

# Band gap engineering in $\text{Cu}_2\text{FeSnS}_4$ nanostructures via single (Ag) and co-substitution (Ag–Mn): Correlating structure, morphology, and optical properties

Research Article

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**Abstract:** In this study, a quaternary  $\text{Cu}_2\text{FeSnS}_4$  (CFTS) nano-compound was prepared and characterized using the solvothermal method, with partial substitution between copper and silver ions to form the  $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{FeSnS}_4$  compound, in addition to a partial co-substitution between iron and manganese ions to form the  $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{SnS}_4$  compound. The aim of the study is to compare single doping and co-doping and their effect on structural, optical, and morphological properties. The X-ray diffraction and Raman spectroscopy results showed that all the prepared compounds have a kesterite crystal structure with the absence of secondary phases, while maintaining the crystalline phase during the substitution process, accompanied by a slight change in the crystal lattice constants. Field emission scanning electron microscopy analysis revealed a clear evaluation in nanoparticle morphology with doping and co-doping. Brunauer–Emmett–Teller analysis indicated a decrease in surface area upon doping. It was also observed that there is a gradual decrease in the energy gap accompanied by strong absorption in the visible region when the doping and co-doping process is carried out. According to these results, the authors confirm that co-doping with silver and manganese is an effective strategy for controlling optoelectronic properties. It also has a clear impact on surface properties, which must be considered to balance maintaining an effective surface area with minimizing the energy gap. Therefore, these co-doped compounds are promising candidates for photocatalysis and thin-film solar cell applications.

**keywords:** Band gap • Nanostructures • Doping • CFTS • Nanoparticles • Optical properties

## 1. Introduction

Solar energy conversion and photocatalytic applications have become widespread recently, and researchers are searching for efficient and low-cost materials such as quaternary semiconductors [1]. These materials are considered alternatives to rare, toxic, and expensive materials such as  $\text{CdTe}$  and  $\text{CuInGeSe}_2$  compounds. Despite their high efficiency in environmental sustainability, which prompted researchers to solve the limitations or problems that reduce the efficiency of alternative materials. Therefore, quaternary chalcogenide materials are considered a good competitor as they are formed from elements

that are abundant in nature and less expensive, in addition to possessing optoelectronic properties that make them suitable for energy conversion applications [1,2]. The  $\text{Cu}_2\text{FeSnS}_4$  (CFTS) compound is suitable for thin-film solar cell applications and for photocatalytic treatment of polluted water [2]. The  $\text{Cu}_2\text{FeSnS}_4$  compound has a stannite or kesterite crystal structure, a direct energy gap in the range of 1.2–1.5 eV, and a high absorption coefficient of  $\geq 10^4 \text{ cm}^{-1}$  [2,3]. Despite these advantages, CFTS compound has some drawbacks that limit its efficiency. These include electron–hole recombination and structural defects, which affect electron transfer between energy bands [1–3]. Therefore, doping or ion substitution is an effective method for improving the optical and electronic properties of the compound. Previous studies have shown that

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introducing additional elements into the crystal lattice modifies the electronic structure by changing the positions of energy levels, which leads to improved optical properties of the compound or, more generally, the compound's response to light radiation [3]. Within this framework, recent studies have proven that silver element improves the optical performance of the compound when incorporated into the crystal lattice. As it possesses electronic properties that enable it to enhance charge transfer and reduce charge recombination, it improves the density of electronic states near the edge of the valence band [4]. In addition to silver, the introduction of other transition elements such as manganese element creates mid-gap states within the energy gap, which leads to a reduction in the energy gap and an expansion of the absorption band, which is one of the most important properties in applications that rely on visible light [5]. Another type of doping, called co-doping, represents an advanced strategy for improving the functional performance of a material. Silver and manganese elements can be used to balance a low energy gap with improved charge separation. Increasing the density of structural defects promotes non-radiative recombination, which negatively affects the performance of the compound [6]. Therefore, careful control is required when using co-doping. On the other hand, analysis of the absorption spectrum determines the nature of electronic transitions and allows for the estimation of the energy gap. Therefore, any change in the layer shape, such as absorption edge shift, will reflect changes in the material's electronic structure due to doping, grain size variations, or surface effects [7]. In addition to the above, the nanostructure of a material plays a crucial role in determining its optical performance. The number of active reaction sites is influenced by the material's nanostructure, including surface area, particle size, and pore distribution. This is understood and analyzed using techniques such as Brunauer–Emmett–Teller (BET) and Field emission scanning electron microscopy (FESEM). Previous studies indicate that the catalytic activity of a material is enhanced by increasing porosity and decreasing particle size, which in turn leads to increased interaction between the material and its surrounding environment [8]. Therefore, the aim of this study is to investigate the effect of doping and co-doping, and to compare them, on the structural and optical properties of the CFTS compound prepared using the solvothermal method. This study is conducted by analyzing the relationship between the compound's absorbance and the energy gap change, and linking these to the performance of photocatalytic applications. Therefore, the authors believe that this manuscript may open new horizons for the development of effective and sustainable materials in environmental and energy applications, as it provides a deeper understanding of the role of

doping and co-doping in improving the physical properties of materials.

