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Extensive Study of Spin Coated CZTS Thin Film Absorbers for Photovoltaic Utilization

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Abstract: ***In this study, we used the sol - gel spin coating method to synthesize Cu_2ZnSnS_4 (CZTS) absorber layers on common glass substrates. We investigated the morphological, optical, and structural characteristics of thin films. Various characterization techniques, including x - ray diffraction (XRD), Raman spectra, scanning electron microscopy (SEM), atomic force microscopy (AFM), and UV - visible spectroscopy, have been used to investigate these films. The XRD analysis revealed a kesterite phase with an intense peak at 28.35° representing the (112) plane. These samples have crystallite size around 5 nm, and lattice parameters a = b = 5.2 Ǻ and c = 8.5 Ǻ. A single strong peak (at 329 cm^{-1}) in the Raman spectrum verifies the development of a single - phase CZTS thin film. The SEM image depicts the homogeneous, compact, and dense surface morphological thin films. The AFM 3D micrographs show spike - like structures with average and root mean square (RMS) roughness of 0.146 nm and 0.203 nm. UV - Visible spectroscopy revealed the direct band gap energy of around 1.52 eV for CZTS thin films. With these characteristics, the fabricated CZTS films are suitable for absorber layers in photovoltaic utilization.***

Keywords: Sol - gel, spin coating, kesterite, single phase, band gap

1. Introduction

Energy utilization is accelerated by the growing need for energy. The utilization of photovoltaic cells, which produce power from an endless source, is the most environmentally friendly and efficient option to address this requirement. Thin film technology, particularly in the field of photovoltaic has garnered a lot of interest as a solution to the problems because of their peculiar size dependant features and wide range of possible applications [1, 2]. Non - traditional energy, based on photovoltaic cells is advantageous for the large duration energy - providing chain. In recent years, maximum conversion efficiencies of *20.8* and *19.6%* for lab - scale devices were achieved by thin film photovoltaic cells based on polycrystalline $CuIn_{1-x}Ga_xSe_2$ and CdTe absorbing materials, respectively. These technologies have also already entered the commercial manufacturing stage [3]. The eventual development of CIGS and CdTe - based photovoltaic cells is constrained by the lack of In and Te in the earth's crust [4]. Thus, the critical components for meeting future demands for clean energy are effective photovoltaic devices made of materials that are both non - hazardous and plentiful on the Earth [5]. In this context, CZTS is a promising candidate for absorber material having a kesterite phase [6]. CZTS belongs to the p - type semiconducting material with a tunable direct energy band gap that varies between *1.4* and *1.6 eV* [7, 8] with a significant absorption coefficient ($>10^4\ cm^{-1}$) [9]. By using zinc (Zn) and tin (Sn) components rather than indium (In) and gallium (Ga), it offers a less expensive and ecologically friendly alternative to $CuIn_xGa_{1-x}Se_2$ (CIGS) and $CuInS_2$ (CIS) [10]. In this regard, the primary studies concentrate on the Cu_2ZnSnS_4 (CZTS) material, which has a pure kesterite phase. After the year 2000, the previously slow - moving investigations on CZTS - based solar cell systems accelerated [11]. Whereas initial samples were mainly produced using vacuum technology, the next generation of effective CZTS absorbing layers was primarily accomplished using sol - gel techniques [12, 13]. The spin coating technique is one of the sol - gel technologies that are typically less expensive, requires minimal previous preparation, and is extremely viable. Furthermore, the spin coating approach is used to create the most effective photovoltaic devices with CZTS absorbing layers [14]. Although there was no deep parameter investigation for the spin - coated CZTS absorber layer development during these studies, many particular fabrication parameters, including annealing temperature [15], crystal arrangement [16], solution characteristics, layer count [17], and spinning rate [18], were altered and their impact was studied. Many researchers already looked into the synthesis of CZTS films using various vacuum as well as non - vacuum - based methods. [19, 20]. The last few years have seen extensive use of a variety of techniques, including chemical bath deposit [21], atomic beam sputtering [22], thermal evaporation [23], RF magnetron sputtering [24], co - evaporation, pulsed laser deposition [25], ion beam sputtering [26], photo - chemical deposition [27], electrochemical deposition [28], spray pyrolysis [29], spin coating [30, 31] and plasma polymerization [32] for the fabrication of thin films for PV applications. Nevertheless, spin coating is now the most widely used method for creating homogeneous thin films of semiconducting materials with thicknesses in the micrometer and nanometer range.

