Effect of Ag-doping on the structural, optical, electrical and photovoltaic properties of thermally evaporated Cadmium Selenide thin films

Ramezan Sahebi, Mahmood Rezaei Roknabadi and Mohammad Behdani
Thin films laboratory, Department of Physics, Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran

1 Author to whom any correspondence should be addressed.
E-mail: ramezan.sahebi@mail.um.ac.ir, roknabad@um.ac.ir and mbehdani@um.ac.i

Keywords: CdSe thin films, Ag-doping, Urbach energy, thermionic emission, semi-transparent solar cell, Schottky junction

Supplementary material for this article is available online

Abstract
To study the capability of the CdSe thin films to use as an absorber layer in semi-transparent thin film solar cells, the structural, optical, electrical and photovoltaic properties of thermally evaporated CdSe thin films (thickness 300 nm) as a function of silver-doping were investigated. A novel and facile method was used to Ag-doping of the samples. Some aqueous solution of silver nitrate (with various concentration) was spin coated onto the surface of CdSe thin films followed by air-annealing to diffuse silver dopants into the layers. The field emission scanning electron microscope (FE-SEM) images showed that the surface of CdSe thin films was improved with our doping method. X-ray diffraction (XRD) analysis revealed the hexagonal structure of the samples. The crystallite size, micro-strain and dislocation density of CdSe thin films were evaluated using XRD patterns. The transmittance spectra in the wavelength range of 400–2500 nm were measured and then used to study other optical parameters. The optical energy band gap was decreased with Ag-doping from 1.96 eV to 1.67 eV. The electrical conductivity of FTO/CdSe:Ag/Al Schottky junction devices was improved by Ag-doping, and the photovoltaic efficiency was increased by Ag-doping form 1.53% for the undoped sample to 2.78% for the sample with the highest doping concentration. Obtained results show that Ag-doped CdSe thin films are a promising candidate to use as an absorber layer in semi-transparent solar cells and colorful photovoltaic windows.

1. Introduction
Semi-transparent solar cells are a kind of photovoltaic cell in which the thickness of the absorber layer is low enough to provide the desired amount of transparency. These solar cells are used as photovoltaic windows in green buildings. Dye-sensitized solar cells (DSSC) are commonly used as photovoltaic windows. Also, a-Si, CdTe and CIGS thin films are used as an absorber layer in semi-transparent thin film solar cells [1–4], but there is no report about the usage of CdSe thin films as an absorber layer in semi-transparent thin film solar cells. Cadmium Selenide (CdSe) is an n-type, reddish semiconductor material. CdSe thin films have been used in photovoltaic devices because of their suitable direct band gap (about 1.74 eV for bulk CdSe material), high absorption coefficient and electrical conductivity [5, 6]. There are many reports about the usage of the CdSe thin films as a window layer in the CdTe based thin film solar cells. Li et al studied the effect of substrate temperature on the performance of the CdSe/window layer/CdTe thin film solar cell. Bao et al reported the usage of oxygenated CdSe thin films as a window layer in the CdTe based thin film solar cells [7]. Moreover, there are many reports about CdSe QD sensitized solar cells [9, 10]. Schottky junction solar cells are a type of solar cell in which the charge separation is performed by the Schottky barrier between the absorber layer and the electrode. There are some reports about the CdSe based Schottky barrier solar cells. Gao et al [11] studied the performance of graphene/CdSe nanobelt/Au Schottky barrier solar cells. They used graphene as a transparent electrode and the Schottky barrier was...
formed at the graphene/CdSe nanobelt interface. The performance of graphene/CdSe nanobelt/Ag Schottky junction solar cell was reported by Zhang et al.[12]. Kumar et al.[13] and Manna et al.[14] studied the electrical properties of Al/CdSe thin film contacts and reported the formation of the Schottky barrier at Al/CdSe interfaces. The aim of the present work is to investigate the capability of CdSe thin films to use as an absorber layer in the semi-transparent Schottky junction thin film solar cells. The thickness of the CdSe thin film was chosen as 300 nm to achieve the required transparency. In this work, we have chosen thermal evaporation technique to fabricate CdSe thin films because it can be used to prepare homogeneous thin films with controlled thickness. CdSe thin films evaporated into the FTO substrates to form ohmic contact and Schottky junction was formed by evaporating aluminum onto the CdSe thin films by using an appropriate mask. The efficiency of the solar cells is related to the physical properties of the absorber layer which can be altered by thermal annealing and metal-doping[15, 16]. Zhao et al.[17] studied the effect of Ag-doping on the electronic and optical properties of CdSe quantum dots by using density functional theory. They reported that silver-doping increases the number of charge carriers and enhances the performance of CdSe QDs for their potential applications in high-efficiency photovoltaic devices. Lee et al.[18] reported that Ag-doped CdSe SQDs exhibit n-type doping behavior which implies the enhancement of charge carriers. Tung et al.[19] studied the effect of Ag-doping on solar cell efficiency of the CdSe QDs sensitized solar cell. They reported that the performance of the cells was improved from 0.82% to 2.72% as the result of Ag-doping. According to the literature, it can be suggested that Ag-doping can alter the performance of CdSe based thin film solar cells. In the present work, we have studied the effect of Ag-doping on the performance of FTO/CdSe/Al semi-transparent Schottky junction solar cells. There are few reports on the Ag-doped CdSe thin films. Kaur and Tripathi[20] studied the properties of annealed and light-soaked Ag-doped CdSe thin films. Also, Kaur et al.[21] reported that the optical and electrical properties of CdSe thin films alter with Ag-doping. In these works, doped CdSe material was synthesized with melt quenching technique, and samples were fabricated by thermal evaporation method. In present work, we have used a novel, facile and inexpensive method to fabricate Ag-doped samples. At first, some silver nitrate aqueous solution (with various concentration to achieve the various amounts of silver-doping) coated onto the surface of CdSe thin films by spin coating technique. Then, these samples were air-annealed to diffuse silver dopants into the layers. Furthermore, the structural, optical, electrical properties of the CdSe thin film were studied as a function of doping concentration, because the performance of samples is related to the physical properties of CdSe thin films. The results showed that CdSe thin films are a promising candidate to utilize as an absorber layer in semi-transparent Schottky junction thin film solar cells and Ag-doping is an effective method to improve the performance of these devices.

