INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Kowsar et al., Vol.9, No.2, June, 2019

Progress in Major Thin-film Solar Cells: Growth Technologies, Layer Materials and Efficiencies

Abu Kowsar*‡, Mashudur Rahaman**, Md. Saidul Islam**, Abdullah Yousuf Imam***, Sumon Chandra Debnath**, Munira Sultana**, Md. Azizul Hoque**, Afrina Sharmin**, Zahid Hasan Mahmood****, Syed Farid Uddin Farhad*

*BCSIR Laboratories Dhaka, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka-1205, Bangladesh.
**Institute of Fuel Research and Development, Bangladesh Council of Scientific and Industrial Research, Dhanmondi, Dhaka-1205, Bangladesh.
***Atmospheric Research Division, Bangladesh Space Research and Remote Sensing Organization, Dhaka-1207, Bangladesh.
****Electrical and Electronics Engineering, University of Dhaka, Ramna, Dhaka-1000, Bangladesh.
(apukowsar@gmail.com, sf1878@my.bristol.ac.uk)

‡ Corresponding Author: Abu Kowsar, Physical Instrumentation Division (PID), BCSIR Laboratories Dhaka, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka-1205, Tel: +88 01722 281618, apukowsar@gmail.com

Received: 22.01.2019 Accepted:05.03.2019

Abstract- Thin film solar cells are desirable due to minimal material usage, cost effective synthesis processes and a promising trend in efficiency rise. In this review paper, remarkable progresses of five major types of thin film solar cell (TFSC) - amorphous silicon (a-Si) solar cell, copper indium gallium selenide (CIGS) solar cell, copper zinc tin sulfide (CZTS) solar cell, cadmium telluride (CdTe) solar cell and dye-sensitized solar cell (DSSC) have been presented from their inception to the state-of-the-art development. Cell configurations, different layers of these cells, their growth procedures, function and modification for working solar cells have also been explored. Critical issues that limit the performance of these cells as well as current scenario have also been addressed. Finally, a summary of this work has been presented as a comparative study among the five major types of TFSCs in terms of the state-of-the-art data for structural, optical, and electrical properties, material availability, toxicity, stability and highest efficiency for helping readers decipher the major challenges for popularization and commercialization of this technology.

Keywords a-Si:H; CIGS; CZTS; CdTe; DSSC; thin-film solar cell.

1. Introduction

The sun is the most abundant source of renewable energy to meet up the present and future global energy demands in tera-watt *(*TW*)* scale deployment. In this direction, solar cell is one of the best possible means for directly converting sunlight into usable energy without producing any harmful by products. In general, there are two approaches for the conversion of harvested sunlight into electricity namely, single junction and multijunction solar cells [1]. Among all types of solar cells, second generation thin film cells are favorable because of their low cost material usage and promising trend in efficiency rise. Although first generation silicon (Si) solar cells are still dominant players in photovoltaic (PV) literatures and covering around 95% of the PV market share globally [2], due to various limitations of this Si-solar cell such as weight, rigidity, cost of Si wafer, expensive processing technologies, alternative low cost materials and device fabrication technologies have been attracted growing interests over the past five decades. This led to the invention of the second generation light weight low cost thin-film solar cells (TFSCs). In TFSCs family, cuprous sulfide-cadmium sulfide (Cu_2S/CdS) single junction is the first reported solar cell developed for space applications that showed high efficiency (~9.1%), and several start-up companies have been established to commercialize this technology but diffusion of copper into CdS matrix and doping of the CdS layer led to long-term performance degradation, for which most of the research activities on Cu_2S/CdS cells were declined [3, 4]. Eventually, other genre of TFSCs took over the researchers and manufacturers interests. Among these TFSCs, amorphous silicon (a-Si) solar cell is preferable to the researcher because of its material availability, non-toxicity, low processing temperature and low cost. Meanwhile, chalcopyrite based CIGS solar cells showed comparable efficiencies to the polycrystalline Si solar cell, but the production cost of this cell is reported to be much lower than that of the polycrystalline Si solar cell [5]. One of the major barriers in commercialization of this cell is the resource limitation, since Indium (In) and Gallium (Ga) are considered as scarce materials. On the other hand, quaternary semiconducting compound Copper Zinc Tin Sulphide (CZTS) is anatomically similar to CIGS but uses the earth-abundant elements that alleviate the material scarcity issue precluding CIGS cell potentials. Recently, a promising binary material: Cadmium Telluride (CdTe) has been showing much promises due to its frequently reported higher efficiencies comparable to polycrystalline Si solar cell [6, 7] despite its growth nature and crystal structure is remarkably different from other p-n junction based TFSCs. As a result, CdTe received more attentions than other TFSC materials as an absorber for achieving highly efficient and low-cost solar cell. Besides, non p-n junction based DSSC cells are unique among the TFSCs in terms of structure, light absorption capacity, electron and hole transport mechanism etc. It is also a promising candidate in TFSC technology, because of its cheap constituent materials without requiring higher purity, therefore, lowers the fabrication cost [8, 9].

Due to the above mentioned strategic key features in selecting solar cell materials, different research groups have been engaged in intensive research and development works as well as periodic literature review for knowing the latest advances in TFSCs. In recent time, review works on (*a*-Si:H) [10], CIGS solar cell [11], CZTS [12, 13], CdTe [14] and DSSC [15] are seen to be reported separately in the literature. Beside these single cell based review work, scientists also published some specific issue based review work of two or three prominent solar cells, such as, T.D. Lee and A.U. Ebong [16] reviewed the technologies and challenges of three major types (*a*-Si:H, CIGS and CdTe) TFSC. But, to the best of our knowledge, there is no such type of review work that covers five major types of TFSC in a single report and provides required information of these cells from their inception to the state-of-the-art development. So, in this paper, we briefly report and compare the evolution of growth technologies, constituent cell materials, critical issues that limit the cell performance, remarkable progress of their efficiencies, and present scenario of five major types of thin film solar cells.

2. Crystalline Silicon (c-Si) Solar Cell

As mentioned above, crystalline silicon (c-Si) PV cells are the dominant players in global photovoltaic market. Usually these cells are developed from the microelectronics technology. The first practical silicon solar cell with 6% efficiency was developed in Bell laboratory in 1954 [17, 18]. And since of its inception, this technology has been treated as one of the important renewable energy sources that could replace the environmentally detrimental fossil fuels. Silicon solar cells are made up of monocrystalline or polycrystalline silicon wafers. To date, the reported highest laboratory energy conversion efficiency of monocrystalline and polycrystalline solar cells are 26.7% and 22.3% respectively [6]. Besides, recently thin-film silicon solar cells are also drawing much attention among the PV community because this technology reduces the amount of active raw material usage in devising the cell. The chemical vapor deposition method is used for depositing silicon thin-film solar cell on suitable substrates from silane gas and hydrogen gas. Thus amorphous silicon, polycrystalline silicon or nanocrystalline silicon can be yielded depending on the deposition parameters and appropriate conditions [19]. In the following section we only discuss the amorphous silicon solar cell, because this cell is promising due to its strategic potentials, technological advantage, and overall low manufacturing cost.

3. Amorphous Silicon (a-Si) Solar Cell

3.1. Inception and remarkable progress

The first amorphous silicon (a-Si) layer was prepared as thin films of Si from silane (SiH_4) gas, deposited in a radio frequency glow discharge chamber in 1965 [20]. Ten years later, University of Dundee reported that the conductivity of a-Si can be increased by several times by doping performed in a gas mixture of phosphine or diborane in the glow discharge ambient [21]. This pure a-Si contains high concentration of defects termed as dangling bonds. Such defect densities could be reduced from 10^{21} cm^{-3} to 10^{15}–10^{16} $cm^{-3}$by flowing hydrogen gas into the deposition chamber. The passivation of these deleterious dangling bonds [22] is called hydrogenation of a-Si (denoted by (a-Si:H)). The first a-Si:H solar cell was fabricated with a reported efficiency of 2.4% by Carlson and Wronski in 1976 [23]. However, due to Staebler–Wronski effect [24], the light-induced change in a-Si:H solar cell has been reported to degrade the efficiency (single-junction cell losses about 30% and triple-junction module losses about 15% of its initial efficiency after about 1000 hours [25, 26]). To overcome this cell degradation over the time, an intrinsic layer was incorporated within the a-Si:H cell for devising a final *p-i-n* structure. The remarkable chronological development of a-Si:H solar cells and materials used in the cell structures are summarized in the table 1.

Table 1. Remarkable chronological development of a-Si:H solar cells

Year	Efficiency improving mechanism employed	Reported efficiency	Researcher/ Organization
1981	First notable progress of efficiency for amorphous silicon solar cell was achieved. For that modifying the film of a-Si:H, the amorphous silicon carbide (a-SiC:H) was fabricated by the plasma decomposition of [SiH_4(1-X)+CH_4(X)] in the presence of B_2H_6 or PH_3 dopant gas system and by utilizing this a- SiC:H, the first a- SiC:H/a- Si:H heterojunction solar cell was developed.	7.14% (S)	Osaka University [27]
1986	Intentional insertion of a thin graded interface layer at the p/i interface of p-i-n device, the overall performance of p-i-n cells was improved.	>8% (S)	Solarex Corp. [28]
1992	Besides single junction p-i-n cells, efficiency of a-Si:H cell was further enhanced by micromorph (Tandem or triple junction) approach. This was done by implementing an a-SiGe:H alloy in tandem and triple junction solar cell structures.	11.2% (M)	USSC [22]
1994	The first 'mixed stacked' a-Si:H/μc-Si:H tandem cell of the world was developed.	9.1% (M)	University of Neuchatel [29]
2000	By combining the active poly-Si cell with a-Si:H cell, a-Si:H/poly-Si/poly-Si cell was fabricated by plasma chemical vapor deposition (CVD) to improve the overall efficiency.	12% (M)	Kaneka Corporation [30]
2004	a-Si:H p-i-n single-junction (S) and tandem (T) cell or multijunction (termed as Micromorph) solar cells have been fabricated by very high frequency low pressure CVD.	9.47% (S) 12.3% (M)	NREL [31]
2015	Highest efficient single junction a-Si:H with improved p-i-n device structure has fabricated using diode and triode PECVD with various deposition rate.	10.2% (S)	AIST [32]
2015	State-of-the-art world highest stabilized efficiency achieved from a-Si:H/μc-Si:H/μc-Si:H triple-junction cells that is fabricated on periodically textured substrate.	13.4% (M)	AIST[33]

* S stands for Single junction and M stands for Micromorph

3.2. Cell Materials, Configuration and Fabrication procedure

To date, a-Si:H solar cell is configured in either the *p-i-n* superstrate or the *n-i-p* substrate sequence. Layer materials of this type of structure have been modified for the performance improvement over the years. The a-Si:H thin film has a direct optical bandgap (E_g) and could be tailored in the range 1.6 – 1.8 eV by changing the substrate temperature or the dilution of silane by hydrogen during processing [34, 35]. In early a-Si:H solar cell, a *p*-type hydrogenated amorphous silicon carbide (*a*-SiC:H) absorber layer was incorporated with a comparatively wide bandgap material known as window layer [27]. In general, a conventional active device consists of a *n*-type window layer of a-SiC:H, an intrinsic a-Si:H absorber layer, and an *p*-type a-Si:H layer. In the latest a-Si:H cell configuration [36], absorber p-i-n layer is deposited on ZnO ($E_g \approx 3.20$ - 3.40 eV [37] transparent conducting oxide (TCO) layer [32, 38]. Initially, indium tin oxide (ITO) layer was used as TCO layer but to date, cheaper alternative: fluorine doped tin oxide (FTO) has been widely used. In addition, this FTO (SnO_2: F) layer has been applied for reducing reflection loss and it serves as the top electrode. The front electrodes should have low electrical resistivity and high optical transmittance in the visible wavelength range for minimizing the ohmic contact loss and optical loss respectively. Usually, Al doped ZnO (AZO) is applied between n-layer and transparent front contact, but in another words, to increase the short-circuit current, the low resistive and high optical transparent ZnO:B [39] layer is applied between n-layer and silver as transparent contact. However, ZnO/Ag has the capability to overcome the adhesion problem between a-Si and metal contact. A schematic diagram of a-Si:H solar cell configuration is shown in Fig. 1