## 2. Preparation and characterization of synthesized compounds

The solvothermal method was used in the preparation of quaternary sulfide compounds, as well as partial substitution and co-substitution of Ag and Mn ions, following previously reported solvothermal reaction procedures with minor modifications [10,11]. Initially, the basic CFTS compound at stoichiometry Cu: Fe: Sn: S = 2:1:1:4 was synthesized using the precursors (0.3966 g  $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ , 0.1886 g  $\text{FeCl}_3$ , 0.26242 g  $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$ , and 0.35411 g  $\text{CH}_4\text{N}_2\text{S}$ ) as primary sources for forming the CFTS compound by dissolving them in 50 ml of the organic solvent ethylene glycol as well as a 0.64 g of polyvinylpyrrolidone as a gapping agent. For the purpose of carrying out the reaction and forming the appropriate crystalline phase, the resulting solution is placed in an autoclave at a temperature of 220°C for 15 h. After that, the solution is cooled to room temperature and then washed several times using ethanol and deionized water to remove impurities and unreacted ions. Finally, the final solution is dried at 100°C for 3 h to obtain a black nanopowder, which is then subjected to the necessary tests. By carrying out the same steps mentioned above, the  $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{FeSnS}_4$  compound was prepared using the precursors (0.3569 g  $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$  and 0.03951 g  $\text{AgNO}_3$ ) by partially replacing Cu with Ag ions, while controlling the molar ratios of the precursors during preparation. To bring about a significant change in the electronic and structural properties of the CFTS compound,  $x = 0.2$  was chosen to avoid excessive distortion of the crystal lattice due to the large ionic radius of the silver ion compared to the copper ion. In addition, and following the same steps as before, the  $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{SnS}_4$  compound was prepared by performing an additional partial replacement of iron ions with manganese ions, which is known as co-substitution using the precursors (0.09432 g  $\text{FeCl}_3$  and 0.1152 g  $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ ). The substitution ratio  $x = 0.5$  was chosen as a result of the closeness or small difference in ionic radii between the iron and manganese ions. This allows for effective co-substitution while maintaining the stability of the crystal structure in the CFTS compound. To gain a comprehensive understanding of the structural composition and its relationship to the optoelectronic properties, the prepared compounds were characterized using the physical and chemical techniques. X-ray diffraction (XRD) (D8 Advance Bruke) with Cu-K radiation as an anode material (wavelength = 0.15406 nm) and operated at

45 kV and 40 mA with minimum step size 2 Theta ( $2\theta$ ) at 0.001 and minimum step size omega at 0.001, and Raman spectroscopy (SENTERRA) with laser wavelength  $\lambda = 532$  nm were used to study the crystal structure parameters, determine the crystalline phase, and detect secondary phases or structural defects. Energy-dispersive X-ray spectroscopy (EDS) (a detector attached to the FESEM) was used to infer the presence of constituent elements in the prepared compounds and confirm the success of the synthesis process. FESEM (Zeiss, PIIJMA-VP) was used to observe the morphology and distribution of the nanoparticles. The surface area, pore size, average pore diameter, and the active sites of reaction were determined from nitrogen adsorption-desorption (ADS-DES) measurements using BET method. Ultraviolet-Visible spectroscopy (UV-Vis) (Shimadzu UV-1800) was used to study the optical properties of the prepared compounds by analyzing the absorption spectrum and calculating the energy gap using the Tauc plot method. It is worth noting that all measurements were performed on dried nanopowders after preparation.

### 3. Results and discussion

#### 3.1 Crystal structure properties

XRD was used to study the effect of partial substitution of both silver and magnesium elements on the crystalline phase of the CFTS compound. As shown in Figure 1 and Table 1, all samples exhibit diffraction patterns at angles

corresponding to the crystal planes (112), (020), and (132) confirming that the crystal structure formed is tetragonal kesterite structure (PDF: 96-152-1530). In addition, the structure of the resulting kesterite is of good purity and phase due to the absence of secondary phase formation, as no additional peaks were observed within the detection limits, indicating the success of the preparation method. This is consistent with previous reports on the preparation of CFTS compound [9]. Previous studies show that the effect of ionic substitution depends not only on ionic size but is also influenced by cation redistribution and the nature of the chemical bonds. This was observed when silver ions were partially introduced into the crystal lattice of the CFTS compound, where a shift in the diffraction peak positions toward higher angles was noted. As summarized in Table 1, reducing structural defects such as  $V_{Cu}$  may lead to a contraction of lattice constants due to the generation of compressive stresses within the crystal lattice, which may be another reason for the shift of the diffraction peaks toward higher angles [10]. The partial incorporation of manganese ions into the crystal lattice may create a balance between the effects of double substitution, leading to a slight modification in the shift of the diffraction peaks. The co-substitution of manganese and silver in the CFTS compound showed a clear effect on the crystal lattice parameters, as evidenced by the decrease in lattice constants and unit cell volume. Substitution generally exhibits behavior related to cation redistribution and degree of crystallinity, generating structural disorder, which serves as an indicator for assessing the degree of regularity or crystal structure [11]. The compound CFTS

