, P. Boguslawski, Theory of the sp-d coupling of transition metal impurities with free carriers in ZnO. Sci. Rep. 11(1), 1–11 (2021)

16. K. Ando, Magneto-Optics of Diluted Magnetic Semiconductors: New Materials and Applications (Springer, Berlin, Heidelberg, 2000), pp. 11–244

17. C. Jagadish, S.J. Pearon, Zinc Oxide Bulk, Thin Films and Nanostructures: Processing, Properties, and Applications (Elsevier, Amsterdam, 2011)

18. W.S. Hu, Z.G. Liu, X.L. Guo, C. Lin, S.N. Zhu, D. Feng, Preparation of c-axis oriented ZnO optical waveguiding films on fused silica by pulsed laser reactive ablation. Mater. Lett. 25(1), 5–8 (1995)

19. N. Mais, J.P. Reithmaier, A. Forchel, M. Kohls, L. Spanhel, G. Müller, Er doped nanocrystalline ZnO planar waveguide structures for 1.55 µm amplifier applications. Appl. Phys. Lett. 75(14), 2005–2007 (1999)

20. S.F. Yu, C. Yuen, S.P. Lau, Y.G. Wang, H.W. Lee, B.K. Tay, Ultraviolet amplified spontaneous emission from zinc oxide ridge waveguides on silicon substrate. Appl. Phys. Lett. 83(21), 4288–4290 (2003)

21. N. Mehan, V. Gupta, K. Sreenivas, A. Mansingh, Effect of annealing on refractive indices of radio-frequency magnetron sputtered waveguiding zinc oxide films on glass. J. Appl. Phys. 96(6), 3134–3139 (2004)

22. A. Taabouche, A. Bouabellou, F. Kermiche, F. Hanini, Y. Bouachiba, A. Grid, T. Kerdjac, Properties of cobalt-doped zinc oxide thin films grown by pulsed laser deposition on glass substrates. Mater. Sci. Semiconduct. Process. 28, 54–58 (2014)

23. Q. Xu, L. Hartmann, S. Zhou, A. Mcklich, M. Helm, G. Bihne, H. Hochmuth, M. Lorentz, M. Grundmann, H. Schmidt, Spin manipulation in Co-doped ZnO. Phys. Rev. Lett. 101, 076601 (2008)

24. J. Cardin, D. Leduc, Determination of refractive index, thickness, and the optical losses of thin films from prism-film coupling measurements. Appl. Opt. 47(7), 894–900 (2008)

25. V. Sokolov, N. Marusin, V. Panchenko, A. Savelyev, V. Seminovog, E. Khaydukov, Determination of refractive index, extinction coefficient and thickness of thin films by the method of waveguide mode excitation. Quant. Electron. 43, 1149 (2013)

26. M. Shatnawi, A.M. Alsmadi, I. Bsoul, B. Salameh, M. Mathai, G. Alnawashi, G.M. Alzoubi, F. Al-Dweri, M.S. Bawa’aneh, Influence of Mn doping on the magnetic and optical properties of ZnO nanocrystalline particles. Results Phys. 6, 1064–1071 (2016)
27. S.M. Hosseini, I. Abdolhosseini Sarsari, P. Kameli, H. Salamat, Effect of Ag doping on structural, optical, and photocatalytic properties of ZnO nanoparticles. J. Alloys Compd. 640, 408–415 (2015)

28. K. Kasirajan, L. Bruno Chandrasekar, S. Maheswari, M. Karunakaran, P. Shunmuga Sundaram, A comparative study of different rare-earth (Gd, Nd, and Sm) metals doped ZnO thin films and its room temperature ammonia gas sensor activity: synthesis, characterization, and investigation on the impact of dopant. Optic. Mater. 121, 111554 (2021)

29. V. Russo, M. Ghidelli, P. Gondoni, C.S. Casari, A. Li Bassi, Multi-wavelength Raman scattering of nanostructured Al-doped zinc oxide. J. Appl. Phys. 115(7), 073508 (2014)

30. A. Calzolari, M.B. Nardelli, Dielectric properties and raman spectra of zno from a first principles finite-differences/finte-fields approach. Scientific reports 3, 2999 (2013)

