Innovative industrial Cu(In,Ga)Se2 thin film solar cell with high characterization using nanoparticles structure

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ABSTRACT

This paper presents new design of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cell based on individual and multiple nanocomposites absorber layer. A theoretical analysis is presented for enhancing the efficiency and characterization of individual and multiple nanocomposites CdS/Cu (In, Ga) Se2 thin film solar cell. Moreover, this paper is achieving high efficiency with a thinner CIGS layer for reducing the direct materials usage and there by the materials costs by adding various metallic nanoparticles in CIGS absorber layer.

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1. INTRODUCTION

Solar energy is a promising alternative energy source due to energy crisis and environmental issues such as global warming effect and pollution. Photovoltaic (PV) power generation is one of the more important renewable sources since it had great many merits such as clean, free maintenance and no noise. However, PV generation system has two disadvantages which are the low conversion efficiency in electric power generation and the changes in several weather conditions. A photovoltaic (PV) system utilizes a solar cell for converting the solar energy to electricity which depends on the photoelectric effect. PV system basically is a cell which may be classified as mono-crystalline, poly-crystalline, organic cell, amorphous, and Nano-PV cells [1, 2]. Recently, Cu(In,Ga)Se2 (CIGS) has been proposed as a hopeful material for thin film solar cells with potential to replace silicon-based solar cells. CIGS solar cells have achieved a high photovoltaic efficiency of 20.3% in laboratory experiments. This is the highest among all types of thin film solar cells [3]. Now that the standard thickness of the Cu(In,Ga)Se2 (CIGS) layer in traditional CIGS thin-film solar cells is 1.5–2 µm, this work aims to decrease standard thickness and loss energy to reduce production costs. A thinner CIGS layer would decrease the direct materials usage and thereby the materials costs. A reduction of materials usage is important for indium and gallium since the supply of these metals might become an issue if CIGS thin-film solar cells are produced in very large volumes (70GWp/year). The deposition time of the CIGS layer could also be decreased for thinner CIGS layers, which would directly lower production costs. When the CIGS layer was decreased to around 0.5 µm the devices became electrically shunted. The shunting was related to the roughness of the film which was of the same order as the film thickness itself. Another potential problem for thinner CIGS layers is that the electrons will be generated closer to the back contact with higher probability for back contact recombination. For CIGS layers thinner than 0.5 µm the indications of enhanced tunnel recombination in the depletion region of the CIGS layer has been observed [4].

The aim of this paper is enhancing the performance of CIGS thin film solar cell based on submicro absorber layer thickness to achieve higher efficiency with reduction of material and so production cost and time. Also, it has been investigated on improving the efficiency and fill factor of CIGS thin film solar cell by using new individual and multiple nanoparticles techniques in the absorber layer for decreasing the dielectric constant and enhancing the energy band gap of absorber layer (CIGS). Therefore, this paper has been investigated on increasing the absorbance of the absorber layer, decreasing the reverse saturation current, decreasing the space-charge region increasing electron–hole generation rate in absorber layer and increasing the external quantum efficiency.

2. MATHEMATICAL MODEL

PV generation resource depends basically on the ability of silicon or other certain materials of transferring the photo-radiation energy from the sun or any other source into moving to charge hence electrical energy [5]. This model uses various metallic nanoparticle for improving the optical properties of the absorber layer material of thin film solar cells that are improving the performance of ZnO/CdS/CIGS/Mo thin film solar cells. Resonant nature of metallic nanoparticles is an advantage to make an opportune option for solar cell applications [6]. The effective dielectric constant ε_{efi} of a nanocomposite absorber material (CIGS in CdS/CIGS thin film solar cell) using individual nanoparticle with spherical metal inclusions can be calculated using the Maxwell-Garnet theory approximates as the following expression [7, 8].

$$\varepsilon_{efi} = \varepsilon_b \frac{(\varepsilon_{mi}+2\varepsilon_b)+2Ƒ(\varepsilon_{mi}-\varepsilon_b)}{(\varepsilon_{mi}+2\varepsilon_b)-Ƒ(\varepsilon_{mi}-\varepsilon_b)} \quad (1)$$

where Ƒ is volume fraction and ε_b is dielectric constant of the semiconductor layer material which can be described using the Drude model as shown [9, 11].

$$\varepsilon_b = \varepsilon_{b\infty}\left(1-\frac{\omega_b^2}{\omega^2+i\omega(\gamma_{mb})}\right) \quad (2)$$