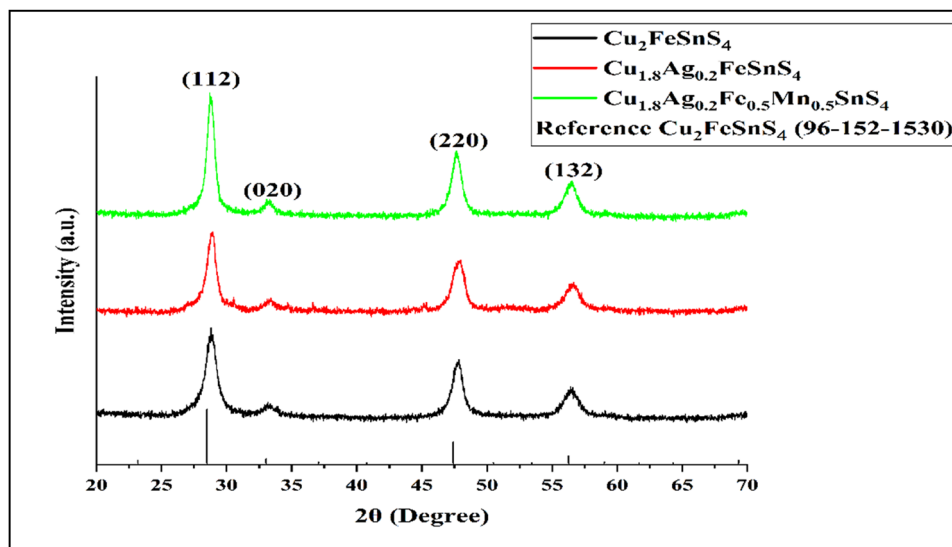


Figure 1. XRD pattern of the synthesized compounds.

has a parameter greater than one, which indicates that the kesterite structure is semi-perfect [12]. Upon the introduction of silver and manganese ions, the parameter decreased, indicating a gradual increase in cationic disorder and the possibility of a partial transition toward a stannite structure. This effect is an important factor directly related to the electronic and optical properties [13]. When silver ions are added, they act as a catalyst for crystal growth, leading to an increase in crystal size and a reduction in defects, thus lowering lattice stress [14]. Meanwhile, manganese ions, when added to the crystal lattice, mitigate or eliminate lattice distortions resulting from ionic distribution imbalances. Therefore, this improvement in structural properties is a positive indicator for enhancing the functional performance of these compounds in photovoltaic applications [12–14].

### 3.2 Raman analysis

To study the effect of secondary phase formation upon doping and co-doping with silver and manganese ions and their effect on the vibrational properties of the CFTS compound, Raman spectroscopy was used as shown in Figure 2. The results showed that the CFTS compound has a distinctive spectral signature, which is attributed to the symmetric vibrational mode A1 at about  $214\text{ cm}^{-1}$  associated with the movement of sulfur atoms within the kesterite structure [15,16]. A shift was observed at the A1 peak toward the higher values at around  $222\text{ cm}^{-1}$  with a decrease in intensity, indicating an increase in bond strength and a reduction in structural defects as a result of cation redistribution [17]. In contrast, a shift is observed in the peak of A1 toward lower values at around  $177\text{ cm}^{-1}$  when substitution with manganese ions, with an increase in peak width, indicating an increase in cationic disorder and lattice distortions as a result of the difference in ionic radius and the nature of the ionic bond between manganese ions and iron ions [18]. As can be seen in Figure 2, there are additional peaks located within the  $(580\text{--}603)\text{ cm}^{-1}$  bands as

well as at  $(900\text{--}930)\text{ cm}^{-1}$ , which are attributed to highly ordered vibrational patterns resulting from multi-phonon scattering processes. The positions and intensity of these peaks have been affected by ion substitution processes [19,20]. The absence of secondary phases such as SnS, FeS,  $\text{Ag}_2\text{S}$ , and MnS confirms the purity and homogeneity of the crystalline phase, which is consistent with previous studies [16,19]. The observed gradual changes in peak positions, intensity, and amplitude are generally a result of a structural shift from a more ordered to a more disordered state upon double substitution. This reinforces the XRD results indicating a fundamental modification of the crystal structure through partial ion substitution, which affects the physical properties of the compound [16,18].

### 3.3 Elemental analysis

EDS was used to analyze the elemental composition of the prepared compounds in order to confirm the proportions of the elements and the success of the partial substitution process, as shown in Figure 3 and Table 2. EDS analysis confirmed the presence of silver and manganese in the substituted samples and provided a semi-quantitative assessment of their elemental distribution. The results indicate the successful introduction or replacement of the elements Ag and Mn in the crystal structure of the CFTS compound and the absence of loss of them. Table 2 shows all the constituent elements of the prepared compounds, including silver and manganese. The XRD and Raman results agree as no separate compounds were observed. A gradual decrease in the copper content from 34.4 to 30.6 at% was noted, along with an increase in the silver content. This indicates the direct substitution of copper ions by silver ions without the formation of secondary phases. It is also noted that the replacement of manganese ions with iron ions is successful, as evidenced by the significant decrease in the iron content from 7.6 to 5.5 at%. This confirms the success of the replacement process within the crystal lattice. On the other hand, the

