Journal of Basic and Environmental Sciences, 8 (2021) 36-46

ISSN
Online:2356-6388
Print : 2536-9202

Research paper **Open Access**

A review of Thin Film Solar Cells

Fady Elhady[1*], Mostafa Fedawy[2], Tarek M. Abdolkader[1]

[1]Department of Basic Engineering sciences,Benha faculty of engineering, Benha University, Benha, Egypt

[2]Electronics and Communications Department, Faculty of Engineering, Arab Academy for Science and Technology and Maritime Transport, Alex, Egypt

Corresponding author's email: fady.elhady@bhit.bu.edu.eg Mostafa Fedaw's email: m.fedawy@aast.edu*
Tarek M. Abdolkader'email: tarek.abdolkader@bhit.bu.edu.eg

***Abstract*;**
Researchers did their best to find an alternative supply of energy to replace fossil fuel, which is crucial for environmental requirements. One of the best candidates is solar energy, which is clean, abundant, and sustainable. To convert this energy into electricity directly, Photovoltaic (PV) solar cells are used, hence these PV solar cells attracted researchers to explore various methods of their development and the possibilities of enhancing their performance. These solar cells passed through many phases of development to achieve low cost and high efficiency starting from the first generation which uses wafer crystalline silicon passing to the second generation which is based on thin films such as amorphous Silicon (a-Si), Cadmium Telluride (CdTe), and Copper Indium Gallium diSelenide (CIGS), reaching the third generation based on perovskite materials. Second generation solar cells nowadays compete with crystalline silicon solar cells because it uses less amount of material which leads to fabrication of module with low cost resulting in higher efficiency compared to the first generation cells. This work reviews thin film solar cells regarding the aspects of development methods, structure, advantages, and disadvantages.

Keywords: *Thin film solar cells, a-Si, CIGS, and CdTe.*
Received; 1 Dec. 2020, Revised form; 24 Dec. 2020, Accepted; 24 Dec. 2020, Available online 1 Jan. 2021.

I. Iintroduction

Sun is the source of light and heat which is clean, costless and sustainable source of energy for generating electricity. The light from sun can be transformed to electrical energy by using solar cells which must achieve the cost effectiveness (i.e high efficiency by using less material) and reliability. These solar cells can be classified into two types (i) traditional solar cells (silicon wafers based solar cells or crystalline silicon based solar cells) (ii) Thin film solar cells which can be divided into two types first type based on silicon such as (amorphous silicon a-Si , polycrystalline silicon and nano-crystalline silicon) the second type based on elements of group six in periodic table such as Cadmium Telluride (CdTe) and Copper Indium Gallium diSelenide (CIGS) [1, 2].

During the previous years, silicon wafers solar cells participated with large percentage in the market of photovoltaic industry but this technology did not achieve cost-effectiveness as the cost of silicon wafers was high which made the cost of the module was high. To overcome this challenge the world was directed for using thin film technologies as these technologies achieved cost effectiveness as they used less amount of materials that made the cost of module was low [3].

Thin film solar cells have advantages as mentioned such as using less amount of materials and can be deposited by various deposition techniques such as techniques that depend on vacuum like (sputtering and thermal evaporation), as well as techniques that depend on liquid like (chemical bath deposition CBD). These thin films can be deposited on substrates to provide them mechanical protection, these substrates can be rigid like (soda lime glass SLG) and flexible such as (polymer ,metallic foils ,plastic ,papers etc), these flexible substrates enable thin films to be used in many applications like (building integrated photovoltaics BIPV) [3, 4].

A-si is used for many mini-applications such as a source of power for calculator, watches as reported at the end of 1980, but a-Si faced challenge as its efficiency degrades with time which is called Wronski-effect. This directed attraction for finding an alternative such as CdTe and CIGS. Although CdTe gives high efficiency and stability, it contains Cd which is a toxic material and harms human and environment. On the other hand, CIGS gives high efficiency with low cost but it contains (gallium Ga and indium In) elements which are not abundant. These challenges that face CdTe and CIGS make them behind c-Si technology in PV market [3, 5]

This work focuses on the comparison between major three types of thin film solar cells which are (a-Si ,CIGS and CdTe). History, structure, deposition techniques, advantages and challenges of these three types will be presents in sections II, III, and IV, respectively. Conclusions will be summarized in section V.

II. AMORPHOUS SILICON SOLAR CELL

Due to the less amount needed of silicon material and the possibility of using deposition techniques with low temperature, a-Si based solar cells attracted researchers for improving their performance .In this section history, structure with deposition technique and challenges with solution will be presented [6].

Emergence and progress of a-Si solar cells

In 1976 David carlson and Wronski made first amorphous silicon thin film solar cell with thickness of 1 μm and gave efficiency of 2.4% by using silane gas (SiH_4) and process of glow discharge as shown in figure 1 [7]. Later in 1980 RCA laboratory made a-Si based solar cell with structure of (P-I-N) ,area of 1.9 cm^2 and using glow discharge deposition , with overall gave efficiency of 6.1 % [8]. Kim et al used photo-CVD technique for depositing undoped a-Si:H layer in separate champer, this cell gave efficiency of 11.2% [9]. In 1993 Katsuya et al made optimization for a-Si solar cell by using zinc oxide (ZnO) as transparent conductive oxide (TCO) , pre-anealing technique and ZnO/Ag/Al as a back reflector , this cell achieved efficiency of 11.9% [10]. Yang et al achieved stabilized conversion efficiency of 13% after 1000 h of light exposure time by using triple – junction structure which consists of (a-Si as top cell) , (a-SiGe) as intermediate and bottom cell as shown in figure 2 [11]. In 2002 Jensen et al made hetero-junction solar cell with efficiency 14.1% from (a-Si/c-Si), such that a-Si layer was deposited by (PECVD plasma enhanced chemical vapor deposition technique) [12]. Later, in 2010 Yan et al obtained stabilized efficiency of 12.5% by using triple junction formed from (a-Si:H/nc-Si:H/ nc-Si:H) [13]. Hairen et al in 2016 reported 11.6% efficiency of tandem solar cell from (a-Si:H/polymer) and 13.2% for triple solar cell from (a-Si:H/ a-Si:H/polymer) [14]. In 2019, Wei lie et al achieved improvement in efficiency reached to 18.45% by using (NIP) structure of a-Si based solar cell with using Nano-pillars arrays and CdS quantum dots [15].

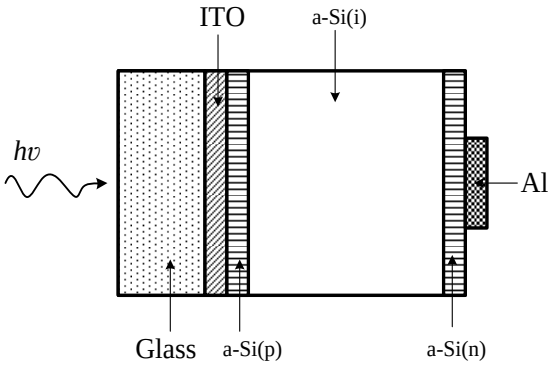

Fig (1): First structure of a-Si solar cell [7].

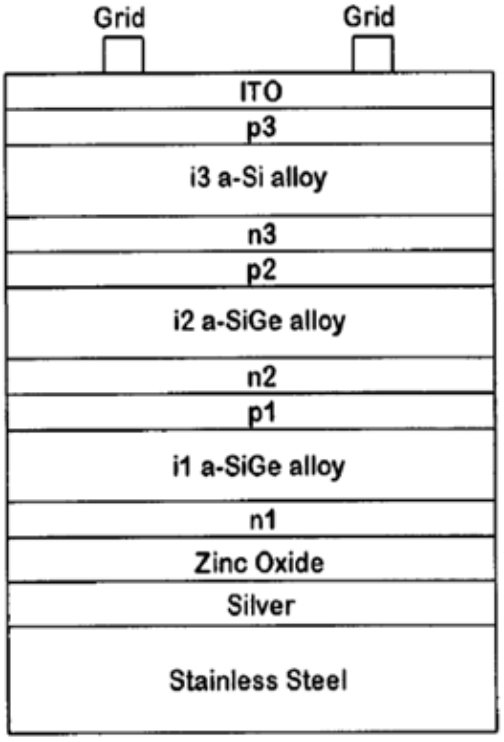

Fig (2): Triple junction structure a-Si solar cell [11]

B. Theory of operation and the structure of a-Si solar cell:

Amorphous silicon solar cell (a-Si) is called drift device as it uses the drift mechanism for transporting photo-generated carriers. Figure 3 which illustrates the theory of operation for a-Si solar cell , generally it consists of (p,i,n layers) such that i-layer which enhances internal electric field, exists between p and n layers. When light reaches the intrinsic layer (i-a-Si), electron-hole pairs will be generated, these photo-generated carriers will be separated by this internal electric field, after that electrons will go to (n-type layer) but holes will go to (p-type layer), then electrodes will collect these charge carriers [16].