$\varepsilon_{b\infty}$ is the infinity dielectric constant of semiconductor layer materials that can be determined as follows:

$$\varepsilon_{b\infty} = \varepsilon_o\left(1+\frac{\omega_b^2}{(E_g)^2}\right) \quad (3)$$

where, γ_mb , ω_b and ε_o are the damping frequency, the plasma angular frequency of semiconductor layer material, and the permittivity of free space, respectively. Using Varshni relation, temperature dependence of the energy band gap 〖 E〗_gin semiconductors used in absorber or window layer can be described as ref. [12, 13]. ε_{mi} is dielectric constant of the metallic inclusion which can be described using the Drude model as shown [13]

$$\varepsilon_{mi} = \varepsilon_{INTRA} + 1 - \frac{\omega_m^2}{\omega^2+i\omega\left(\gamma_m+\left(\frac{3v_{fi}}{4R_i}\right)\right)} \quad (4)$$

where γ_m is the macroscopic damping constant due to the dispersion of the electrons by the ions of the system of metallic material, R_i is the metallic inclusion radius, ω_m , v_{fi} are the plasma angular frequency and the fermi velocity of the metallic material. ε_{INTRA} is the contribution from the intra-band transitions. The electron–hole pair generation rate in the nanocomposite absorber layer using individual metallic nanoparticles can be written as [14]

$$G_i(\lambda) = \frac{\alpha_{bi}(\lambda)e^{-\alpha_w(d_w)}[1-R(\lambda)]\lambda\emptyset(\lambda)}{hc} \quad (5)$$

where, λ is the wave length, $\emptyset(\lambda)$ is the intensity of the solar spectral, c is the speed of light, h is the Plank constant. $\alpha_{bi}(\lambda)$ is the absorption coefficient of the nanocomposites absorber layer using individual nanoparticles, and α_w is the absorption coefficient of the window layer in nanocomposite thin film solar cell. $\alpha_b(\lambda)$ *and* α_w are the absorption coefficient of the nanocomposite absorber layer or window layer that can be calculated by the Beer-Lambert's law as following expression [15].

$$\alpha(\lambda) = \frac{2.303 \times A_t}{d_t} \quad (6)$$

A_t is the absorbance of the nanocomposite absorber or window layer that calculated as follows:

$$A_t = 1 - T_{tef} - R_{tef} \quad (7)$$

where d_t is the thickness of the layer, $R_{tef}$and T_{tef} are the reflectance and transmittance of layer depend on the refractive index of layer and the refractive index of substrate layer that has been evaluated by the ref [16]. The refractive index of front layer material (ZnO) was calculated using sellmeier equations [17]. Moreover, the refractive index of thin film window layer (CdS) as substrate film doping semiconductor for front layer or as thin film layer material was calculated as follows [16]

$$n = \sqrt{\frac{|\varepsilon_b| + \varepsilon_{reb}}{2}} \quad (8)$$

The refractive index of nanocomposite absorber layer material (CIGS) using individual nanoparticles was calculated by equation (8) using real and absolute value of effective dielectric constant of nanocomposite absorber layer material ε_{refi} , $|\varepsilon_{efi}|$. The substrate layer material of absorber layer is metallic material (Mo). The dielectric constant of the metallic material ε_m can be described as [13].

$$\varepsilon_m = \varepsilon_{INTRA} + 1 - \frac{\omega_m^2}{\omega^2 + i\omega(\gamma_m)} \quad (9)$$

The refractive index of substrate film absorber layer material was calculated by using Eq. 8 by using dielectric constant of metallic material ε_m . The forward diode current for nanocomposite cells using individual nanoparticles $J_{diode}(V)$ was calculated based on ref. [18, 19]:

$$J_{diode}(V) = J_{0i}\left[\exp\left(\frac{Q(V + J(V)R_{ser})}{nKT}\right) - 1\right] \quad (10)$$

$$J_{0i} = \frac{W_i Q\sqrt{N_{con}N_{val}\exp\left(-\frac{E_{gbi}}{KT}\right)}}{\sqrt{ŧ_e ŧ_h}} \quad (11)$$

$$W_i = \sqrt{\frac{2\varepsilon_0\varepsilon_{efi}(V_{bi} - V)}{Q(N_a - N_d)}} \quad (12)$$

where, V_{bi} is the built-in potential.$N_a - N_d$ is the concentration of uncompensated acceptors (the total concentration of acceptors minus the total concentration of donors). V is the applied voltage. J_{0i} is reverse saturation current density in nanocomposite cells. N_{con} and N_{val} are the effective state densities in the conduction and valence bands that depend on the effective mass of electrons and holes. R_{ser} is the series resistance. n is diode ideality factor. T is absolute temperature. K is boltzman constant. $ŧ_e$ is the electron lifetime. $ŧ_h$ is the hole lifetime. E_{gbi} is the energy band gap of nanocomposites absorber layer material that has been affected by the metallic nanoparticles. The energy band gap of a semiconductor increases with decreasing dielectric constant with respect to various empirical rules and expressions of refractive index and energy band gap [18]. Many attempts have been made to correlate the energyband gap to the refractive index of semiconductors. Moss was the first to find arelation between the refractive index and the energy band gap. Ravindra and Srivastava suggested another relation. Reddy and Anjaneyulu proposed alogarithmical form of refractive index as afunction of energy band gap [20-22]. Herve´and Vandamme proposed an overall relation based on the classical oscillator theory. Based on Reddy and Anjaneyulu formula, the energy band gap of nanocomposites absorber layer material E_{gbi} has been calculated by the following expression [22]:

$$E_{gbi} = \frac{36.3}{e^{n_{fi}}} \quad (13)$$

$J_{phi}(V)$ is total photo generated current density using individual nanoparticles which obtained by integrating over all incident photon wavelengths of the solar spectrum [14].