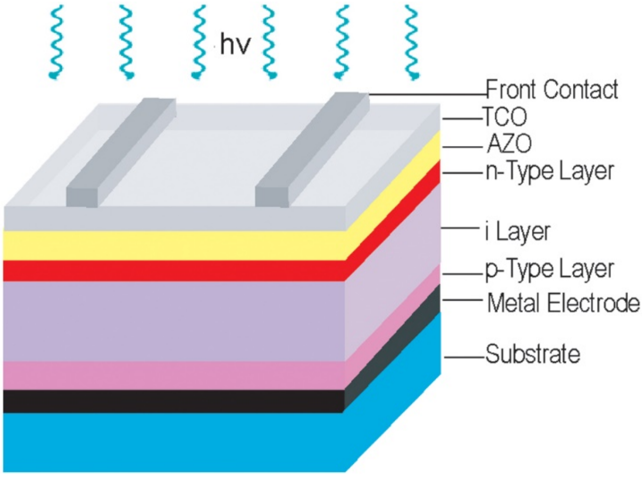

Fig. 1. Schematic diagram of a-Si:H solar cell adopted from [40]

Apart from this single junction configuration, a-Si solar cell could be configured as tandem or micromorph form. Here, it should be noted that hydrogenated amorphous silicon germanium (a-SiGe:H) is a desirable absorber material for stacked or micromorph solar cells due to its reported low bandgap ($E_g = 1.39–1.53$ eV) [27, 41].

In a-Si:H thin film solar cell, absorbed photon in intrinsic layer creates an electron-hole pair and electric field induced across the intrinsic layer causes the electrons to drift towards the n-layer and the holes towards the p-layer. For improving the cell performance, a thin graded interface layer has been used to reduce the p/i interface defects which is responsible for low short circuit current and open circuit voltage [28, 38]. However, conventional a-Si:H cells are deposited on either SnO_2 or ZnO coated glass as front contact TCO. Plasma enhanced chemical vapor deposition (PECVD) is the widely used deposition method for devising this solar cell. However, other fabrication methods such as hot-wire CVD, photo CVD, sputtering, and electron cyclotron resonance chemical vapor deposition (ECR CVD) have also been applied in fabricating high efficient solar cells [42-45].

3.3 *Critical issues*

In our present study, we have found that the three most critical issues regarding material properties and device structure that impeding the performance and reliability of a-Si:H cell are: (1) light management schemes, (2) Staebler–Wronski Effect (SWE) and (3) Faster deposition processes. To increase the performance of this thin film cell significantly from the current level, these critical issues must be addressed. For the improvement of light scattering properties, optoelectronic quality of the front TCO material must be improved [10]. Staebler–Wronski effect is still under discussion, so it must be better understood for finding a suitable way to impede light-induced evolution of bonded-hydrogen [46] from the cell material. Development of faster deposition processes are required for high- throughput manufacturing of this solar cell with same level efficiency achieved so far[47].

4. CIGS Solar Cell

4.1. *Inception and remarkable progress*

History of CIGS thin-film solar cell accounts that, the first $CuInSe_2$ (CIS) thin film was synthesized by Hahn in 1953 [48] and Bell Laboratories proposed this material as a photovoltaic material in 1974 [49]. The first $CuInSe_2$/CdS heterojunction photovoltaic devices were developed by coating of an evaporated n-type CdS atop the single crystal of p-$CuInSe_2$ in 1974 [50] and CIS solar cells started to receive much attention when the first high-efficiency (9.4%) thin film cells were reported by Boeing in 1981 [51]. To date, NREL is a leading research organization in CIGS solar cell development. Time to time they report remarkable improvements of efficiency of CIGS solar cell on rigid glass substrate. The record efficiencies of this solar cell reported by NREL were 17.1% in 1995 [52], 18·8% in 1999 [53] and 19.9% in 2008 [54]. For depositing absorber layer, glass substrate is the most commonly used substrate; however, current trend is to develop flexible solar cells on metal foils [55-57] and polyimide flexible substrate [58-60]. In 1992, Mo, Ti, and Al foils have been used for the first time by International Solar Electric Technology (ISET) for flexible solar cells [61] and state-of-the-art highest efficiency CIGS solar cells were prepared on polymer foil 2013 [62] . Notable chronological development of CIGS solar cells deposited on both rigid glass substrate (R) and flexible glass substrate (F) are summarized in table 2.

Table 2 Chronological development of CIGS solar cells

Year	Efficiency improving mechanism employed	Reported efficiency (Substrate type)	Researcher/ Organization
1976	First notable progresses of efficiency for CIGS thin film solar cell were achieved. The CIGS (p-$CuInSe_2$/n-CdS) photovoltaic cell was developed through two modes of operation (illumination through $CuInSe_2$ or through CdS.) under 100 mW/cm^2 tungsten-	4.5% (R)	University of Maine [63]

	halogen illumination for 1.2 cm^2 devices.		
1981	First high efficiency $CuInSe_2$ solar cell was made by vacuum deposition coating of an evaporated n-type CdS atop the crystalline p-$CuInSe_2$ onto inexpensive substrates.	9.4% (R)	Boeing [51]
1993	The absorber layer has been deposited on flexible Mo foil by using an e-beam evaporation process with subsequent selenization.	8.3% (F)	AIST [61]
1995	Incorporation of Ga into the CIS matrix to raise the absorber bandgap, open-circuit voltage and a fill factor that led to achieve high efficiency CIGS cell fabricated by PVD of the constituent elements on the Mo-coated soda lime glass substrate.	17.1% (R)	NREL [52]
1996	Using alternative of metal foils substrate, the first report in the use of polyimide as a flexible substrate and a CIGS cell was developed by a two-step process of sputtering metal precursors.	8.7% (F)	ISET [58]
1999	A ZnO/CdS/Cu(In,Ga)Se_2/Mo polycrystalline thin-film solar cell was deposited on glass substrate that led to additional improvement of efficiency.	18·8% (R)	NREL [53]
2008	The performance of this cell has been further improved by the reduction of recombination during CIGS deposition. This reduction of recombination was achieved by terminating the three stage deposition processing with a Ga-poor (In-rich) layer.	19.9% (R)	NREL [54, 62]
2010	The highest efficiency achieved for Mo substrate where CIGS absorber layer deposited on Mo flexible substrate by using a three-stage co-evaporation process.	14.6% (F)	AIST [64]
2011	The highest efficiency achieved for Al foil substrate where CIGS cells were fabricated on flexible Al foil by using non-vacuum low cost printing setup.	17.1% (F)	Nano Solar & EMPA [5]
2012	The highest achieved efficiency for Mo/Ti-coated stainless steel (SS) substrates where CIGS cells were fabricated without an additional metal-oxide or metal-nitride impurity diffusion barrier using roll-to-roll processing.	17.7% (F)	EMPA [65]
2013	Based on flexible substrate, highest achieved efficiency for CIGS solar cells were prepared on polymer foil.	20.4% (F)	EMPA [62]
2017	Champion CIGS solar cell was fabricated by CIS absorber engineering and enhanced surface treatment of the absorber layer using a co-evaporation process on rigid glass substrate.	22.5% (R)	AIST [66]

Note: AIST: Institute for Advanced Industrial Science and Technology, ZSW: Zentrum für Sonnenenergie- und Wasserstoff-Forschung, ISET: International Solar Electric Technology, Inc., EMPA: Swiss Federal Laboratories for Materials Science and Technology.

4.2. Cell materials, configuration and fabrication procedure

The active materials of CIGS solar cells are composed of direct band gap tetrahedrally bonded compound-element semiconductors having chalcopyrite crystal structure. CIGS solar cell has been formed by alloying any proportion of $CuInSe_2$ with $CuGaSe_2$. However, most of the high performance devices maintain a ratio of Ga to (In + Ga) in the range of 0.25–0.35 [67] and this Ga content is varied to tune the band gap to values 1.04 eV for $CuInSe_2$ and 1.68 eV for $CuGaSe_2$ [35, 68]. At the very beginning, $CuInSe_2$ solar cell was a simple p-$CuInSe_2$/n-CdS heterojunction [63] but present day CIGS solar cell has been configured in structure: substrate/Mo/CIGS/CdS/i-ZnO/AZO/metal contact (Al) [69-72]. A typical configuration of a CIGS solar cell is shown in fig. 2.

For a rigid substrate, soda lime glass (SLG) is commonly used. However, flexible substrates such as polyimide or metal foil also have also been intensively used in this technology [73]. In CIGS solar cell, a sputtered molybdenum (Mo) layer is used as a back contact as well as a reflector to bounce the most unabsorbed light back into the absorber layer. A p-type CIGS absorber layer is grown on sputtered Mo layer. In state-of-the-art high efficiency CIGS solar cell, the absorber layers are grown by physical vapor deposition such as thermal co-evaporation at high temperature (~ 600 ^{0}C) and a two stage process such as sputtering of precursor layers followed by selenization in Se vapor or H_2Se gas [5].

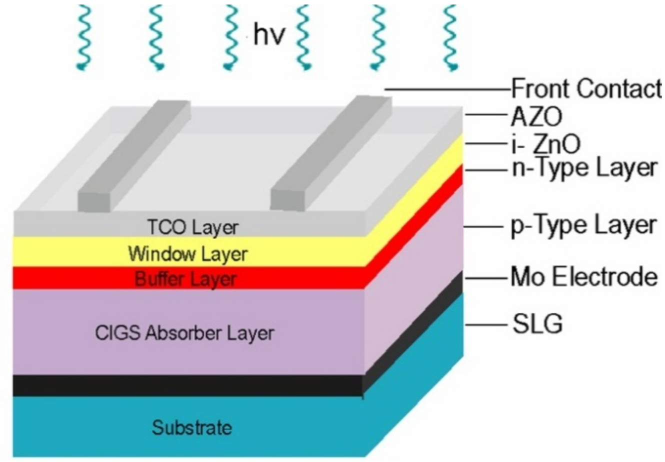

Fig. 2. Schematic diagram of CIGS solar cell adopted from [74]

A thin n-type buffer layer is put atop the absorber. Usually chemical bath deposited CdS is used as buffer layer but in consideration of environmental and hazardous effect, extensive research has been conducted for developing cadmium (Cd) free buffer layers. Moreover, ZnS, ZnSe, ZnO, (Zn,Mg)O, $In(OH)_3$, In_2S_3, In_2Se_3, $InZnSe_x$, SnO_2 and SnS_2 have been used as buffer layer and these layers are deposited by various growth methods such as metal organic chemical vapor deposition (MOCVD), chemical bath deposition (CBD), electrodeposition, sputtering, thermal evaporation, atomic layer deposition (ALD), ion layer gas reaction (ILGAR) [75], and pulsed laser deposition(PLD) . For avoiding surface damage of CdS layer an in intrinsic ZnO layer (i-ZnO) which is capped by a relatively thicker Al:ZnO(AZO) layer is added atop the buffer layer. Chemical vapor deposition method is merely used to deposit the ZnO layer [76]. The AZO layer is used as a TCO to collect and transport electrons out of the cell while transmitting as much light as possible.