2. Experimental

The CdSe thin films were deposited onto glass and FTO coated glass substrates using an Edwards 306 A coating system. The CdSe powder (Aldrich, 99.99%) was used as source material. At first, substrates were cleaned with subsequent sonication in detergent, ethanol, acetone and deionized water, and then blow dry with nitrogen. Thin film deposition was carried out at a vacuum of 4 × 10⁻⁶ mbar and at room temperature. The thickness of thin films and the deposition rate were monitored by using a quartz crystal system. The deposition rate was about 0.5 Å/s, and the thickness of samples was about 300 nm. After deposition, the samples were air-annealed at the temperatures of 300 °C for 90 min. It must be mentioned that the undoped sample in this paper is a sample that once air-annealed at 300 °C for 90 min. Then, some samples were silver-doped via spin coating (2500 rpm, 15 s) of silver nitrate solution in deionized water (0.002, 0.004, 0.006 and 0.008 M which will be called, S₁, S₂, S₃ and S₄, respectively in this paper) onto the surface of samples. Furthermore, these samples were air-annealed again at 300 °C for 90 min to diffuse dopants into the CdSe thin films. Undoped and Ag-doped CdSe thin films which deposited onto the glass substrates were used to study the structural and optical properties. Undoped and Ag-doped CdSe thin films which deposited onto the FTO coated glass substrates were used to fabricate Schottky junction solar cells (FTO/CdSe/Al and FTO/CdSe:Ag/Al devices) to investigate the electrical and photovoltaic properties. At the end of the fabrication process, aluminum as the top electrode was evaporated onto FTO/CdSe samples using an appropriate mask. The effective area of the top electrode is 9 mm². It is worthwhile to mention that, the transparency of CdSe thin films was reduced by increasing the doping concentration higher than 0.008 M and it was not suitable to use as an absorber layer in semi-transparent solar cells, so we did not study higher doping concentration in the present work. The surface morphology of the CdSe thin films was investigated using field emission scanning electron microscopy (FE-SEM; MIRA3 TESCAN). The elemental composition of the Ag-doped specimens was studied by EDX analysis (MIRA3 TESCAN). The structural properties of undoped and Ag-doped CdSe thin films were studied by using an x-ray diffractometer (Cu Kα, Explorer-GNR). The optical transmittance of thin films was measured in the wavelength range of 400–2500 nm by using Perkin Elmer lambda-9 UV/Vis/NIR spectrophotometer. The photovoltaic characterization was
carried out under AM 1.5 illumination by using SIM-1030 (Sharif Solar, solar simulator) and a homemade I-V meter.

