**A review of recent advances of kesterites thin films based on magnesium, iron, and nickel for photovoltaic application: Insights into synthesis, characterization and optoelectronic properties**

Nelson Mauricio Espinel Pérez **1,2\***, Enrique Vera López **1**, Jairo Alberto Gómez Cuaspud **1\*,** Juan Bautista Carda Castelló **3**.

**1**Grupo de Investigación en Integridad y Evaluación de Materiales (GIEM). Instituto para la Investigación e Innovación en Ciencia y Tecnología de Materiales (INCITEMA). Universidad Pedagógica y Tecnológica de Colombia. Av. Central del Norte 39-115. Tunja - Boyacá, Colombia.

**2**Servicio Nacional de Aprendizaje (Sena). Centro Minero. Vereda Morcá Sector Batá. Sogamoso - Boyacá, Colombia.

**3** Universidad Jaume I. Grupo de Química Inorgánica y Orgánica. Castellón de la Plana. Campus del Riu Sec. Castellón de la Plana. España.

**Supplementary Data**

**Data Availability**

The data underlying this article are available in the article and in this online supplementary material.

|  |  |  |
| --- | --- | --- |
| **Reference** | **Description** | **DOI or URL link** |
| (1) | **Article**:  Photovoltaic solar cell technologies: analysing the state of the art. Nat Rev Mater. 2019;4:269–85. | <https://doi.org/10.1038/s41578-019-0097-0> |
| (2) | **Report:**  IEA. Renewables 2021, Analysis and forecast to 2026. International Energy Agency (IEA) Publications International. 2021. | <https://iea.blob.core.windows.net/assets/5ae32253-7409-4f9a-a91d-1493ffb9777a/Renewables2021-Analysisandforecastto2026.pdf>  (16 November 2023, date last accessed) |
| (3) | **Article:**  Recent development in earth-abundant kesterite materials and their applications. Sustainability. 2020;12:5138. | <https://doi.org/10.3390/su12125138> |
| (4) | **Article:**  Emerging inorganic compound thin film photovoltaic materials: Progress, challenges and strategies. Materialstoday. 2020;41:120-142. | <https://doi.org/10.1016/j.mattod.2020.09.002> |
| (5) | **Article:**  Progress in thin film CIGS photovoltaics – Research and development, manufacturing, and applications. Prog Photovoltaics Res Appl. 2016;25:645–67. | <https://doi.org/10.1002/pip.2811> |
| (6) | **Article Review:**  Thin film solar cell technologies and challenges: a review. Renew Sustain Energy Rev. 2017;70:1286-12. | <https://doi.org/10.1016/j.rser.2016.12.028> |
| (7) | **Article Review:** Kësterite thin films for photovoltaics: a review. EPJ Photovoltaics. 2012;3:35004. | <https://doi.org/10.1051/epjpv/2012008> |
| (8) | **Book:**  Springer Handbook of Electronic and Photonic Materials. 1st ed. New York: Springer. New York; 2006. | <https://doi.org/10.1007/978-0-387-29185-7> |
| (9) | **Article:**  The electrical and optical properties of kesterites. JPhys Energy. 2019;1:044002. | <https://doi.org/10.1088/2515-7655/ab29a0> |
| (10) | **Article:**  Guo Y, Wang Q, et al. A New Silicon Phase with Direct Band Gap and Novel Optoelectronic Properties. Sci Rep. 2015;5. | <https://doi.org/10.1038/srep14342> |
| (11) | **Thesis (repository):** Obtención de estructuras calcopirita (CIGS) y kesterita (CZTS) como absorbedores para dispositivos fotovoltaicos de capa fina mediante métodos de síntesis de bajo coste. Ph.D. thesis. Universidad Jaume I, Castellon de la Plana, España; 2016. | <http://dx.doi.org/10.6035/14104.2016.178468>  (16 November 2023, date last accessed). |
| (12) | **Article:**  Richter A, Hermle M, et al. Reassessment of the limiting efficiency for crystalline silicon solar cells. IEEE J Photovoltaics. 2013;3:1184-91. | <https://doi.org/10.1109/JPHOTOV.2013.2270351> |