$$J_{phi}(V) = \int_0^{\infty} J_{Ti}(\lambda.V)d\lambda \tag{14}$$

The net *external* current density from a solar cell using individual nanoparticles is [23]

$$J_{ind}(V) = J_{phi}(V) - J_{diode}(V) - \left(\frac{V+J(V)R_{ser}}{R_{sh}}\right) \tag{15}$$

The open circuit voltage equation is expressed as [19].

$$V_{oci} = \left(\frac{KT}{Q}\right)\ln\left[\frac{J_{phi}}{J_O} + 1\right] \tag{16}$$

The output power density from solar cell using individual nanoparticles calculated by the following equation [24]

$$P_{ind} = J_{ind} \times V \tag{17}$$

The calculation of fill factor to an excellent accuracy [19, 24].

$$Fill\ Factor = \frac{P_{maxi}}{V_{oci} \times J_{phi}} \tag{18}$$

P_{maxi} is the maximum point of output power density that determined from $P_{ind} - V$ curve. The final equation for the efficiency of the solar cell is [24]

$$n_i = \frac{J_{phi} V_{oci} Fill\ Factor}{P_{in}} \times 100 \tag{19}$$

where, P_{in} is the input power density. The external quantum efficiency $EQEi(\lambda)$ is defined as the ratio of electrical charges extracted from a solar cell to the number of incident photons. It has been calculated by the following equation [25].

$$EQEi(\lambda) = \frac{J_{phi}(\lambda)}{Q\emptyset(\lambda)} \tag{20}$$

In case of our proposal design of using multiple nanocomposites thin film solar cell, the effective dielectric constant ε_{efj} of multiple nanocomposite absorber material is using second type nanoparticles with spherical metal inclusions calculated by the equation

$$\varepsilon_{efj} = \varepsilon_{efi} \frac{(\varepsilon_{mj}+2\varepsilon_{efi})+2Ƒ(\varepsilon_{mj}-\varepsilon_{efi})}{(\varepsilon_{mj}+2\varepsilon_{efi})-Ƒ(\varepsilon_{mj}-\varepsilon_{efi})} \tag{21}$$

where, ε_{efi} is dielectric constant of base matrix. Ƒ is volume fraction. ε_{mj} is dielectric constant of the second type metallic inclusion that can be describe using the Drude model as follows:

$$\varepsilon_{mj} = \varepsilon_{INTRj} + 1 - \frac{\omega_{pj}^2}{\omega^2 + i\omega\left(\gamma_{mj} + (\frac{3v_{fj}}{4R_j})\right)} \tag{22}$$

where, γ_{mj} is the macroscopic damping constant due to the dispersion of the electrons by the ions of the system of second type metallic inclusion. R_j is second type metallic inclusion radius. ω_{pj} is the plasma angular frequency of second type inclusion material. v_{fj} is the fermi velocity of second type nanoparticles. ε_{INTRj} is the contribution from the intra-band transitions of second type inclusion material. Whatever, the refractive index of nanocomposite absorber material that is using multiple nanoparticles n_{fj} (CIGS) as substrate film semiconductor for window layer or as thin film layer material was calculated by Eq.8 using the effective dielectric constant ε_{efj} of multiple nanocomposite absorber material. Note, Eq. 13 succeeded to estimate the effect of adding the second type nanoparticles fillers on the energy band gap E_{gbj} based on the effective dielectric constant of multiple nanocomposites absorber layer ε_{efj}.

The reverse saturation current density and the width of the depletion layer changed due to changing in the dielectric constant and energy band gap of absorber layer according to calculations of effective dielectric constant of multiple nanocomposites absorber layer material ε_{efj}. On the other hand, the electron–hole pair generation rate in the nanocomposite absorber layer using multiple metallic nanoparticles can be calculated by using Eq. 5 according to the absorption coefficient of the multiple nanoparticles absorber layer and window layer $\alpha_{bj}(\lambda)$, α_w. The absorption coefficient of the multiple nanocomposites absorber $\alpha_{bj}(\lambda)$ can be calculated by the Beer-Lambert's law with Eq.'s (6-8), it has been used the new refractive index of multiple nanocomposites absorber layer material n_{fj}. Also, adding second type nanoparticles affect on the performance of nanocomposites thin film solar cell by changing the net external current density, open circuit voltage, fill factor and efficiency of nanocomposites thin film solar cell. The net external current density, open circuit voltage, fill factor and efficiency of multiple nanocomposites thin film solar cell have been calculated based on Eq. (15-20) by using the new generation rate and depletion width of the multiple nanocomposites cell.

