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Original Research Paper

Physics

PHOTOELECTROCHEMICAL SOLAR CELL CHARACTERIZATION OF IN DOPED CD0.8ZN0.2SE THIN FILMS

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ABSTRACT The photoelectrochemical properties on chemically synthesized In doped Cd0.8Zn0.2Se thin films have been studied to assess its suitability to convert solar energy into electrical energy. The electrode was prepared from an aqueous alkaline medium consisting of Cd2+ and Zn2+ ions simultaneously in a definite volume stoichiometric proportion. The photoelectrochemical (PEC) cell of the configuration In:Cd0.8Zn0.2Se / 1M (NaOH +Na2S + S) / C is fabricated to study the current-voltage (I-V) characteristics in dark and under illumination. The photovoltaic power output curves have been obtained under 25 mW/ cm2 light intensity. The power conversion efficiency ( ) and fill factor (ff) are obtained.

KEYWORDS : Photoelectrochemical cell, In doped Cd0.8Zn0.2Se electrode, efficiency, fill factor.

INTRODUCTION

The rapid increase in global energy demand and the environmental problems associated with fossil fuels have intensified research efforts toward the development of renewable and sustainable energy sources. Solar energy is considered one of the most promising alternatives because it is abundant, environmentally friendly, and inexhaustible. Among the various solar energy conversion technologies, photovoltaic and photoelectrochemical (PEC) solar cells have attracted considerable attention due to their potential for efficient and low-cost solar energy conversion [1–4].

Thin-film semiconductor materials play a crucial role in the development of efficient solar energy conversion devices. Compared with bulk materials, thin films require smaller amounts of material, offer flexibility in fabrication, and can be deposited on large-area substrates using relatively simple and inexpensive techniques. Among the various semiconductor materials investigated for solar cell applications, II–VI compound semiconductors such as CdSe, CdS, ZnSe, and their ternary alloys have been extensively studied due to their direct band gap, high absorption coefficient, and favorable optoelectronic properties [5–8].

Cadmium selenide (CdSe) is a well-known II–VI semiconductor with a direct band gap of about 1.7 eV and a high optical absorption coefficient ($>10^4$ cm^{-1}), making it suitable for photovoltaic and photoelectrochemical applications. CdSe thin films have been widely investigated for use in solar cells, photo detectors, and optoelectronic devices due to their excellent photosensitivity and high photoconductivity [9–11]. However, the performance of CdSe-based devices can be further improved by alloying or doping with other elements to tailor their structural, optical, and electrical properties.

Alloying CdSe with ZnSe leads to the formation of the ternary compound $Cd_{1-x}Zn_xSe$, which allows tuning of the band gap and lattice parameters by controlling the Zn concentration. This band-gap engineering approach enables optimization of the material properties for various optoelectronic applications. In particular, CdZnSe thin films have shown promising characteristics such as improved thermal stability, enhanced optical transparency, and better charge transport properties compared to pure CdSe [12–14]. These characteristics make CdZnSe an attractive candidate for solar energy conversion devices, especially in PEC solar cells.

Doping of semiconductor thin films is another important approach to enhance their electrical and optoelectronic performance. Incorporation of suitable dopants can modify the carrier concentration, electrical conductivity, and defect structure of the material. Indium (In) is widely used as a donor dopant in II–VI semiconductors and has been reported to improve the crystallinity, electrical conductivity, and photoresponse of CdSe-based thin films [15–17]. The introduction of indium atoms into the CdZnSe lattice can create additional charge carriers and reduce recombination losses, thereby improving the efficiency of photoelectrochemical devices.

Photoelectrochemical solar cells operate on the principle of a semiconductor–electrolyte junction, where the semiconductor thin film acts as a photoelectrode. When illuminated with light of energy greater than the band gap, electron–hole pairs are generated in the semiconductor. These charge carriers are separated by the built-in electric field at the semiconductor–electrolyte interface and participate in electrochemical reactions, resulting in the generation of photocurrent and photovoltage [18–20]. The performance of PEC solar cells strongly depends on the structural, optical, and electrical properties of the semiconductor photoelectrode. Therefore, the development of optimized semiconductor materials with suitable band gap, high crystallinity, and improved electrical conductivity is essential for enhancing PEC solar cell performance. In this context, indium-doped $Cd_{0.8}Zn_{0.2}Se$ thin films represent a promising material system due to the combined advantages of Zn alloying and In doping. The present work focuses on the preparation of In-doped $Cd_{0.8}Zn_{0.2}Se$ thin films and the investigation of their photoelectrochemical properties for solar cell applications.