Regarding figure 3, which shows the structure of (a-Si:H) solar cell, it contains (substrate, TCO transparent conductive oxide, p-type layer, intrinsic layer ,n-type layer , back reflector layer and back contact). These layers will be discussed according to requirements, materials and deposition techniques points of view.

From literature there are different materials used as Substrate layer such as glass, sheet steel, polyimide foils, polymer as polyethylene terephtalate (PET), polyethylene (PE) and graphene paper [17]. As known transparent conductive oxide (TCO) is used as front contact in the case of p-i-n thin film solar cells [18]. TCO should satisfy some requirements: (1) it should be transparent enough (i.e its optical absorption should be low for the range from ultraviolet to infrared) [18, 19], (2) its lateral electrical conductivity should be high, (3) its contact resistance with adjacent layer should be low [19], (4) it should be inactive for the case of hydrogen plasma [20], and (5) it should be able to achieve light trapping to enhance absorption in absorber layers and decrease thickness which is important

for reducing light induced degradation (Staebler-Wronski effect) [18].

There are various materials and deposition techniques used for fabricating TCO such as: zinc oxide (ZnO) which is more favourable because its deposition temperature and material cost are low, Fluorine doped tin oxide SnO_2 (SnO_2:F) [18, 20], hydrogen-doped In_2O_3 (IO:H) films [19], aluminum doped zinc oxide(AZO) [21], oxide-metal-oxide (OMO) structures like AZO-Ag-AZO [22], amorphous indium zinc oxide (a-IZO) thin films [19]. Deposition techniques used for fabricating TCO layer such as: low pressure chemical vapor deposition (LP-CVD) technique for fabricating ZnO [18], expanding thermal plasma CVD technique for depositing textured ZnO and atmospheric pressure chemical vapor deposition (APCVD) for making Fluorine doped zinc oxide ZnO:F and SnO_2:F [20], RF magnetron sputtering for aluminum doped zinc oxide(AZO) also (a-IZO) thin films [19, 21].

Because the role of p-type layer is very important as it is used as window layer so it should achieve some essential requirements: (1) its band gap is wide, (2) dark and photo-conductivity are high, and (3) activation energy is low [23]. Various materials and deposition techniques can be used for fabrication of p-type material such as amorphous silicon oxide (SiO_x), hydrogenated amorphous silicon carbide (a-SiC:H) and p-type hydrogenated amorphous silicon oxide (p-a-SiO:H) layer which are prepared by plasma enhanced chemical vapor deposition technique (PECVD) [23]. µc-$Si_{1-x}C_x$ films which can be deposited by using hot wire chemical vapor deposition (HWCVD) method [24], by using radio frequency plasma enhanced chemical vapor deposition technique (RF-PECVD) p-type hydrogenated nano-crystalline silicon (nc-Si:H) with wide band gap and high conductivity can be fabricated and used as window layer [25], also by using (filtered cathodic vacuum arc deposition technique) (FCVA) ,Boron doped tetrahedral amorphous carbon (ta-C:B) can be manufactured [26], also wide optical band gap and high work function Transition Metal Oxides (TMO) layers can be used as thermally evaporated dopant-free MoO_x because they have higher band-gap, their absorption coefficient is low and they are more transparent material as compared to a-Si:H(p) and µc-SiOx:H(p) layers [27].

Absorber layer can be fabricated by using various materials and deposition techniques such as (a-Si:H) and (a-SiGe:H) which can be deposited by using (RF-PECVD) [28], µc-Si:H can be deposited by high using 13.56MHz PECVD [29], hydrogenated amorphous silicon films (a-Si:H) that can be fabricated by using Hot-wire chemical vapor deposition (HWCVD) [30], also (a-Si:H) films can be made by using atmospheric pressure plasma chemical vapor deposition (AP-PECVD) technique [31], hydrogenated polymorphous and nano-crystalline silicon films(pm-Si:H,nc-Si:H) can be deposited by HW- and RF-PECVD [32], i-a-SiC:H films can be deposited by using (VHF-PECVD) technique [6], Proto-crystalline silicon (pc-Si:H) which can be fabricated by using moderate pressure and radio frequency (RF, 13.56 MHz) [33].

But for n-layer the materials used such as (a-Si:H, µc-Si:H) which can be fabricated by using (PECVD) [29]. Common back reflector layer is ZnO/Ag which can be made by using the sputtering method [34]. Silver Ag and Aluminium Al are common materials used as Back contact materials [28].

C. Advantages and challenges of a-Si solar cell:

Hydrogenated amorphous silicon (a-Si:H) solar cell offers some advantages such as:

- It uses direct band gap material (a-Si:H) with bandgap energy of about 1.75 eV and it has high absorption coefficient. This helps for absorbing solar spectrum effectively using less amount of Si material [35, 36].
- It can be deposited using low temperature processes which allows low cost flexible substrates such as stainless steel, metal foils and plastics [35, 36].
- It uses abundant material like silicon and it does not use heavy metals such as (Cd) or rare metals as (In, or Te) [36].
- It can be deposited on large area substrates which allows for producing (a-Si:H) module solar panels [36].
- Due to its homogenous appearance, it can be used in building-integrated photovoltaic (BIPV) applications [36].

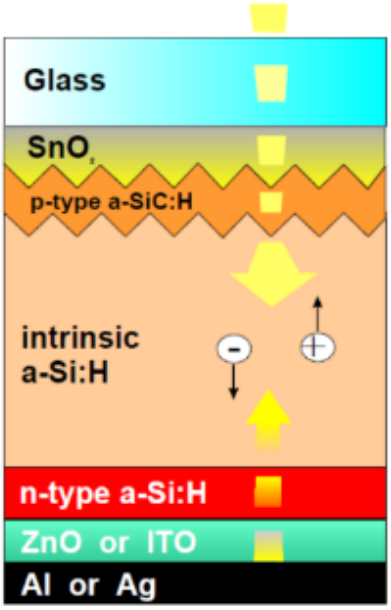

Fig (3): structure of a-Si solar cell [16].

On the other hand, this solar cell faces some challenges:

- As a result of the high density of states of the band gap of (a-Si:H) material, this material has low ability of transporting carriers efficiently and the diffusion length is very short [37].
- Decreased efficiency and degradation in performance due to light exposure which, is called (Staebler-Wronski) effect [38].

III. COPPER INDIUM GALLIUM DISELENIDE(CIGS) SOLAR CELL

A. History of CIGS(Cu(In,Ga)Se_2)

In 2001, Y.Hagiwara et al attained an efficiency of 18% for CIGS based solar cells, this was achieved by using structure of (MgF_2/ZnO:B/i-ZnO/CdS/CIGS/Mo). This because using ZnO:B as a window layer helped for increasing the transmittance of light near the infrared region [39]. On the other hand, in 2004, M.Kaelin et al satisfied an efficiency of only 13.6% by using paste coating technique which is non-vacuum technique used for depositing CIGS layer [40]. Akira et al in 2006 used ZnS(O,OH) as a buffer layer which could be deposited by ultra-sonic chemical bath deposition(US-CBD) to improve the CIGS solar cell performance [41]. Efficiency of 12.8% for CIGS based solar cell was achieved by using chromium free steel as a substrate because it was stable for high temperature processes of CIGS deposition, this work was done by R.Wuerz et al in 2009 [42]. In 2010 Sunghun Jung et al reached to CIGS based solar cell efficiency of 15.56% by using Ga/(In+Ga) ratio of value 0.27, which was the best ratio achieved at that time [43]. R.Wuerz in 2012 studied the effect of using enameled steel as a substrate on the performance of CIGS based solar cells. They recorded cell efficiency of 17.6% for cell and module efficiency of 15% for module [44]. In 2014 Fabian Pianezzi et al proposed CIGS based solar cell with efficiency of 20% by using alkaline elements for doping absorber layer using (post deposition treatment PDT). They used NaF and KF for this purpose [45]. Tim Kodalle et al in 2018 used rubidium fluoride post deposition treatment RF-PDT to raise efficiency of CIGS solar cell by 0.8% [46]. In 2019 Seongyeon kim et al achieved efficiency of 14.52% by using In_2S_3 as a buffer layer and doping it with 3% of tin (Sn^{4+}) [47].