2. Literature Survey

Ozdal et al. [33] reported that the chemical composition, particle size, surface morphology, crystal structure, and thickness of thin films were examined concerning the impacts of spin velocity, solution molarity, stabilizer quantity, drying, and additional annealing conditions. Heat treatment has a significant impact on the synthesized CZTS thin film's quality. To achieve the best heat treatment results, a variety of drying, and annealing environments were applied. It has been discovered that stoichiometric CZTS absorbing thin layers may be synthesized in under - regulated and advantageous annealing environments. Islam et al. [34] reported that CZTS thin films have been created on glass slides using spin coating techniques at a variety of speeds. Using a variety of characterisation techniques the produced samples' optical, structural, and morphological characteristics have been investigated. For CZTS - 1 and CZTS - 2 samples, the energy band gap has been identified to be *1.50 eV* and *1.45 eV*, respectively. Urbach energy and steepness parameters for the CZTS - 1 sample are *0.99 eV* and *0.026*, while for the CZTS - 2 sample *0.95 eV* and *0.027*, respectively. According to the XRD analysis, the dominant peak for both films was located at (112), which corresponds to a 2θ value of *28.437°*. The texture architecture for CZTS thin films was identified using SEM investigation. Ziti et al. [35] investigated how the annealing temperature affects the structural, optical, and electrical characteristics of Cu_2ZnSnS_4 thin film formed by the sol - gel process and fabricated through the spin coating method. These specimens were annealed in the air for 10 minutes at *300°C*, *325°C*, and *350°C* temperatures. The development of the kesterite phase of CZTS is confirmed by Raman and X - ray diffraction spectra. Based on the transmission and absorption data provided by the UV - Visible spectrometer (in the *350* to *1000 nm* range), the optical characteristics have been determined. The energy band gap value varies between *1.5* and *1.63 eV*, and the four - probe technique revealed improved electric resistivity from *0.1* to *0.15* (*Ω. cm*). These synthesized films are a useful material for an absorbing layer in photovoltaic devices due to their superior resistivity and ideal energy band gap value.

3. Problem Definition

In this study, we have synthesized the Cu_2ZnSnS_4 (CZTS) thin films using sol - gel spin coating technique, on the glass substrates. The optical, structural, surface morphological, and surface topographical characteristics of these films have identified.

4. Methodology

4.1 Preparation of a sol - gel precursor

In the beginning, *0.02 M* of $ZnCl_2$ and *0.04* M of $CuCl_2.2H_2O$ have been dissolved in *50 mL* of 2 - Methoxy ethanol, and the mixture was heated to *50 °C* on a hot plate with a magnetic stirrer for *30 minutes*. Following the addition of *0.02 M* of $SnCl_2.2H_2O$, *0.16* M of thiourea ($SC(NH_2)_2$), and 30 drops of monoethanolamine (MEA) to the abovementioned solution. A clear yellow solution was obtained after an hour of magnetic stirring at *50 °C* on a hot plate.

4.2 Fabrication of CZTS thin film

Initially, the glass slides were cleaned with distilled water, isopropyl alcohol, and acetone respectively. The thin film deposited glass slides were then placed on a heated plate for *4 minutes* at *105°C* after being spin - coated with the precursor solution at *2000* revolutions per minute. This technique was carried out three to four times to produce thin films of the desired thickness. Finally, these synthesized films were annealed in the air for *10 minutes* at *350°C.*

4.3 Characterization Techniques

The CZTS thin films were analysed using various techniques. An X - ray diffraction spectrometer (XRD; Panalytical X Pert Pro using CuKα radiation) was applied to determine the crystallinity of thin films. A UV - Vis spectrometer (LAMBDA 750 Perkin Elmer) was used to study the optical characteristics of Cu_2ZnSnS_4 thin films in the *200 - 800 nm* wavelength range. Raman spectroscopy (STR 500 CONFOCAL MICRO) was used to get the Raman spectra at ambient temperature. Surface morphology was analyzed using a ZEISS scanning electron microscopy (SEM). The surface topography was determined using Bruker's atomic force microscopy (AFM).