3. Results and discussions

3.1. Surface morphological and structural properties

The surface morphology of undoped and Ag-doped CdSe thin films was investigated using FE-SEM images, as shown in figure 1. As can be seen, figure 1(a), the surface of the undoped sample is cracked that caused as the result of thermal annealing. (The surface of pristine deposited CdSe thin films is homogeneous, as shown in Supplementary file). It can be due to the difference in thermal expansion coefficients between CdSe thin film and substrate [22]. Such behavior was reported by Punitha et al [23] and Chandar et al [24] for annealed CdTe thin films. As can be observed in figure 1, the surface of Ag-doped samples is cracked too, but the surface of these samples is less cracked than the undoped sample. It can be caused by the Ag-doping process. Silver dopants that penetrate into the cracks bond with the atoms of the crack’s walls. These bonds, like an adhesive, bond the atoms of the two sides of the crack’s walls together. As mentioned in the experimental part, samples were air-annealed at 300 °C for 90 min after the spin coating of silver nitrate solution. Thermal annealing provides the required energy to break weaker bonds between the atoms of the CdSe layer [25], so these atoms will be moved together by the driving force caused by the mentioned bonds between silver dopants and these atoms. This can lead to nucleation and growth of the CdSe crystallites in the cracks and fill them. This phenomenon can be responsible for reducing the surface cracks of the doped samples compared to undoped ones.

XRD patterns of the undoped and Ag-doped CdSe thin films are shown in figure 2. The observed diffraction peaks are in agreement with the standard data (JCPDS File no. 08-0459) and CdSe thin films have hexagonal (würztite) structure. No peaks related to Ag or Ag₂Se are observed in diffraction patterns. The preferred orientation of all samples is along (002) plane. The crystallinity of the S₁ sample is improved sharply compared to the undoped sample. It can be attributed to the enhancement of the surface quality and decrease of surface cracks after silver-doping. Also, the crystallinity is decreased by increasing the doping concentration. It can be due to the entrance of silver dopants as localized defects into the CdSe layer.

The lattice constants of hexagonal structure (a) and (c) were calculated using the following equation [26] and tabulated in table 1.
\[
\left( \frac{\beta}{\cos \theta} \right) = \frac{4}{\lambda} \left( \frac{\lambda}{a^2} \left( h^2 + hk + k^2 \right) \right) + \frac{I^2}{\varepsilon^2}
\]

where \( a \) and \( c \) are the lattice constants, \( h, k \) and \( l \) are Miller indices and \( d_{hkl} \) is the interplanar crystal spacing that can be calculated using Bragg's formula.

As can be seen in table 1, there is a difference between calculated and standard lattice parameters. It can be interpreted that samples are under strain due to the deposition, annealing and Ag-doping. The micro-strain and average crystallite size of the thin films can be calculated using Williamson-Hall equation [27],

\[
\beta = \frac{0.9 \lambda}{D \cos \theta} + 4\varepsilon \tan \theta
\]

where \( \beta \) is the full width at half maximum (FWHM) of diffraction peaks, \( \lambda \) is the wavelength of x-ray, \( \theta \) is the Bragg angle and \( \varepsilon \) is the micro-strain. The values of micro-strain and average crystallite size were evaluated from the slope and intercept of \( \beta \cos \theta \) versus \( \sin \theta \) plots, as shown in figure 3. The obtained results are listed in table 2.

The negative slope means that specimens are under the compressive strain and the positive slope indicates the presence of tensile strain in the samples [28]. It is found that three specimens, S1, S2 and undoped samples are under compressive strain. The value of the mentioned micro-strain decreases with silver-doping and increasing the doping concentration. It can be due to the larger radius of dopant atoms which leads to the expansion of the crystal lattice. The type of micro-strain is changed to tensile strain with increasing the doping concentration for S3 and S4 specimens and its value increased with increasing the doping concentration. The entrance of dopant atoms into the crystal lattice decreases the crystallinity of the samples and increases the value of micro-strain. As can be seen, the crystallite size increases with Ag-doping and increasing the doping concentration that can be due to the difference between the ionic radius of Ag\(^{+}\) (0.115 nm) and host Cd\(^{2+}\) (0.097 nm) ions. The entrance of larger silver ions into the crystallites makes them increase their size. Also, decreasing of crystallite size with

---

**Table 1. Calculated and standard lattice parameters of undoped and Ag-doped CdSe thin films.**

| Sample  | Lattice parameter (a) (Å) | Lattice parameter (c) (Å) |
|---------|---------------------------|---------------------------|
|         | Calculated                | Standard                  |
| Undoped | 4.3413                    | 6.9359                    |
|         | 4.2990                    | 7.01                      |
| S1      | 4.3052                    | 7.0522                    |
| S2      | 4.3120                    | 7.0237                    |
| S3      | 4.3087                    | 7.0503                    |
| S4      | 4.3084                    | 7.0244                    |