3. RESULTS AND ANALYSIS

3.1. Selected Materials and Parameters

The aim of this work is improving the efficiency and performance of ZnO/CdS/CIGS/Mo traditional model based on sub micro absorber layer thickness for achieving high efficiency with less absorber layer thickness and saving the cost of materials by using individual and multiple nanofillers of selected metallic materials in CIGS absorber layer of CdS/CIGS model [6]. Tables 1-3 depict the main parameters of usage materials and parameters of individual and multiple nanocomposites thin film models; the results have been obtained by using nanometallic fillers radii 1nm and under illumination condition of AM1.5 solar irradiations.

Table 1**.** Parameters of usage materials in individual and multiple nanocomposites thin film solar cells models [3, 12, 26]

Parameters	CIGS	CdS
Band gap (eV) at zero Kelvin	1.25	2.58
Band gap parameter α (eVK^{-1}) $\times 10^{-4}$	1.02	4.202
Band gap parameterβ (K)	272	147
Electron mobility (cm^2/Vs)	100	350
Hole mobility (cm^2/Vs)	25	50
Electron carrier density (cm^{-3})$\times 10^{13}$	5.7	41
Effective mass of electron	0.09	0.2
Effective mass of holes	0.75	0.7

Table 2. Parameters of proposal individual and multiple nanocomposites thin film solar cells models [4]

Parameters	CdS/CIGS
Absorber layer thickness(nm)	360
Window layer thickness(nm)	40
Front layer thickness (nm)	450
Electron lifetime (s)	16×10^{-7}
Hole lifetime (s)	$1 \cdot 6 \times 10^{-5}$
$N_a - N_d$ the concentration of uncompensated acceptors (cm-3)	7.56×10^{13}
Diode quality factor	1.5
Series resistance (Ω. Cm^2)	2.5
Shunt resistance (Ω. Cm^2)	320

Table 3. Characteristics of usage materials as substrate layer or fillers in absorber layer for nanocomposites thin film models [27]-[30]

Material	Plasma angular frequency ($\omega_p 10^{16}$rad/s)	Damping constant (γ_m 10^{13} s^{-1})	Fermi velocity (v_f 10^6m/s)
CIGS	0.0386	19.5	-
Cesium (Cs)	0.54	0.756	0.75
Lithium (Li)	1.22	1.85	1.29
Copper (Cu)	1.03	5.26	1.57
Silver (Ag)	1.40	2.80	1.39
Aluminum (Al)	1.09	12.4	2.03
Molybdenum (Mo)	0.19	1.13	-

3.2. Individual and Multiple CdS/CIGS nanocomposites design

Figure 1 depicts the energy band gap of CIGS nanocomposites with various volume fractions. The energy band gap of CIGS enhanced by increasing the volume fraction at wavelength 500nm. Cesium has been the best inclusion used for increasing the energy band gap of CIGS. Figure 2 depicts the refractive index and dielectric constant of CIGS nanocomposites with various volume fractions. The refractive index and dielectric constant of CIGS nanocomposites decreased by increasing the concentration of Silver, Copper, Lithium, Aluminum or Cesium metallic nanofillers in the CIGS base matrix

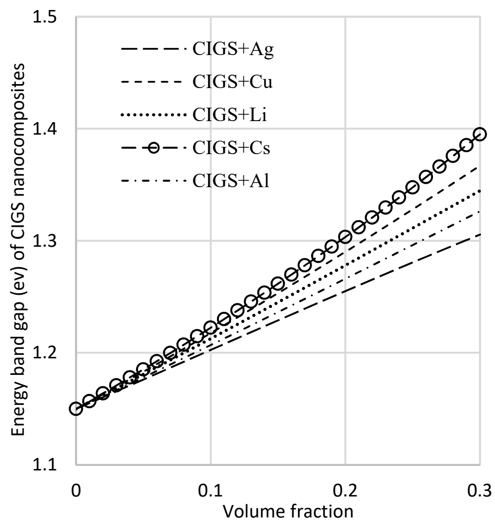

Figure 1. Effect of metallic nanoparticles on the energy band gap of CIGS

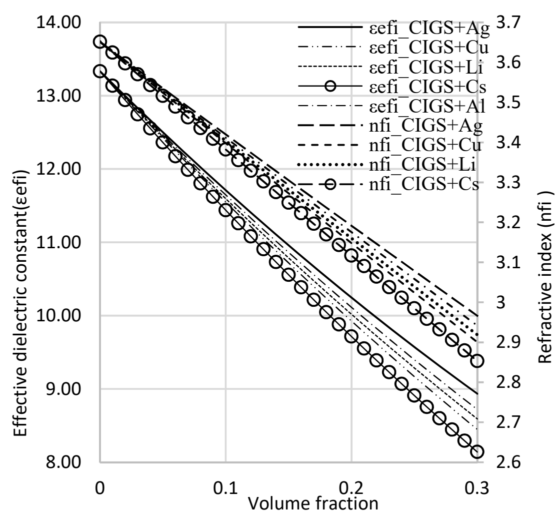

Figure 2. Dielectric constant and refractive index of CIGS nanocomposites with various volume fractions

Figures 3 and 4 show J-V and P-V characteristics of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cells using individual nanoparticles. Using 20wt.% of Silver, Copper, Lithium, Aluminum or Cesium individual nanoparticles in CIGS absorber layer enhanced the short circuit current density, open circuit voltage and output power density of CdS/CIGS nanocomposites thin film solar cell. Using 20wt.%Cesium nanoparticles in absorber layer has been the best inclusion for improving the J-V and P-V characteristics of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cell at room temperature.