4.3. Critical issues

In this review, we have identified that the critical issues of CIGS solar cells are: (1) developing a viable deposition process onto a flexible substrate at lower temperatures, (2) CdS buffer layer conventionally deposited by CBD that presents the greatest health concerns due to the use of carcinogenic Cd, thiourea, and the generation of waste solutions. Selenium (Se) does not show highly toxicity but compounds of Se such as H_2Se are extremely toxic [77]. (3) Material availability is also a major concern of the CIGS solar cell. Most of the constituent elements of this solar cell are abundant in the earth crust except the scarce metal Indium (In) and Gallium (Ga). Therefore, resource limitations as well as ecological issues shed a negative light on the practical potential of the CIGS solar cells in the case of terawatt scale deployment (and refs. there in). The search of alternative less toxic materials compared to CIGS solar cell gave birth to the CZTS solar cell made out of entirely earth abundant elements.

5. CZTS Solar Cell

5.1. Inception and remarkable progress

The first CZTS material was developed in 1967 by Nitsche et al. [78] using the chemical vapor transport method and its photovoltaic effect was observed by Ito et al. [79] in 1988. The first CZTS thin-film solar cell with efficiency of 0.66% reported by Katagiri et al. [80, 81] in 1997 using a vacuum-deposition method. The remarkable progress in the development of CZTS solar cells are presented in table 3.

Table 3 Remarkable choronological development of CZTS solar cells

Year	Efficiency improving mechanism employed	Progress of Efficiency	Researcher/ Organization
1997	First notable improvement of efficiency of CZTS solar cell was achieved by developing a thin film of Cu_2ZnSnS_4 with a standard CdS/ZnO window layer by thermal evaporation of the elements or chalcogenide binaries in high vacuum.	2.3%	ZSW [82]
2007	An inline-type vacuum apparatus was introduced for the first time to achieve better quality of CZTS films than previously developed which truly lead to increase the efficiency. This CZTS solar cell was fabricated by three RF sources co-	5.7%	Nagaoka National College of Technology [83]

	sputtering continued with vapor phase sulfurization method.		
2009	Efficiency of CZTS was further notably increased by the same research group. Here absorber layer of CZTS was developed using three radio frequency sources co-sputtering followed by annealing in sulfurized atmosphere.	6.7%	Nagaoka National College of Technology [84]
2010	Applying another novel techniques, kesterites CZTS solar cell was prepared from earth abundant materials by using composite liquid deposition approach which merging the concepts of solution and particle- based coating for chalcogenide materials.	9.6%	IBM [85]
2012	High efficiency kesterite CZTS solar cell was developed by hydrazine process, which improved the open circuit voltage, short circuit current, fill factor etc. that ultimately increased the device performance.	11.1%	IBM [86]
2013	State-of-the-art champion CZTS solar cell has been developed by pure hydrazine solution along with targeted Cu-poor and Zn-rich conditions that improved CZTSSe absorber quality which yield the heights efficiency.	12.6%	IBM [87]

5.2. Cell materials, configuration and fabrication procedure

CZTS is a direct bandgap quaternary semiconducting compound. Kesterite crystal structure is most common structure for CZTS cells; beside this, chalcopyrite structure [88], wurtzite structure [89] and stannite structure [90] are reported in literature. However stannite and kieserite both forms can be coexist [91, 92]. The optical bandgap of stoichiometric kesterite-CZTS estimated theoretically is 1.50 eV [91] and experimentally, it is varied in the range 1.4 - 1.5 eV [93]. Its universally recognized raman shift peak is 338 cm^{-1} [94]. The electrical resistivity of CZTS thin films is varied from $10^{-3}\Omega\cdot cm$ to $10^{-1}\Omega\cdot cm$ [91].

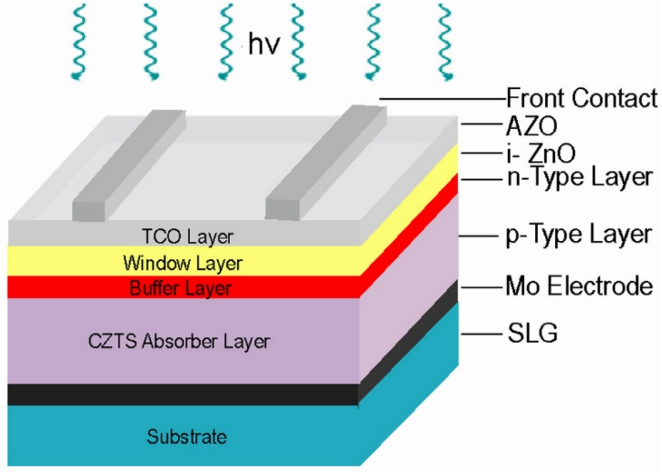

Fig. 3. Schematic diagram of CZTS solar cell adopted from [95]

Most of the CZTS cell consists of a sputtering-deposited Mo coated soda lime glass, a p-type CZTS absorber layer in contact with CBD grown n-type CdS buffer layer to form p-n junction (beside this CdS buffer layer, another high bandgap materials such as CdZnS also found in literature [96]), a thin layer of AZO is used as a window layer atop the CdS layer for preventing leakage. Metallic contacts made up of Ni/Al grid is separately deposited on both TCO and Mo layer. A schematic diagram of a typical CZTS solar cell is shown in fig.3. Several fabrication methods including vacuum-base, vacuum-free and solution process have been commonly used for CZTS absorber layer deposition [97-100]. The frequently used physical vapor methods are e-beam evaporation [93, 101], direct current (DC)/radio-frequency (RF) magnetron sputtering deposition [102], co-evaporation or electron beam evaporation [93], hybrid sputtering [94], thermal evaporation [103], pulsed laser deposition [104].

5.3. Critical issues

The major advantage of CZTS is that its raw materials are low cost, earth abundant and nontoxic [98] and about five times cheaper than CIGS [7]. However, in this review work, we have found a number of critical issues such as (1) toxic element of CdS buffer layer, (2) defect control of absorber, (3) pure CZTS phase generation and secondary phase detection and (4) bandgap engineering. Two toxic elements such as selenium (Se) and cadmium (Cd) are frequently used in CZTS precursors to grow high quality CZTS thin films. Although Se and Cd are toxic element but CZTS solar cell does not show toxicity. Besides, other non-toxic solvent-based process has been used for the deposition of a CZTS absorber layer [105].

6. CdTe Solar Cell

6.1. Inception and remarkable progress

CdTe crystal was synthesized chemically for the first time by Margottet in 1879 [106] and its *p*-type and *n*-type conductivity was reported for the first time by doping foreign impurity by Jenny and Bube in 1954 [107] and Loferski proposed it as a photovoltaic material in 1956 [108]. First single-crystal homojunction CdTe solar cell was demonstrated by Rappaport of about 2% efficiency fabricated by diffusion of Indium into *p*-type CdTe crystals in 1959 [109]. The historical development of CdTe solar cells are summarized in the table 4 below.

Table 4 Remarkable chronological development of CdTe solar cells

Year	Efficiency improving mechanism employed	Reported Efficiency	Researcher/ Organization
1972	The first notable progress of efficiency for a CdTe thin film heterojunction solar cell was reported. This graded gap thin film cell was prepared in a 3-step process, where high temperature vapor phase deposition (VPD) was used for CdTe film and high vacuum evaporation was used for CdS film.	6%	Bonnet and Rabenhorst [110]
1977	To prepare CdS/CdTe heterojunction solar cell, a CdS film was deposited on a chemically polished CdTe absorber by vacuum evaporation and introducing window layer (In_2O_3: Sn) by RF sputtering.	7.9%	Stanford University [111]
1979	Fabricated CdTe thin film solar cell by close-space vapor transport deposition of p-type arsenic-doped CdTe films onto n-type crystals.	>7%	CNRS [112]
1982	Fabricated a CdTe shallow homojunction cell by close space vapor transport deposition technique to form p-type CdTe epitaxial layer upon a single crystal n-type CdTe layer.	11%	CNRS [113]
1993	Another remarkable progress of CdTe solar cell is to combine the $CdCl_2$ with thin- film CdS/CdTe heterojunction cell. Where n-CdS buffer layer was prepared by chemical bath deposition and *p*- CdTe absorber layer was deposited by close- spaced sublimation.	15.8%	University of South Florida [114]
2001	Employing vapor $CdCl_2$ treatments and refinements of window-layer processing had led to additional improvements of this cell deposited on mesa glass substrate.	16.5%	NREL [115]
2009	Beside the CdTe solar cell deposition on rigid glass substrate, a CdS/CdTe cell was deposited on flexible lightweight polyimide film by using low temperatures (<450°C) vacuum evaporation technique and a subsequent annealing step in air where the materials are heated up and cooled down to harden them.	12.4%	EMPA [62]
2011	Significant improvement on the efficiency of heterojunction CdTe solar cell was reported compared to the previous cells developed by EMPA . Here the absorber layer of CdS/CdTe cell was developed by close space sublimation method.	17.3%	First solar Inc. [116]
2016	State-of-the-art highest efficient heterojunction CdTe solar cell has been developed by close space sublimation method.	22.1%	First Solar Inc. [6]

6.2. Cell materials, configuration and fabrication procedure

In CdTe crystal, the tetrahedral atomic coordination leads to diamond structure in monatomic solids and zincblende and wurtzite structures in binary solids [117]. The reported value of the bandgap of CdTe found in the literature are 1.44 eV; 1.464 eV; 1.50 eV; 1.51 eV and 1.56 eV at 300 K [22]. This CdTe solar cells could be configured both in substrate and superstrate arrangement. However, the state-of-the-art high efficiency cells are found to be configured in superstrate arrangement [118, 119]. In early configuration, vacuum-evaporated CdS window layer and chemical vapor deposited CdTe absorber layer deposited on Mo substrate [110]. But, to date, the TCO works as window layer and CdS deployed as buffer layer. SnO_2, In_2O_3: Sn, ZnO, Cd_2SnO_4 are frequently used as TCO seen in literature. For TCO, typically fluorine-doped tin oxide (FTO) and undoped tin oxide (TO) bilayers has been deposited on the glass by MOCVD. The TCO serves as the front contact and lateral current carrying conductor. The CdS window layer could be deposited by CBD [119], sputter deposition [120] and close-spaced sublimation (CSS) [121]. Most of the CdTe absorber layer has been deposited by CSS on glass substrate and CdTe layer is then $CdCl_2$-vapor treated by CSS. It is reported that $CdCl_2$ treatment increases grain size, which significantly increase the conversion efficiency [121]. A schematic diagram of a typical CdTe solar cell is given in figure-4.

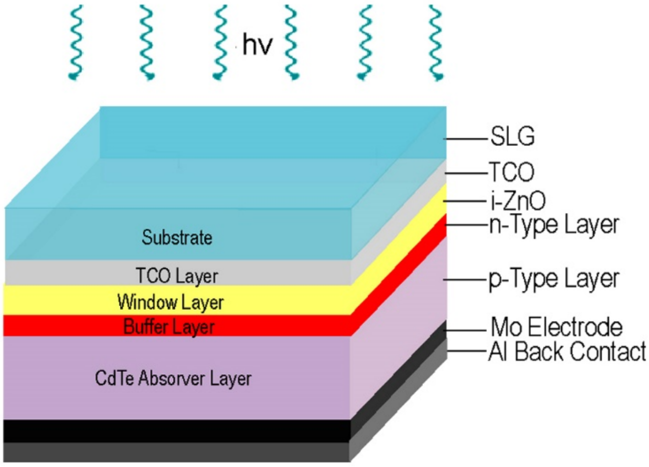

Fig. 4. Schematic diagram of CdTe solar cell adopted from [122]

The ZnTe:Cu/Ti back contact is deposited using a multi-source vacuum processing chamber. Several methods have been employed to deposit CdTe absorber layer for solar cell [35], such as physical vapor deposition (PVD), CSS, sputter deposition, electrodeposition, MOCVD, spray deposition, screen-print deposition and sintering but the best performing CdTe-based devices are fabricated using CSS [118, 123].