| Sample                                                                     | $2\theta^\circ$ |       |       |       | Crystal size (Å) | Strain (%) | Lattice constants |                | Disorder parameter $\eta = c/2a$ | Unit cell volume $V = a^2c\text{ (Å}^3\text{)}$ |
|----------------------------------------------------------------------------|-----------------|-------|-------|-------|------------------|------------|-------------------|----------------|----------------------------------|-------------------------------------------------|
|                                                                            |                 |       |       |       |                  |            | $a\text{ (Å)}$    | $c\text{ (Å)}$ |                                  |                                                 |
| CFTS                                                                       | 28.47           | 33.23 | 47.71 | 56.41 | 53               | 2.376      | 5.3876            | 11.007         | 1.022                            | 319.49                                          |
| $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{FeSnS}_4$                             | 28.81           | 33.30 | 47.95 | 56.52 | 64.5             | 2.105      | 5.3618            | 10.733         | 1.000874                         | 308.57                                          |
| $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{SnS}_4$ | 28.75           | 33.17 | 47.77 | 56.39 | 87.25            | 1.518      | 5.3812            | 10.716         | 0.9957                           | 310.31                                          |

**Table 1.** Crystal structure parameters of the synthesized compounds.

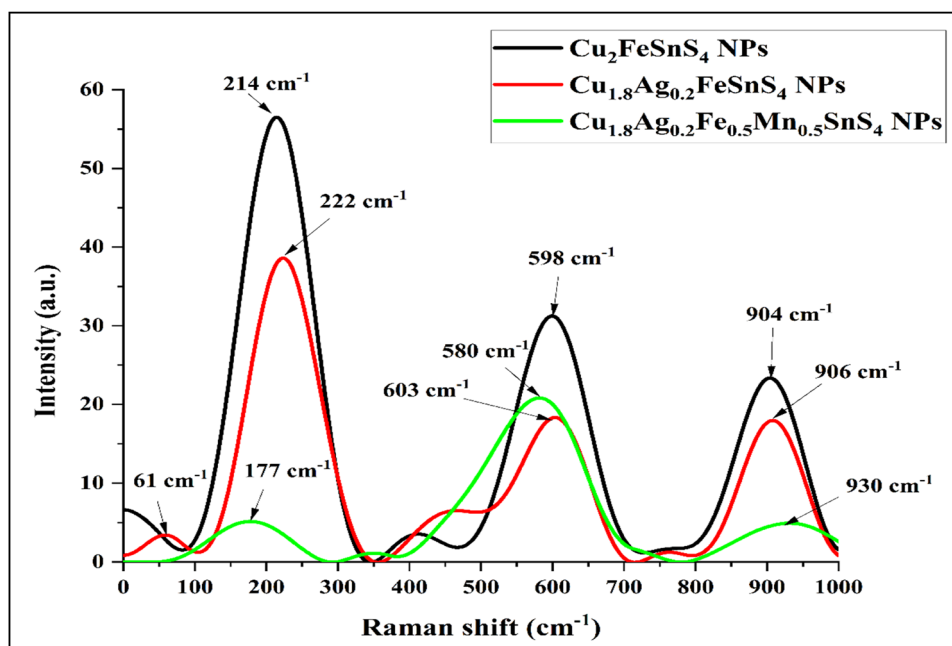


Figure 2. Raman spectrum of the synthesized compounds.

percentage of sulfur is an important factor in maintaining the electronic structure of the material.

Accordingly, it is noted that the percentage is almost constant, about 41%, for all samples, which indicates stability in the sulfide lattice and no significant loss during the preparation process. Furthermore, the gradual decrease in the  $\frac{\text{Cu}}{\text{Fe} + \text{Sn} + \text{Ag} + \text{Mn}}$  ratio indicates a transition of the system toward the Cu-poor, where structural defects such as Cu anti-site defects are reduced, which in turn improves the electronic properties of the material [20,21]. Conversely, the decrease in the  $\frac{\text{S}}{\text{Cu} + \text{Fe} + \text{Sn} + \text{Ag} + \text{Mn}}$  ratio indicates a gradual decrease in sulfur, which contributes to the generation of some vacancies defects, but within limits that ensure the formation of a stable phase [22]. Overall, the EDS results indicate that the ion substitution process was successful using the solvothermal method without phase separation or the creation of secondary phases. A finding confirmed by the XRD and Raman results. These ratios in Table 2 may contribute to improving the physical properties of the prepared compounds.

### 3.4 Morphological analysis

To understand the effect of introducing silver and manganese ions into the crystal lattice of the CFTS compound on

the nature of surface growth and particle distribution, the morphological properties of the prepared compound nanoparticles were studied using FESEM as shown in Figure 4. The results showed that the CFTS nanoparticles have an irregular morphology consisting of clumped, flake-like particles with a heterogeneous distribution. This finding is consistent with the small crystal size and relatively high lattice stress observed in the XRD results [16]. When partial replacement of silver ions with copper ions is performed, a regular morphological evolution toward hierarchical flower-like microspheres consisting of tightly packed nanosheets was observed. This morphological convert indicates that silver ions affect the crystallization mechanisms and the rate of crystal growth, acting as a growth-directing agent [17], which led to an increase in crystal size and a decrease in lattice stress, as shown by the XRD results. This led to the creation of particles with highly ordered three-dimensional structures. On the other hand, when manganese ions are introduced as a co-substitution with silver ion substitution, the degree of regularity in the distribution and creation of nanoparticles has decreased through increased interference between particles with the appearance of distortions in the nanosheets, but the hierarchical structure in general has not changed. This result indicates that the introduction of manganese ions leads to an increase in nucleation sites [18] and consequently a disruption in the crystal growth process. It is worth noting that XRD