Figures 5 and 6 show the metallic nanoparticles concentration that affect on the generation rate and absorption coefficient in absorber layer and depletion width of CdS/CIGSnanocomposites thin film solar cell. The increase in the concentration of metallic nanoparticles of the absorber layer CdS/CIGS thin film solar cell decreased the depletion width of CdS/CIGS nanocomposites thin film solar cell. On the other side, the electron-hole generation rate and the absorption coefficient of CIGS enhanced with increasing the volume fraction of nanofillers of selected metallic materials. Cesium has been the best inclusion that used for decreasing the space charge region and increasing both the generation rate and the absorption coefficient of CIGS in CdS/CIGS nanocomposites thin film solar cell. Copper has been the second order for decreasing the depletion width of cell and increasing both the generation rate and the absorption coefficient of CIGS.

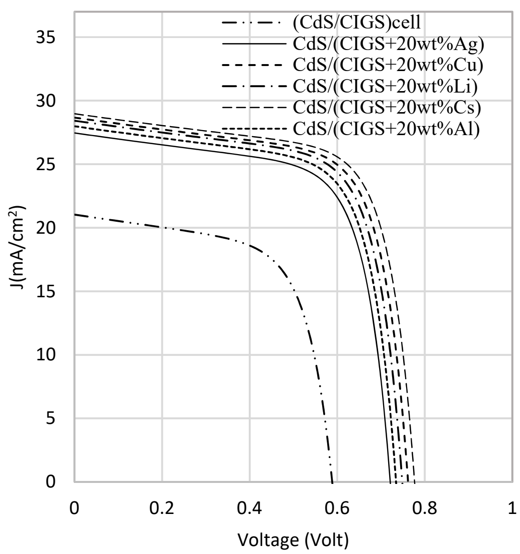

Figure 3. J-V characteristics of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cells using individual nanoparticles

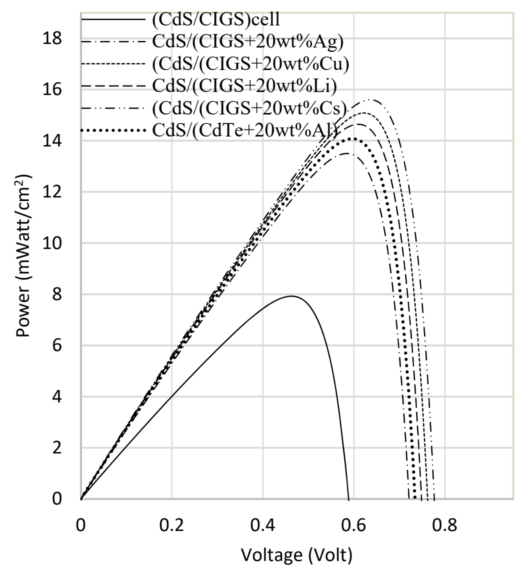

Figure 4. P-V characteristics of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cells using individual nanoparticles

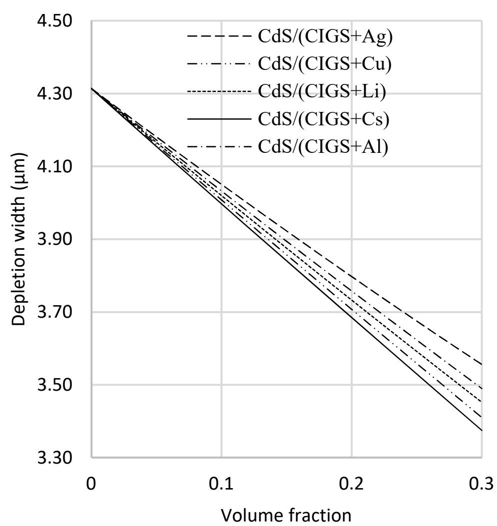

Figure 5. Metallic nanoparticles concentration effect on depletion width of CdS/CIGS nanocomposites thin film solar cell