31. X.F. Wang, J.B. Xu, B. Zhang, H.G. Yu, J. Wang, X. Zhang, J.G. Yu, Q. Li, Signature of intrinsic high-temperature ferromagnetism in cobalt-doped zinc oxide nanocrystals. Adv. Mater. 18(18), 2476–2480 (2006)

32. E. Louise, F. Wladimir, L. Douglas, M. Eduardo, Annealing effects on the structural and optical properties of ZnO nanostructures. Mater. Res. 21, e20170936 (2018)

33. X. Wang, J. Xu, X. Yu, K. Xue, J. Yu, X. Zhao, Structural evidence of secondary phase segregation from the Raman vibrational modes in Zn1-xcoxo (0 < x < 0.6). Appl. Phys. Lett. 91(3), 031908 (2007)

34. Marcel S.: ZnO-based semiconductors studied by Raman spectroscopy: semimagnetic alloying, doping, and nanostructures. PhD thesis, Universität Würzburg (2008)

35. D. Thongam, J. Gupta, N. Sahu, Effect of induced defects on the properties of ZnO nanocrystals: surfactant role and spectroscopic analysis. SN Appl. Sci. 1, 1030 (2019)

36. R. Ponnumasam, D. Sivasubramanian, P. Sreekanth, V. Gandhiraj, R. Philip, G.M. Bhalerao, Nonlinear optical interactions of Co: Zno nanoparticles in continuous and pulsed mode of operations. RSC Adv. 5, 80756–80765 (2015)

37. H. Ndeiimbake, S. Colis, G. Schmerber, D. Müller, J.J. Grob, L. Gravier, C. Jan, E. Beaurepaire, A. Dina, As-doping effect on magnetic, optical and transport properties of Zn0.9Co0.1O diluted magnetic semiconductor. Chem. Phys. Lett. 421(1), 184–188 (2006)

38. M. Naem, S.K. Hasanain, A. Mumtaz, Electrical transport and optical studies of ferromagnetic cobalt doped ZnO nanoparticles exhibiting a metal-insulator transition. J. Phys. 20(2), 025210 (2007)

39. O. Gencyllmaz, F. Atay, İ. Akyüz, Photoluminescence, ellipsometric, optical and morphological studies of sprayed Co-doped ZnO films. Mod. Phys. Lett. B 30(15), 1650171 (2016)

40. F. Akhtari, S. Zorriasatein, M. Farahmandjou, S.M. Elahi, Structural, optical, thermoelectrical, and magnetic study of zn1-xcoxo (0 < x < 0.10) nanocrystals. Int. J. Appl. Ceram. Technol. 15(3), 723–733 (2018)

41. B. Salameh, A.M. Alsadi, M. Shatnawi, Effects of co concentration and annealing on the magnetic properties of Co-doped ZnO films: role of oxygen vacancies on the ferromagnetic ordering. J. Alloys Compd. 835, 155287 (2020)

42. A.S. Risbud, N.A. Spaldin, Z.Q. Chen, S. Stemmer, R. Seshadri, Magnetism in polycrystalline cobalt-substituted zinc oxide. Phys. Rev. B 68, 205202 (2003)

43. K.J. Kim, Y.R. Park, Spectroscopic ellipsometry study of optical transitions in Zn1-xcoxo alloys. Appl. Phys. Lett. 81(8), 1420–1422 (2002)

44. S. Sahoo, V. Sivasubramanian, S. Dhara, A.K. Arora, Excitation energy dependence of electron–phonon interaction in ZnO nanoparticles. Solid State Commun. 147(7), 271–273 (2008)

45. A. Mahroug, S. Boudjadar, S. Hamrit, L. Guerbous, Structural, morphological and optical properties of undoped and Co-doped ZnO thin films prepared by sol–gel process. J. Mater. Sci. 25(11), 4967–4974 (2014)

46. Y. Bouabicha, A. Mammeri, A. Bouabellou, O. Rabia, S. Saidi, A. Taabouche, B. Rahal, L. Benharrant, H. Serrar, M. Boudissa, Optoelectronic and birefringence properties of weakly Mg-doped ZnO thin films prepared by spray pyrolysis. J. Mater. Sci. 33(9), 6689–6699 (2022)