B. Structure and deposition techniques for CIGS solar cell:

Figure 4 shows the simple structure of solar cell, which basically consists of (substrate, back contact, absorber layer, buffer layer and window layer). These layers and their materials and deposition techniques will be discussed in hereinafter. First, substrate layer can be made from different materials with different deposition methods such as soda-lime glass [39], flexible substrates like metallic foils and polymers [4]. Soda lime glass is commonly used because its cost is low and is thermally stable. In addition, it contains sodium Na which diffuses from it to the absorber layer hence it will improve the structure of absorber layer [48]. Second, substrate can be made from flexible materials like metal foils (stainless steel, titanium and Kovar® (Fe/Ni/Co alloy) or ceramic sheet as zirconia or polymer (polyimide). These flexible substrates are very useful because they can be used in many applications and allow for roll-to-roll process which helps for minimizing the cost, also metallic foils showed their ability to be an alternative for rigid glass substrate because they can withstand high temperature, so the absorber layer with high temperature can be deposited. Regarding, metallic foils stainless steel is a promising flexible substrate because it has high thermal and chemical stability, and its thermal coefficient is low. Although the flexible substrates have advantages, they also have some disadvantages especially for metallic foils because at high temperature the detrimental elements diffuses into the absorber layer also the flexible substrates need additional layer to provide sodium Na [40, 44, 49, 50].

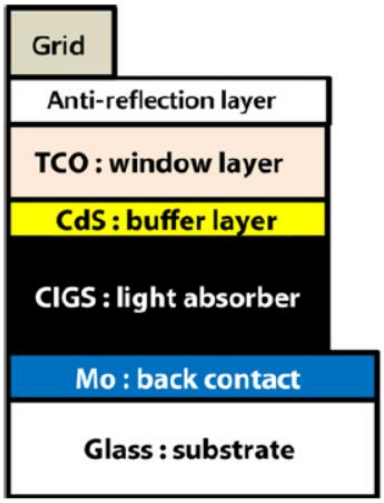

Fig (4): simple structure of CIGS solar cell [48]

There are some requirements for back contact layer such as its electrical resistivity should be low, its optical reflectance should be high, it should provide good adhesion with substrate layer, it should have high stability against corrosive selenization process used for forming absorber layer and it should make ohmic contact with absorber layer [51]. From these requirements many materials were investigated to get one that fulfills these requirements such as molybdenum (Mo) films, Al_2O_3-doped ZnO ceramic, F doped tin oxide (SnO_2:F) and indium tin oxide (ITO) which can be fabricated using DC-sputtering RF-magnetron sputtering also Ni, Au,Au/Be, Pt ,Al, Ag, Cu also Molybdenum bilayer thin films comprising seed and bulk layers, but the commonly used back contact is sputtered Mo because it has high conductivity, good ohmic contact with absorber layer through Mo_2Se layer that is formed between Mo layer and absorber layer. It helps for diffusion of Na from glass substrate into absorber layer and it has high chemical and thermal stability (inertness) against corrosive process such as selenization of absorber layer [48, 50, 51, 52, 53, 54, 55, 56].

In general absorber layer is preferred to be a direct band gap material with high absorption coefficient. In addition, the diffusion length should be high but the velocity of recombination should be low [50]. For CIGS based solar cell, the absorber layer is CIGS whose band gap can be controlled by varying the content of Ga or S. It is a direct band gap material with high absorption coefficient which enables the use of thin material and reducing the energy used for fabrication in addition of being chemically stable [48, 54, 57, 58]. There are different deposition techniques for fabricating this layer such as (in-line evaporation process, elemental co evaporation, flash evaporation, chemical bath deposition, single-source evaporation, RF sputtering, electro-deposition, molecular beam epitaxy (MBE) system, a reactive co-sputtering) [52, 59, 60, 61].

Buffer layer plays important role in CIGS based solar as it helps absorber layer to be chemically and mechanically stable. It allows for reducing interface recombination, and helps for making good band alignment between absorber

and window layer [49, 62, 63]. This layer should be n-type material and has a wide band gap to form hetero-junction and reducing losses due to light absorption in this layer, respectively [62, 63]. Various materials are used for fabricating this layer such as [cadmium sulfide (CdS) and [non-Cd buffer materials like SnO2, In(OH)3, In_2S_3,$Sn(S,O)_2$, ZnSe, Zn(Se,OH) , In(OH,S), ZrO_2, ZnS, ZnO , $Zn(OH)_2$, ZnInSe ,Zn(O,S,OH) and Mg-doped ZnO thin films (Zn, Mg)O] [39, 40, 62,64,65]. These materials can be fabricated using different techniques such as [chemical bath deposition (CBD), chemical bath deposition (US-CBD), atomic layer deposition(ALD), electro-deposition (ED) and ion layer gas reaction (ILGAR)] [58, 62]. It was mentioned that there are different materials used as buffer layer but the commonly used one is CdS. However, it has some issues such as parasitic absorption of light due to small band gap (E_g=2.4 eV) and harmful element like Cd that exists in this layer, thus, it is preferred to use free-Cd layer with wide band gap material such as zinc oxide (ZnO) or ZnS. They have band gaps of 3.3 and 3.7 eV, respectively. This leads the increase of external quantum efficiency in short wavelength range [62, 63, 64, 66].

Window layer or transparent conductive oxide (TCO) should achieve some requirements to increase the efficiency of solar cell: (1) it should be highly transparent for light to decrease the possibility of light absorption in this layer, (2) it should have high conductivity to be able to collect photo-generated carriers effectively [65, 67]. There are different materials that can fulfill these requirements like [boron-doped ZnO (ZnO:B) layer, Al-doped ZnO (ZnO:Al) Fluorine doped tin oxide (SnO2:F), Mg doped ZnO (ZMO) film] [39, 64, 68]. These layers can be deposited by RF magnetron sputtering, DC-magnetron sputtering MOCVD atmospheric pressure chemical vapor deposition (APCVD) deposition technique [39, 64, 65, 69]. (ZnO:B) has high optical transmittance while Al-doped ZnO (ZnO:Al) leads to losses due to optical absorption of light near the infrared region [39, 69].

C. Advantages of CIGS based solar cell:

i. This solar cell presents high efficiency compared to other solar cells.

ii. It uses less amount of material of CIGS absorber layer due to its high absorption coefficient, so, its fabrication process is lower in cost.

iii. It has long term stability.

iv. The band gap of its absorber layer can be tuned to match solar spectrum. This leads to enhancement of light absorption.

v. It is compatible with flexible substrates [56, 57, 67, 70, 71, 72].

IV. CADMIUM TELLURIDE SOLAR CELL

A. Birth and progress of cadmium telluride(CdTe) solar cells

In 1980, Nobuo Nakayama et al achieved efficiency of 6.3 % for solar cell based on CdS/CdTe, by using borosilicate glass as a substrate whose area is 4*4 cm^2 and using repeating screen printing and employing heating of CdS,CdTe and C pastes [73]. Later in 1991 T.L.Chu et al made breakthrough such that they made CdS/CdTe based solar cell with efficiency of 13.4% by depositing CdS and CdTe layers by using aqueous solution and close spaced sublimation (CSS), respectively [74]. J.Britt and C.Ferekides in 1993 announced about CdS/CdTe based solar cell with efficiency of 15.8 %. This was achieved by using CdS/CdTe Heterojunction in which CdS and CdTe layers were deposited by chemical vapor deposition and close spaced sublimation, respectively [75]. In 1997, Tetsuga et al fabricated CdS/CdTe based solar cell of 16% by using (metal organic chemical vapor deposition) for fabrication CdS with thickness of 5 nm and close spaced sublimation for depositing CdTe, using indium tin oxide (ITO)/ glass as a substrate [76]. Xuanzhi Wu in 2004 increased the efficiency of CdTe based solar cell to a value of 16.5%, using structure of (cadmium stannate CTO/zinc tin oxide ZTO/CdS/CdTe) [77]. The efficiency of CdS/CdTe based solar cell was improved to reach 17.5% in 2006 through the work of Arturo morales-Acevedo by making improvement for F.F and Vo.c, by the control of doping of CdS and CdTe and making better ohmic contact to CdTe [78]. Naba R.Paudel and Yanfa Yan made CdTe based solar cell with efficiency of 15.5% in 2013 by using (fluoride doped tin oxide FTO) coating soda-lime glass, radio frequency sputtering for fabricating CdS layer in atmosphere of small amount of oxygen and close space sublimation for depositing CdTe [79]. In 2018, Tom Baines et al achieved efficiency of 13.5% by using structure of SnO_2 /CdSe/CdTe/ by replacing CdS with CdSe due to existence of Se, $CdTe_{1-x}$ Se_x was formed due to diffusion of Se into CdTe layer. This led to the band-gap grading which increased lifetime of charge carriers and Voc [80].