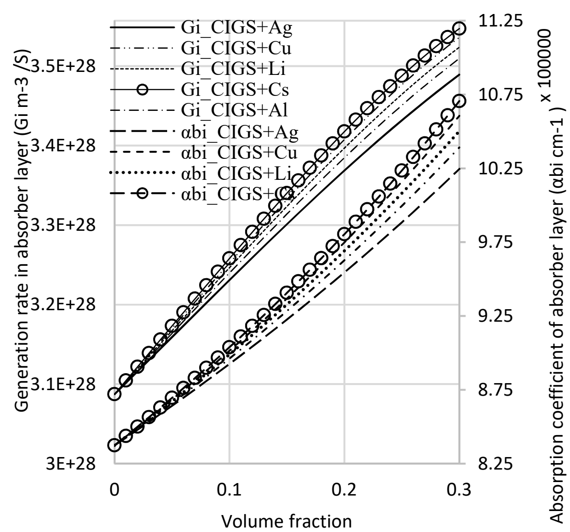

Figure 6. Metallic nanoparticles concentration effect on the generation rate and absorption coefficient in absorber layer of CdS/CIGSnanocomposites thin film solar cell

Figure 7 shows the metallic nanoparticles concentration effect on the external quantum efficiency with increasing the wave length. Using 20wt.% of metallic nanoparticles (Copper, Lithium, Cesium, Aluminum or Silver) enhanced the external quantum efficiency of CdS/CIGS nanocomposites thin film solar cells with increasing the wave length. Figure 8 shows energy conversion efficiency and Fill Factor of CdS/CIGS nanocomposites thin film solar cells. It is cleared that the increase of metallic nanoparticles concentration in the absorber layer of CdS/CIGS nanocomposites thin film solar cells increased the energy conversion efficiency and fill factor of CdS/CIGS nanocomposites thin film solar cells. Cesium is the best filler for increasing the efficiency of CdS/CIGS nanocomposites thin film solar cell, however, Silver is the least one for enhancing the energy conversion efficiency and fill factor of the cell. Figures 9 and 10 depict the energy band gap, refractive index and dielectric constant of (CIGS) multiple nanocomposites with various volume fractions at wave length 500nm. Moreover, increasing volume fraction of Copper, Lithium, Silver or Cesium nanoparticles in (CIGS+20wt.%Al) nanocomposite absorbsr layer has been reduced the dielectric constant, refractive index and increased the energy band gap of (CIGS+20wt.%Al) nanocomposite.

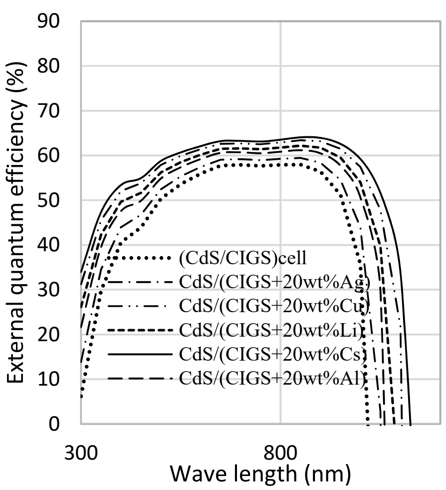

Figure 7. External quantum efficiency of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cells using individual nanoparticle

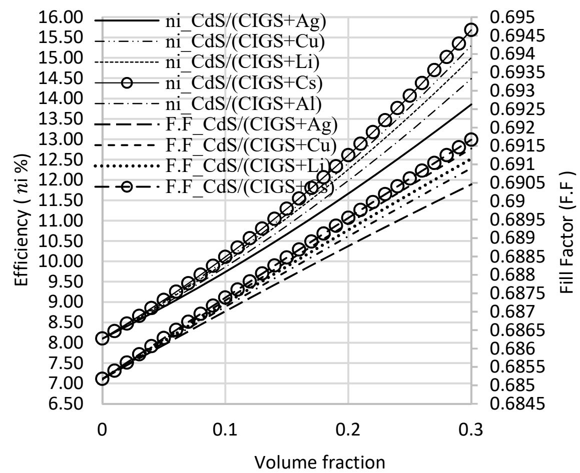

Figure 8. Metallic nanoparticles concentration effect on the fill factor and efficiency of ZnO/CdS/CIGS/Mo nanocomposites thin film solar cells

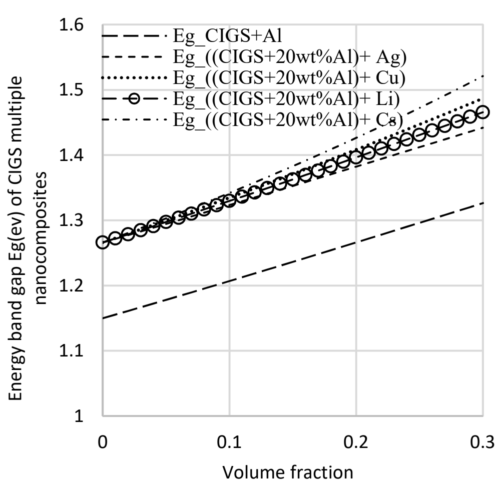

Figure 9. Energy band gap of CIGS multiple nanocomposites with various volume fraction