5. Results and Discussion

5.1 Structural characteristics

Fig.1 (a) depicts the XRD spectrum of synthesized CZTS thin films. The diffraction peaks occur in the vicinity of angles 2θ equal to *28.35°*, and *49.0°* which are in agreement with diffraction at the planes (*112*), and (*220*) respectively. The presence of these peaks confirms the formation of a kesterite phase having a tetragonal structure. This is supported by the JCPDS # 26 - 0575 card [36]. It demonstrates that no further secondary sulphide compounds were identified in the prepared thin film.

The Debye–Scherer formula -

$$D = \frac{0.9\lambda}{\beta\cos\theta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $\lambda = 1.54\,Å$ and β is the full width at half maximum (FWHM); may be applied to calculate the crystallite size (*D)* of the samples. The relation between *d* - spacing, miller indices (*h k l*) and lattice constants (*a*=*b*, *c*) for tetragonal geometry is given by -

$$\frac{1}{d^2} = \frac{h^2+k^2}{a^2} + \frac{l^2}{c^2} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which can be used to calculate the values of lattice parameters.

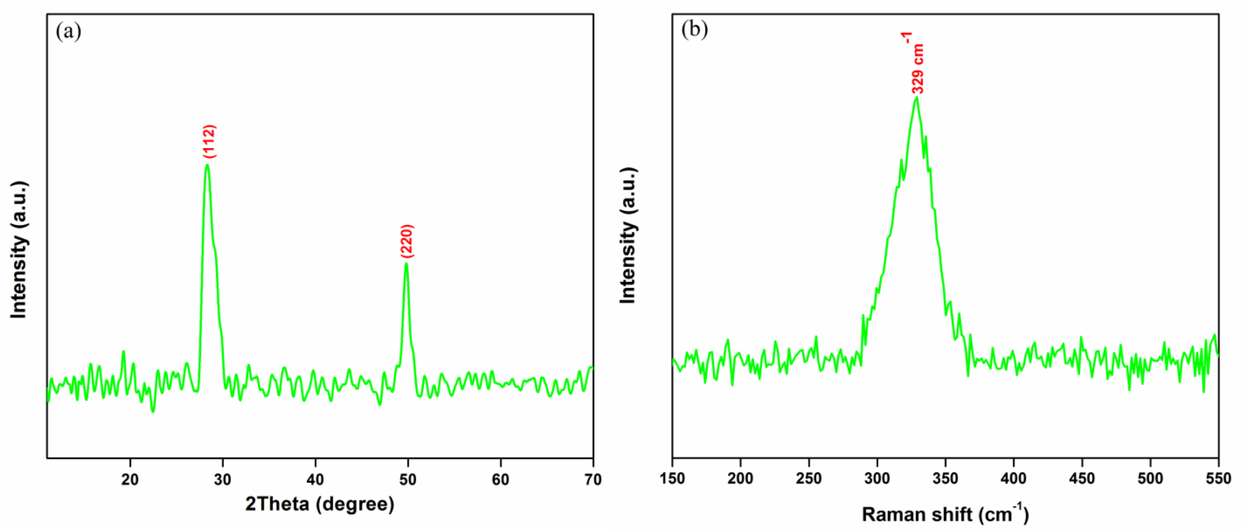

Figure 1: (a) XRD spectra of Cu_2ZnSnS_4 film, and (b) Raman spectra of Cu_2ZnSnS_4 film

The tetragonal distortion (Δ) and dislocation density (*δ*) of synthesized CZTS thin films can be calculated using the formulas-

$$\Delta = 2 - \frac{c}{a} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\text{and } \delta = \frac{1}{D^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The calculated values of FWHM (*β*), crystallite size (*D*), inter - planar spacing (*d*), lattice constants (*a=b*, *c*), tetragonal distortion (Δ) and dislocation density (δ) of synthesized thin films are shown in Table 1.