B. Basic structure with fabrication method of CdTe solar cell:

In this section the basic structure of CdTe based solar cell will be presented and different deposition techniques for the layers that form this cell also will be investigated. Figure 5 shows the simple structure of CdTe based solar cell which consists of (substrate, front contact, window layer, absorber layer and finally back contact). At first from literature the common materials used as substrate layer are soda lime glass, borosilicate glass which are rigid substrates also metal foils and polymer which are flexible substrates [81, 82,83].

Later, front contact or TCO plays an important role as it is used as an electrode to collect carriers (i.e current collection). This layer should achieve some requirements to be suitable for the use in the CdTe based solar cell: (1) it should be made from highly transparent material to allow for passing light efficiently, (2) it should have low sheet resistance, (3) it should be thermally and chemically stable and (4) it should has ability to make good adhesion with glass substrate [81, 84, 85, 86, 87]. TCO can be made from different materials by different deposition methods such as: tin oxide (SnO_x) or indium–tin oxide In_2O_3 (ITO). It is well known that ITO has sheet resistance that is lower than of SnO_x, but ITO isn't stable during processes of depositing the other layer [84]. Cadmium stannate (Cd_2SnO_4, or CTO) which can be deposited by RF magnetron Sputtering preserves high mobility with high carrier concentration. Moreover, it has high conductivity and has high optical transmission [85, 88, 89, 90]. F-doped SnO_2 film fabricated by using pyrosol technique is highly transparent with low-resistance property [91]. Al-doped ZnO (ZnO:Al) which can be fabricated by using Radio-frequency (RF)-sputtering has

the advantages of high transparency for visible light, high electron mobility and large ability for transporting carriers [86].

The next layer for TCO is window layer ,this layer plays a vital role in CdTe based solar cell as it allows for photons with high energy to pass through it. In addition, it forms junction with absorber layer which creates electric field to separate the minority carriers before they recombine [87, 92]. Window layer should fulfill some conditions for making solar cell with high efficiency: (1) this layer should match absorber layer, (2) it should have low resistivity, (3) it should be highly transparent for light, (4) it shouldn't be thick to avoid absorption of light and shouldn't be very thin to avoid short circuiting and (5) it is preferred for this layer has optical band gap [87, 93]. Regarding materials and deposition techniques, CdS can be deposited by physical vapor deposition method (PVD) or by chemical bath deposition (CBD) and close space sublimation (CSS) [84, 94]. Oxygenated amorphous CdS layer (a-CdS:O) can be prepared by RF sputtering. This layer offers some advantages such as its amorphous structure and its higher optical band gap compared to CdS material so this layer helps for enhancing J_{sc} [77, 95]. Cadmium zinc sulfide ($Cd_{1-x}Zn_xS$) can be set up by using chemical bath deposition (CBD), vacuum evaporation, metal organic chemical vapor deposition, or spray pyrolysis etc. The optical band gap of this material can be tuned which is considered as an important advantage [96]. Moreover, CdSe can be used as window layer because of its ability for enhancing photocurrent due to the diffusion of Se into absorber layer CdTe. In addition, chemical bath deposition (CBD), spray pyrolysis, pulsed laser deposition (PLD) and radio frequency magnetron sputtering can be used for depositing this material [97].

Before presenting deposition, techniques used for preparing absorber layer the features of this layer should be presented. CdTe is a p-type material which is used for absorbing light so it is called absorber layer, it is II–VI compound semiconductor material with direct band gap of optimum value (~1.5 eV). It has high absorption coefficient for visible light (>10^5 cm^{-1}) ,it can be deposited by low cost fabrication process[77, 82, 92, 94, 98, 99]. This layer can be deposited by close space sublimation (CSS), electro-deposition, metal-organic chemical vapor deposition (MOCVD), Pulsed laser deposition (PLD),or vapor phase condensation [82, 84, 100, 101].

It is very useful to investigate back contact because this layer affects the performance of the CdTe based solar cell. Back contact layer helps for improving the performance of solar cell if it satisfies some requirements as follows: (1) it should have work function > 4.5 eV for forming ohmic contact with absorber layer, (2) it should also be able to reflect the transmitted light back into the absorber layer and (3) it should be stable [87,102,103]. Materials used for back contact are Cu-loaded graphite which can minimize series resistance and enhancing stability [84], Molybdenum (Mo) which can be deposited by RF sputtering at room temperature [104], Nano-crystalline (NC) FeS_2 with higher thermal stability [105].

There are some challenges that face CdTe based solar cell like:

i. Losses that result from recombination at the interface of CdTe/CdS.
ii. It is difficult to dope CdTe layer.
iii. Difficulty for making ohmic contact with back contact because the electron affinity of CdTe is high and there is no metal which has work function higher than this value.
iv. Losses due to parasitic absorption that occurred in window layer (CdS).
v. Te isn't abundant element and also Cd is toxic element [4, 94, 106, 107, 108].

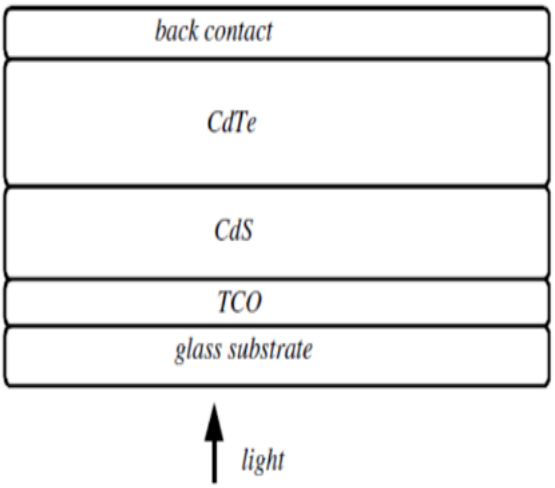

Fig (5): Basic structure of CdTe solar cell [81]

Conclusion

This review article presented comparison between three types of thin film solar cells (a-Si, CIGS and CdTe), it outlined various materials and fabrication methods in addition to merits and issues for each type. Although a-Si based solar cell offers some advantages, it suffers from performance degradation when it is exposed to light, this issue stops its progress in the PV market. On the other hand, CIGS and CdTe based solar cells offer high efficiency with long term stability. In addition, they use less amount of material because of their high absorption coefficient in the visible range. This helps these two types of cells to be a promising candidate for crystalline silicon solar cell. Based on this article, extended work can be done on CIGS based solar cells because the challenges that face this type is little compared to CdTe solar cells, so, this will motivate elaborate research on CIGS based solar cells.

REFERENCES

[1] M. Kaur, H. Singh, A review: Comparison of Silicon Solar cells and thin film solar cells, Int. J. Core Eng. Manag. 3 (2016) 1–9.

[2] M.A. Green, Thin-film solar cells: Review of materials, technologies and commercial status, J. Mater. Sci. Mater. Electron. 18 (2007) 15–19. https://doi.org/10.1007/s10854-007-9177-9.

[3] T.D. Lee, A.U. Ebong, A review of thin film solar

cell technologies and challenges, Renew. Sustain. Energy Rev. 70 (2017) 1286–1297.
https://doi.org/10.1016/j.rser.2016.12.028.