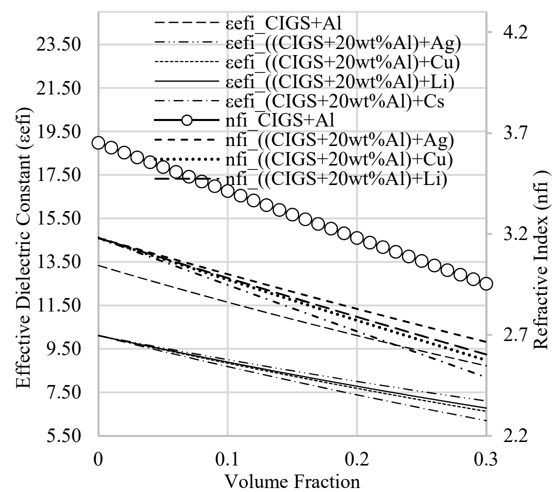

Figure 10. Dielectric constant and refractive index of CIGS multiple nanocomposites with various volume fractions

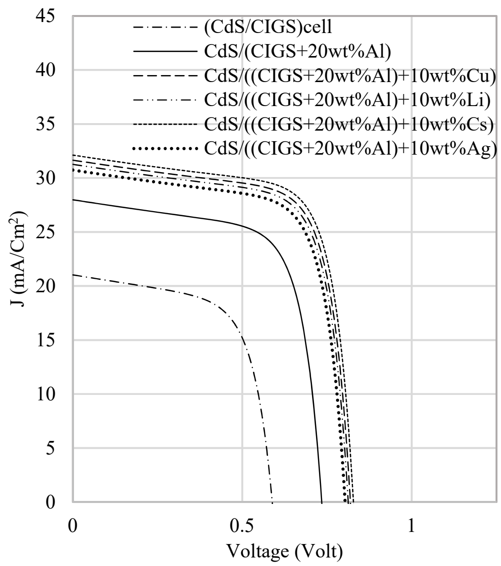

Figure 11. J-V characteristics of CdS/(CIGS+20wt.%Al) nanocomposites thin film solar cells using multiple nanoparticles

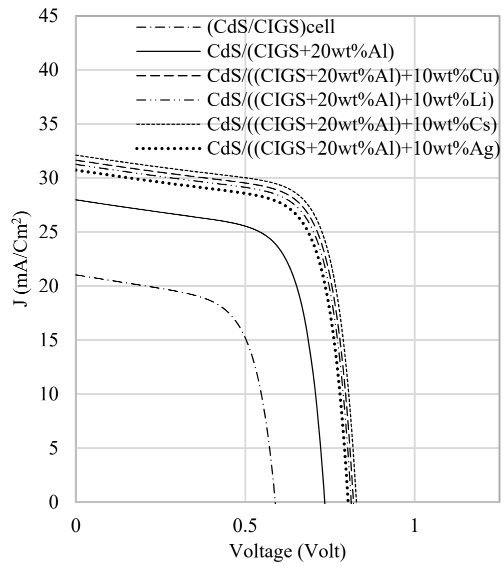

Figure 12. P-V characteristics of CdS/(CIGS+20wt.%Al) nanocomposites thin film solar cell using multiple nanoparticles

Figures 13 and 14 describe that adding individual or multiple metallic nanoparticles in CIGS layer is increased the pair electron-hole generation rate in CIGS absorber layer for CdS/CIGS thin film solar cell. The usage of Cesium as second type nanoparticles is the best inclusion for improving the absorption and generation rate in absorber layer of CdS/CIGS nanocomposites thin film solar cell. Moreover, using Silver, Cupper, Lithium or Cesium in CIGS+20wt.%Al nanocomposites absorber layer are decreasing the space charge region in CdS/CIGS nanocomposites thin film solar cell.

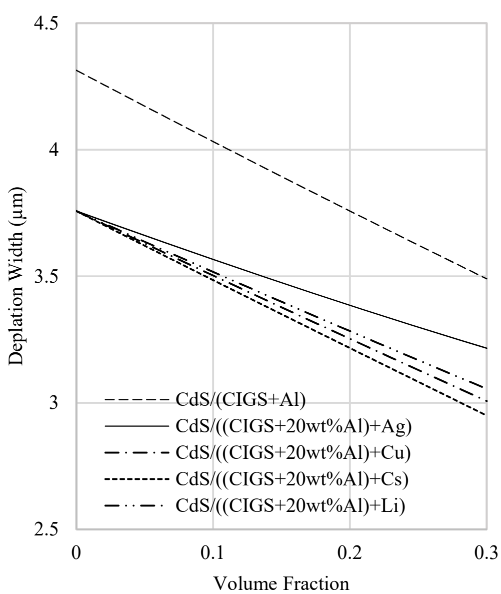

Figure 13. Depletion width of CdS/ (CIGS +20wt.%Al) nanocomposites thin film solar cell with various volume fraction of multiple nanoparticles