Experimental details

Preparation of photoelectrodes of different In-doped $Cd_{0.8}Zn_{0.2}Se$ thin films

The photoelectrodes of In-doped $Cd_{0.8}Zn_{0.2}Se$ thin films were deposited on FTO coated glass substrates procured from Sigma-Aldrich (Mumbai). The electrode thickness was increased by repeating the number of depositions.

Construction of photoelectrochemical (PEC) solar cell

The photoelectrochemical (PEC) solar cells were prepared using the In-doped $Cd_{0.8}Zn_{0.2}Se$ thin films (1% to 5%) deposited on FTO glass substrates as photoelectrodes, polysulphide as an electrolyte and graphite as the counter electrode. The configuration of the PEC cell is as below:

In:$Cd_{0.8}Zn_{0.2}Se$ | 1M (Na_2S + S + NaOH) | C

RESULTS AND DISCUSSION

Current-voltage (I-V) characteristics

Figure 1. shows the current–voltage (I–V) characteristics of undoped and indium (In) doped $Cd_{0.8}Zn_{0.2}Se$ thin films measured in a photoelectrochemical (PEC) solar cell configuration using a saturated calomel electrode (SCE) as a reference electrode. The measurements were carried out to evaluate the influence of In doping concentration (0–5%) on the photoresponse and charge transport properties of the semiconductor photoelectrode.

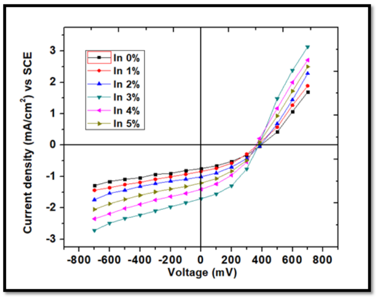


Fig. 1. I-V Characteristics of In doped Cd0.8Zn0.2Se thin films/1M polysulphide/C photoelectrochemical cells.

It is observed that the current density increases with increasing forward bias voltage for all samples, indicating improved carrier transport and reduced recombination losses. Among the investigated samples, the thin film doped with 3% indium shows the highest photocurrent density, reaching 3.2 mA cm^{-2} at about 800 mV. This enhancement in photocurrent can be attributed to the improved electrical conductivity and increased carrier concentration resulting from indium incorporation into the Cd0.8Zn0.2Se lattice. Indium atoms act as donor impurities, introducing additional free electrons that facilitate efficient charge transport within the semiconductor film [21-22].

At lower doping concentrations (1–2%), a moderate increase in current density is observed compared to the undoped sample. This improvement is mainly due to the reduction in grain boundary resistance and improved crystallinity of the thin films. However, when the doping concentration increases beyond the optimum level (4–5%), a slight decrease in photocurrent is observed compared with the 3% doped sample. This behavior may be attributed to the formation of defect states and increased carrier recombination centers caused by excessive dopant incorporation, which adversely affects the PEC performance [23-24].

Mott–Schottky Analysis of In-doped Cd0.8Zn0.2Se Thin Films

The figure 2 presents the Mott–Schottky plots (1/C^2 vs. applied potential) of undoped and indium-doped Cd0.8Zn0.2Se thin films measured in a photoelectrochemical (PEC) cell using a saturated calomel electrode (SCE) as the reference electrode. Mott–Schottky analysis is an important electrochemical technique used to determine key semiconductor parameters such as flat band potential (Vfb) and donor carrier concentration (Nd). These parameters provide valuable information about the electronic properties of semiconductor photoelectrodes used in PEC solar cells.

From the extrapolation of the linear region of the Mott–Schottky plots to the voltage axis, the flat band potential (Vfb) can be estimated and tabulated in Table 1. In the present case, the flat band potential is found to be −1023 mV vs SCE. The flat band potential represents the condition where the space-charge region at the semiconductor–electrolyte interface disappears, and it is an important parameter for understanding band alignment and charge transfer processes in PEC systems. A more negative flat band potential generally favors efficient charge separation and enhances the photocatalytic or photoelectrochemical performance of semiconductor electrodes [25-26].

It can also be observed that the slope of the Mott–Schottky plots decreases with increasing indium doping concentration up to 3%, which indicates an increase in the donor carrier concentration within the semiconductor films. According to the Mott–Schottky equation, the donor density is inversely proportional to the slope of the 1/C^2 versus potential plot. Therefore, the reduced slope for the 3% In-doped film suggests that indium incorporation introduces additional donor states in the Cd0.8Zn0.2Se lattice, thereby increasing the electron concentration and improving electrical conductivity.