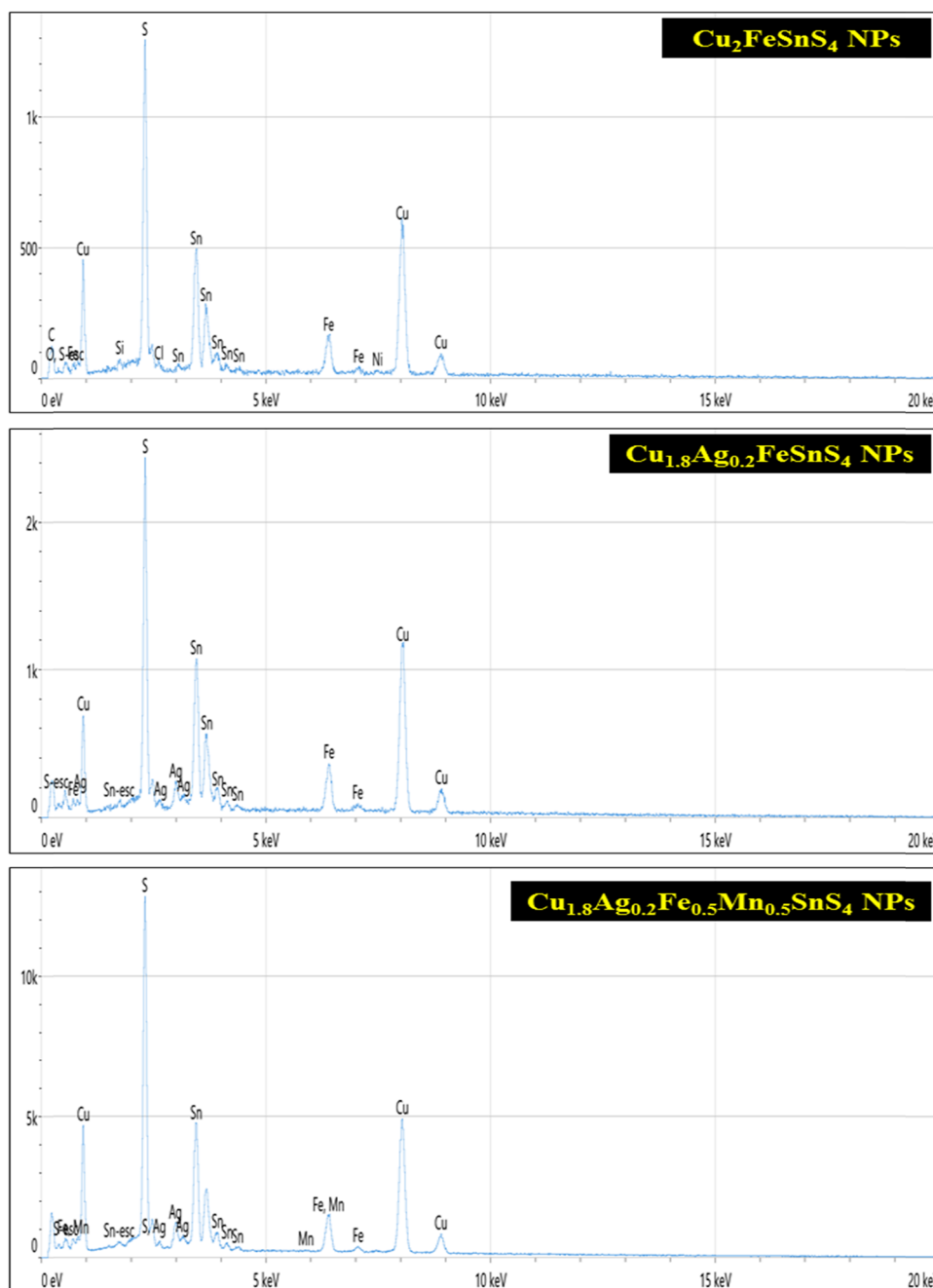


Figure 3. EDS spectrum of the synthesized compounds.

analysis confirms the nanoscale nature of the prepared compounds, showing crystalline sizes ranging from 5.3 to 8.7 nm. Although the FESEM exhibits a flower-like, clustered morphology with micrometer dimensions, it is naturally composed of nanocrystals that accumulated during the growth process. Therefore, it can be said

that these microcrystalline clusters do not contradict the nanoscale properties determined by XRD. Raman spectroscopy results, which showed an increase in cationic disorder, are consistent with this finding, confirming that structural changes directly influence morphological characteristics.

| Elements                   | Atomic (%) |                                                |                                                                            |
|----------------------------|------------|------------------------------------------------|----------------------------------------------------------------------------|
|                            | CFTS       | $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{FeSnS}_4$ | $\text{Cu}_{1.8}\text{Ag}_{0.2}\text{Fe}_{0.5}\text{Mn}_{0.5}\text{SnS}_4$ |
| Cu                         | 34.4       | 33.6                                           | 30.6                                                                       |
| Ag                         | 0          | 2.5                                            | 3.4                                                                        |
| Fe                         | 7.6        | 6.9                                            | 5.5                                                                        |
| Mn                         | 0          | 0                                              | 7.3                                                                        |
| Sn                         | 16.8       | 16.2                                           | 12.5                                                                       |
| S                          | 41.2       | 40.8                                           | 40.7                                                                       |
| Cu/(Fe + Sn + Ag + Mn)     | 1.41       | 1.31                                           | 1.07                                                                       |
| S/(Cu + Fe + Sn + Ag + Mn) | 0.70       | 0.69                                           | 0.68                                                                       |