[4] M. Powalla, S. Paetel, E. Ahlswede, R. Wuerz, C.D. Wessendorf, T. Magorian Friedlmeier, Thin-film solar cells exceeding 22% solar cell efficiency: An overview on CdTe-, Cu(In,Ga)Se 2 -, and perovskite-based materials, Appl. Phys. Rev. 5 (2018). https://doi.org/10.1063/1.5061809.

[5] A. Kowsar, M. Rahaman, M.S. Islam, A.Y. Imam, S.C. Debnath, M. Sultana, M.A. Hoque, A. Sharmin, Z.H. Mahmood, S.F.U. Farhad, Progress in major thin-film solar cells: Growth technologies, layer materials and efficiencies, Int. J. Renew. Energy Res. 9 (2019) 579–597.

[6] I.A. Yunaz, K. Hashizume, S. Miyajima, A. Yamada, M. Konagai, Fabrication of amorphous silicon carbide films using VHF-PECVD for triple-junction thin-film solar cell applications, Sol. Energy Mater. Sol. Cells. 93 (2009) 1056–1061.
https://doi.org/10.1016/j.solmat.2008.11.048.

[7] D.E. Carlson, C.R. Wronski, Amorphous silicon solar cell, Appl. Phys. Lett. 28 (1976) 671–673. https://doi.org/10.1063/1.88617.

[8] D.E. Carlson, Recent Developments in Amorphous Silicon Solar Cells., Sol. Energy Mater. 3 (1980) 503–518. https://doi.org/10.1016/0165-1633(80)90002-7.

[9] W.Y. Kim, H. Tasaki, M. Konagai, K. Takahashi, Use of a carbon-alloyed graded-band-gap layer at the p/i interface to improve the photocharacteristics of amorphous silicon alloyed p-i-n solar cells prepared by photochemical vapor deposition, J. Appl. Phys. 61 (1987) 3071–3076. https://doi.org/10.1063/1.337806.

[10] K. Tabuchi, W.W. Wenas, A. Yamada, M. Konagai, K. Takahashi, Optimization of zno films for amorphous silicon solar cells, Jpn. J. Appl. Phys. 32 (1993) 3764–3769.
https://doi.org/10.1143/JJAP.32.3764.

[11] J. Yang, A. Banerjee, S. Guha, Triple-junction amorphous silicon alloy solar cell with 14.6% initial and 13.0% stable conversion efficiencies, Appl. Phys. Lett. 70 (1997) 2975–2977. https://doi.org/10.1063/1.118761.

[12] N. Jensen, R.M. Hausner, R.B. Bergmann, J.H. Werner, U. Rau, Optimization and characterization of amorphous/crystalline silicon heterojunction solar cells, Prog. Photovoltaics Res. Appl. 10 (2002) 1–13.
https://doi.org/10.1002/pip.398.

[13] B. Yan, G. Yue, X. Xu, J. Yang, S. Guha, High efficiency amorphous and nanocrystalline silicon solar cells, Phys. Status Solidi Appl. Mater. Sci. 207 (2010) 671–677. https://doi.org/10.1002/pssa.200982886.

[14] H. Tan, A. Furlan, W. Li, K. Arapov, R. Santbergen, M.M. Wienk, M. Zeman, A.H.M. Smets, R.A.J. Janssen, Highly Efficient Hybrid Polymer and Amorphous Silicon Multijunction Solar Cells with Effective Optical Management, Adv. Mater. 28 (2016) 2170–2177. https://doi.org/10.1002/adma.201504483.

[15] W. Li, Y. Cai, L. Wang, P. Pan, J. Li, G. Bai, Q. Ren, Fabrication and characteristics of N-I-P structure amorphous silicon solar cells with CdS quantum dots on nanopillar array, Phys. E Low-Dimensional Syst. Nanostructures. 109 (2019) 152–155.
https://doi.org/10.1016/j.physe.2019.01.017.

[16] M. Zeman, Introduction to photovoltaic solar energy, Sol. Cells. 10.1016/J. (2006) 1–13.

[17] C. Koch, M. Ito, M. Schubert, Low-temperature deposition of amorphous silicon solar cells, Sol. Energy Mater. Sol. Cells. 68 (2001) 227–236. https://doi.org/10.1016/S0927-0248(00)00249-X.

[18] J. Meier, U. Kroll, S. Dubail, S. Golay, S. Fay, J. Dubail, A. Shah, Efficiency enhancement of amorphous silicon p-i-n solar cells by LP-CVD ZnO, Conf. Rec. IEEE Photovolt. Spec. Conf. 2000-Janua (2000) 746–749. https://doi.org/10.1109/PVSC.2000.915991.

[19] M. Morales-Masis, S. Martin De Nicolas, J. Holovsky, S. De Wolf, C. Ballif, Low-Temperature High-Mobility Amorphous IZO for Silicon Heterojunction Solar Cells, IEEE J. Photovoltaics. 5 (2015) 1340–1347.
https://doi.org/10.1109/JPHOTOV.2015.2450993.

[20] J. Löffler, R. Groenen, J.L. Linden, M.C.M. Van de Sanden, R.E.I. Schropp, Amorphous silicon solar cells on natively textured ZnO grown by PECVD, Thin Solid Films. 392 (2001) 315–319.
https://doi.org/10.1016/S0040-6090(01)01050-1.

[21] F.H. Wang, H.P. Chang, C.C. Tseng, C.C. Huang, H.W. Liu, Influence of hydrogen plasma treatment on Al-doped ZnO thin films for amorphous silicon thin film solar cells, Curr. Appl. Phys. 11 (2011) S12–S16. https://doi.org/10.1016/j.cap.2010.11.109.

[22] M. Theuring, M. Vehse, K. Von Maydell, C. Agert, AZO-Ag-AZO transparent electrode for amorphous silicon solar cells, Thin Solid Films. 558 (2014) 294–297.
https://doi.org/10.1016/j.tsf.2014.02.042.

[23] A. Sarker, A.K. Barua, Development of high quality p-type hydrogenated amorphous silicon oxide film and its use in improving the performance of single junction amorphous silicon solar cells, Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap. 41 (2002) 765–769. https://doi.org/10.1143/jjap.41.765.

[24] S. Miyajima, A. Yamada, M. Konagai, Highly conductive microcrystalline silicon carbide films deposited by the hot wire cell method and its application to amorphous silicon solar cells, Thin Solid Films. 430 (2003) 274–277. https://doi.org/10.1016/S0040-6090(03)00132-9.

[25] Z. Hu, X. Liao, H. Diao, Y. Cai, S. Zhang, E. Fortunato, R. Martins, Hydrogenated p-type

nanocrystalline silicon in amorphous silicon solar cells, J. Non. Cryst. Solids. 352 (2006) 1900–1903. https://doi.org/10.1016/j.jnoncrysol.2006.02.010.

[26] J. Han, M. Tan, J. Zhu, S. Meng, B. Wang, S. Mu, D. Cao, Photovoltaic characteristics of amorphous silicon solar cells using boron doped tetrahedral amorphous carbon films as p -type window materials, Appl. Phys. Lett. 90 (2007). https://doi.org/10.1063/1.2539767.

[27] K. Mallem, Y.J. Kim, S.Q. Hussain, S. Dutta, A.H.T. Le, M. Ju, J. Park, Y.H. Cho, Y. Kim, E.C. Cho, J. Yi, Molybdenum oxide: A superior hole extraction layer for replacing p-type hydrogenated amorphous silicon with high efficiency heterojunction Si solar cells, Mater. Res. Bull. 110 (2019) 90–96.

https://doi.org/10.1016/j.materresbull.2018.10.018.

[28] X. Deng, X. Liao, S. Han, H. Povolny, P. Agarwal, Amorphous silicon and silicon germanium materials for high-efficiency triple-junction solar cells, Sol. Energy Mater. Sol. Cells. 62 (2000) 89–95

. https://doi.org/10.1016/S0927-0248(99)00139-7.

[29] B. Rech, T. Roschek, J. Müller, S. Wieder, H. Wagner, Amorphous and microcrystalline silicon solar cells prepared at high deposition rates using RF (13.56 MHz) plasma excitation frequencies, Sol. Energy Mater. Sol. Cells. 66 (2001) 267–273.

https://doi.org/10.1016/S0927-0248(00)00183-5.