| (13) | **Article:**  Solar cell efficiency tables (Version 55). Prog Photovoltaics Res Appl. 2020;28:3-15. | <https://doi.org/10.1002/pip.3228> |
| (14) | **Article:**  Device characteristics of CZTSSe thin-film solar cells with 12.6% efficiency. Adv Energy Mater. 2014;4. | <https://doi.org/10.1002/aenm.201301465> |
| (15) | **Thesis (repository):** Síntesis y caracterización de Cu2ZnSnS4 impurificado con Se para aplicaciones en celdas solares. M.Sc. thesis. Universidad de Ciencias y Artes de Chiapas, Tuxtla Gutiérrez, México; 2015. | <https://repositorio.unicach.mx/handle/20.500.12753/708?show=full>  (16 November 2023, date last accessed) |
| (16) | **Thesis (repository):** Síntesis y caracterización de películas delgadas del semiconductor Cu2ZnSnS4 y su uso como capa absorbente en celdas solares. Ph.D.thesis. Universidad Nacional de Colombia, Bogotá, Colombia; 2014. | <https://repositorio.unal.edu.co/handle/unal/52170>  (16 November 2023, date last accessed) |
| (17) | **Article:**  In-depth resolved Raman scattering analysis for the identification of secondary phases: Characterization of Cu2ZnSnS4 layers for solar cell applications. Appl Phys Lett. 2011;98:2011-14. | <https://doi.org/10.1063/1.3587614> |
| (18) | **Article:**  First Principles Calculations of Defect Formation in In-Free Photovoltaic Semiconductors Cu2ZnSnS4 and Cu2ZnSnSe4. Thin Solid Films. 2011;50:04DP07. | <https://doi.org/10.1016/j.tsf.2011.01.094> |
| (19) | **Article:**  Preparation and characterization of Cu2ZnSnSe4 thin films grown from ZnSe and Cu2SnS3 precursors in a two stage process. Rev Elem. 2012;2:117-131. | <https://doi.org/10.1088/1742-6596/480/1/012007> |
| (20) | **Article:**  Kesterites—a challenging material for solar cells. Prog Photovoltaics Res Appl. 2012;20:512-19. | <https://doi.org/10.1002/pip.2156> |
| (21) | **Article-review:**  Strategic review of secondary phases, defects and defect complexes in kesterite CZTS-Se solar cells. Energy Environ Sci. 2015;8:3134-59. | <https://doi.org/10.1039/c5ee02153g> |
| (22) | **Article:**  Classification of lattice defects in the kesterite Cu2ZnSnS4 and Cu2ZnSnSe4 earth-abundant solar cell absorbers. Adv Mater. 2013;25:1522-39. | <https://doi.org/10.1002/adma.201203146> |
| (23) | **Thesis (repository):** Caracterización por espectroscopia Raman de semiconductores Cu2ZnSnS4 para nuevas tecnologías fotovoltaicas. Ph.D.thesis. Universidad de Barcelona, Barcelona, España; 2013. | <http://hdl.handle.net/2445/54689>  (16 November 2023, date last accessed). |
| (24) | **Article:**  Point defects, compositional fluctuations, and secondary phases in non-stoichiometric kesterites: a review. JPhys Energy. 2020;2. | <https://doi.org/10.1088/2515-7655/ab4a25> |
| (25) | **Article:**  Improving Carrier-Transport Properties of CZTS by Mg Incorporation with Spray Pyrolysis. ACS Appl Mater Interfaces. 2019;11:25824–32. | <https://doi.org/10.1021/acsami.9b05244> |
| (26) | **Article:**  Effect of Mg doping on Cu2ZnSnS4 solar cells prepared by DMFbased solution method. Opt Mater (Amst). 2021;117. | <https://doi.org/10.1016/j.optmat.2021.111211> |
| (27) | **Article:**  Fabrication of Cu2ZnSnS4 thin films from ball-milled nanoparticle inks under various annealing temperatures. Nanomaterials. 2019;9:1615. | <https://doi.org/10.3390/nano9111615> |