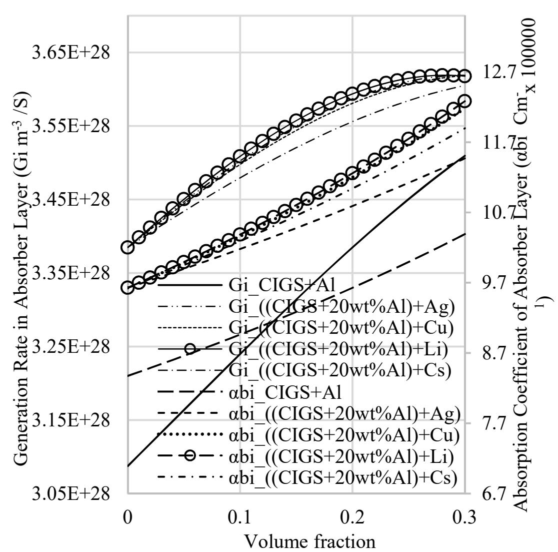

Figure 14. Generation rate and absorption coefficient of absorber layer in CdS/ (CIGS +20wt.%Al) nanocomposites thin film solar cell with various volume fraction of multiple nanoparticle

Figures 15 and 16 show the performance of efficiency and Fill Factor of CdS/ (CIGS +20wt.%Al) nanocomposites thin film solar cells with varying volume fraction of multiple nanoparticles. Increasing the concentration of Aluminum individual metallic nanoparticles or using 20wt.% Al and increasing the concentration of Silver, Copper, Cesium, or lithium in the absorber layer of CdS/CIGS thin film solar cell enhanced the energy conversion efficiency, Fill Factor and external quantum efficiency of CdS/CIGS thin film solar cell.

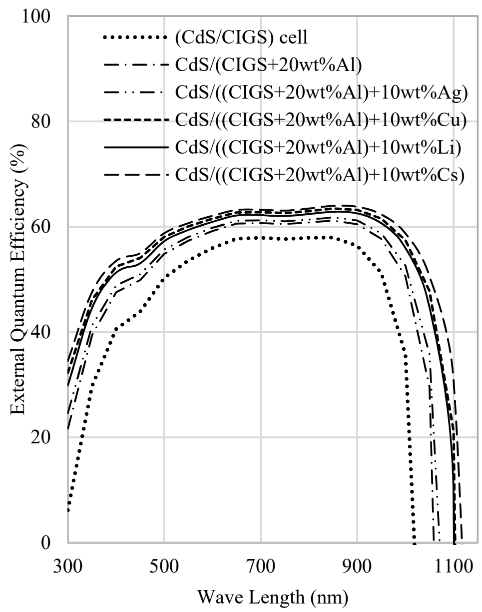

Figure 15. External quantum efficiency of CdS/(CIGS+20wt.%Al) nanocomposites thin film solar cell using multiple nanoparticles

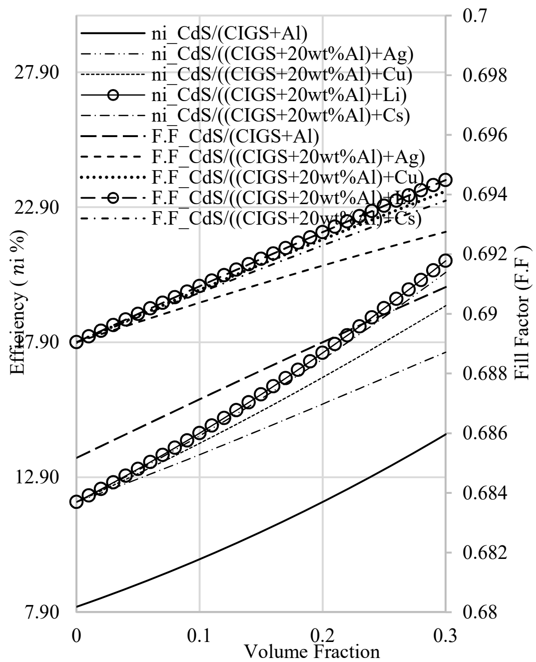

Figure 16. Efficiency and Fill Factor of CdS/ (CIGS+20wt.%Al) nanocomposites thin film solar cell with variousvolume fraction of multiple nanoparticles

4. CONCLUSION

Using Cesium as individual nanofillers in CIGS base matrix has been the best filler for enhancing the optical characteristics of CIGS material and the performance of CdS/CIGS thin film cell which based on submicro absorber layer thickness. However, adding Aluminum or Silver as individual nanoparticles have been the least for improving PV cell performance. For multiple nanocomposites, it has been succeded to design 10wt.% of Cesium as asecond type nanofiller in (CIGS+20wt.%Al) nanocomposite absorber layer to obtain the best enhancent in performance of CdS/(CIGS+20wt.%Al) nanocomposite cell. Adding individual and multiple nanofillers of selected metallic materials in submicro CIGS absorber layer of CdS/CIGS model succeded for enhancing the performance of CIGS thin film solar cell and achieved high efficiency with less usage material and so saving the production cost and time.

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