**Table 2.** Elemental composition of the synthesized compounds.

### 3.5 Surface area and porosity analysis

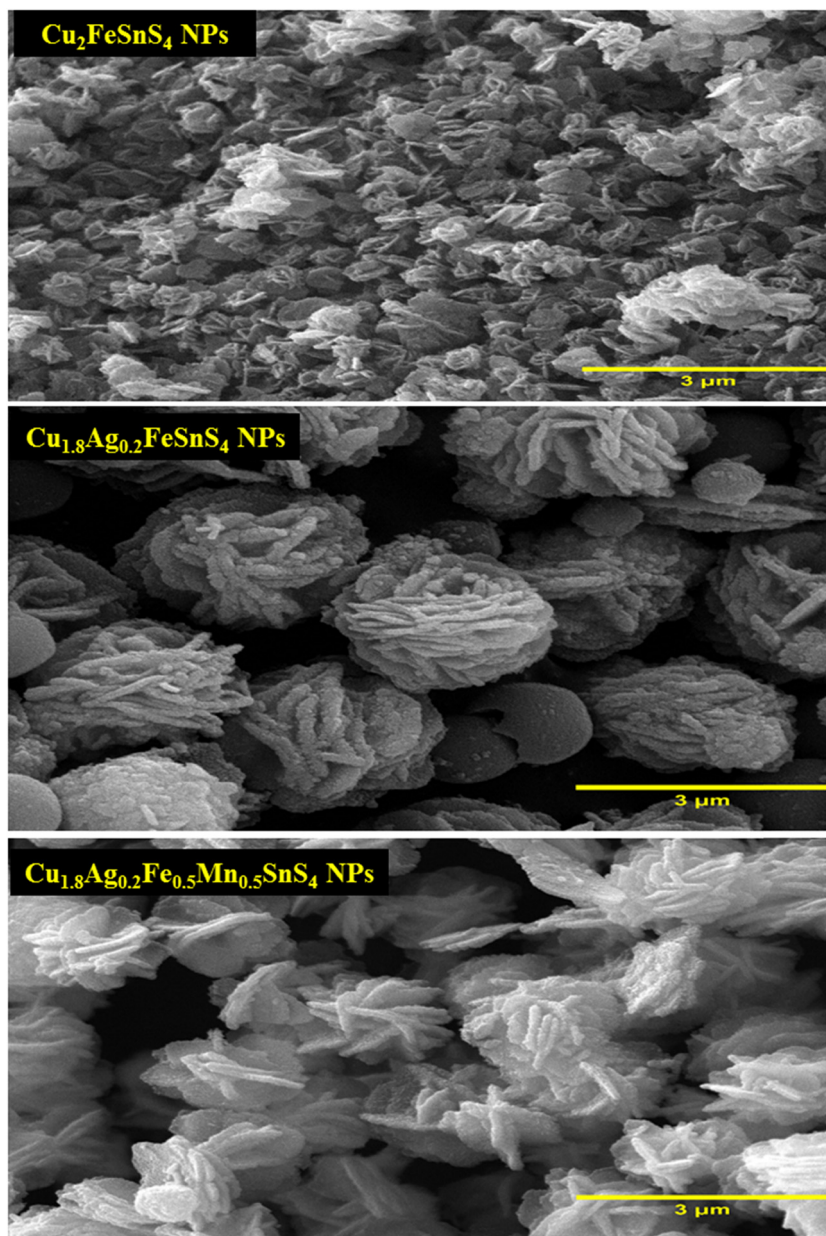
Using nitrogen ADS–DES measurements, the surface properties and porous structure of the prepared compounds were examined, and the BET method was used to determine the specific surface area as shown in Table 3 and Figure 5. The results show that the CFTS compound consists of nanoparticles with a specific surface area, but this does not directly reflect the highest catalytic activity. The results showed that the efficiency of photocatalysis does not depend solely on the surface area of the nanoparticles, but is also affected by the electronic structure and the process of electron–hole pair separation, in addition to the nature of the surface activity sites.

Recent studies have confirmed that mesoporous materials, although they have a high surface area which improves the ADS and mass transfer process, need an improved electronic structure in order to achieve the highest catalytic efficiency [19]. In this context, silver ions improve crystalline and electronic properties by reducing hole–electron recombination, acting as an electron sink, which leads to an increase in the lifetime of charge carriers, thus improving the efficiency of catalytic activity [20]. However, the introduction of manganese ions enhances the light absorption process and contributes to improving the charge separation process by creating energy levels within the energy gap and increasing the density of effective surface defects [21]. Therefore, the decrease in surface area upon partial replacement with silver ions reflects a convert in the catalytic mechanism from a system dependent on surface ADS to a system that is fundamentally dependent on electronic modification and synergy between the input elements. Furthermore, partial

co-substitution between silver and manganese ions improves the efficiency of charge carrier transport and separation, which is a crucial factor in enhancing photocatalysis. This has been confirmed by previous studies, which have shown that co-substitution is more efficient than single-substitution because it achieves a synergistic effect in reducing the energy gap and preventing rapid charge recombination [22]. Based on the above, it can be concluded that co-substitution has an effective strategy in improving the properties of the material despite the low surface area of the nanoparticles. This confirms the importance of the electronic engineering of the material, which plays an important and crucial role in enhancing the efficiency of photocatalysis compared to the surface area of the particles.