| (28) | **Thesis (repository):** Solution processed Cu2ZnSn(SxSe1-x)4 thin films based on binary and ternary chalcogenide nanoparticle precursors and their application in solar cells. Ph.D. thesis. Technical University of Berlin, Germany; 2013. | <https://depositonce.tu-berlin.de/bitstreams/3b7d5844-9ffe-43b8-8a2c-7c33253bc2b4/download>  (16 November 2023, date last accessed). |
| (29) | **Article:**  Growth of Cu2ZnSnS4 (CZTS) thin films using short sulfurization periods. Mater Res Express. 2019;6. | <https://doi.org/10.1088/2053-1591/aaff78> |
| (30) | **Article:**  Strategies to reduce the open-circuit voltage deficit in Cu2ZnSn(S,Se)4 thin film solar cells. Electron Mater Lett. 2017;13:373–92. | <https://doi.org/10.1007/s13391-017-7118-1> |
| (31) | **Article:**  Reduction of interface recombination current for higher performance of p+-CZT(SxSe1-x)/p-CZTS/n-CdS thin-film solar cells using Kesterite intermediate layers. Sol Energy. 2020;204:489–500. | <https://doi.org/10.1016/j.solener.2020.04.096> |
| (32) | **Article:**  Enhancing the open-circuit voltage and efficiency of CZTS thin-film solar cells via band-offset engineering. Opt Quantum Electron. 2020;52. | <https://doi.org/10.1007/s11082-019-2180-6> |
| (33) | **Article:**  Cu2ZnSnSe4 thin-film solar cells by thermal co-evaporation with 11.6% efficiency and improved minority carrier diffusion length. Adv Energy Mater. 2015;5. | <https://doi.org/10.1002/aenm.201401372> |
| (34) | **Article:**  Cu2ZnSnS4 photovoltaic cell with improved efficiency fabricated by high-temperature annealing after CdS buffer-layer deposition. Prog Photovoltaics Res Appl. 2016;25:14–22. | <https://doi.org/10.1002/pip.2837> |
| (35) | **Article:**  Doping and alloying of kesterites. JPhys Energy. 2019;1. | <https://doi.org/10.1088/2515-7655/ab23bc> |
| (36) | **Article:**  Efficiency Enhancement of Cu2ZnSn(S,Se)4 Solar Cells via Alkali Metals Doping. Adv Energy Mater. 2016;6. | <https://doi.org/10.1002/aenm.201502386> |
| (37) | **Article:**  Atomistic consideration of earth-abundant chalcogenide materials for photovoltaics: Kesterite and beyond. J Mater Res. 2018;33:3986–98. | <https://doi.org/10.1557/jmr.2018.350> |
| (38) | **Article:**  Effects of cation composition on carrier dynamics and photovoltaic performance in Cu2ZnSnSe4 monocrystal solar cells. Sol Energy Mater Sol Cells. 2020;205. | <https://doi.org/10.1016/j.solmat.2019.110255> |
| (39) | **Article:**  Highly efficient solution-processed CZTSSe solar cells based on a convenient sodium-incorporated post-treatment method. J Energy Chem. 2020;40:196– 203. | <https://doi.org/10.1016/j.jechem.2019.03.029> |
| (40) | **Article:**  Complex Interplay between Absorber Composition and Alkali Doping in High-Efficiency Kesterite Solar Cells. Adv Energy Mater. 2018;8. | <https://doi.org/10.1002/aenm.201701760> |
| (41) | **Article:**  Solution processing route to Na incorporation in CZTSSe nanoparticle ink solar cells on foil substrate. J Mater Sci Mater Electron. 2019;30:7883–7889. | <https://doi.org/10.1007/s10854-019-01108-3> |
| (42) | **Article:**  Revealing the Role of Potassium Treatment in CZTSSe Thin Film Solar Cells. Chem Mater. 2017;29:4273–81. | <https://doi.org/10.1021/acs.chemmater.7b00418> |
| (43) | **Article:**  Influence of alkali metals (Na, Li, Rb) on the performance of electrostatic spray-assisted vapor deposited Cu2ZnSn(S,Se)4 solar cells. Sci Rep. 2016;6. | <https://doi.org/10.1038/srep22109> |
| (44) | **Thesis (repository):** Density functional theory study of copper zinc tin sulphide (Cu2ZnSnS4) doped with calcium and barium. University of Venda, Thohoyandou, Sudafrica; 2020. | <http://hdl.handle.net/11602/1665>  (16 November 2023, date last accessed). |