[30] A. Currao, V.R. Reddy, M.K. Van Veen, G. Calzaferri, R.E.I. Schropp, Water splitting with silver chloride photoanodes and amorphous silicon solar cells, Final Progr. Proc. IS T's SPSTJ's - AgX 2004 Int. Symp. Silver Halide Technol. Forefr. Silver Halide Imaging. (2004) 201–204.

[31] H. Kakiuchi, M. Matsumoto, Y. Ebata, H. Ohmi, K. Yasutake, K. Yoshii, Y. Mori, Characterization of intrinsic amorphous silicon layers for solar cells prepared at extremely high rates by atmospheric pressure plasma chemical vapor deposition, J. Non. Cryst. Solids. 351 (2005) 741–747.

https://doi.org/10.1016/j.jnoncrysol.2004.08.271.

[32] S.A. Filonovich, P. Alpuim, L. Rebouta, J.E. Bourée, Y.M. Soro, Hydrogenated amorphous and nanocrystalline silicon solar cells deposited by HWCVD and RF-PECVD on plastic substrates at 150 °C, J. Non. Cryst. Solids. 354 (2008) 2376–2380.

https://doi.org/10.1016/j.jnoncrysol.2007.09.030.

[33] M. Stuckelberger, M. Despeisse, G. Bugnon, J.W. Schüttauf, F.J. Haug, C. Ballif, Comparison of amorphous silicon absorber materials: Light-induced degradation and solar cell efficiency, J. Appl. Phys. 114 (2013) 0–10. https://doi.org/10.1063/1.4824813.

[34] T. Nishimoto, M. Takai, H. Miyahara, M. Kondo, A. Matsuda, Amorphous silicon solar cells deposited at high growth rate, J. Non. Cryst. Solids. 299–302 (2002) 1116–1122.

https://doi.org/10.1016/S0022-3093(02)00942-0.

[35] C.H. Hsu, Y.P. Lin, H.J. Hsu, C.C. Tsai, Enhanced spectral response by silicon nitride index matching layer in amorphous silicon thin-film solar cells, J. Non. Cryst. Solids. 358 (2012) 2324–2326.

https://doi.org/10.1016/j.jnoncrysol.2011.12.102.

[36] Y.H. Chen, Y.T. Liu, C.F. Huang, J.C. Liu, C.C. Lin, Improved photovoltaic properties of amorphous silicon thin-film solar cells with an un-doped silicon oxide layer, Mater. Sci. Semicond. Process. 31 (2015) 184–188. https://doi.org/10.1016/j.mssp.2014.11.042.

[37] R. Ambrosio, M. Moreno, A. Torres, A. Carrillo, I. Vivaldo, I. Cosme, A. Heredia, Deposition and characterization of amorphous silicon with embedded nanocrystals and microcrystalline silicon for thin film solar cells, J. Alloys Compd. 643 (2015) S27–S32. https://doi.org/10.1016/j.jallcom.2014.11.105.

[38] J.W. Schüttauf, B. Niesen, L. Löfgren, M. Bonnet-Eymard, M. Stuckelberger, S. Hänni, M. Boccard, G. Bugnon, M. Despeisse, F.J. Haug, F. Meillaud, C. Ballif, Amorphous silicon-germanium for triple and quadruple junction thin-film silicon based solar cells, Sol. Energy Mater. Sol. Cells. 133 (2015) 163–169.

https://doi.org/10.1016/j.solmat.2014.11.006.

[39] Y. Hagiwara, T. Nakada, A. Kunioka, Improved Jsc in CIGS thin film solar cells using a transparent conducting ZnO:B window layer, Sol. Energy Mater. Sol. Cells. 67 (2001) 267–271.

https://doi.org/10.1016/S0927-0248(00)00291-9.

[40] M. Kaelin, D. Rudmann, A.N. Tiwari, Low cost processing of CIGS thin film solar cells, Sol. Energy. 77 (2004) 749–756.

https://doi.org/10.1016/j.solener.2004.08.015.

[41] A. Ichiboshi, M. Hongo, T. Akamine, T. Dobashi, T. Nakada, Ultrasonic chemical bath deposition of ZnS(O,OH) buffer layers and its application to CIGS thin-film solar cells, Sol. Energy Mater. Sol. Cells. 90 (2006) 3130–3135.

https://doi.org/10.1016/j.solmat.2006.06.032.

[42] R. Wuerz, A. Eicke, M. Frankenfeld, F. Kessler, M. Powalla, P. Rogin, O. Yazdani-Assl, CIGS thin-film solar cells on steel substrates, Thin Solid Films. 517 (2009) 2415–2418.

https://doi.org/10.1016/j.tsf.2008.11.016.

[43] S. Jung, S.J. Ahn, J.H. Yun, J. Gwak, D. Kim, K. Yoon, Effects of Ga contents on properties of CIGS thin films and solar cells fabricated by co-evaporation technique, Curr. Appl. Phys. 10 (2010) 990–996. https://doi.org/10.1016/j.cap.2009.11.082.

[44] R. Wuerz, A. Eicke, F. Kessler, S. Paetel, S. Efimenko, C. Schlegel, CIGS thin-film solar cells and modules on enamelled steel substrates, Sol. Energy Mater. Sol. Cells. 100 (2012) 132–137.

https://doi.org/10.1016/j.solmat.2012.01.004.

[45] F. Pianezzi, P. Reinhard, A. Chirilă, B. Bissig, S. Nishiwaki, S. Buecheler, A.N. Tiwari, Unveiling the

effects of post-deposition treatment with different alkaline elements on the electronic properties of CIGS thin film solar cells, Phys. Chem. Chem. Phys. 16 (2014) 8843–8851. https://doi.org/10.1039/c4cp00614c.

[46] T. Kodalle, M.D. Heinemann, D. Greiner, H.A. Yetkin, M. Klupsch, C. Li, P.A. van Aken, I. Lauermann, R. Schlatmann, C.A. Kaufmann, Elucidating the Mechanism of an RbF Post Deposition Treatment in CIGS Thin Film Solar Cells, Sol. RRL. 2 (2018) 1–9. https://doi.org/10.1002/solr.201800156.

[47] S.Y. Kim, M.S. Mina, K. Kim, J. Gwak, J.H. Kim, Application of a Sn4+ doped In2S3 thin film in a CIGS solar cell as a buffer layer, Sustain. Energy Fuels. 4 (2019) 362–368. https://doi.org/10.1039/c9se00778d.

[48] D. Lee, K. Yong, Non-vacuum deposition of CIGS absorber films for low-cost thin film solar cells, Korean J. Chem. Eng. 30 (2013) 1347–1358.

https://doi.org/10.1007/s11814-013-0101-0.

[49] V.S. Saji, S.-M. Lee, C.-W. Lee, CIGS Thin Film Solar Cells by Electrodeposition, J. Korean Electrochem. Soc. 14 (2011) 61–70

. https://doi.org/10.5229/jkes.2011.14.2.061.

[50] K.B. Kim, M. Kim, J. Baek, Y.J. Park, J.R. Lee, J.S. Kim, C. Jeon, Influence of Cr thin films on the properties of flexible CIGS solar cells on steel substrates, Electron. Mater. Lett. 10 (2014) 247–251.

https://doi.org/10.1007/s13391-013-3158-3.

[51] W. Li, X. Yan, A.G. Aberle, S. Venkataraj, Adhesion Improvement and Characterization of Magnetron Sputter Deposited Bilayer Molybdenum Thin Films for Rear Contact Application in CIGS Solar Cells, Int. J. Photoenergy. 2016 (2016).

https://doi.org/10.1155/2016/2124087.

[52] T. Negami, T. Satoh, Y. Hashimoto, S. Shimakawa, S. Hayashi, M. Muro, H. Inoue, M. Kitagawa, Production technology for CIGS thin film solar cells, Thin Solid Films. 403–404 (2002) 197–203. https://doi.org/10.1016/S0040-6090(01)01524-3.

[53] T. Nakada, Microstructural and diffusion properties of CIGS thin film solar cells fabricated using transparent conducting oxide back contacts, Thin Solid Films. 480–481 (2005) 419–425

. https://doi.org/10.1016/j.tsf.2004.11.142.

[54] A.C. Badgujar, S.R. Dhage, S. V. Joshi, Process parameter impact on properties of sputtered large-area Mo bilayers for CIGS thin film solar cell applications, Thin Solid Films. 589 (2015) 79–84.

https://doi.org/10.1016/j.tsf.2015.04.046.