### 3.6 Optical absorption behavior and band gap engineering

UV-Vis spectroscopy was used to study the optical properties of the prepared compounds as shown in Figure 6. It was observed that all the prepared compounds exhibited a strong absorption peak in the UV region, which then extended into the visible region. It was also noted that the CFTS compound had a direct energy gap of 1.53 eV, which is suitable for photocatalytic applications and thin-film solar cells. When silver ions were introduced into the CFTS compound, the energy gap decreased to 1.44 eV, which indicates a modification of the electronic structure and an increase in hybridization between the orbitals of the constituent elements [18]. This result indicates an improvement in light absorption in the visible field as a result of the introduction of noble elements, which in turn modify energy levels close to the valence band [20]. When the co-substitution process with silver and manganese was performed in the CFTS compound, a clear decrease in the energy gap to 1.41 eV was also observed. This result is attributed to the fact that the introduction of manganese ions leads to the creation of energy levels within the energy gap, which facilitates the electronic transition and also leads to the shift of the absorption edge toward larger wavelengths [21]. The process of substitutional doping can lead to an increase in defect density, potentially resulting in the formation of charge recombination centers. This has been indicated in some previous studies [18–21] and is reflected in this work by a relative decrease in absorption intensity in the visible spectrum. This confirms that partial substitution can be beneficial or detrimental depending on the concentration and nature of the substituents used [22]. In general, a delicate balance must be struck between reducing the energy gap and avoiding an increase in recombination centers when using substitutional



**Figure 4.** Nanoparticle morphology of the synthesized compounds.

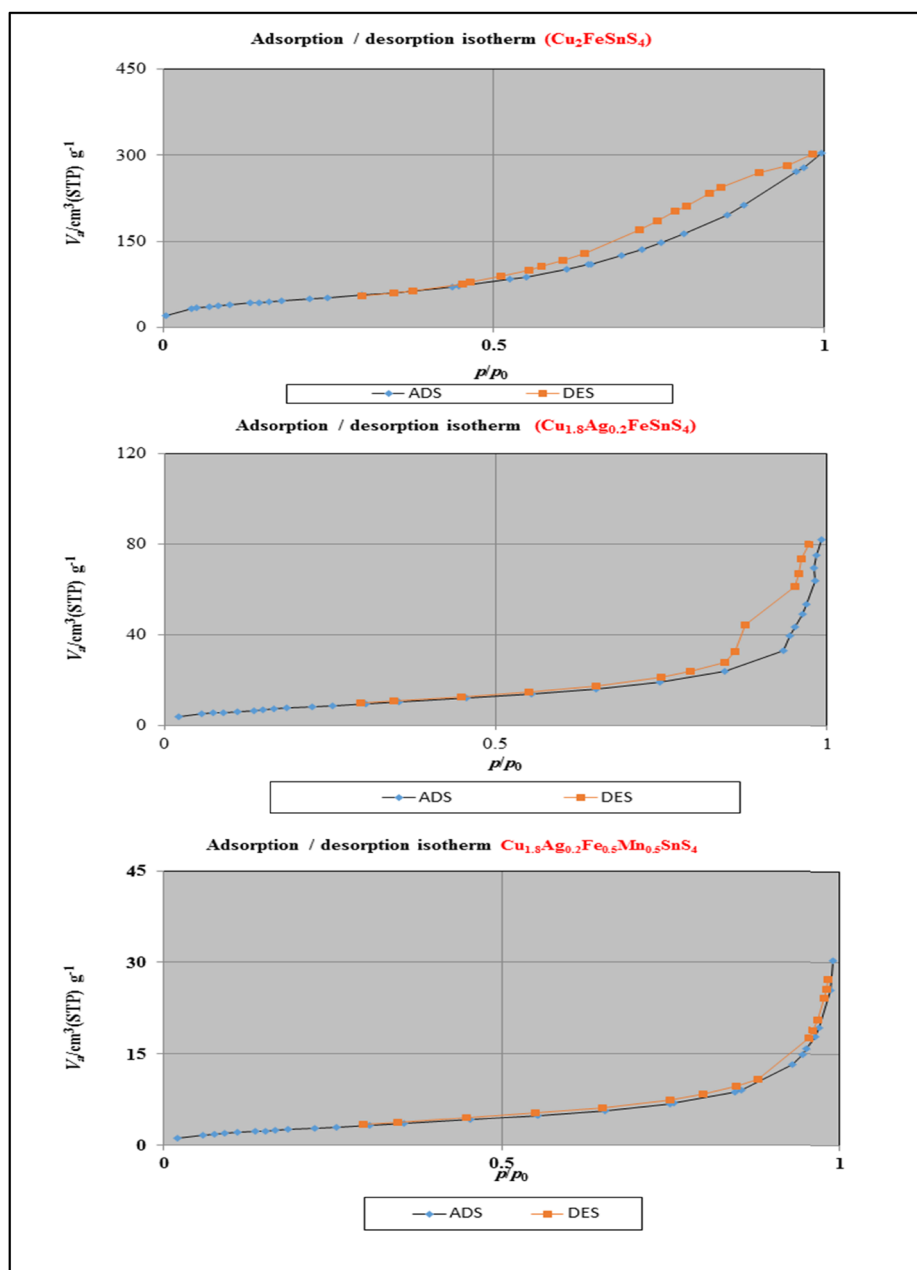
| Compounds                                                                                | Surface area (m <sup>2</sup> /g) | Total pore volume (cm <sup>3</sup> /g) | Mean pore diameter (nm) |
|------------------------------------------------------------------------------------------|----------------------------------|----------------------------------------|-------------------------|
| CFTS                                                                                     | 174.81                           | 0.462                                  | 10.581                  |
| Cu <sub>1.8</sub> Ag <sub>0.2</sub> FeSnS <sub>4</sub>                                   | 30.851                           | 0.125                                  | 16.249                  |
| Cu <sub>1.8</sub> Ag <sub>0.2</sub> Fe <sub>0.5</sub> Mn <sub>0.5</sub> SnS <sub>4</sub> | 10.778                           | 0.045                                  | 17.061                  |