| (45) | **Article:**  Role of Na and Ca as Isovalent Dopants in Cu2ZnSnS4 Solar 43 Cells. ACS Sustain Chem Eng. 2019;7:5792–800. | <https://doi.org/10.1021/acssuschemeng.8b05348> |
| (46) | **Article:**  Electronic and optical properties of Cu2XSnS4 (X = Be, Mg, Ca, Mn, Fe, and Ni) and the impact of native defect pairs: a review. J Appl Phys. 2017;121. | <https://doi.org/10.1063/1.4984115> |
| (47) | **Article:**  Cation Substitution in Earth-Abundant Kesterite Photovoltaic Materials. Adv Sci. 2018;5. | <https://doi.org/10.1002/advs.201700744> |
| (48) | **Article:**  Trigonal Cu2IISnVI4 (II = Ba, Sr and VI = S, Se) quaternary compounds for earth-abundant photovoltaics. Phys Chem Chem Phys. 2016;18:4828–34. | <https://doi.org/10.1039/c5cp06977g> |
| (49) | **Article:**  Synthesis and characterizations of Cu2MgSnS4 thin films with diferent sulfuration temperatures. Mater Lett. 2019;242:58–61. | <https://doi.org/10.1016/j.matlet.2019.01.102> |
| (50) | **Article:**  Synthesis and characterization of photoelectrochemical and photovoltaic Cu2BaSnS4 thin films and solar cells. J Mater Chem C. 2017;5:6406–19. | <https://doi.org/10.1039/c7tc01678f> |
| (51) | **Article:**  Earth-Abundant Chalcogenide Photovoltaic Devices with over 5% Efficiency Based on a Cu2BaSn(S,Se)4 Absorber. Adv Mater. 2017;29. | <https://doi.org/10.1002/adma.201606945> |
| (52) | **Article:**  Oxygenated CdS Buffer Layers Enabling High Open-Circuit Voltages in Earth-Abundant Cu2BaSnS4 Thin-Film Solar Cells. Adv Energy Mater. 2017;7. | <https://doi.org/10.1002/aenm.201601803> |
| (53) | **Article:**  Sol-gel solution-processed Cu2SrSnS4 thin films for solar energy harvesting. Thin Solid Films. 2020;697. | <https://doi.org/10.1016/j.tsf.2020.137828> |
| (54) | **Article:**  Wide Band Gap Cu2SrSnS4 Solar Cells from Oxide Precursors. ACS Appl Energy Mater. 2019;2:7340–4. | <https://doi.org/10.1021/acsaem.9b01322> |
| (55) | **Article:**  Defect suppression in multinary chalcogenide photovoltaic materials derived from kesterite: Progress and outlook. J Mater Chem A. 2020;8:24920–42. | <https://doi.org/10.1039/d0ta08202c> |
| (56) | **Article:**  Cu2ZnSnS4 solar cells with over 10% power conversion efficiency enabled by heterojunction heat treatment. Nat Energy. 2018;3:764–72. | <https://doi.org/10.1038/s41560-018-0206-0> |
| (57) | **Article:**  Efficient visible-light-driven water splitting performance of sulfidation-free, solution processed Cu2MgSnS4 thin films: Role of post-drying temperature. Sol Energy. 2020;203:284–95. | <https://doi.org/10.1016/j.solener.2020.04.027> |
| (58) | **Article:**  Induced effects by the substitution of Zn in Cu2ZnSnX4 (X = S and Se). Thin Solid Films. 2016;603:224–9. | <https://doi.org/10.1016/j.tsf.2016.02.005> |
| (59) | **Article:**  Fabrication of Cu2CoSnS4 thin films by a facile spray pyrolysis for photovoltaic application. Sol Energy. 2017;158:89–99. https://doi.org/10.1016/j.solener.2017.09.036 | <https://doi.org/10.1016/j.solener.2017.09.036> |
| (60) | **Article:**  Synthesis of new earth-abundant kesterite Cu2MgSnS4 nanoparticles by hot-injection method. Chem Lett. 2014;43:1149–51. | <https://doi.org/10.1246/cl.140208> |
| (61) | **Article:**  A new wide band gap thermoelectric quaternary selenide Cu2MgSnSe4. J Appl Phys. 2015;118:155101. | <https://doi.org/10.1063/1.4933277> |
| (62) | **Article:**  The structural, morphological and optical-electrical characteristic of Cu2XSnS4 (X:Cu,Mg) thin films fabricated by novel ultrasonic co-spray pyrolysis. Mater Lett. 2016;172:68–71. | <https://doi.org/10.1016/j.matlet.2016.02.088> |