**Figure 2.** X-ray diffraction patterns of the undoped and Ag-doped CdSe thin films.
Doping was reported for Sb\(^{29}\) and Zn-doped CdSe thin films\(^{30}\) that have smaller ionic radius dopants. As can be observed, the value of crystallite size decreases for sample S4 compared to sample S3. Such behavior was reported for Ag-doped ZnO thin films in which the average crystallite size increases with silver-doping and then decreases for larger doped samples\(^{31}\). It can be attributed to the incorporation of dopant atoms in the grain boundary of crystallites that act to pin grain boundaries and therefore limit grain boundary mobility which leads to the reduction of the crystallite grain size\(^{31–33}\). The micro-strain increases with Ag-doping and increasing the doping concentration, that can be due to the entrance of Ag atoms in the CdSe structure. Furthermore, the dislocation density \(\delta\) of the thin films was calculated using the following equation\(^{34}\) and tabulated in table 2.

\[
\delta = \frac{1}{D^2}
\]

The dislocation density is an imperfection in the crystal structure. It is observed that the value of \(\delta\) decreases with silver-doping and increasing the doping concentration. This parameter is related to the average crystallite size because the crystallite boundaries as an imperfection in the crystal structure are decreased by increasing the average crystallite size.

Moreover, to prove the existence of silver in the doped CdSe thin films, energy dispersive x-ray analysis (EDX) was used. Figure 4 shows the EDX patterns of doped specimens deposited onto glass substrates. The tables of relative elemental composition confirm that these samples consist of cadmium, selenium and silver. The peaks of oxygen and silicon in EDX patterns are corresponding to the glass substrates. Also, the peaks of gold in

![Figure 3. Variation of \(3\cos\theta\) with \(\sin\theta\) for the undoped and Ag-doped CdSe thin films.](image)

Table 2. Structural parameters of undoped and Ag-doped CdSe thin films.

| Sample | D (nm) | \(\varepsilon \times 10^{-4}\) | \(\delta \times 10^{12} \text{ cm}^{-2}\) |
|--------|--------|----------------|------------------|
| Undoped | 6      | −50           | 2.78             |
| S1     | 9.2    | −28           | 1.18             |
| S2     | 13.3   | −1.5          | 0.56             |
| S3     | 14.7   | 14            | 0.46             |
| S4     | 13.5   | 21            | 0.55             |
EDX patterns are corresponding to the ultra-thin gold layer which coated onto the surface of samples for FE-SEM analysis.

3.2. Optical properties

To investigate the optical properties of undoped and Ag-doped CdSe thin films, the transmittance spectra were measured in the wavelength range of 400–2500 nm and shown in figure 5. All samples are highly transparent in the near-infrared region, and the transmission decreases rapidly with decreasing the wavelength at the visible region. The energy of photons in the near-infrared region is lower than forbidden band gap energy and can’t excite electrons from the valence band to the conduction band of CdSe thin films. It means the low absorption of energy in this region. The energy of photons in the visible region is higher than NIR region that can be absorbed by excited electrons as well as other trap levels which may exist in the band gap. The transmission decreases with increasing doping concentration which implies that silver dopants incorporated into the trap levels in the forbidden band gap [35].

To find more, the absorption coefficient, \(\alpha\), of the samples was investigated by using following relation [23],

\[
\alpha = \frac{1}{d} \ln \left( \frac{1}{T} \right)
\]

(4)

where \(d\) is the thickness of thin films and \(T\) is the transmittance. The variation of \(\alpha\) with photon energy is shown in figure 6. As can be seen, the absorption coefficient increases with increasing doping concentration. This indicates that diffused silver dopants act as trap centers and increase the absorption coefficient which can be proved by studying the Urbach energy of samples. Also, another absorption mechanism can be proposed for the Ag-doped samples. Silver acts as an n-type dopant for CdSe thin films [19], it means that the charge carrier concentration in conduction band increases with silver-doping. These extra electrons can incorporate in the absorption of incident photon’s energy via electron-photon interaction and consequently increase the absorption coefficient. All samples have high absorption in visible region that introduce them as a promising candidate for use as an absorber layer in the thin film solar cells.

To study the tailing of the density of states into the normally forbidden energy, the Urbach energy, the following equation [36] was used,
\[ \alpha = \alpha_0 \exp \left( \frac{h\nu}{E_u} \right) \]  

where \( \alpha \) is the absorption coefficient, \( \alpha_0 \) is a constant and \( E_u \) is the width of the Urbach tail (Urbach energy). As can be seen in figure 7, the variation of \( \ln(\alpha) \) with \( h\nu \) is linear near the absorption edge, and Urbach energy can be evaluated from the slope of this region. From table 3, the Urbach energy of CdSe thin films increases with Ag-doping and increasing doping concentration. Silver dopants which added to the CdSe crystal structure act as localized states in the forbidden band gap, these localized states are a kind of traps and increasing the doping concentration means to increase the trap levels in the forbidden band gap.