Table 1: The values of β, *D*, *d*, *a=b*, *c*, Δ, and δ for CZTS thin film sample.

Sample	$\beta_{(112)}$ (deg.)	*D* (*nm*)	*d* (Å)	*a=b* (Å)	*c* (Å)	Δ	δ (nm^{-2})
CZTS	1.49	5.5	1.8	5.2	8.5	0.36	0.04

For identifying the phase of CZTS, a Raman spectrometer is an effective technique. Fig.1 (b) shows the Raman spectrum of the synthesized CZTS thin film sample. It contains a single intense peak at around *329* cm^{-1} which belongs to the *A* vibrational mode of CZTS [37]. The Raman spectrum does not contain any extra peak corresponding to additional sulphide compounds. Thus, the existence of a single intense peak verifies the formation of a single - phase CZTS thin film [38].

5.2 Optical characteristics

Optical parameters including absorbance (A), transmittance (T), and band gap (Eg) are crucial for choosing a good absorber material for thin film photovoltaic. The optical properties of CZTS films were investigated using an ultraviolet - visible spectrophotometer. Fig 2 (a) and 2 (b) represents the graphs between absorbance vs wavelength and % transmittance vs wavelength for CZTS samples, respectively.

One may use the following relation, to determine the thin film's absorption coefficient (α) [39] –

$$\alpha = 2.303\frac{A}{t}$$

where *A* and *t* indicate the absorbance and thickness of the thin film, respectively. The coefficient of absorption of the thin films, which was determined from the transmittance spectrum, turned out to be 10^4 cm^{-1} in the visible range. This larger value shows that these thin films may absorb the majority of the incident light. The optical band gap value of thin film samples can be determined using the Tauc formula [40] –

$$(\alpha h\nu)^2 = \beta\,(h\nu - Eg)$$

where β and E_g denote energy independent constant and energy band gap, respectively.