| (63) | **Article:**  Physical properties evolution of sprayed Cu2MgSnS4 thin films with growth parameters and vacuum annealing. Superlattices Microstruct. 2020;147. | <https://doi.org/10.1016/j.spmi.2020.106711> |
| (64) | **Article:**  Crystallographic and Luminescence Characteristics of the Cu2MgSnSe4 Quaternary Compound and Cu2-xMgSnSe4 (0 < x ≤ 0.15) Copper-Deficient Solid Solutions. Inorg Mater. 2021;57:3–9. | <https://doi.org/10.1134/S0020168521010118> |
| (65) | **Article:**  Investigation on Cu2MgSnS4 thin film prepared by spray pyrolysis for photovoltaic and humidity sensor applications. Opt Mater (Amst). 2022;127. | <https://doi.org/10.1016/j.optmat.2022.112296> |
| (66) | **Article:**  Partial and total substitution of Zn by Mg in the Cu2ZnSnS4 structure. Crystals. 2020;10:1–10. | <https://doi.org/10.3390/cryst10070578> |
| (67) | **Article:**  Boosting the electrical properties of Cu2ZnSn(S,Se)4 solar cells via low amounts of Mg substituting Zn. ACS Appl Energy Mater. 2020;3:11177–82. | <https://doi.org/10.1021/acsaem.0c02121> |
| (68) | **Article:**  Mg dopant in Cu2ZnSnSe4: An n-type former and a promoter of electrical mobility up to 120 cm2V-1s-1. J Solid State Chem. 2014;215:122–7. | <https://doi.org/10.1016/j.jssc.2014.03.034> |
| (69) | **Article:**  Fabrication of Cu2(ZnxMg1-x)SnS4 thin films by pulsed laser deposition technique for solar cell applications. Mater Sci Semicond Process. 2018;76:50–4. | <https://doi.org/10.1016/j.mssp.2017.12.010> |
| (70) | **Article:**  Effect of magnesium incorporation on solution-processed kesterite solar cells. Front Chem. 2018;6. | <https://doi.org/10.3389/fchem.2018.00005> |
| (71) | **Article:**  Design of I2-II-IV-VI4 semiconductors through element substitution: The thermodynamic stability limit and chemical trend. Chem Mater. 2014;26:3411–7. | <https://doi.org/10.1021/cm500598x> |
| (72) | **Article:**  Investigation of optimum Mg doping content and annealing parameters of Cu2MgxZn1-xSnS4 thin films for solar cells. Nanomaterials. 2019;9. | <https://doi.org/10.3390/nano9070955> |
| (73) | **Article:**  Hollow Spheres Consisting of SnS Nanosheets Conformally Coated with S-Doped Carbon for Advanced Lithium-/Sodium-Ion Battery Anodes. ChemElectroChem. 2020;7:914–21. | <https://doi.org/10.1002/celc.201901923> |
| (74) | **Article:**  XPS analysis and characterization of thin films Cu2ZnSnS4 grown using a novel solution based route. Mater Sci Semicond Process. 2015;39:492–8. | <https://doi.org/10.1016/j.mssp.2015.05.064> |
| (75) | **Article:**  Facile hydrothermal synthesis of hydrotropic Cu2ZnSnS4 nanocrystal quantum dots: Band-gap engineering and phonon confinement effect. J Mater Chem A. 2013;1:3182–6. | <https://doi.org/10.1039/c3ta00357d> |
| (76) | **Article:**  Investigation on the selenization treatment of kesterite Cu2Mg0.2Zn0.8Sn(S,Se)4 films for solar cell. Nanomaterials. 2019;9. | <https://doi.org/10.3390/nano9070946> |
| (77) | **Article:**  Synthesis of Cu2ZnSnS4 thin films by a precursor solution paste for thin film solar cell applications. ACS Appl Mater Interfaces. 2013;5:4162–5. | <https://doi.org/10.1021/am401210w> |
| (78) | **Article:**  Fabrication of Cu2ZnSnS4 solar cells with 5.1% efficiency via thermal decomposition and reaction using a non-toxic sol-gel route. J Mater Chem A. 2014;2:500– 9. | <https://doi.org/10.1039/c3ta13533k> |
| (79) | **Article:**  Impact of selenium composition variation in CZTS solar cell. Optik (Stuttg). 2021;234. | <https://doi.org/10.1016/j.ijleo.2021.166421> |