According to the transmittance spectra of the undoped and silver-doped samples, there is a red shift in the absorption edge of the specimens. The optical energy band gap of the undoped and Ag-doped thin films was evaluated by using the following equation [37]:

\[ \alpha h\nu = B (h\nu - E_g)^\frac{1}{2} \]  

where \( E_g \) is the optical energy band gap and \( B \) is a constant. Figure 8 shows the variation of \( (\alpha h\nu)^2 \) as a function of \( h\nu \) for undoped and Ag-doped CdSe thin films. The value of \( E_g \) was evaluated via extrapolating the linear region of \( (\alpha h\nu)^2 \) versus \( h\nu \) plots to \( (\alpha h\nu)^2 = 0 \), shown in figure 8, and tabulated in table 3. It is observed that the optical

**Figure 5.** Variation of the transmittance with the wavelength for the undoped and Ag-doped CdSe thin films.

**Figure 6.** Variation of the absorption coefficient with the photon energy for the undoped and Ag-doped CdSe thin films.
Figure 7. Plots of the $\ln(\alpha)$ versus $h\nu$ for the undoped and Ag-doped CdSe thin films.

Table 3. Variation of the optical energy band gap and Urbach energy of CdSe thin films with respect to Ag-doping.

| Sample | $E_g$ (eV) | $E_u$ (meV) |
|--------|------------|-------------|
| Undoped| 1.96       | 150         |
| $S_1$  | 1.9        | 191         |
| $S_2$  | 1.89       | 240         |
| $S_3$  | 1.79       | 258         |
| $S_4$  | 1.67       | 291         |
energy band gap decreases with Ag-doping and increasing doping concentration from 1.96 eV to 1.79 eV. The decrement of the optical band gap is in agreement with the extension of localized states in the band gap, because increasing the tailing of trap levels in the forbidden band gap decreases the width of this region \([20, 38]\). Also, it can be due to the enhancement in the lattice disorder by the entrance of dopant atoms into the host crystal structure \([39]\). The decrease of the optical energy band gap indicates that Ag-doping can improve the performance of the CdSe based thin film solar cells.

3.3. Electrical and photovoltaic properties

The current-voltage characteristic of FTO/CdSe:Ag/Al devices in the dark condition is shown in figure 9. As can be seen, the conductivity of the samples is increased by increasing doping concentration that can be due to the enhancement of charge carrier concentration as the result of Ag-doping \([19]\). Such behavior is reported by Sharma et al \([40]\) for CdSe:Ag thin films fabricated by using the chemical bath deposition technique. Also, it can be attributed to the change of the crystallinity of samples, reduction of compressive micro-strain and dislocation density, increasing the crystallite size and decrement of barrier height between the electrode and CdSe thin films \([41, 42]\). The increase of conductivity indicates that Ag-doping can improve the performance of CdSe thin films in the solar cell structure. The observed rectification behavior in I-V curves implies that Schottky contact formed
between the CdSe thin film and aluminum electrode (CdSe/Al) [43]. The formation of CdSe/Al Schottky contact was reported by other researchers [14, 44, 45]. It is suggested that the thermionic emission may be the dominant conduction mechanism under forward bias, (FTO wired positive).

The relation between current and applied voltage in this theory is given by [46]:

$$I = I_0 \left( \exp \left( \frac{qV}{nkT} \right) - 1 \right)$$  \hspace{1cm} (7)

where $n$ is the diode ideality factor, $k$ is the Boltzmann constant and $I_0$ is the saturation current which can be expressed as:

$$I_0 = AA^*T^2 \exp \left( \frac{q\Phi_b}{kT} \right)$$  \hspace{1cm} (8)

where $A$ is the effective area, $A^*$ is Richardson constant and $\Phi_b$ is the barrier height between CdSe thin films and aluminum electrode. The values of $n$ were evaluated from the linear region of the $\text{Ln}(I)$ versus $V$ plots, figure 10, and tabulated in table 4. Also, the value of barrier height was calculated by using the following equation:

$$\Phi_b = \frac{kT}{q} \ln \left( \frac{AA^*T^2}{I_0} \right)$$  \hspace{1cm} (9)

As can be seen in table 4, the obtained values for the ideality factor are varied in the range of 5.02–6.55, and the calculated values of barrier height are varied between 0.67 eV and 0.61 eV. It is observed that the barrier height decreases with silver-doping and increasing the doping concentration. It can be attributed to the variation of the optical band gap with air-annealing because the value of the Fermi energy varies as a function of optical band gap energy and barrier height is related to the Fermi energy of CdSe thin films. The value of the ideality factor decreases with silver-doping and increasing the doping concentration which is in agreement with the decrement of barrier height.