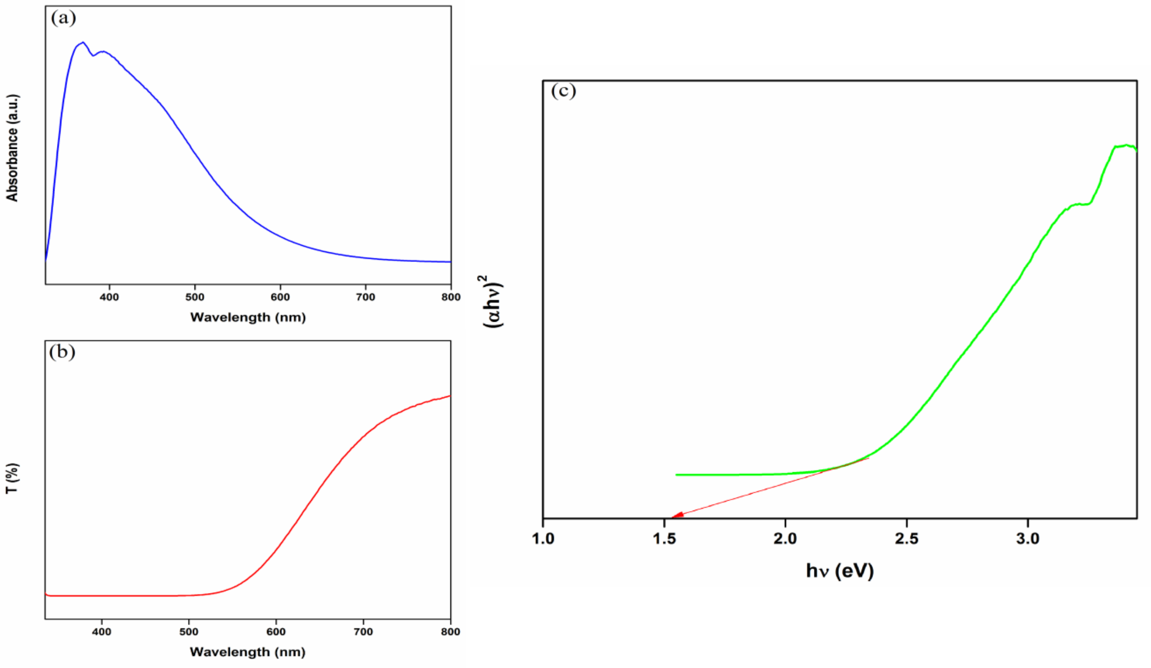

Figure 2: (a) Absorbance vs. wavelength, (b) Transmittance vs. wavelength, and (c) $(\alpha h\nu)^2$ vs. $(h\nu)$ graph of CZTS thin film.

Fig 3 (c) displays the graph between $h\nu$ and $(\alpha h\nu)^2$ for CZTS thin film sample. The band gap value (Eg) of the sample is given by the intersection of the tangent drawn to the graph between $h\nu$ and $(\alpha h\nu)^2$, and the $h\nu$ axis. The estimated value of the energy band gap from the aforementioned graph is around *1.52 eV*. This band gap value is considered ideal for PV cells [41]. These optical characteristics suggest that the synthesized CZTS films are perfect for photovoltaic applications.

5.3 Surface analysis

The surface morphological characteristics of thin films have been identified by scanning electron microscope (SEM). Fig.3 (a) displays the surface SEM images of the CZTS thin films. The entire region of the CZTS thin film has identical surface features. The observed value of the average grain size of these synthesized thin films is about 32 *nm*. Also, these samples have a compact structure with the absence of fractures. Consequently, the thin films' reported average crystalline size of *5.5 nm* (from XRD analysis) points to their compact polycrystalline nature. Thus, the synthesized thin films may be a viable option for photovoltaic studies.

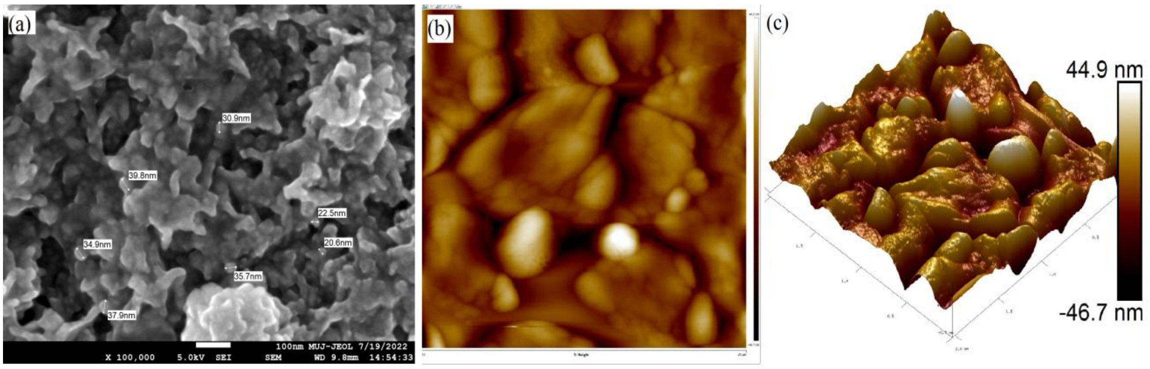

Figure 3: (a) SEM image, (b) 2D AFM micrograph, and (c) 3D AFM micrograph for Cu_2ZnSnS_4 thin film

The surface topography of synthesized thin films has been investigated by atomic force microscopy (AFM). Fig.3 (b) and 3 (c) display the 2D and 3D micrographs of the synthesized CZTS thin film samples, respectively. The 2D micrograph shows that CZTS thin film consists of almost spherical grains. The 3D micrograph shows a spike - like structure over the entire thin film surface with a vertical height between *+44.9 nm* and *- 46.7 nm*. On the basis of AFM images, the average and root mean square (RMS) roughness have been estimated to be *0.146 nm* and *0.203 nm*, respectively.