| (80) | **Article:**  High Recovery of Selenium from Kesterite-Based Photovoltaic Cells. Eur J Inorg Chem. 2020;2020:2203–9. | <https://doi.org/10.1002/ejic.202000261> |
| (81) | **Thesis (repository):** Síntesis, estudio estructural y propiedades magnéticas de nuevos materiales pertenecientes a los sistemas Cu2-II-Sn-VI4(II = Fe, Mn y VI = S, Se) Y Ba-CeMn-O. Ph.D. thesis. Universidad Industrial de Santander, Bucaramanga, Colombia. 2014. | <https://noesis.uis.edu.co/handle/20.500.14071/9652>  (16 November 2023, date last accessed). |
| (82) | **Article:**  A new colloidal precursor cooperative conversion route to nanocrystalline quaternary copper sulfide. Mater Res Bull. 2004;39:237–41. | <https://doi.org/10.1016/j.materresbull.2003.09.035> |
| (83) | **Article:**  Synthesis and Characterization of Cu2FeSnS4–Cu2MnSnS4 Solid Solution Microspheres. Materials (Basel). 2020;13:4440. | [**https://doi.org/10.3390/ma13194440**](https://doi.org/10.3390/ma13194440) |
| (84) | **Article:**  Solvothermal synthesis of Cu2Zn1-xFexSnS4 nanoparticles and the influence of annealing conditions on drop-casted thin films. Semicond Sci Technol. 2016;31:045004. | <https://doi.org/10.1088/0268-1242/31/4/045004> |
| (85) | **Article:**  Vibrational properties of stannite and kesterite type compounds: Raman scattering analysis of Cu2(Fe,Zn)SnS4. J Alloys Compd. 2012;539:190–4. | <https://doi.org/10.1016/j.jallcom.2012.06.042> |
| (86) | **Article:**  Next generation promising Cu2(ZnxFe1-x)SnS4 photovoltaic absorber material prepared by pulsed laser deposition technique. Mater Lett [Internet]. 2014 Dec;137:147–9. | <https://doi.org/10.1016/j.matlet.2014.08.118> |
| (87) | **Article:**  Structural and optical properties of Cu2M(M: Zn, Fe, Co, Ni)SnSe4 nanoparticles synthesized via heating up method. Optik (Stuttg). 2018;169:242– 8. | <https://doi.org/10.1016/j.ijleo.2018.05.052> |
| (88) | **Article:**  Dft investigation on the electronic, magnetic, mechanical properties and strain effects of the quaternary compound Cu2FeSnS4. Crystals. 2020;10:509. | <https://doi.org/10.3390/cryst10060509> |
| (89) | **Article:**  A solution approach to p-type Cu2FeSnS4 thin-films and pn-junction solar cells: Role of electron selective materials on their performance. Sol Energy Mater Sol Cells. 2017;160:233–40. | <https://doi.org/10.1016/j.solmat.2016.10.037> |
| (90) | **Article:**  Electronic and optical properties of Cu, CuO and Cu2O studied by electron spectroscopy. J Phys Condens Matter. 2012;24:175002. | <https://doi.org/10.1088/0953-8984/24/17/175002> |
| (91) | **Article:**  Analysis of XPS spectra of Fe2+ and Fe3+ ions in oxide materials. Appl Surf Sci. 2008;254:2441–9. | <https://doi.org/10.1016/j.apsusc.2007.09.063> |
| (92) | **Article:**  Effect of sulfur concentration on structural, optical and electrical properties of Cu2FeSnS4 thin films for solar cells and photocatalysis applications. Superlattices Microstruct. 2018;124:17–29. | <https://doi.org/10.1016/j.spmi.2018.09.033> |
| (93) | **Article:**  Effect of substrate temperature on physical properties of Cu2FeSnS4 thin films for photocatalysis applications. Mater Sci Eng B. 2020;254:114509. | <https://doi.org/10.1016/j.mseb.2020.114509> |
| (94) | **Article:**  Investigation the influence of Fe (III) doping in Cu2ZnSnS4 semiconductor: Structural, optical and magnetic properties. Optik (Stuttg). 2019;179:505– 13. | <https://doi.org/10.1016/j.ijleo.2018.10.138> |