[55] D. Zhou, H. Zhu, X. Liang, C. Zhang, Z. Li, Y. Xu, J. Chen, L. Zhang, Y. Mai, Sputtered molybdenum thin films and the application in CIGS solar cells, Appl. Surf. Sci. 362 (2016) 202–209.

https://doi.org/10.1016/j.apsusc.2015.11.235.

[56] K.H. Ong, R. Agileswari, B. Maniscalco, P. Arnou, C.C. Kumar, J.W. Bowers, M.B. Marsadek, Review on substrate and molybdenum back contact in CIGS thin film solar cell, Int. J. Photoenergy. 2018 (2018). https://doi.org/10.1155/2018/9106269.

[57] T. Nakada, Invited Paper: CIGS-based thin film solar cells and modules: Unique material properties, Electron. Mater. Lett. 8 (2012) 179–185.

https://doi.org/10.1007/s13391-012-2034-x.

[58] S. Lee, E.S. Lee, T.Y. Kim, J.S. Cho, Y.J. Eo, J.H. Yun, A. Cho, Effect of annealing treatment on CdS/CIGS thin film solar cells depending on different CdS deposition temperatures, Sol. Energy Mater. Sol. Cells. 141 (2015) 299–308.

https://doi.org/10.1016/j.solmat.2015.05.052.

[59] D. Xia, J. Li, M. Xu, X. Zhao, Electrodeposited and selenized CIGS thin films for solar cells, J. Non. Cryst. Solids. 354 (2008) 1447–1450. https://doi.org/10.1016/j.jnoncrysol.2007.02.097.

[60] T. Sakurai, H. Uehigashi, M.M. Islam, T. Miyazaki, S. Ishizuka, K. Sakurai, A. Yamada, K. Matsubara, S. Niki, K. Akimoto, Temperature dependence of photocapacitance spectrum of CIGS thin-film solar cell, Thin Solid Films. 517 (2009) 2403–2406. https://doi.org/10.1016/j.tsf.2008.11.051.

[61] J. Kim, H.S. Lee, N.M. Park, Post-annealing effect on the reactively sputter-grown CIGS thin films and its influence to solar cell performance, Curr. Appl. Phys. 14 (2014) S63–S68

. https://doi.org/10.1016/j.cap.2013.11.040.

[62] Z.H. Li, E.S. Cho, S.J. Kwon, Mg-doped ZnO thin films deposited by the atomic layer chemical vapor deposition for the buffer layer of CIGS solar cell, Appl. Surf. Sci. 314 (2014) 97–103.

https://doi.org/10.1016/j.apsusc.2014.06.136.

[63] W. Witte, S. Spiering, D. Hariskos, Substitution of the CdS buffer layer in CIGS thin-film solar cells: Status of current research and record cell efficiencies, Vak. Forsch. Und Prax. 26 (2014) 23–27.

https://doi.org/10.1002/vipr.201400546.

[64] S. Sharbati, S.H. Keshmiri, J.T. McGoffin, R. Geisthardt, Improvement of CIGS thin-film solar cell performance by optimization of Zn(O,S) buffer layer parameters, Appl. Phys. A Mater. Sci. Process. 118 (2014) 1259–1265. https://doi.org/10.1007/s00339-014-8825-1.

[65] K. Cheng, J. Liu, R. Jin, J. Liu, X. Liu, Z. Lu, Y. Liu, X. Liu, Z. Du, Surface microstructure evolution of highly transparent and conductive Al-doped ZnO thin films and its application in CIGS solar cells, Appl. Surf. Sci. 409 (2017) 124–131.

https://doi.org/10.1016/j.apsusc.2017.03.044.

[66] J. Xiang, X. Huang, G. Lin, J. Tang, C. Ju, X. Miao, CIGS thin films for Cd-free solar cells by one-step sputtering process, J. Electron. Mater. 43 (2014) 2658–2666. https://doi.org/10.1007/s11664-014-3108-3.

[67] J.C. Chang, J.W. Guo, T.P. Hsieh, M.R. Yang,

D.W. Chiou, H. Te Cheng, C.L. Yeh, C.C. Li, S.Y. Chu, Effects of substrate temperature on the properties of transparent conducting AZO thin films and CIGS solar cells, Surf. Coatings Technol. 231 (2013) 573–577. https://doi.org/10.1016/j.surfcoat.2012.02.007.

[68] M. Wang, J. Yi, S. Yang, Z. Cao, X. Huang, Y. Li, H. Li, J. Zhong, Electrodeposition of Mg doped ZnO thin film for the window layer of CIGS solar cell, Appl. Surf. Sci. 382 (2016) 217–224.

https://doi.org/10.1016/j.apsusc.2016.03.232.

[69] S.Y. Guo, L. Sahoo, G. Sosale, A.E. Delahoy, Textured, doped, ZnO thin films produced by a new process for a-Si and CIGS solar cell application, Photovolt. Cell Modul. Technol. 6651 (2007) 66510B. https://doi.org/10.1117/12.736084.

[70] K.J. Hsiao, J. Da Liu, H.H. Hsieh, T.S. Jiang, Electrical impact of MoSe2 on CIGS thin-film solar cells, Phys. Chem. Chem. Phys. 15 (2013) 18174–18178. https://doi.org/10.1039/c3cp53310g.

[71] M. Moradi, R. Teimouri, M. Saadat, M. Zahedifar, Buffer layer replacement: A method for increasing the conversion efficiency of CIGS thin film solar cells, Optik (Stuttg). 136 (2017) 222–227. https://doi.org/10.1016/j.ijleo.2017.02.037.

[72] S. Kuk, Z. Wang, S. Fu, T. Zhang, Y.Y. Yu, J. Choi, J.H. Jeong, D.J. Hwang, Nanosecond laser scribing of CIGS thin film solar cell based on ITO bottom contact, Appl. Phys. Lett. 112 (2018). https://doi.org/10.1063/1.5010340.

[73] H. Search, C. Journals, A. Contact, M. Iopscience, I.P. Address, Screen Printed Thin Film CdS / CdTe Solar Cell, 703 (n.d.).

[74] T.L. Chu, S.S. Chu, C. Ferekides, C.Q. Wu, J. Britt, C. Wang, 13.4% efficient thin-film CdS/CdTe solar cells, J. Appl. Phys. 70 (1991) 7608–7612. https://doi.org/10.1063/1.349717.

[75] J. Britt, C. Ferekides, Thin-film CdS/CdTe solar cell with 15.8% efficiency, Appl. Phys. Lett. 62 (1993) 2851–2852. https://doi.org/10.1063/1.109629.

[76] H. Search, C. Journals, A. Contact, M. Iopscience, I.P. Address, 16 . 0 % Efficient Thin-Film CdS / CdTe Solar Cells, 6304 (n.d.).

[77] X. Wu, High-efficiency polycrystalline CdTe thin-film solar cells, Sol. Energy. 77 (2004) 803–814. https://doi.org/10.1016/j.solener.2004.06.006.

[78] A. Morales-Acevedo, Thin film CdS/CdTe solar cells: Research perspectives, Sol. Energy. 80 (2006) 675–681. https://doi.org/10.1016/j.solener.2005.10.008.

[79] N.R. Paudel, Y. Yan, Fabrication and characterization of high-efficiency CdTe-based thin-film solar cells on commercial SnO2:F-coated soda-lime glass substrates, Thin Solid Films. 549 (2013) 30–35. https://doi.org/10.1016/j.tsf.2013.07.020.

[80] T. Baines, G. Zoppi, L. Bowen, T.P. Shalvey, S. Mariotti, K. Durose, J.D. Major, Incorporation of CdSe layers into CdTe thin film solar cells, Sol. Energy Mater. Sol. Cells. 180 (2018) 196–204. https://doi.org/10.1016/j.solmat.2018.03.010.

[81] N. Romeo, A. Bosio, V. Canevari, A. Podestà, Recent progress on CdTe/CdS thin film solar cells, Sol. Energy. 77 (2004) 795–801.

https://doi.org/10.1016/j.solener.2004.07.011.

[82] N. Romeo, A. Bosio, R. Tedeschi, V. Canevari, Growth of polycrystalline CdS and CdTe thin layers for high efficiency thin film solar cells, Mater. Chem. Phys. 66 (2000) 201–206. https://doi.org/10.1016/S0254-0584(00)00316-3.