6.3. Critical Issues

Constituent elements of CdTe cell Cd and Te, respectively, are toxic and scarce materials. Cd is obtained as a by-product of zinc refining process from ore and at present it is an abundant material. In contrast, Te is obtained as a by-product of copper refining process from ore and it is a rare earth material [124]. As mentioned earlier, Cd is recognized as a carcinogenic elements, and classified as an environmentally hazardous material, but the compound CdTe itself is reported to be less toxic and very stable material [125]. Again the main perceived risks during the active lifetime of a CdTe solar panel are leaching out of broken modules and fire hazards. So toxicity of Cd and scarcity of Te are main critical issues limiting the commercialization potentials of this kind of solar cell.

7. DSSC Solar Cell

7.1. Inception and remarkable progress

Research on the photoelectric effect on organic dye was discovered at the end of nineteenth century. James Moser first observed that the photoelectric effect on silver plates was enhanced in the presence of erythrosine dye in 1887 [126] and in 1968, it was discovered that illuminated organic dyes can generate electricity at oxide electrodes in electrochemical cells [127]. Based on the experiment of understanding and simulating of the primary processes in photosynthesis, the dye sensitization solar cell (DSSC) principle was demonstrated and discussed in 1972 at University of California (UC), Berkeley [128]. However, in 1988, today's dye sensitized solar cell was co-invented by Brian O'Regan (who first invented the TiO_2 film) and Michael Grätzel (who invented the organic dye) at UC Berkeley and later, based on dye-sensitized colloidal TiO_2 films, a low cost, high efficiency cell has been developed by the aforementioned researchers at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland in 1991[129] and coined the term Grätzel cell. The summary of remarkable progress in the development of DSSC solar cell is given in table 5.

Table 5 Remarkable chronological development of DSSCs

Year	Efficiency improving mechanism employed	Reported efficiency	Researcher/ Organization
1991	First notable improvement of efficiency for DSSC was achieved. This device was created based on an optically transparent film of TiO2 particles of 10-µm-thick and few nanometers in size. It was coated with a monolayer of charge-transfer dye to sensitize the film, a low cost, high efficiency cell has been developed.	7.1-7.9%	EPFL [129]

2003	For achieving the high temperature stability an amphiphilic ruthenium dye Z-907 {*cis*-RuLL'(SCN)$_2$ (L= 4,4'-dicarboxylic acid-2,2'-bipyridine, L' = 4,4'-dinonyl-2,2'-bipyridine)} was used in conjunction with a quasi-solid-state polymer gel electrolyte. By this way a stable quasi-solid-state dye-sensitized solar cell was fabricated.	6.1%	EPFL [130]
2006	Instead of liquid electrolytes, first successful solid-hybrid dye-sensitized solar cells were reported . Backside illuminated dye sensitized solar cells was fabricated using N719 sensitized TiO_2 nanotube which was synthesized using anodization of Ti foils in electrolyte containing KF, $NaHSO_4$ and trisodium citrate.	4.24%	Pennsylvania State University [131]
2007	Intensive research with a wide variety of low-cost organic dyes based on porphyrin was conducted. The porphyrins were used for preparing dye-sensitized TiO_2 low-cost excitonic cells using an iodide/tri-iodide (I^-/I_3^-) redox electrolyte.	5.6%	Massey University [132, 133]
2008	A new solvent-free liquid redox electrolyte consisting of three salts was used in replacement of organic solvents. This ternary melt was used in conjunction with a TiO_2 film and the amphiphilic heteroleptic ruthenium complex Z907Na. This lead to achieve an excellent stability.	8.2%	EPFL, Changchun Institute of Applied Chemistry [134][137]
2011	Yella et al, reported a mesoscopic porphyrin-sensitized (designated YD2-***o***-C8**)** solar cells with cobalt (II/III)–based redox electrolyte instead of using I^-/I_3^- redox electrolyte that limited the efficiency of dye-sensitized solar cells.	12.3%	EPFL, National Chung Hsing University [135]
2013	Michael Graetzel et al. reported the state-of-the-art highest efficient solid state mesoscopic dye sensitized solar cell. They fabricated this cell using a hybrid perovskite $CH_3NH_3PbI_3$ dye that subsequently deposited in two-step method from the separated solutions of CH_3NH_3I and PbI_2.	15.0%	EPFL, Max-Planck-Institute for Solid-State Research [136]

7.2. Cell materials, configuration and fabrication procedure

With respect to the materials and layer structure, DSSC is unique from the other types of thin-film solar cell. The DSSC is comprised of multiple layers stacked between two electrodes. Each electrode has a TCO film. Initially Indium-Tin-Oxide (ITO) is used as TCO layer, but, ITO has a low thermal stability of resistance, for this limitation, at present FTO is widely used. Moreover, other material also found in literature such as ZnO, Nb_2O_5 [137]. TiO_2 nanoparticles are sintered and bound to the FTO layer of an electrode.

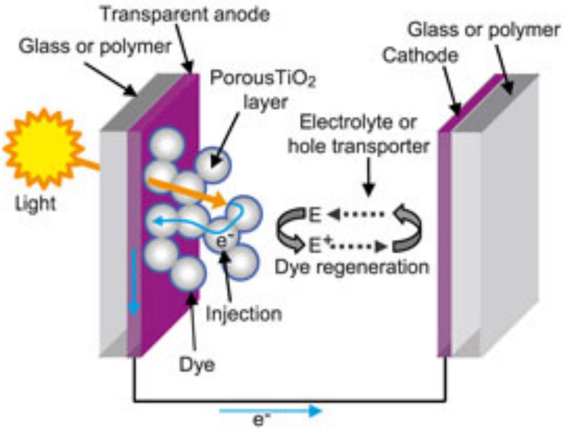

Fig. 5. A typical structure of a dye-sensitized solar cell

Dye is then absorbed into the TiO_2 layer. Likewise, platinum nanoparticles are sintered onto the FTO layer of the opposite electrode and both electrodes are then connected with either a two or three part liquid epoxy or a polymer sealant melts. Cell construction is completed with the incorporation of the electrolyte into the center of the cell [138]. A general structure of a typical DSSC is shown in Figure-5.

A ruthenium dye was initially employed in the DSSC, but, to date, several organic dyes [139, 140] and inorganic dyes [141] have been reported for this genre. Grätzel first used organic liquid electrolyte containing LiI/I_2. Later, many kinds of liquid electrolytes containing I^-/I_3^- redox couple and high dielectric constant organic solvents such as acetonitrile (AcN), ethylene carbonate (EC), 3-methoxypropionitrile (MePN), propylenecarbonate (PC), γ-butyrolactone (GBL), and *N*-methylpyrrolidone (NMP) have been investigated and found the photovoltaic effectiveness to some present day DSSCs[142, 143]. In replace of liquid electrolyte as the hole-transporting medium, solid-state hole-transporting medium has also been used in this solar cell [144, 145]. To the best of authors' knowledge, widely used preparation techniques of TCO process by spin-coating or dip-coating, hydrothermal layer found in literature listed as spray pyrolysis technique, chemical vapor deposition (CVD), sol–gel method [146]. For TiO_2 deposition, screen printing [147], spray coating [148], electrophoretic deposition [149], spin coating [150] are used method in this field.

7.3. Critical Issues

Most of the raw materials of DSSCs are cheap and environmentally benign and fabrication procedure of this thin film cell is very simple. But a number of expensive materials such as platinum and ruthenium are still used in this cell. Long-term durability of the dye, leakage of liquid electrolyte for DSSC poses a major challenge in commercialization of this kind of cell usable in all weather. DSSCs are still in research and development stage, but for these cells, recently used polymer or metal foil substrates instead of glass substrate promote them towards the commercialization[151, 152].

8. Discussion

The main focus of this review work is to elucidate the remarkable progress of efficiencies of major five TFSCs along with the evolution of their fabrication procedures. Notable chronological improvements of these cells have been depicted in fig. 6.

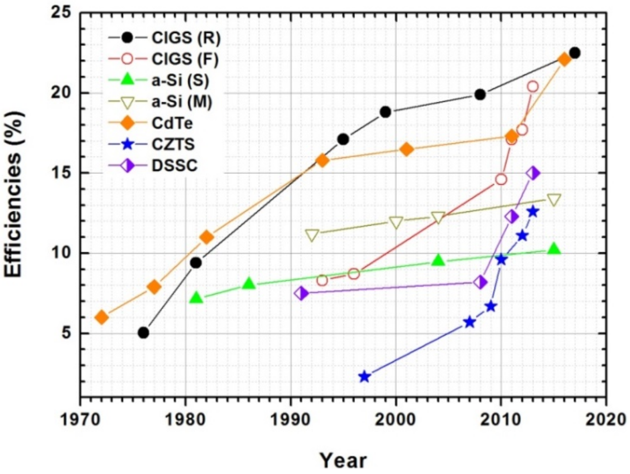

Fig. 6. Historic record efficiencies of major types thin film solar cells (Lab scale)

As can be seen, two separate efficiency lines (both single junction (S) and micromorph (M) cell) have been drawn for a-Si:H solar cells. The *a*-Si:H solar cell was initially fabricated as single junction solar cell but two- and three- junction (multijunction) cell configurations have also been developed for increasing the efficiency as well as the reliability [36]. In fact, multijunction solar cells are designed to capture the entire solar spectrum and overcome the single junction solar cell efficiency limitation [1, 153, 154]. However, due to higher bandgap and absorption coefficient, 90% of the visible radiation would be absorbed only in 1 micrometer amorphous thin film [22], but, due to the short crystalline order in a-Si film and the dangling bonds, the performance of this solar cell is not viable compared to the crystalline silicon solar cell. So, for improving the efficiency of this cell, reduction of reflection loss and enhancement of optical absorption is required. At the same time, surface textured substrate layer in combination with an antireflection coating must be introduced [155].

To date, CIGS cells have the comparable efficiencies to the polycrystalline Si solar cell. These cells could be deposited on both rigid glass substrate or flexible substrate and it was observed that the efficiency is higher when the cell is deposited on rigid substrate, i.e., soda lime glass substrate due to the positive effect of Na. In figure 6, two separate efficiency lines also can be seen for CIGS solar cell, one is based on rigid substrate (R) and another is for flexible substrate (F). Notice that the efficiency of CIGS cells deposited on flexible substrate gradually progressing towards the cell deposited on rigid substrate. It is already mentioned that manufacturing cost of this cell is lower than that of crystalline solar cell but scarcity of In and Ga is still the vital challenge. Most of the buffer layer of CIGS contain toxic cadmium content, which is another bottleneck limiting the potential of this solar cell. Similar to (CIGS), the CdTe is one of the most investigated materials among the second generation thin film solar cells. However, there are some issues regarding to its cost of raw materials and toxicity. CZTS is another promising thin film solar cell which is anatomically similar structured like CIGS. That is, fabrication procedure of different layers such as buffer, window and TCO layer of CZTS is also similar to CIGS cell. Beside these, DSSC cells are unique among the TFSCs in terms of cell structure and constituent materials. This solar cell is the promising likewise the CZTS because of earth abundance of its constituent elements and their environmentally benign nature. Therefore, CZTS is one of the most desirable and adorable PV materials despites its' reported efficiency is lower compared to the CIGS and CdTe. A summary of the five TFSCs research works has been presented in table 6 as a comparative data for structural, optical, and electrical properties, material availability, toxicity, stability and highest efficiency.