6. Conclusion

In the research work, CZTS thin films were effectively synthesized by the sol - gel spin coating method on glass substrates. The XRD analysis revealed a kesterite phase with an intense peak at *28.35°* representing the (112) plane. Raman spectrum displays a single intense peak at $329\ cm^{-1}$. The synthesis of the single - phase CZTS thin film is verified by the absence of additional Raman peaks. As a consequence, the Raman analysis of CZTS thin films validates the X - ray diffraction observations. The UV -

Visible spectroscopy revealed that the direct band gap energy of the thin film is around *1.52 eV*, which is in the optimal band gap range for absorber material. The SEM image depicts the homogeneous, compact, and dense surface morphological thin films having grain sizes around *32 nm*. The AFM images show that CZTS thin film contains almost flat surfaces. With these characteristics, the fabricated CZTS films are suitable for absorber layers in photovoltaic utilization.

7. Future Scope

The suggested sol - gel spin coating technique may provide an appropriate way to fabricate CZTS thin films with improved crystallinity and advantageous optical properties for solar applications. In the future, cheaper and easier synthesis process will be able to form non - polluting CZTS thin films, which may be utilized to fabricate effective thin film solar cells.

References

[1] Pearce, J. (2009). Photovoltaic: A Path to Sustainable Futures. *Futures, 34 (7),* 663 - 674.

[2] Green, M. A., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E. D. (2014). Solar cell efficiency tables (version 43). *Prog. Photovolt: Res. Appl., 22,* 1–9.

[3] Kahraman, S., Çetinkaya, S., Podlogar, M., Bernik, S., Çetinkara, H. A., Güder, H. S. (2013). Effects of the sulfurization temperature on sol gel - processed Cu2ZnSnS4 thin films. *Ceramics International, 39,* 9285 - 9292.

[4] Green, M. A. (200). *Power to the people: sunlight to electricity using solar cells*, UNSW Press.

[5] Green, M. A. (2006). Consolidation of thin - film photovoltaic technology: the coming decade of opportunity, *Prog. Photovolt: Res. Appl., 14,* 383 - 392.

[6] Zhang, K., Tao, J., He, J., Wang, W., Sun, L., Yang, P., Chu, J. (2014). Composition control in Cu2ZnSnS4 thin films by a sol–gel technique without sulfurization. *J Mater Sci: Mater Electron, 25,* 2703–2709.

[7] Yeh, M. Y., Lee, C. C., Wuu, D. S. (2009). Influences of synthesizing temperatures on the properties of Cu2ZnSnS4 prepared by sol–gel spin - coated deposition. *J Sol - Gel Sci Technol, 52,* 65–68.

[8] Xu, J., Cao, Z., Yang, Y., Xie, Z. (2015). Characterization of Cu2ZnSnS4 thin films on flexible metal foil substrates. *J Mater Sci: Mater Electron, 26,* 726–733.

[9] Bonazzi, P., Bindi, L., Bernardini, G. P., Menchetti, S. (2003). A model for the mechanism of incorporation of Cu, Fe and Zn in the stannite–kësterite series, Cu2FeSnS4–Cu2ZnSnS4. *Can. Mineral., 41,* 639 - 647.

[10] Hall, S., Szymanski, J., Stewart, J. (1978). Kesterite, Cu<2) (Zn, Fe) SnS<4), and stannite, Cu<2) (Fe, Zn) SnS<4), structurally similar but distinct minerals. *Can. Mineral., 16,* 131 - 137.

[11] Song, X., Ji, X., Li, M., Lin, W., Luo, X., Zhang, H. (2014). A review on development prospect of CZTS based thin film solar cells. *Int. J. Photoenergy, 2014,* 11.

[12] Dong, L., Cheng, S., Lai, Y., Zhang, H., Jia, H. (2017). Sol - gel processed CZTS thin film solar cell on flexible molybdenum foil. *Thin Solid Films, 626,* 168 - 172.