| (95) | **Article:**  Synthesis, structure, optics and electrical properties of Cu2FeSnS4 thin film by sputtering metallic precursor combined with rapid thermal annealing sulfurization process. Mater Lett. 2015;151:61–3. | <https://doi.org/10.1016/j.matlet.2015.03.046> |
| (96) | **Article:**  Effect of annealing atmosphere on quaternary chalcogenide-based counter electrodes in dye-sensitized solar cell performance: synthesis of Cu2FeSnS4 and Cu2CdSnS4 nanoparticles by thermal decomposition process. RSC Adv. 2017;7:15139–48. | <https://doi.org/10.1039/c6ra28889h> |
| (97) | **Article:**  Effects of sulfurization on the optical properties of Cu2ZnxFe1-xSnS4 thin films. Opt Mater (Amst). 2017;72:702–9. | <https://doi.org/10.1016/j.optmat.2017.07.031> |
| (98) | **Article:**  Fabrication of quaternary Cu2FeSnS4 (CFTS) nanocrystalline fibers through electrospinning technique. J Mater Sci. 2014;50:777–83. | <https://doi.org/10.1007/s10853-014-8637-x> |
| (99) | **Article:**  Photo-electrochemical properties and electronic band structure of kesterite copper chalcogenide Cu2-II-Sn-S4 (II = Fe, Co, Ni) thin films. RSC Adv. 2016;6:96025–34. | <https://doi.org/10.1039/c6ra15700a> |
| (100) | **Article:**  Profound optical analysis for novel amorphous Cu2FeSnS4 64 thin films as an absorber layer for thin film solar cells. Ceram Int. 2020;46:18778–84. | <https://doi.org/10.1016/j.ceramint.2020.04.195> |
| (101) | **Article:**  Growth and Characterization of Cu2Zn1-xFexSnS4 Thin Films for Photovoltaic Applications. Materials (Basel). 2020;13:1471. | <https://doi.org/10.3390/ma13061471> |
| (102) | **Article:**  Low-cost hydrothermal synthesis and characterization of pentanary Cu2ZnxNi1-xSnS4 nanoparticle inks for thin film solar cell applications. Mater Sci Semicond Process. 2017;63:127–36. | <https://doi.org/10.1016/j.mssp.2017.02.015> |
| (103) | **Article:**  Structural, Electronic, and Optical Properties of Cu2NiSnS4: A Combined Experimental and Theoretical Study toward Photovoltaic Applications. Chem Mater. 2017;29:3133–42. | <https://doi.org/10.1021/acs.chemmater.7b00149> |
| (104) | **Article:**  Electrical properties of Ag/p-Cu2NiSnS4 thin film Schottky diode. Mater Today Commun. 2021;28:102697. | <https://doi.org/10.1016/j.mtcomm.2021.102697> |
| (105) | **Article:**  Optical and morphological properties of tetragonal Cu2ZnSnS4 thin films grown from sulphide precursors at lower temperatures. Semicond Phys Quantum Electron Optoelectron. 2014;17:284–90. | <https://doi.org/10.15407/spqeo17.03.284> |
| (106) | **Article:**  Marigold flower like structured Cu2NiSnS4 electrode for high energy asymmetric solid state supercapacitors. Sci Rep. 2020;10:19198. | <https://doi.org/10.1038/s41598-020-75879-9> |
| (107) | **Article:**  Development of Cu2NiSnS4 based thin film solar cells without a sulfurization step. Mater Sci Semicond Process. 2020;107:104811. | <https://doi.org/10.1016/j.mssp.2019.104811> |
| (108) | **Article:**  Optical and thermoelectric properties of chalcogenide based Cu2NiSnS4 nanoparticles synthesized by a novel hydrothermal route. Mater Lett. 2015;152:155–8. | <https://doi.org/10.1016/j.matlet.2015.03.083> |
| (109) | **Article:**  Element substitution of kesterite Cu2ZnSnS4 for efficient counter electrode of dye-sensitized solar cells. Sci Rep. 2018;8:8714. | <https://doi.org/10.1038/s41598-018-26770-1> |
| (110) | **Article:**  Cu2NiSnS4/Graphene Nanohybrid as a newer counter electrode to boost-up the photoconversion efficiency of dye sensitized solar cell. ES Energy Environ. 2022;18:65–74. | <https://doi.org/10.30919/esee8c753> |