Thin-film solar cells cover around 4.5% of worldwide photovoltaic market share where a-Si:H covers 0.3%, CIGS covers 1.9% and CdTe covers 2.3% of the market share in 2018 [1]**.** Both CIGS and CdTe solar cell enjoy the advantage of their matured fabrication technology, presently their efficiency is comparable with multicrystalline silicon solar cell but their cost is comparatively lower than this type of Si solar cell. Both of these cells can be deposited on either rigid glass substrate or flexible glass substrate, both can be configured in either superstrate or substrate stacks. However, both of them use scarce and toxic materials which are the major limitations of these cells. Again, efficiency of a-Si:H is relatively lower in compare with CIGS and CdTe. and reduced after a certain time. In contrast, CZTS and DSSC are most promising solar cells in thin film family, because of raw materials' abundance, environmentally benign nature, low-cost as well as easy to synthesis and processing techniques. These solar cells are still in research and development phase, so its market share is not mentionable but their progress slowly moving forwards for commercializing in global PV market.

Table 6 Comparison of different properties of five major types thin film solar cell

Properties	a-Si:H Cell	CIGS Cell	CZTS Cell	CdTe Cell	DSSC Cell (approx.)
Crystal Structure	NA	Chalcopyrite	Kesterite, Chalcopyrite, Wurtzite [89], Stannite [90]	Diamond, Zincblende, Wurtzite	NA
Lattice constant	NA	*a* = 0.56–0.58nm *c* = 1.10–1.15nm	*a* = 0.5435 nm *c* = 1.0843 nm	0.648 nm	NA
Bandgap	1.6–1.8 eV [35, 38]	1.04eV ($CuInSe_2$) 1.68eV ($CuGaSe_2$)[68]	1.4~1.5eV [92, 93, 95]	1.50 eV [22]	3.2-3.35eV TiO_2 [156] 1.7 eV Dye [157]
Absorption Co-efficient	$>10^5$ cm^{-1} [22]	$>10^5$ cm^{-1} [158]	10^4 cm^{-1} [86]	$>5\times10^5 cm^{-1}$ [159]	Adjusted [160]
Acceptor Concentr Ation	4.3×10^{16} cm^{-3} Ionized [161]	10^{15}–$10^{16}/cm^3$ [162]	$10^{16}cm^{-3}$ to $10^{18}cm^{-3}$ [163-165]	$>10^{14}cm^{-3}$ [123]	$10^{18}cm^{-3}$ for Hole transport medium [160]
Hole Mobility	0.3 cm^2 /V.s [166]	250cm^2/V.s $CuGaSe_2$ [167]	0.1-30 cm^2/V.s [79]	50–80 cm^2/V.s [168]	1350 $\times10^{-3}$ cm^2/V.s [160]
Electron mobility	2 cm^2 /Vs [166]	90-900 cm^2 /Vs [169]	>5 cm^2/Vs [157]	500–1000 cm^2/Vs [168]	450 $\times10^{-4}$ cm^2/Vs [160]
Toxicity	Non-toxic	Less toxic	Non-toxic	Toxic	Non-toxic
Material availability	Available	In and Ga are limited	Available	Cd is available Te is limited	Available
Stability	Efficiency Less stable	Very stable	Very stable	stable	Less stable (Dye)
Highest Efficiency	13.4%	22.5%	12.6%	22.1%	15%
Market Share	0.3%	1.9%	R&D phase	2.3%	R&D phase

*Exact data is not available

9. Conclusion

In this article, remarkable development, constituent cell materials, fabrication procedures of major types thin film solar cells have been reviewed. Modification of the layers in cell configuration from the primitive cell to the state-of-the-art cell has been discussed with possible inclusion of new raw materials and fabrication process. Limitations for which performance of these cells are still below market-dominant silicon solar cell have also been discussed. The record efficiency, to date, for a-Si:H, CIGS, CZTS, CdTe and Dye sensitized solar cell (DSSC) is 13.4%, 22.5%, 12,6%, 22.1% and 15% respectively. Among them, CZTS and DSSC are still in research and development phase while the efficiencies of CIGS and CdTe solar cell are comparable with the c-Si solar cells efficiency. However the manufacturing process of c-Si cell poses more challenges than thin film solar cells. So, thin film PV technologies are believe to be the most promising for terawatt scale PV deployment among the existing renewable energy technologies that could mitigate present as well as future energy crisis. Therefore, extensive research efforts must be given to overcome the critical issues related to the TFSCs for popularization as well as for viable commercialization.

Acknowledgements

A. Kowsar *et al.*, gratefully acknowledge the support of Industrial Physics Division, BCSIR Labs, Dhaka within the scope of R&D project (D-18-FY-2016-19) of Bangladesh Council of Scientific and Industrial Research (BCSIR).

References

[1] A. Kowsar and S. F. U. Farhad, "High Efficiency Four Junction III-V Bismide Concentrator Solar Cell: Design, Theory, and Simulation," *International Journal of Renewable Energy Research (IJRER),* vol. 8, pp. 1762-1769, 2018.

[2] *Fraunhofer ISE: Photovoltaics Report* Available: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html Accessed date: Sept 22, 2018.

[3] Y. Wu, C. Wadia, W. Ma, B. Sadtler, and A. P. Alivisatos, "Synthesis and photovoltaic application of copper (I) sulfide nanocrystals," *Nano letters,* vol. 8, pp. 2551-2555, 2008.

[4] L. Partain, C. Dean, J. Duisman, P. McLeod, T. Peterson, and R. Weiss, "Degradation of Cu/SUB x/S/CdS in hot, moist air: experiment and theory," in *Conf. Rec. IEEE Photovoltaic Spec. Conf.;(United States)*, 1982.

[5] P. Reinhard, A. Chirila, P. Blosch, F. Pianezzi, S. Nishiwaki, S. Buechelers, *et al.*, "Review of progress toward 20% efficiency flexible CIGS solar cells and manufacturing issues of solar modules," in *Photovoltaic Specialists Conference (PVSC), Volume 2, 2012 IEEE 38th*, 2012, pp. 1-9.

[6] G. M. A., H. Yoshihiro, D. E. D., L. D. H., H.-E. Jochen, and H.-B. A. W.Y., "Solar cell efficiency tables (version 52)," *Progress in Photovoltaics: Research and Applications,* vol. 26, pp. 427-436, 2018.

[7] O. Schultz, S. Glunz, and G. Willeke, "ACCELERATED PUBLICATION: Multicrystalline silicon solar cells exceeding 20% efficiency," *Progress in Photovoltaics: Research and Applications,* vol. 12, pp. 553-558, 2004.

[8] M. Grätzel, "Photoelectrochemical cells," *nature,* vol. 414, p. 338, 2001.

[9] A. Hagfeldt and M. Grätzel, "Molecular photovoltaics," *Accounts of Chemical Research,* vol. 33, pp. 269-277, 2000.

[10] M. Stuckelberger, R. Biron, N. Wyrsch, F.-J. Haug, and C. Ballif, "Review: Progress in solar cells from hydrogenated amorphous silicon," *Renewable and Sustainable Energy Reviews,* vol. 76, pp. 1497-1523, 2017.

[11] J. Ramanujam and U. P. Singh, "Copper indium gallium selenide based solar cells–a review," *Energy & Environmental Science,* vol. 10, pp. 1306-1319, 2017.

[12] X. Liu, Y. Feng, H. Cui, F. Liu, X. Hao, G. Conibeer, *et al.*, "The current status and future prospects of kesterite solar cells: a brief review," *Progress in Photovoltaics: Research and Applications,* vol. 24, pp. 879-898, 2016.

[13] S. Zhuk, A. Kushwaha, T. K. S. Wong, S. Masudy-Panah, A. Smirnov, and G. K. Dalapati, "Critical review on sputter-deposited Cu2ZnSnS4 (CZTS) based thin film photovoltaic technology focusing on device architecture and absorber quality on the solar cells performance," *Solar Energy Materials and Solar Cells,* vol. 171, pp. 239-252, 2017/11/01/ 2017.

[14] J.-H. Yang, W.-J. Yin, J.-S. Park, J. Ma, and S.-H. Wei, "Review on first-principles study of defect properties of CdTe as a solar cell absorber," *Semiconductor Science and Technology,* vol. 31, p. 083002, 2016.

[15] J. Gong, K. Sumathy, Q. Qiao, and Z. Zhou, "Review on dye-sensitized solar cells (DSSCs): Advanced techniques and research trends," *Renewable and Sustainable Energy Reviews,* vol. 68, pp. 234-246, 2017/02/01/ 2017.

[16] T. D. Lee and A. U. Ebong, "A review of thin film solar cell technologies and challenges," *Renewable and Sustainable Energy Reviews,* vol. 70, pp. 1286-1297, 2017.

[17] D. M. Chapin, C. Fuller, and G. Pearson, "A new silicon p- n junction photocell for converting solar radiation into electrical power," *Journal of Applied Physics,* vol. 25, pp. 676-677, 1954.

[18] A. Kowsar, A. Y. Imam, M. Rahaman, M. S. Bashar, M. S. Islam, S. Islam, *et al.*, "Comparative study on the efficiencies of silicon solar cell," *IOSR Journal of Applied Physics (IOSR-JAP), ISSN,* pp. 2278-4861, 2014.

[19] R. Collins, A. Ferlauto, G. Ferreira, C. Chen, J. Koh, R. Koval, *et al.*, "Evolution of microstructure and phase in amorphous, protocrystalline, and microcrystalline silicon studied by real time spectroscopic ellipsometry," *Solar energy materials and solar cells,* vol. 78, pp. 143-180, 2003.

[20] H. Sterling and R. Swann, "Chemical vapour deposition promoted by rf discharge," *Solid-State Electronics,* vol. 8, pp. 653-654, 1965.

[21]W. Spear and P. Le Comber, "Substitutional doping of amorphous silicon," *Solid state communications,* vol. 17, pp. 1193-1196, 1975.

[22]J. Poortmans and V. Arkhipov, *Thin film solar cells: fabrication, characterization and applications* vol. 5: John Wiley & Sons, 2006.

[23]D. E. Carlson and C. R. Wronski, "Amorphous silicon solar cell," *Applied Physics Letters,* vol. 28, pp. 671-673, 1976.

[24]A. Kolodziej, C. Wronski, P. Krewniak, and S. Nowak, "Silicon thin film multijunction solar cells," *OPTOELECTRONICS REVIEW,* pp. 339-345, 2000.

[25]D. Staebler and C. Wronski, "Reversible conductivity changes in discharge- produced amorphous Si," *Applied physics letters,* vol. 31, pp. 292-294, 1977.

[26]R. Mickelsen and W. Chen, "Polycrystalline thin-film CuInSe2 solar cells," in *16th Photovoltaic Specialists Conference*, 1982, pp. 781-785.

[27]Y. Tawada, H. Okamoto, and Y. Hamakawa, "a- SiC: H/a- Si: H heterojunction solar cell having more than 7.1% conversion efficiency," *Applied Physics Letters,* vol. 39, pp. 237-239, 1981.

[28]R. Arya, A. Catalano, and R. Oswald, "Amorphous silicon p- i- n solar cells with graded interface," *Applied physics letters,* vol. 49, pp. 1089-1091, 1986.

[29]J. Meier, S. Dubail, R. Fluckiger, D. Fischer, H. Keppner, and A. Shah, "Intrinsic microcrystalline silicon (/spl mu/c-Si: H)-a promising new thin film solar cell material," in *Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference-1994, 1994 IEEE First World Conference on*, 1994, pp. 409-412.

[30]K. Yamamoto, M. Yoshimi, Y. Tawada, Y. Okamoto, and A. Nakajima, "Thin film Si solar cell fabricated at low temperature," *Journal of Non-Crystalline Solids,* vol. 266, pp. 1082-1087, 2000.