[13] Tao, H., Cao, F., Zhang, C., Chen, S., Tan, B., Tao, J. (2017). In - situ growth of CuZnSnS nanoparticles on thiol reduce graphene oxide for CuZnSnS - sensitized solar cells. *J. Alloys Compd., 698,* 114 - 120.

[14] Sun, K., Yan, C., Liu, F., Huang, J., Zhou, F., Stride, J. A., Green, M., Hao, X. (2016). Over 9% Efficient Kesterite Cu2ZnSnS4 Solar Cell Fabricated by Using Zn1–xCdxS Buffer Layer. *Adv. Energy Mater., 6,* 1600046.

[15] Chen, R., Fan, J., Liu, C., Zhang, X., Shen, Y., Mai, Y. (2016). Solution - Processed One - Dimensional ZnO[at]CdS Heterojunction toward Efficient Cu2ZnSnS4 Solar Cell with Inverted Structure. *Sci. Rep., 6,* 35300.

[16] Su, Z., Tan, J. M. R., Li, X., Zeng, X., Batabyal, S. K., Wong, L. H. (2015). Cation Substitution of Solution-Processed Cu2ZnSnS4 Thin Film Solar Cell with over 9% Efficiency. *Adv. Energy Mater., 5,* 1500682.

[17] Wang, W., Shen, H., Wong, L. H., Su, Z., Yao, H., Li, Y. (2016). A 4.92% efficiency Cu2ZnSnS4 solar cell from nanoparticle ink and molecular solution. *RSC Adv., 6,* 54049 - 54053.

[18] Yu, Y., Ge, J., Prabhakar, T., Yan, Y. (2014). Effects of spin speed on the properties of spin - coated Cu2ZnSnS4 thin films and solar cells based on DMSO solution. *IEEE,* 0448 - 0451

[19] Tanaka, K., Moritake, N., Oonuki, M., Uchiki, H. (2008). Pre - annealing of precursors of Cu2ZnSnS4 thin films prepared by sol–gel sulfurizing method. *Jpn. J. Appl. Phys., 47,* 598.

[20] Chaudhuri, T. K., Tiwari, D. (2012). Earth - abundant non - toxic Cu2ZnSnS4 thin films by direct liquid coating from metal–thiourea precursor solution. Sol. Energy Mater. Sol. Cells, 101, 46–50.

[21] Lokhande, C. D. (19910. Preparation of silver sulphide from chemically deposited silver filmsMater. *Chem. Phys., 28,* 1 - 10.

[22] Pawar, S. M., Pawar, B. S., Moholkar, A. V., Choi, D. S., Yun, J. H., Moon, J. H., Kolekar, S. S., Kim, J. H. (2010). Single step electrosynthesis of Cu2ZnSnS4 (CZTS) thin films for solar cell application. *Electrochimica Acta, 55 (12),* 4057–4061.

[23] Faraj, M. G., Ibrahim, K. (2015). Investigation of the Structural Properties of Thermally Evaporated Aluminium Thin Films on Different Polymer Substrates. *International Journal of Thin Films Science and Technology, 4 (1),* 27 - 30.

[24] Kumar, B. R., Rao, T. S. (2011). Effect of substrate temperature on structural and optical properties of Zinc Aluminum Oxide thin films prepared by DC reactive magnetron sputtering technique. *Journal of Ovonic Research, 7,* 115 – 123.

[25] Venkatachalam, S., Kanno, Y. (2009). Preparation and characterization of nano and microcrystalline ZnO thin films by PLD. *Current Applied Physics, 9,* 1232–1236.

[26] Zhou, Z. B., Cui, R. Q., Pang, Q. J., Hadi, G. M., Ding, Z. M., Li, W. Y. (2002). Schottky solar cells with amorphous carbon nitride thin films prepared by ion beam sputtering technique. *Solar Energy Materials and Solar Cells, 70 (4)*, 487–493.