**Table 3.** Porous parameters of the synthesized compounds.

doping with silver and manganese, which is a crucial factor in improving optical properties.

## 4. Conclusion

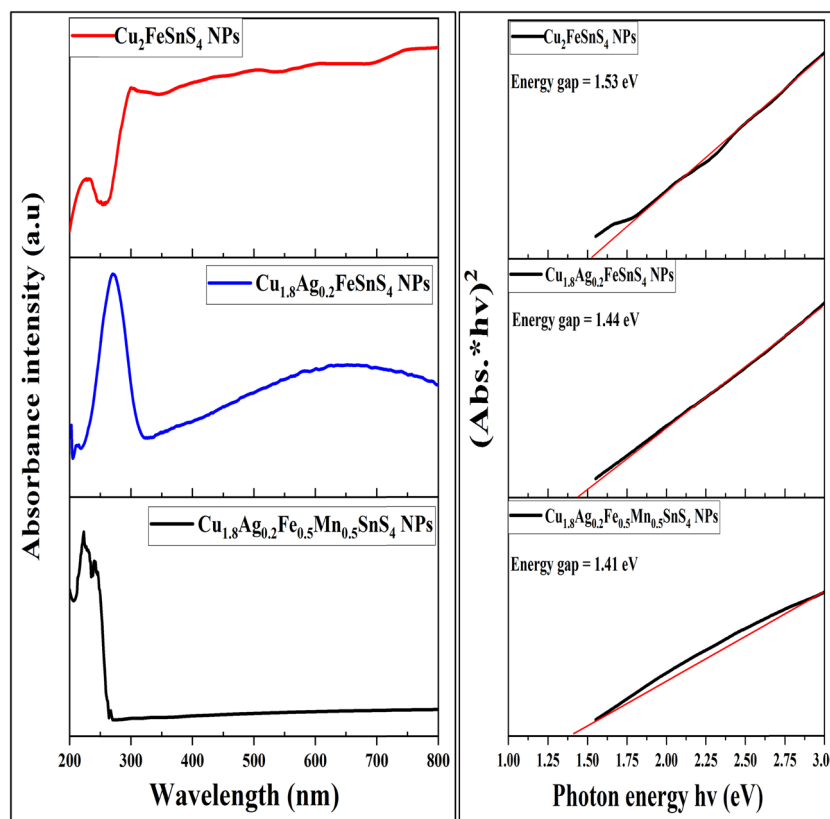
The results demonstrated the relationship between the crystal structure and functional properties of the CFTS compound by comparing doping and co-doping. It was



**Figure 5.** ADS and DES of the synthesized nanoparticles.

concluded that the crystallinity of the CFTS compound and the morphology of its nanoparticles can be improved by partial substitution between copper and silver ions. Furthermore, when silver and manganese ions are co-substituted with copper and iron ions, the electronic structure of the CFTS compound is modified by the addition of extra energy levels within the energy gap. Although both substitutions significantly reduced the energy gap, thus enhancing light absorption in the visible field, a decrease

in the surface area of the nanoparticles and an increase in structural disorder were observed. In contrast, while doped compounds exhibit improved optical response, they suffer from particle aggregation and reduced porosity. Therefore, it can be concluded that there should be an ideal balance in the doping strategy for quaternary chalcogenides between the crystalline structure and the electronic structure, rather than focusing on improving one property to obtain better performance in optical



**Figure 6.** Absorption spectrum and energy band gap of the synthesized compounds.

applications. This study also opens avenues for future research focusing on catalytic conditions and doping ratios to achieve a balance between surface area and energy gap, which in turn enhances the performance of photocatalytic applications and thin-film solar cells.

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The authors declare that no funding was received for this work.

## Author contributions

The idea of investigation and the manuscript draft were done by corresponding author Hussein M. H. The

preparation of samples was done by Rawaa Majid Thamer. The interpretation of the results was done by both authors.

## Conflict of interest statement

The authors declare no conflict of interest.

## Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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