[31]J. Meier, J. Spitznagel, U. Kroll, C. Bucher, S. Fay, T. Moriarty*, et al.*, "Potential of amorphous and microcrystalline silicon solar cells," *Thin Solid Films,* vol. 451, pp. 518-524, 2004.

[32]T. Matsui, A. Bidiville, K. Maejima, H. Sai, T. Koida, T. Suezaki*, et al.*, "High-efficiency amorphous silicon solar cells: impact of deposition rate on metastability," *Applied Physics Letters,* vol. 106, p. 053901, 2015.

[33]H. Sai, T. Matsui, T. Koida, K. Matsubara, M. Kondo, S. Sugiyama*, et al.*, "Triple-junction thin-film silicon solar cell fabricated on periodically textured substrate with a stabilized efficiency of 13.6%," *Applied Physics Letters,* vol. 106, p. 213902, 2015.

[34]E. Arushanov, L. Essaleh, J. Galibert, J. Leotin, and S. Askenazy, "Shubnikov-De Haas oscillations in n-CuInSe2," *Physica B: Condensed Matter,* vol. 184, pp. 229-231, 1993.

[35]A. Luque and S. Hegedus, *Handbook of photovoltaic science and engineering*: John Wiley & Sons, 2011.

[36]M. Stuckelberger, R. Biron, N. Wyrsch, F.-J. Haug, and C. Ballif, "Progress in solar cells from hydrogenated amorphous silicon," *Renewable and Sustainable Energy Reviews,* vol. 76, pp. 1497-1523, 2017.

[37]S. F. U. Farhad, N. I. Tanvir, S. Hossain, M. S. Bashar, M. Sultana, and N. Khatun, "Facile synthesis of oriented Zinc Oxide seed layer for the subsequent hydrothermal growth of Zinc Oxide Nanorods," *Bangladesh J. Sci. Ind. Res.,* vol. 54, issue 4, pp. 233 - 244, 2018.

[38]D. Derkacs, S. Lim, P. Matheu, W. Mar, and E. Yu, "Improved performance of amorphous silicon solar cells via scattering from surface plasmon polaritons in nearby metallic nanoparticles," *Applied Physics Letters,* vol. 89, p. 093103, 2006.

[39]S. Faÿ, J. Steinhauser, N. Oliveira, E. Vallat-Sauvain, and C. Ballif, "Opto-electronic properties of rough LP-CVD ZnO: B for use as TCO in thin-film silicon solar cells," *Thin Solid Films,* vol. 515, pp. 8558-8561, 2007.

[40]L. M. Fraas, "The Dream of Thin Film PV," in *Low-Cost Solar Electric Power*, ed: Springer, 2014, pp. 73-79.

[41]S. R. Jadkar, J. V. Sali, S. T. Kshirsagar, and M. G. Takwale, "Narrow band gap, high photosensitivity a-SiGe:H films prepared by hot wire chemical vapor deposition (HW-CVD) method," *Materials Letters,* vol. 52, pp. 399-403, 2002/02/01/ 2002.

[42]M. I. Kabir, S. A. Shahahmadi, V. Lim, S. Zaidi, K. Sopian, and N. Amin, "Amorphous silicon single-junction thin-film solar cell exceeding 10% efficiency by design optimization," *International Journal of Photoenergy,* vol. 2012, 2012.

[43]R. Chittick, J. Alexander, and H. Sterling, "The preparation and properties of amorphous silicon," *Journal of the Electrochemical Society,* vol. 116, pp. 77-81, 1969.

[44]W. Spear and P. Le Comber, "Substitutional doping of amorphous silicon," *Solid state communications,* vol. 88, pp. 1015-1018, 1993.

[45]H. Águas, S. K. Ram, A. Araújo, D. Gaspar, A. Vicente, S. A. Filonovich*, et al.*, "Silicon thin film solar cells on commercial tiles," *Energy & Environmental Science,* vol. 4, pp. 4620-4632, 2011.

[46]H. Tanimoto, H. Arai, H. Mizubayashi, M. Yamanaka, and I. Sakata, "Light-induced hydrogen evolution from hydrogenated amorphous silicon: Hydrogen diffusion by formation of bond centered hydrogen," *Journal of Applied Physics,* vol. 115, p. 073503, 2014.

[47]X. Deng and E. A. Schif, "Amorphous Silicon–based Solar Cells," in *Handbook of Photovoltaic Science and Engineering*, A. L. a. S. Hegedus, Ed., ed: John Wiley & Sons, Chichester, 2003, pp. 505 - 565.

[48] U. Rau and H. W. Schock, "Cu (In, Ga) Se 2 solar cells," in *Clean Electricity from Photovoltaics*, ed: World Scientific, 2001, pp. 277-345.

[49]J. Shay and J. Wernick, "Ternary chalcopyrite semiconductors: Growth, electronic properties and applications (Pergamon Press, Oxford, 1974)."

[50]S. Wagner, J. Shay, P. Migliorato, and H. Kasper, "CuInSe2/CdS heterojunction photovoltaic detectors," *Applied Physics Letters,* vol. 25, pp. 434-435, 1974.

[51]R. Mickelsen and W. Chen, "Development of a 9.4% efficient thin-film CuInSe2/CdS solar cell," in *15th photovoltaic specialists conference*, 1981, pp. 800-804.

[52]J. Tuttle, M. Contreras, T. Gillespie, K. Ramanathan, A. Tennant, J. Keane*, et al.*, "Accelerated publication 17.1% efficient Cu (In, Ga) Se2- based thin- film solar cell," *Progress in Photovoltaics: Research and Applications,* vol. 3, pp. 235-238, 1995.

[53]M. A. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon*, et al.*, "Progress toward 20% efficiency in Cu (In, Ga) Se2 polycrystalline thin- film solar cells," *Progress in Photovoltaics: Research and applications,* vol. 7, pp. 311-316, 1999.

[54]I. Repins, M. Contreras, M. Romero, Y. Yan, W. Metzger, J. Li*, et al.*, "Characterization of 19.9%-efficient CIGS absorbers," in *Photovoltaic Specialists Conference, 2008. PVSC'08. 33rd IEEE*, 2008, pp. 1-6.

[55]T. Satoh, Y. Hashimoto, S.-i. Shimakawa, S. Hayashi, and T. Negami, "Cigs solar cells on flexible stainless steel substrates," in *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE*, 2000, pp. 567-570.

[56]R. Wuerz, A. Eicke, M. Frankenfeld, F. Kessler, M. Powalla, P. Rogin*, et al.*, "CIGS thin-film solar cells on steel substrates," *Thin Solid Films,* vol. 517, pp. 2415-2418, 2009.

[57]C. Shi, Y. Sun, Q. He, F. Li, and J. Zhao, "Cu (In, Ga) Se2 solar cells on stainless-steel substrates covered with ZnO diffusion barriers," *Solar Energy Materials and Solar Cells,* vol. 93, pp. 654-656, 2009.

[58]B. M. Başol, V. K. Kapur, C. R. Leidholm, A. Halani, and K. Gledhill, "Flexible and light weight copper indium diselenide solar cells on polyimide substrates," *Solar Energy Materials and Solar Cells,* vol. 43, pp. 93-98, 1996.

[59]G. M. Hanket, U. P. Singh, E. Eser, W. N. Shafarman, and R. W. Birkmire, "Pilot-scale manufacture of Cu (InGa) Se/sub 2/films on a flexible polymer substrate," in *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE*, 2002, pp. 567-570.

[60]H. Zachmann, S. Heinker, A. Braun, A. Mudryi, V. Gremenok, A. Ivaniukovich*, et al.*, "Characterisation of Cu (In, Ga) Se2-based thin film solar cells on polyimide," *Thin Solid Films,* vol. 517, pp. 2209-2212, 2009.

[61]B. M. Başol, V. K. Kapur, A. Halani, and C. Leidholm, "Copper indium diselenide thin film solar cells fabricated on flexible foil substrates," *Solar Energy Materials and Solar Cells,* vol. 29, pp. 163-173, 1993.

[62]M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 42)," *Progress in Photovoltaics: Research and Applications,* vol. 5, pp. 827-837, 2013.

[63]L. Kazmerski, F. White, and G. Morgan, "Thin- film CuInSe2/CdS heterojunction solar cells," *Applied Physics Letters,* vol. 29, pp. 268-270, 1976.

[64]S. Niki, M. Contreras, I. Repins, M. Powalla, K. Kushiya, S. Ishizuka*, et al.*, "CIGS absorbers and processes," *Progress in Photovoltaics: Research and Applications,* vol. 18, pp. 453-466, 2010.

[65]F. Pianezzi, A. Chirilă, P. Blösch, S. Seyrling, S. Buecheler, L. Kranz*, et al.*, "Electronic properties of Cu (In, Ga) Se2 solar cells on stainless steel foils without diffusion barrier," *Progress in Photovoltaics: Research and Applications,* vol. 20, pp. 253-259, 2012.

[66]Y. H. Jyh-Lih Wu, Takuya Kato, Hiroki Sugimoto, Veronica Bermudez, "New World Record Efficiency up to 22.9% for Cu(In,Ga)(Se,S)2 Thin-Film Solar Cells ", 2018.

[67]P. Jackson, R. Würz, U. Rau, J. Mattheis, M. Kurth, T. Schlötzer*, et al.*, "High quality baseline for high efficiency, Cu (In1− x, Gax) Se2 solar cells," *Progress in Photovoltaics: Research and Applications,* vol. 15, pp. 507-519, 2007.

[68]W. N. Shafarman and L. Stolt, "Cu (InGa) Se2 Solar Cells," *Handbook of photovoltaic science and engineering,* pp. 567-616, 2003.

[69]P. Jackson, D. Hariskos, E. Lotter, S. Paetel, R. Wuerz, R. Menner*, et al.*, "New world record efficiency for Cu (In, Ga) Se2 thin- film solar cells beyond 20%," *Progress in Photovoltaics: Research and Applications,* vol. 19, pp. 894-897, 2011.

[70]A. Chirilă, S. Buecheler, F. Pianezzi, P. Bloesch, C. Gretener, A. R. Uhl*, et al.*, "Highly efficient Cu (In, Ga) Se 2 solar cells grown on flexible polymer films," *Nature materials,* vol. 10, p. 857, 2011.

[71]I. Repins, M. A. Contreras, B. Egaas, C. DeHart, J. Scharf, C. L. Perkins*, et al.*, "19· 9%- efficient ZnO/CdS/CuInGaSe2 solar cell with 81· 2% fill factor," *Progress in Photovoltaics: Research and applications,* vol. 16, pp. 235-239, 2008.

[72]N. D. Sankır, E. Aydın, and E. Uğur, "Spray pyrolized copper indium gallium sulfide abosrober layers for thin film solar cells," in *2013 International Conference on Renewable Energy Research and Applications (ICRERA)*, 2013, pp. 559-561.

[73]N. G. Dhere, "Toward GW/year of CIGS production within the next decade," *Solar Energy Materials and Solar Cells,* vol. 91, pp. 1376-1382, 2007.

[74]L. Van Puyvelde, J. Lauwaert, F. Pianezzi, S. Nishiwaki, P. Smet, D. Poelman, *et al.*, "Influence of an Sb doping layer in CIGS thin-film solar cells: a photoluminescence study," *Journal of Physics D: Applied Physics,* vol. 47, p. 045102, 2013.

[75]D. Hariskos, S. Spiering, and M. Powalla, "Buffer layers in Cu (In, Ga) Se2 solar cells and modules," *Thin Solid Films,* vol. 480, pp. 99-109, 2005.

[76]K. Kushiya, Y. Tanaka, H. Hakuma, Y. Goushi, S. Kijima, T. Aramoto, *et al.*, "Interface control to enhance the fill factor over 0.70 in a large-area CIS-based thin-film PV technology," *Thin Solid Films,* vol. 517, pp. 2108-2110, 2009.