The J-V characteristic property of specimens under AM1.5 illumination is shown in figure 11. The photovoltaic parameters such as efficiency, short circuit current density ($J_{SC}$), open-circuit voltage ($V_{OC}$) and

![Figure 10. Semi-log forward bias I-V curves of the FTO/CdSe/Al devices in dark condition.](image-url)
filling factor (FF) are calculated by using following relations [47] and listed in table 5.

\[
FF = \frac{V_n I_m}{V_{OC} I_{SC}}
\]

\[
\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} \times 100\% \quad (11)
\]

As can be seen, the efficiency of samples is increased from 1.53% for the undoped sample to 2.78% for the highest doped sample, sample S4. The value of JSC is increased from 10.07 to 13.43 mA cm⁻², which can be due to the enhancement of photocarriers concentration caused by Ag-doping. The trap levels in the band gap are increased by silver doping. Incident photons can excite electrons from the trap levels to the conduction band and increase the photocarriers concentration. Also, the increase of JSC incorporated can be attributed to the reduction of compressive micro-strain and dislocation density, increasing the crystallite size and decrement of barrier height between the electrode and CdSe thin films as the result of silver-doping [41]. The results show that Ag-doped CdSe thin films are a promising candidate to use as an absorber layer in semi-transparent thin film solar cells.

### 3.4. Conclusion

In this work, a novel, facile and inexpensive method was used to dope silver into thermally evaporated CdSe thin films, and structural, optical, electrical and photovoltaic properties of samples were investigated as a function of doping concentration. In summary, the surface homogeneity of CdSe thin films was improved with Ag-doping. The hexagonal structure of CdSe thin films didn’t change with Ag-doping. Crystallite size, micro-strain and dislocation density of specimens were studied as a function of doping concentration. The transmittance spectra were measured at the wavelength range of 400–2500 nm. The optical energy band gap was decreased (from 1.96 eV to 1.67 eV), and Urbach energy was increased (from 150 meV to 291 meV) as the result of Ag-doping. Rectification behavior in I-V characterization of samples revealed that thermionic emission is the dominant conduction mechanism. The photovoltaic efficiency of FTO/CdSe:Ag/Al samples improved from 1.53% to 2.78% by Ag-doping. Obtained results suggest that silver-doped CdSe thin films are a promising candidate to use as an absorber layer in semi-transparent solar cells and colorful photovoltaic windows.

### Table 5. Photovoltaic parameters of the FTO/CdSe/Al devices.

| Sample | JSC (mA/cm²) | VOC (V) | FF | η (%) |
|--------|--------------|---------|----|-------|
| Undoped | 10.07 | 0.31 | 0.49 | 1.53 |
| S₁ | 11.6 | 0.36 | 0.47 | 1.95 |
| S₂ | 12.58 | 0.39 | 0.46 | 2.24 |
| S₃ | 13.05 | 0.4 | 0.48 | 2.51 |
| S₄ | 13.43 | 0.41 | 0.51 | 2.78 |

Figure 11. I-V characteristic curves of the FTO/CdSe/Al devices under illumination condition.
Acknowledgments

The authors acknowledge the Ferdowsi University of Mashhad for supporting this research via the Grant No. 3/46721. One of authors wants to acknowledge Dr Nasrin Azad for good discussion.

ORCID iDs

Ramezan Sahebi  https://orcid.org/0000-0001-7345-1564
Mahmood Rezaei Roknabadi  https://orcid.org/0000-0003-4271-9593