[83] S.B. and A.N.T. Christina Gretener*, Julian Perrenoud, Lukas Kranz, Luisa Kneer, Rafael Schmitt, CdTe/CdS thin film solar cells grown in substrate configuration, Prog. Photovoltaics Res. Appl. 21 (2013) 1580–1586. https://doi.org/10.1002/pip.2233.

[84] S.N. Alamri, A.W. Brinkman, Effect of the transparent conductive oxide on the performance of thin film CdS/CdTe solar cells, J. Phys. D. Appl. Phys. 33 (2000). https://doi.org/10.1088/0022-3727/33/1/101.

[85] P. Veluchamy, M. Tsuji, T. Nishio, T. Aramoto, H. Higuchi, S. Kumazawa, S. Shibutani, J. Nakajima, T. Arita, H. Ohyama, A. Hanafusa, T. Hibino, K. Omura, Pyrosol process to deposit large-area SnO2:F thin films and its use as a transparent conducting substrate for CdTe solar cells, Sol. Energy Mater. Sol. Cells. 67 (2001) 179–185. https://doi.org/10.1016/S0927-0248(00)00279-8.

[86] A. Gupta, A.D. Compaan, All-sputtered 14% CdS/CdTe thin-film solar cell with ZnO: Al transparent conducting oxide, Appl. Phys. Lett. 85 (2004) 684–686. https://doi.org/10.1063/1.1775289.

[87] H.A. Mohamed, Dependence of efficiency of thin-film CdS/CdTe solar cell on optical and recombination losses, J. Appl. Phys. 113 (2013). https://doi.org/10.1063/1.4794201.

[88] H. Cd, S.C. Cdte, P.T.S. Cells, X. Wu, R. Ribelin, R.G. Dhere, D.S. Albin, T.A. Gessert, S. Asher, D.H. Levi, A. Mason, H.R. Moutinho, P. Sheldon, HIGH-EFFICIENCY Cd,SnOJZn,SnOJZn,Cd,.,S/CdS/CdTe POLYCRYSTALLINE THIN-FILM SOLAR CELLS, (n.d.) 470–474.

[89] X. Wu, S. Asher, D.H. Levi, D.E. King, Y. Yan, T.A. Gessert, P. Sheldon, Interdiffusion of CdS and Zn2SnO4 layers and its application in CdS/CdTe polycrystalline thin-film solar cells, J. Appl. Phys. 89 (2001) 4564–4569. https://doi.org/10.1063/1.1351539.

[90] K. Jeyadheepan, M. Thamilselvan, K. Kim, J. Yi, C. Sanjeeviraja, Optoelectronic properties of R-F magnetron sputtered Cadmium Tin Oxide (Cd2SnO4) thin films for CdS/CdTe thin film solar cell applications, J. Alloys Compd. 620 (2015) 185–191. https://doi.org/10.1016/j.jallcom.2014.09.056.

[91] A. Hanafusa, T. Aramoto, M. Tsuji, T. Yamamoto, T. Nishio, P. Veluchamy, H. Higuchi, S. Kumazawa, S. Shibutani, J. Nakajima, T. Arita, H. Ohyama, T. Hibino,

K. Omura, Highly e $ cient large area (10 . 5 %, 1376 cm) thin- " lm CdS / CdTe solar cell, 67 (2001).

[92] R.K. Sharma, K. Jain, A.C. Rastogi, Growth of CdS and CdTe thin films for the fabrication of n-CdS/p-CdTe solar cell, Curr. Appl. Phys. 3 (2003) 199–204. https://doi.org/10.1016/S1567-1739(02)00201-8.

[93] R. Mendoza-Pérez, G. Santana-Rodríguez, J. Sastre-Hernández, A. Morales-Acevedo, A. Arias-Carbajal, O. Vigil-Galan, J.C. Alonso, G. Contreras-Puente, Effects of thiourea concentration on CdS thin films grown by chemical bath deposition for CdTe solar cells, Thin Solid Films. 480–481 (2005) 173–176. https://doi.org/10.1016/j.tsf.2004.11.060.

[94] K.D. Dobson, I. Visoly-fisher, G. Hodes, D. Cahen, Stability of CdTe / CdS thin- " lm solar cells, Sol. Energy Mater. Sol. Cells. 62 (2000) 295–325.

[95] Y. Zhang, J. Zhou, C. Dehart, A. Duda, B. To, N. Renewable, WITH AN OXYGENATED AMORPHOUS CdS (aCdS : O) WINDOW LAYER, IEEE Conf. Publ. (2002) 531–534.

[96] J. Zhou, X. Wu, G. Teeter, B. To, Y. Yan, R.G. Dhere, T.A. Gessert, CBD-Cd1-xZnxS thin films and their application in CdTe solar cells, Phys. Status Solidi Basic Res. 241 (2004) 775–778. https://doi.org/10.1002/pssb.200304218.

[97] C. Li, F. Wang, Y. Chen, L. Wu, J. Zhang, W. Li, X. He, B. Li, L. Feng, Characterization of sputtered CdSe thin films as the window layer for CdTe solar cells, Mater. Sci. Semicond. Process. 83 (2018) 89–95. https://doi.org/10.1016/j.mssp.2018.04.022.

[98] C.S. Ferekides, U. Balasubramanian, R. Mamazza, V. Viswanathan, H. Zhao, D.L. Morel, CdTe thin film solar cells: Device and technology issues, Sol. Energy. 77 (2004) 823–830. https://doi.org/10.1016/j.solener.2004.05.023.

[99] S. Chander, M.S. Dhaka, CdCl2 treatment concentration evolution of physical properties correlation with surface morphology of CdTe thin films for solar cells, Mater. Res. Bull. 97 (2018) 128–135. https://doi.org/10.1016/j.materresbull.2017.08.038.

[100] B. Li, J. Liu, G. Xu, R. Lu, L. Feng, J. Wu, Development of pulsed laser deposition for CdS/CdTe thin film solar cells, Appl. Phys. Lett. 101 (2012). https://doi.org/10.1063/1.4759116.

[101] L.I. Nykyruy, R.S. Yavorskyi, Z.R. Zapukhlyak, G. Wisz, P. Potera, Evaluation of CdS/CdTe thin film solar cells: SCAPS thickness simulation and analysis of optical properties, Opt. Mater. (Amst). 92 (2019) 319–329. https://doi.org/10.1016/j.optmat.2019.04.029.

[102] S.H. Demtsu, J.R. Sites, Effect of back-contact barrier on thin-film CdTe solar cells, Thin Solid Films. 510 (2006) 320–324. https://doi.org/10.1016/j.tsf.2006.01.004.

[103] K.H. and J.R. Sites, Electron reflector to enhance photovoltaic efficiency: application to thin-film CdTe solar cells, Prog. Photovoltaics Res. Appl. 20 (2012) 486–489. https://doi.org/10.1002/pip.1143.

[104] H. Zhao, A. Farah, D. Morel, C.S. Ferekides, The effect of impurities on the doping and VOC of CdTe/CdS thin film solar cells, Thin Solid Films. 517 (2009) 2365–2369. https://doi.org/10.1016/j.tsf.2008.11.041.

[105] K.P. Bhandari, P. Koirala, N.R. Paudel, R.R. Khanal, A.B. Phillips, Y. Yan, R.W. Collins, M.J. Heben, R.J. Ellingson, Iron pyrite nanocrystal film serves as a copper-free back contact for polycrystalline CdTe thin film solar cells, Sol. Energy Mater. Sol. Cells. 140 (2015) 108–114. https://doi.org/10.1016/j.solmat.2015.03.032.

[106] A. Balcioglu, R.K. Ahrenkiel, F. Hasoon, Deep-level impurities in CdTe/CdS thin-film solar cells, J. Appl. Phys. 88 (2000) 7175–7178. https://doi.org/10.1063/1.1326465.

[107] A.E. Abken, Chemical stability of sputtered Mo / Sb 2 Te 3 and Ni / Sb 2 Te 3 layers in view of stable back contacts for CdTe / CdS thin film solar cells, 73 (2002) 391–409.

[108] J.M. Kephart, R. Geisthardt, W.S. Sampath, Sputtered, Oxyg enated CdS Window Layers for Higher Current in CdS/CdTe Thin Film Solar Cells, (2011) 854–858.