[77]V. Fthenakis and P. Moskowitz, "Thin- film Photovoltaic Cells: Health and Environmental Issues in their Manufacture Use and Disposal," *Progress in Photovoltaics: Research and Applications,* vol. 3, pp. 295-306, 1995.

[78]R. Nitsche, D. Sargent, and P. Wild, "Crystal growth of quaternary 122464 chalcogenides by iodine vapor transport," *Journal of Crystal Growth,* vol. 1, pp. 52-53, 1967.

[79]K. Ito and T. Nakazawa, "Electrical and optical properties of stannite-type quaternary semiconductor thin films," *Japanese Journal of Applied Physics,* vol. 27, p. 2094, 1988.

[80]H. Katagiri, M. Nishimura, T. Onozawa, S. Maruyama, M. Fujita, T. Sega, *et al.*, "Rare-metal free thin film solar cell," in *Power Conversion Conference-Nagaoka 1997., Proceedings of the*, 1997, pp. 1003-1006.

[81]H. Katagiri, N. Sasaguchi, S. Hando, S. Hoshino, J. Ohashi, and T. Yokota, "Preparation and evaluation of Cu2ZnSnS4 thin films by sulfurization of E B evaporated precursors," *Solar Energy Materials and Solar Cells,* vol. 49, pp. 407-414, 1997.

[82]T. M. Friedlmeier, N. Wieser, T. Walter, H. Dittrich, and H. Schock, "Heterojunctions based on Cu2ZnSnS4 and Cu2ZnSnSe4 thin films," in *Proceedings of the 14th European Conference of Photovoltaic Science and Engineering and Exhibition*, 1997.

[83]K. Jimbo, R. Kimura, T. Kamimura, S. Yamada, W. S. Maw, H. Araki, *et al.*, "Cu2ZnSnS4-type thin film solar cells using abundant materials," *Thin solid films,* vol. 515, pp. 5997-5999, 2007.

[84]H. Katagiri, K. Jimbo, W. S. Maw, K. Oishi, M. Yamazaki, H. Araki, *et al.*, "Development of CZTS-based thin film solar cells," *Thin Solid Films,* vol. 517, pp. 2455-2460, 2009.

[85]T. K. Todorov, K. B. Reuter, and D. B. Mitzi, "High-efficiency solar cell with earth- abundant liquid-processed absorber," *Advanced materials,* vol. 22, pp. E156-E159, 2010.

[86]T. K. Todorov, J. Tang, S. Bag, O. Gunawan, T. Gokmen, Y. Zhu, *et al.*, "Beyond 11% efficiency: characteristics of state- of- the- art Cu2ZnSn (S, Se) 4 solar cells," *Advanced Energy Materials,* vol. 3, pp. 34-38, 2013.

[87]W. Wang, M. T. Winkler, O. Gunawan, T. Gokmen, T. K. Todorov, Y. Zhu, *et al.*, "Device characteristics of CZTSSe thin- film solar cells with 12.6% efficiency," *Advanced Energy Materials,* vol. 4, p. 1301465, 2014.

[88]D. B. Mitzi, O. Gunawan, T. K. Todorov, K. Wang, and S. Guha, "The path towards a high-performance solution-processed kesterite solar cell," *Solar Energy Materials and Solar Cells,* vol. 95, pp. 1421-1436, 2011/06/01/ 2011.

[89]X. Lu, Z. Zhuang, Q. Peng, and Y. Li, "Wurtzite Cu 2 ZnSnS 4 nanocrystals: a novel quaternary semiconductor," *Chemical Communications,* vol. 47, pp. 3141-3143, 2011.

[90]J. Paier, R. Asahi, A. Nagoya, and G. Kresse, "Cu 2 ZnSnS 4 as a potential photovoltaic material: a hybrid Hartree-Fock density functional theory study," *Physical Review B,* vol. 79, p. 115126, 2009.

[91]S. Chen, X. Gong, A. Walsh, and S.-H. Wei, "Crystal and electronic band structure of Cu 2 ZnSn X 4 (X= S and Se) photovoltaic absorbers: First-principles insights," *Applied Physics Letters,* vol. 94, p. 041903, 2009.

[92]A. Wangperawong, J. King, S. Herron, B. Tran, K. Pangan-Okimoto, and S. Bent, "Aqueous bath process for deposition of Cu2ZnSnS4 photovoltaic absorbers," *Thin Solid Films,* vol. 519, pp. 2488-2492, 2011.

[93]H. Katagiri, K. Saitoh, T. Washio, H. Shinohara, T. Kurumadani, and S. Miyajima, "Development of thin film solar cell based on Cu2ZnSnS4 thin films," *Solar Energy Materials and Solar Cells,* vol. 65, pp. 141-148, 2001.

[94]X. Wang, Z. Sun, C. Shao, D. M. Boye, and J. Zhao, "A facile and general approach to polynary semiconductor nanocrystals via a modified two-phase method," *Nanotechnology,* vol. 22, p. 245605, 2011.

[95]M. Jiang and X. Yan, "Cu2ZnSnS4 thin film solar cells: present status and future prospects," in *Solar Cells-Research and Application Perspectives*, ed: InTech, 2013.

[96]S. Akhanda, R. Matin, M. Bashar, A. Kowsar, and M. Rahaman, "Experimental Study on Structural, Optical and Electrical Properties of Chemical Bath Deposited CdZnS Thin Films. J Fundam Renewable Energy Appl 7: 222. doi: 10.4172/20904541.1000222 Volume 7• Issue 1• 1000222.

[97]S. Akhanda, R. Matin, M. Bashar, M. Sultana, A. Kowsar, M. Rahaman, *et al.*, "Effect of annealing atmosphere on structural and optical properties of CZTS thin films prepared by spin-coating," *Bangladesh Journal of Scientific and Industrial Research,* vol. 53, pp. 13-20, 2018.

[98]S. K. Swami, A. Kumar, and V. Dutta, "Deposition of kesterite Cu2ZnSnS4 (CZTS) thin films by spin coating technique for solar cell application," *Energy Procedia,* vol. 33, pp. 198-202, 2013.

[99]H. Katagiri, N. Ishigaki, T. Ishida, and K. Saito, "Characterization of Cu2ZnSnS4 thin films prepared by vapor phase sulfurization," *Japanese Journal of Applied Physics,* vol. 40, p. 500, 2001.

[100]S. Azmi, M. Nohair, M. El Marrakchi, E. Khoumri, and M. Dabala, "Effect of the Complexing Agents on the Properties of Electrodeposited CZTS Thin Films," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2018, pp. 1346-1351.

[101]M. Cao and Y. Shen, "A mild solvothermal route to kesterite quaternary Cu2ZnSnS4 nanoparticles," *Journal of Crystal Growth,* vol. 318, pp. 1117-1120, 2011.

[102]H. Yoo and J. Kim, "Comparative study of Cu2ZnSnS4 film growth," *Solar Energy Materials and Solar Cells,* vol. 95, pp. 239-244, 2011.

[103]B. A. Schubert, B. Marsen, S. Cinque, T. Unold, R. Klenk, S. Schorr*, et al.*, "Cu2ZnSnS4 thin film solar cells by fast coevaporation," *Progress in Photovoltaics: Research and Applications,* vol. 19, pp. 93-96, 2011.

[104]K. Moriya, K. Tanaka, and H. Uchiki, "Cu2ZnSnS4 thin films annealed in H2S atmosphere for solar cell absorber prepared by pulsed laser deposition," *Japanese Journal of Applied Physics,* vol. 47, p. 602, 2008.

[105]K. Woo, Y. Kim, and J. Moon, "A non-toxic, solution-processed, earth abundant absorbing layer for thin-film solar cells," *Energy & Environmental Science,* vol. 5, pp. 5340-5345, 2012.

[106]J. Margottet, "Researches on sulphur, selenium, and tellurium alloys," in *Annales Scientifiques de l'École Normale Superieure*, 1879, pp. 247-298.

[107]D. A. Jenny and R. H. Bube, "Semiconducting cadmium telluride," *Physical Review,* vol. 96, p. 1190, 1954.

[108]J. J. Loferski, "Theoretical considerations governing the choice of the optimum semiconductor for photovoltaic solar energy conversion," *Journal of Applied Physics,* vol. 27, pp. 777-784, 1956.

[109]P. Rappaport, "The photovoltaic effect and its utilization," *Solar Energy,* vol. 3, pp. 8-18, 1959.

[110]D. Bonnet and H. Rabenhorst, "New results on the development of a thin-film p-CdTe-n-CdS heterojunction solar cell," in *Photovoltaic Specialists Conference, 9 th, Silver Spring, Md*, 1972, pp. 129-132.

[111]K. Mitchell, A. L. Fahrenbruch, and R. H. Bube, "Photovoltaic determination of optical- absorption coefficient in CdTe," *Journal of Applied Physics,* vol. 48, pp. 829-830, 1977.

[112]J. Mimila-Arroyo, Y. Marfaing, G. Cohen-Solal, and R. Triboulet, "Electric and photovoltaic properties of CdTe pn homojunctions," *Solar energy materials,* vol. 1, pp. 171-180, 1979.

[113]G. Cohen-Solal, D. Lincot, and M. Barbe, "High efficiency shallow p+ nn+ cadmium telluride solar cells," in *Fourth EC Photovoltaic Solar Energy Conference*, 1982, pp. 621-626.

[114]J. Britt and C. Ferekides, "Thin- film CdS/CdTe solar cell with 15.8% efficiency," *Applied Physics Letters,* vol. 62, pp. 2851-2852, 1993.

[115]X. Wu, J. Keane, R. Dhere, C. DeHart, D. Albin, A. Duda*, et al.*, "16.5%-efficient CdS/CdTe polycrystalline thin-film solar cell," in *Proceedings of the 17th European photovoltaic solar energy conference*, 2001.

[116]A. Morales-Acevedo, "Design of Very thin CdTe Solar Cells with High Efficiency," *Energy Procedia,* vol. 57, pp. 3051-3057, 2014/01/01/ 2014.

[117]Y. Yan, M. Al-Jassim, K. Jones, S.-H. Wei, and S. Zhang, "Observation and first-principles calculation of buried wurtzite phases in zinc-blende CdTe thin films," *Applied Physics Letters,* vol. 77, pp. 1461-1463, 2000.

[118]N. R. Paudel, M. Young, P. J. Roland, R. J. Ellingson, Y. Yan, and A. D. Compaan, "Post-deposition processing options for high-efficiency sputtered CdS/CdTe solar cells," *Journal of Applied Physics,* vol. 115, p. 064502, 2014.

[119]W. Rance, J. Burst, D. Meysing, C. Wolden, M. Reese, T. Gessert*, et al.*, "14%-efficient flexible CdTe solar cells on ultra-thin glass substrates," *Applied Physics Letters,* vol. 104, p. 143903, 2014.

[120]N. Romeo, A. Bosio, R. Tedeschi, and V. Canevari, "Growth of polycrystalline CdS and CdTe thin layers for high efficiency thin film solar cells," *Materials Chemistry and Physics,* vol. 66, pp. 201-206, 2000.

[121]N. Romeo, A. Bosio, V. Canevari, and A. Podesta, "Recent progress on CdTe/CdS thin film solar cells," *Solar Energy,* vol. 77, pp. 795-801, 2004.

[122]N. Khan, K. Rahman, F. Haque, N. Dhar, M. Islam, M. Akhtaruzzaman*, et al.*, "Design optimization of CdTe thin film solar cells from numerical analysis," in *8th International Conference on Electrical and Computer Engineering*, 2014, pp. 508-511.