References

[1] Lee H M and Yoon J H 2018 Power performance analysis of a transparent DSSC BIPV window based on 2 year measurement data in a full-scale mock-up Appl. Energy 225 1013–21
[2] Peng J, Carcuia D C, Thanachareonkit A, Lee E S, Goudey H and Selkowitz S E 2019 Study on the overall energy performance of a novel c–Si based semitransparent solar photovoltaic window Appl. Energy 242 854–72
[3] Sun J and Isasiennak J 2017 Semi-transparent solar cells J. Phys. D: Appl. Phys. 50 093001
[4] Shin M J, Jo J H, Cho A, Gwak J, Yun J H, Kim K, Ahn S K, Park J H, Yoo J and Jeong I 2019 Semi-transparent photovoltaics using ultra-thin Cu (In, Ga) Se2 absorber layers prepared by single-stage co-evaporation Sol. Energy 181 276–84
[5] El-Menawy E and Azab A 2018 Optical, electrical and photoelectrical properties of nanocrystalline cadmium selenide films for photosensor applications Optik 168 217–27
[6] Mathuri S, Ramamaruthi K and Babu R R 2017 Influence of deposition distance and substrate temperature on the CdSe thin films deposited by electron beam evaporation technique Thin Solid Films 625 138–47
[7] Li C, Wang F, Chen Y, Wu L, Zhang J, Li W, He X, Li B and Peng L 2018 Characterization of spattered CdSe thin films as the window layer for CdTe solar cells Mat. Sci. Semicon. Proc. 83 89–95
[8] Bao Z, Liu L, Yang X, Tang P, Yang K, Lu H, He S, Liu J, Liu X and Li B 2017 Synthesis and characterization of novel oxygenated CdSe window layer for CdTe thin film solar cells Mat. Sci. Semicon. Proc. 63 12–7
[9] Chen Z, Wei C, Li S, Li X, Dong S and Zhang W 2018 CdS/CdSe co-sensitized hierarchical nanosheet-constructed NiO microballs for quantum-dot-sensitized solar cells Optik 172 86–90
[10] Liu D, Liu J, Liu J, Liu S, Wang C, Ge Z, Hao X, Du N and Xiao H 2020 The photovoltaic performance of CdS/CdSe quantum dots co-sensitized solar cells based on zinc titanium mixed metal oxides Physica E 115 11669
[11] Gao Z, Jin W, Li Y, Song Q, Wang Y, Yang K, Wang S and Dai L 2015 Flexible solar cells based on CdSe nanobelt/graphene Schottky junctions J. Mater. Chem. C 3 4511–4
[12] Zhang L, Fan L, Li Z, Shi E, Li X, Li H, Ji C, Jia Y, Wei J and Wang K 2011 Graphene-CdSe nanobelt solar cells with tunable configurations Nano Res. 4 891–900
[13] Kumar V, Sharma S K, Kumar S, Hussain M and Sharma T 2010 Growth and characterisation of screen-printed CdSe films Phil. Mag. Lett. 90 493–501
[14] Mann A, Saha S and Saha S 2017 Fabrication and characterization of Al/n–CdSe schottky barrier under DIFFERENT annealing temperatures Chalcogenide Lett. 14 283–9
[15] Liu M, Chen Z, Xue Q, Cheung S H, So S K Y, Yin H L and Cao Y 2018 High performance low-bandgap perovskite solar cells based on a high-quality mixed Sn–Pb perovskite film prepared by vacuum-assisted thermal annealing J. Mater. Chem. A 6 16347–54
[16] Zhao W, Yao Z, Yu F, Yang D and Liu S 2018 Alkali metal doping for improved CH3NH3PbI3 perovskite solar cells Adv. Sci. 5 1700131
[17] Zhao F, Xiao H, Bai X and Zu X 2019 Effects of Ag doping on the electronic and optical properties of CdSe quantum dots Phys. Chem. Chem. Phys. 21 16108–19
[18] Lee S M, Lim H, Lee Y and Bang J 2019 Facile in situ synthesis of Ag-doped CdSe supra–quantum dots and their characterization ChemPhysChem 20 1885–9
[19] Tung H T, Van Thuan D, Kiat J H and Phuc D H 2019 Ag+ ion doped on the CdSe quantum dots for quantum-dot-sensitized solar cells’ application Appl. Phys. A 125 505
[20] Kaur J and Tripathi S 2015 Thermally and optical-induced effect on optical and electrical parameters of Ag-doped CdSe thin films Acta Metal. Sin.-Engl. 28 591–9
[21] Kaur J, Kaur R and Tripathi S 2019 Silver dopant-induced effect on structural and optoelectronic properties of CdSe thin films acta metal Sin.-Engl. 32 541–9
[22] Rupp G M, Téllez H, Druse J, Limbeck A, Ishihara T, Kühner J and Fleig J 2015 Surface chemistry of La 0.6 Sr 0.4 CoO 3–δ thin films and its impact on the oxygen surface exchange resistance J. Mater. Chem. A 3 22759–69
[23] Puniitha K, Sivakumar R, Sanjeeviraj C and Ganesan V 2015 Influence of post-deposition heat treatment on optical properties derived from UV–vis of cadmium telluride (CdTe) thin films deposited on amorphous substrate Appl. Surf. Sci. 344 89–100
[24] Chander S, Purohit A, Lal C and Dhaka M 2017 Enhancement of optical and structural properties of vacuum evaporated CdTe thin films Mater. Chem. Phys. 185 202–9