[27] Ichimura, M., Shibayama, K., Masui, K. (2004). Fabrication of SnO2 thin films by a photochemical deposition method. *Thin Solid Films, 466 (2),* 34 - 36.

[28] Gregory, B. W., Stickney, J. L. (1991). Electrochemical atomic layer epitaxy (ECALE). *Journal of Electroanalytical Chemistry and Interfacial Electrochemistry, 300 (2)*, 543 - 563.

[29] Chouikh, F., Beggah, Y., Aida, M. S. (2014). Physical Properties of Undoped and Doped ZnO Thin Films Prepared by Spray Pyrolysis for Photovoltaic Application. *International Journal of Thin Films Science and Technology, 3 (2),* 51 - 56.

[30] Swami, S. K., Kumar, A., Dutta, V. (2013). Deposition of Kesterite Cu2ZnSnS4 (CZTS) Thin Films by Spin Coating Technique for Solar Cell Application. *Energy Procedia, 33,* 198 – 202.

[31] Patel, J., Mighri, F., Ajji, A., Tiwari, D., Chaudhuri, T. K. (2014). Spin - coating deposition of PbS and CdS thin films for solar cell application. *Applied. Physics A, 117,* 1791–1799.

[32] Kabir, H., Rahman, M. M., Roy, T. S., Bhuiyan, A. H. (2012). Structural and Optical Properties of Plasma Polymerized Pyromucic Aldehyde Thin Films. *International Journal of Mechanical & Mechatronics Engineering, 12 (5),* 30 - 34.

[33] Özdal, T., Kavak, H. (2017). Comprehensive analysis of spin coated copper zinc tin sulfide thin film absorbers. *Journal of Alloys and Compounds, 725,* 644 - 651.

[34] Islam, S., Hossain, M. A., Kabir, H., Rahaman, M., Bashar, M. S., Gafur, M. A., Kabir, A., Bhuiyan, M. M. R., Ahmed, F., Khatun, N. (2015). Optical, Structural and Morphological Properties of Spin Coated Copper Zinc Tin Sulfide Thin Films. *Int. J. Thin. Fil. Sci. Tec., 4 (3),* 155 - 161.

[35] Ziti, A., Hartiti, B., Labrim, H., Fadili, S., Ridah, A., Belhorma, B., Tahri, M., Thevenin, P. (2019). Study of kesterite CZTS thin films deposited by spin coating technique for photovoltaic applications. *Superlattices and Microstructures, 127,* 191 - 200.

[36] Kamoun, N., Bouzouita, H., Rezig B. (2017). Fabrication and characterization of Cu_2ZnSnS_4 thin films deposited by spray pyrolysis technique. *Thin Solid Films, 515 (15),* 5949.

[37] Yazici, S., Olgar, M. A., Akca, F. G., Cantas, A., Kurt, M., Aygun, G., Tarhan, E., Yanmaz, E., Ozyuzer, L. (2015). Growth of Cu2ZnSnS4 absorber layer on flexible metallic substrates for thin film solar cell applications. *Thin Solid Films., 589,* 563–573.

[38] Awadallah, O., Cheng, Z. V. (2016). In Situ Raman Monitoring of Cu2ZnSnS4 Oxidation and Related Decomposition at Elevated Temperatures. *IEEE J. Photovolt., 6,* 764–769.

[39] Kumar, Y. B. K., Babu, G. S., Bhaskar, P. U., Raja, V. S. (2009). Preparation and characterization of spray - deposited Cu2ZnSnS4 thin films. *Solar Energy Materials& Solar Cells, 93,* 1230–1237.

[40] Tauc, J., Grigorivic, R., Vancu, A. (1996). Optical Properties and Electronic Structure of Amorphous Germanium. A. *Phys. Stat. Sol., 15,* 627.

[41] Zhao, Y., Tao, W., Liu, J., Wei, A. (2015). Rapid synthesis of Cu2ZnSnS4 nanocrystalline thin films directly on transparent conductive glass substrates by microwave irradiation. *Mater. Lett., 148,* 63–66.

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