[123]K. D. Dobson, I. Visoly-Fisher, G. Hodes, and D. Cahen, "Stability of CdTe/CdS thin-film solar cells," *Solar Energy Materials and Solar Cells,* vol. 62, pp. 295-325, 2000.

[124]C. Candelise, M. Winskel, and R. Gross, "Implications for CdTe and CIGS technologies production costs of indium and tellurium scarcity," *Progress in Photovoltaics: Research and Applications,* vol. 20, pp. 816-831, 2012.

[125]J. Skarp, Y. Koskinen, S. Lindfors, A. Rautiainen, and T. Suntola, "Development and evaluation of CdS/CdTe

thin film PV cells," in *Tenth EC Photovoltaic Solar Energy Conference*, 1991, pp. 567-569.

[126]J. Moser, "Notiz über Verstärkung photoelektrischer Ströme durch optische Sensibilisirung," *Monatshefte für Chemie/Chemical Monthly,* vol. 8, pp. 373-373, 1887.

[127]H. Gerischer, M. Michel-Beyerle, F. Rebentrost, and H. Tributsch, "Sensitization of charge injection into semiconductors with large band gap," *Electrochimica Acta,* vol. 13, pp. 1509-1515, 1968.

[128]H. Tributsch, "Reaction of excited chlorophyll molecules at electrodes and in photosynthesis," *Photochemistry and Photobiology,* vol. 16, pp. 261-269, 1972.

[129]B. O'regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films," *nature,* vol. 353, p. 737, 1991.

[130]P. Wang, S. M. Zakeeruddin, J. E. Moser, M. K. Nazeeruddin, T. Sekiguchi, and M. Grätzel, "A stable quasi-solid-state dye-sensitized solar cell with an amphiphilic ruthenium sensitizer and polymer gel electrolyte," in *Materials For Sustainable Energy: A Collection of Peer-Reviewed Research and Review Articles from Nature Publishing Group*, ed: World Scientific, 2011, pp. 88-93.

[131]M. Paulose, K. Shankar, O. K. Varghese, G. K. Mor, B. Hardin, and C. A. Grimes, "Backside illuminated dye-sensitized solar cells based on titania nanotube array electrodes," *Nanotechnology,* vol. 17, p. 1446, 2006.

[132]W. M. Campbell, K. W. Jolley, P. Wagner, K. Wagner, P. J. Walsh, K. C. Gordon*, et al.*, "Highly efficient porphyrin sensitizers for dye-sensitized solar cells," *The Journal of Physical Chemistry C,* vol. 111, pp. 11760-11762, 2007.

[133]Q. Wang, W. M. Campbell, E. E. Bonfantani, K. W. Jolley, D. L. Officer, P. J. Walsh*, et al.*, "Efficient light harvesting by using green Zn-porphyrin-sensitized nanocrystalline TiO2 films," *The Journal of Physical Chemistry B,* vol. 109, pp. 15397-15409, 2005.

[134]Y. Bai, Y. Cao, J. Zhang, M. Wang, R. Li, P. Wang*, et al.*, "High-performance dye-sensitized solar cells based on solvent-free electrolytes produced from eutectic melts," *Nature materials,* vol. 7, p. 626, 2008.

[135]A. Yella, H.-W. Lee, H. N. Tsao, C. Yi, A. K. Chandiran, M. K. Nazeeruddin*, et al.*, "Porphyrin-sensitized solar cells with cobalt (II/III)–based redox electrolyte exceed 12 percent efficiency," *science,* vol. 334, pp. 629-634, 2011.

[136]J. Burschka, N. Pellet, S.-J. Moon, R. Humphry-Baker, P. Gao, M. K. Nazeeruddin*, et al.*, "Sequential deposition as a route to high-performance perovskite-sensitized solar cells," *Nature,* vol. 499, p. 316, 2013.

[137]M. Grätzel, "Dye-sensitized solar cells," *Journal of Photochemistry and Photobiology C: Photochemistry Reviews,* vol. 4, pp. 145-153, 2003.

[138]O. Eyecioglu, M. Beken, O. Yagcı, and O. Icelli, "Effect of Boric Acid Doped Pedot: PSS Layer on the Photovoltaic Parameters of P3HT: PCBM Based PV Cell," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2018, pp. 973-975.

[139]S.-L. Li, K.-J. Jiang, K.-F. Shao, and L.-M. Yang, "Novel organic dyes for efficient dye-sensitized solar cells," *Chemical Communications,* pp. 2792-2794, 2006.

[140]H. Zhou, L. Wu, Y. Gao, and T. Ma, "Dye-sensitized solar cells using 20 natural dyes as sensitizers," *Journal of Photochemistry and Photobiology A: Chemistry,* vol. 219, pp. 188-194, 2011.

[141]J. D. Roy-Mayhew and I. A. Aksay, "Graphene materials and their use in dye-sensitized solar cells," *Chemical reviews,* vol. 114, pp. 6323-6348, 2014.

[142]J. Wu, Z. Lan, S. Hao, P. Li, J. Lin, M. Huang*, et al.*, "Progress on the electrolytes for dye-sensitized solar cells," *Pure and Applied Chemistry,* vol. 80, pp. 2241-2258, 2008.

[143]B. Lee, J. He, R. P. Chang, and M. G. Kanatzidis, "All-solid-state dye-sensitized solar cells with high efficiency," *Nature,* vol. 485, p. 486, 2012.

[144]B. O'Regan and D. T. Schwartz, "Large enhancement in photocurrent efficiency caused by UV illumination of the dye-sensitized heterojunction TiO2/RuLL 'NCS/CuSCN: initiation and potential mechanisms," *Chemistry of Materials,* vol. 10, pp. 1501-1509, 1998.

[145]A. Konno, G. Kumara, R. Hata, and K. Tennakone, "Effect of imidazolium salts on the performance of solid-state dye-sensitized photovoltaic cell using copper iodide as a hole collector," *Electrochemistry,* vol. 70, pp. 432-434, 2002.

[146]S. Wu, S. Yuan, L. Shi, Y. Zhao, and J. Fang, "Preparation, characterization and electrical properties of fluorine-doped tin dioxide nanocrystals," *Journal of colloid and interface science,* vol. 346, pp. 12-16, 2010.

[147]S. Ito, P. Chen, P. Comte, M. K. Nazeeruddin, P. Liska, P. Péchy*, et al.*, "Fabrication of screen- printing pastes from TiO2 powders for dye- sensitised solar cells," *Progress in photovoltaics: research and applications,* vol. 15, pp. 603-612, 2007.

[148]Y. Zhang, L. Wu, E. Xie, H. Duan, W. Han, and J. Zhao, "A simple method to prepare uniform-size nanoparticle TiO2 electrodes for dye-sensitized solar cells," *Journal of Power Sources,* vol. 189, pp. 1256-1263, 2009.

[149]T. Miyasaka and Y. Kijitori, "Low-temperature fabrication of dye-sensitized plastic electrodes by electrophoretic preparation of mesoporous TiO2 layers," *Journal of the Electrochemical Society,* vol. 151, pp. A1767-A1773, 2004.

[150]E. Lancelle-Beltran, P. Prené, C. Boscher, P. Belleville, P. Buvat, S. Lambert*, et al.*, "Nanostructured hybrid solar

cells based on self-assembled mesoporous titania thin films," *Chemistry of materials,* vol. 18, pp. 6152-6156, 2006.

[151]N. Ikeda and T. Miyasaka, "Plastic and solid-state dye-sensitized solar cells incorporating single-wall carbon nanotubes," *Chemistry letters,* vol. 36, pp. 466-467, 2007.

[152]S. Ito, G. Rothenberger, P. Liska, P. Comte, S. M. Zakeeruddin, P. Péchy*, et al.*, "High-efficiency (7.2%) flexible dye-sensitized solar cells with Ti-metal substrate for nanocrystalline-TiO 2 photoanode," *Chemical Communications,* pp. 4004-4006, 2006.

[153]M. I. A Kowsar, KR Mehzabeen, ZH Mahmood, "Study on the Efficiency of the GaInP2/GaAs/Ge Multijunction Solar Cell," in *Proc. of International Conference on Environmental Aspects of Bangladesh,BEN, Japan*, 2010, pp. 116-119.

[154]A. Kowsar, S. F. U. Farhad, S. N. Sakib, "Effect of the Bandgap, Sun Concentration and Surface Recombination Velocity on the Performance of a III-V Bismide Multijunction Solar Cells," *International Journal of Renewable Energy Research (IJRER),* vol. 8, pp. 2218-2227, 2018.

[155]W. Palz, *Photovoltaic Solar Energy Conference: Proceedings of the International Conference, Held at Cannes, France, 27–31 October 1980*: Springer Science & Business Media, 2012.

[156]Z. Wang, U. Helmersson, and P.-O. Käll, "Optical properties of anatase TiO2 thin films prepared by aqueous sol–gel process at low temperature," *Thin Solid Films,* vol. 405, pp. 50-54, 2002.

[157]B. Shin, O. Gunawan, Y. Zhu, N. A. Bojarczuk, S. J. Chey, and S. Guha, "Thin film solar cell with 8.4% power conversion efficiency using an earth- abundant Cu2ZnSnS4 absorber," *Progress in Photovoltaics: Research and Applications,* vol. 21, pp. 72-76, 2013.

[158]B. J. Stanbery, "Copper indium selenides and related materials for photovoltaic devices," *Critical reviews in solid state and materials sciences,* vol. 27, pp. 73-117, 2002.

[159]A. Rakhshani, "Electrodeposited CdTe—optical properties," *Journal of applied physics,* vol. 81, pp. 7988-7993, 1997.

[160]S. Fonash, *Solar cell device physics*: Elsevier, 2012.

[161]G. Swartz, "Computer model of amorphous silicon solar cell," *Journal of Applied Physics,* vol. 53, pp. 712-719, 1982.

[162]J. T. Heath, J. D. Cohen, and W. N. Shafarman, "Bulk and metastable defects in CuIn 1− x Ga x Se 2 thin films using drive-level capacitance profiling," *Journal of Applied Physics,* vol. 95, pp. 1000-1010, 2004.

[163]J. J. Scragg, P. J. Dale, L. M. Peter, G. Zoppi, and I. Forbes, "New routes to sustainable photovoltaics: evaluation of Cu2ZnSnS4 as an alternative absorber material," *physica status solidi (b),* vol. 245, pp. 1772-1778, 2008.

[164]P. Fernandes, P. Salomé, A. Da Cunha, and B.-A. Schubert, "Cu2ZnSnS4 solar cells prepared with sulphurized dc-sputtered stacked metallic precursors," *Thin Solid Films,* vol. 519, pp. 7382-7385, 2011.

[165]F. Liu, K. Zhang, Y. Lai, J. Li, Z. Zhang, and Y. Liu, "Growth and characterization of Cu2ZnSnS4 thin films by dc reactive magnetron sputtering for photovoltaic applications," *Electrochemical and Solid-State Letters,* vol. 13, pp. H379-H381, 2010.

[166]J. Liang, E. A. Schiff, S. Guha, B. Yan, and J. Yang, "Hole-mobility limit of amorphous silicon solar cells," *Applied physics letters,* vol. 88, p. 063512, 2006.

[167]S. Siebentritt, "Hole transport mechanisms in CuGaSe2," *Thin Solid Films,* vol. 480, pp. 312-317, 2005.

[168]*First solar reports largest quarterly decline in CdTe module cost per-watt since 2007.* https://cleantechnica.com/2013/11/07/first-solar-reports-largest-quarterly-decline-cdte-module-cost-per-watt-since-2007/, Accessed date: Sept 29, 2013.

[169]H. Neumann and R. Tomlinson, "Relation between electrical properties and composition in CuInSe2 single crystals," *Solar Cells,* vol. 28, pp. 301-313, 1990.