[25] Koth H M, Dabban M, Abdel-Latif A and Hafiz M 2012 Annealing temperature dependence of the optical and structural properties of selenium-rich CdSe thin films J. Alloy. Compd. 512 115–20
[26] Santosh T, Bangera K V and Shivakumar G 2017 Effect of Bi doping on the properties of CdSe thin films for optoelectronic device applications Mater. Sci. Semicon. Proc. 68 114–7
[27] Sanhueza F, Valdebenito E, Udayabaskar R, Salvo C, Sahlevani S F, Elgueta E, Parra M, Bello H and Mangalaraja R 2019 Effect of ultrasonic sonication time on the structural, optical and antibacterial properties of ceria nanomaterials Mater. Res. Express 6 085035
[28] Yahmadi B, Kamoun N, Guasch C and Bennaceur R 2011 Synthesis and characterization of nanocrystallized In2S3 thin films via CBD technique Mater. Chem. Phys. 127 239–47
[29] Mathuri S, Ramamaruthi K and Babu R R 2018 Effect of Sn incorporation on the structural, optical, morphological and electrical properties of CdSe thin films deposited by electron beam evaporation technique Thin Solid Films 660 23–30
[30] Thanikaiarasar S, Perumal R and Venkatamuthukumar J 2019 Influence of Zinc incorporation in electrodeposited CdSe thin films from aqueous acidic media J. Mater. Sci., Mater. Electron. 30 1506–9
[31] Dehimi M, Touam T, Chebouche A, Boudjouan E, Djouadi D, Solard J, Fischer A, Boudrioua A and Doghmane A 2015 Effects of low Ag doping on physical and optical waveguide properties of highly oriented sol-gel ZnO thin films. Adv. Cond. Matter Phy. 2015 1–10
[32] Sanchez-Juarez A, Tiburcio-Silver A, Ortiz A, Zironi E and Rickards J 1998 Electrical and optical properties of fluorine-doped ZnO thin film. Mater. Res. Express 6 025908
[33] Kuo S-T, Tuan W-H, Shieh J and Wang S-F 2007 Effect of Ag on the microstructure and electrical properties of ZnO. J. Eur. Ceram. Soc. 27 4521–7
[34] Taleblou M, Borhani E, Yarmand B and Kolahi A R 2018 Modification of the structural and optical properties of Fe-doped SnS2 thin film. Mater. Res. Express 6 025908
[35] Punitha K, Sivakumar R, Sanjeeviraja C, Sathe V and Ganesan V 2014 Physical properties of electron beam evaporated CdTe and CdTe: Cu thin films J. Appl. Phys. 116 213502
[36] Azim-Araghi M and Sahebi R 2014 Investigation in morphology and optical properties of electron beam gun evaporated nanostructured Bromoindium phthalocyanine thin films Physica B 433 165–9
[37] Saritha K, Rasool S, Reddy K R, Tivanov M, Saad A, Trofimova A and Gremenok V 2019 Optical and electrical properties of thermally co-evaporated SnS1−xSe x alloy films J. Mater. Sci., Mater. Electron. 28 3140–50
[38] Raut V S, Lokhande C D and Killedar V V 2017 Synthesis and studies on effect of indium doping on physical properties of electrodeposited CdSe thin films J. Mater. Sci., Mater. Electron. 28 3140–50
[39] Choudhary R, Chauhan R and Sharma A 2018 Ar+ ion implantation induced surface, structural and optical modifications in cadmium selenide thin films J. Electron. Mater. 47 5889–95
[40] Sharma K C, Sharma R and Garg J C 1992 Effect of silver dopant on optical and electrical properties of solution-grown cadmium selenide thin films Jpn. J. Appl. Phys. 31 742
[41] Sharma M and Tripathi S 2012 Temperature dependent current-voltage (IV) characteristics of Al/n-Cadmium Selenide-Polyvinyl alcohol (Al/n-CdSe-PVA) Schottky diode Opt Adv Mater.-Rapid Commun 6 200–4
[42] Patel S, Purohit A, Chander S, Kannan M and Dhaka M 2018 Towards post-NH4Cl treatment on CdSe thin films for solar cell applications Vacuun 153 43–7
[43] Azim-Araghi M and Sahebi R 2014 Effect of temperature and post-deposition annealing on Schottky barrier characterization of Bromoindium phthalocyanine/aluminum interfaces Physica B 433 144–8
[44] Sharma B 2013 Metal–Semiconductor Schottky Barrier Junctions and Their Applications (Springer US: Springer Science & Business Media) (https://doi.org/10.1007/978-1-4684-4655-5)
[45] Al-Zahra A, Abdullah A and Al-Kabbi A 2017 Effect of substrate temperature on the structure and optical properties of PVP: n-CdSe nanocomposite thin films and its Schottky Diodes performance Chalcogenide Lett. 14 1457–64
[46] Rana V S, Rajput J K, Pathak T K and Purohit I 2019 Cu sputtered Cu/ZnO Schottky diodes on fluorine doped tin oxide substrate for optoelectronic applications Thin Solid Films 679 79–85
[47] Shinde S, Dubal D, Ghodake G and Fulari V 2014 Synthesis and characterization of chemically deposited flower-like CdSe@CdTe. 6Te0. 4 thin films for solar cell application Mater. Lett. 126 17–9