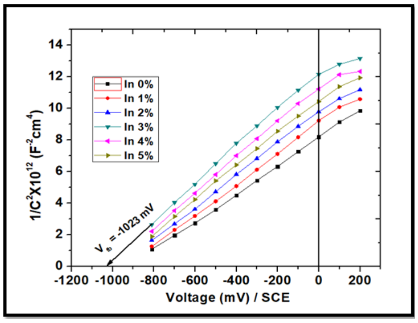


Fig. 2. The Mott–Schottky plots of undoped and indium-doped Cd0.8Zn0.2Se thin films

Table 1. Estimated values of flat band potential and carrier concentration.

In doping	Vfb (mv)	ND X 10^{18} cm^{-3}	nd	nL	B (eV)
0%	930	5.47	1.38	1.27	0.57
1%	944	5.66	1.33	1.25	0.54
2%	955	5.82	1.29	1.21	0.53
3%	1023	6.01	1.24	1.19	0.51
4%	1006	5.87	1.31	1.23	0.55
5%	978	5.71	1.36	1.26	0.56

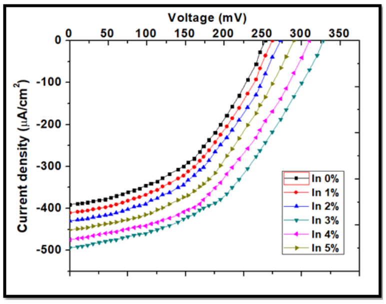
Power output characteristics

The figure 3 illustrates the power output characteristics of undoped and indium-doped $Cd_{0.8}Zn_{02}Se$ thin films measured in a photoelectrochemical (PEC) solar cell configuration. The current density is plotted as a function of applied voltage for different indium doping concentrations ranging from **0% to 5%.**

From the figure, it is evident that the magnitude of current density increases with increasing indium doping concentration up to 3%. The undoped film shows a current density of approximately −391 A cm^{-2} at low voltage, while the 3% In-doped film exhibits the highest current density of about −494 A cm^{-2} in the same region. The estimated photoelectrochemical parameters are tabulated in Table 2. This enhancement indicates that moderate indium doping significantly improves the charge transport properties of the $Cd_{0.8}Zn_{02}Se$ thin films. The improvement can be attributed to the substitution of Cd^{2+} ions with In^{3+} ions in the crystal lattice, which introduces additional donor states and increases the free electron concentration.

The higher carrier density facilitates efficient transport of photogenerated electrons and reduces recombination losses within the semiconductor layer [27-30].

Fig. 3. The power output characteristics of undoped and In doped Cd0.8Zn02Se thin films.



The results indicate that controlled indium doping effectively enhances the electrical conductivity and photocurrent generation of Cd0.8Zn02Se thin films. The improved photoresponse observed for the optimally doped film suggests that these materials are promising candidates for photoelectrode applications in photoelectrochemical solar cells. The enhanced PEC performance is primarily attributed to increased donor carrier concentration, improved charge separation efficiency, and reduced recombination losses in the semiconductor layer [31-32].

Among the investigated samples, the 3% indium-doped film demonstrates the best photoelectrochemical response, which suggests that this doping concentration provides an optimal balance between increased carrier concentration and minimal defect formation. However, when the indium concentration increases further to 4% and 5%, the improvement in photocurrent becomes less pronounced. Excessive doping can introduce structural defects, impurity scattering, and recombination centers that limit the mobility and lifetime of charge carriers.

Table 1. Estimated photoelectrochemical parameters of In doped $Cd_{0.8}Zn_{02}Se$ thin films.

In doping	Isc (μA)	Voc (mV)	FF (%)	Rs ( )	Rsh (k)	(%)	Eg (eV)
0%	391	253	46.62	195	3.02	1.82	1.95
1%	410	262	47.60	183	3.14	1.94	2.02
2%	430	273	48.36	177	3.33	2.27	2.11
3%	494	328	49.73	163	3.48	2.57	2.15
4%	474	310	46.15	182	3.27	2.44	2.18
5%	451	292	45.18	193	3.16	2.38	2.20

CONCLUSION

The indium doping significantly enhances the photoelectrochemical performance of Cd0.8Zn0.2Se thin films, with an optimum doping level around 3%, which provides the best balance between increased carrier concentration and minimal recombination losses. The Mott–Schottky analysis confirms that indium doping significantly modifies the electronic structure of Cd0.8Zn0.2Se thin films by increasing donor carrier concentration and shifting the flat band potential. The optimal doping concentration around 3% In results in improved charge transport properties and enhanced photoelectrochemical activity. The controlled indium doping effectively enhances the electrical conductivity and photocurrent generation of Cd0.8Zn02Se thin films. The enhanced PEC performance is primarily attributed to increased donor carrier concentration, improved charge separation efficiency, and reduced recombination losses in the semiconductor layer.

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