47. Y.H. Elbashar, A.E. Omran, J.A. Khaliel, A.S. Abdel-Rahman, H.H. Hassan, Ultraviolet transmitting glass matrix for low power laser lens. Nonlinear Opt. Quant. Opt. 49, 247–265 (2018)

48. J.K. Furdyna, Diluted magnetic semiconductors. J. Appl. Phys. 64(4), R29–R64 (1988)

49. S. Venkataprasad Bhat, F.L. Deepak, Tuning the bandgap of ZnO by substitution with Mn2+, Co2+ and Ni2+. Solid State Commun. 135(6), 345–347 (2005)

50. A. Wang, B. Zhang, X. Wang, N. Yao, Z. Gao, Y. Ma, L. Zhang, H. Ma, Nano-structure, magnetic and optical properties of Co-doped ZnO films prepared by a wet chemical method. J. Phys. D 41(21), 215308 (2008)

51. K.T.R. Reddy, V. Supriya, Y. Murata, M. Sugiyama, Effect of Co-doping on the properties of Zn1-xcoxo films deposited by spray pyrolysis. Surf. Coat. Technol. 231, 149–152 (2013)

52. Z. Aghagoli, M. Ardyanian, Synthesis and study of the structure, magnetic, optical and methane gas sensing properties of cobalt doped zinc oxide microstructures. J. Mater. Sci. 29(9), 7130–7141 (2018)

53. B. Choudhury, M. Dey, A. Choudhury, Defect generation, d-d transition, and band gap reduction in Cu-doped TiO2 nanoparticles. Int. Nano Lett. 3, 25 (2013)
54. A. Salah, A.M. Saad, A.A. Aboud, Effect of Co-doping level on physical properties of ZnO thin films. Opt. Mater. 113, 110812 (2021)
55. B. Gharbi, A. Taabouche, M. Brella, R. Gheriani, Y. Bouachiba, A. Bouabellou, F. Hanini, S.L. Barouk, H. Serrar, B. Rahal, Spray pyrolysis synthesized and ZnO-NiO nanstructured thin films analysis with their nanocomposites for waveguiding applications. Semiconductors 55, 37–43 (2021)
56. R. Ulrich, R. Torge, Measurement of thin film parameters with a prism coupler. Appl. Opt. 12(12), 2901–2908 (1973)
57. I.J. Kurland, H.L. Bertoni, Birefringent prism couplers for thin-film optical waveguides. Appl. Opt. 17(7), 1030–1037 (1978)
58. V. Adimule, B.C. Yallur, D. Bhowmik, A.H.J. Gowda, Dielectric properties of P3BT doped ZrY2O3/CoZrY2O3 nanostructures for low cost optoelectronics applications. Trans. Electric. Electron. Mater. 23, 288–303 (2021)
59. Y. Bouachiba, A. Taabouche, A. Bouabellou, F. Hanini, C. Sedrati, H. Merabti, TiO2 waveguides thin films prepared by sol-gel method on glass substrates with and without ZnO underlayer. Mater. Sci. Poland 38(3), 381–385 (2020)
60. F. Yakuphanoglu, A. Cukurovali, İ Yılmaz, Single-oscillator model and determination of optical constants of some optical thin film materials. Physica B 355(3), 210–216 (2004)
61. R. Orainy, Single oscillator model and refractive index dispersion properties of ternary ZnO films by sol gel method. J. Sol-Gel Sci. Technol. 70, 47–52 (2014)
62. X.-Y. Gao, H.-L. Feng, J.-M. Ma, Z.-Y. Zhang, J.-X. Lu, Y.-S. Chen, S.-E. Yang, J.-H. Gu, Analysis of the dielectric constants of the Ag2O film by spectroscopic ellipsometry and single-oscillator model. Physica B 405(7), 1922–1926 (2010)
63. K.A. Aly, Optical band gap and refractive index dispersion parameters of AsxSe70-30Te30-x (0 ≤ x ≤ 30 at.% amorphous films. Appl. Phys. A 99(4), 913–919 (2010)
64. T. Okamoto, M. Yamamoto, I. Yamaguchi, Optical waveguide absorption sensor using a single coupling prism. J. Opt. Soc. Am. A 17(10), 1880–1886 (2000)

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