A Review on the Improvisation of Fill Factor in CdS/CdTe Solar Cells

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Abstract

CdS/CdTe solar cells are recognized as one of the most promising and efficient solar cells in second-generation photovoltaic technology. Owing to their simplicity of fabrication and cost-effectiveness, researchers are focusing on improving conversion efficiency to make it a front-line solution for the energy crisis. In the path to improvise efficiency, the fill factor plays a vital role. Still, it is challenging to determine the factors that influence the fill factor and improve it in line with the improvisation of efficiency since, most of the time, they are not improved in tandem. This paper summarises the improvisation of the fill factor of CdS/CdTe solar cells developed elsewhere by different deposition techniques and treatments from the mid-1960s.

Keywords: CdS/CdTe solar cell, Fill factor, Thin film solar cell

1. Introduction

The energy crisis is the most crucial factor that adversely affects technological development. The widely used non-renewable energy sources of coal, oil, and gases are insufficient to fulfil the electricity demand. Their use adversely contributes to increasing environmental pollution and global warming. The usage of renewable energy sources such as hydropower, wind power, geothermal and solar energy must be exploited more to overcome upcoming energy crises. Solar energy is the most abundant and reliable source of electricity generation method among the renewable sources. The photovoltaic cells are the potential candidate for generating electricity cost-effectively in an environmentally friendly manner.

The photovoltaic panels fulfil about 3.72% of the electricity requirement of the world [1]. These photovoltaic cells have surpassed four generations. Still, the crystalline silicon solar cells of the 1st generation and the thin-film solar cells of CdS/CdTe and copper indium gallium selenide (CIGS) of the 2nd generation dominate the world's photovoltaic market. When compared with traditional silicon solar cells, the CdTe has not been able to reach its maximum theoretical efficiency (η) value of 32% [2]. Hence, researchers worldwide have put efforts into reaching the maximum efficiency of CdS/CdTe cells. Therein, attention has been paid to increasing the open-circuit voltage (V_{OC}), short circuit current (I_{SC}), and fill factor (FF) of the devices. This article described such efforts taken in the research area since the 1960s.

1.1 Device structure and deposition technique

A solar cell basically consists of a window and an absorber layer capable of creating a p-n junction. In CdS/CdTe solar cells, n-CdS is used as a window layer and p-CdTe as an absorber layer. The cell structure can have either substrate or superstrate configuration, as shown in Fig. 1 (a) and (b). In the early days, the substrate configuration was predominant but later shifted towards superstrate configuration with the use of conducting glass substrate to deposit the n-CdS layer, followed by the deposition of p-CdTe.
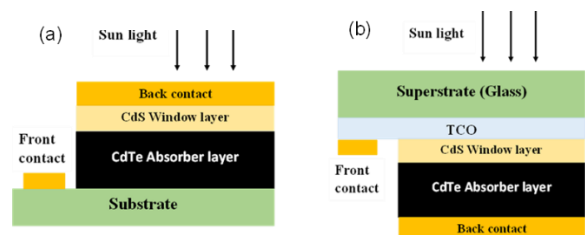

Fig. 1. (a) The substrate configuration (b) superstrate configuration of CdS/CdTe solar cell

Many techniques have been employed for the deposition of n-CdS and p-CdTe materials, which can be simply listed as either physical or chemical deposition techniques. The physical deposition techniques can further be divided into thermal and sputtering methods, while the chemical deposition technique can be categorized as gas-phase and liquid-phase deposition techniques. The physical deposition techniques are performed under high temperature and high

vacuum environments, while the chemical deposition techniques are by chemical reactions in a chemical bath. The close-spaced sublimation (CSS), thermal evaporation (TE), electron beam evaporation (EBE), pulsed laser deposition (PLD), and molecular-beam epitaxy (MBE) can be clustered as thermal modes of physical deposition techniques. The glow discharge DC sputtering, radio frequency sputtering, and magnetron sputtering are few examples of the sputtering method. Chemical vapor deposition (CVD), thermal nitridation, thermal polymerization, and ion implantation technique can be named under gas-phase deposition techniques. Electrodeposition (ED), spray pyrolysis, chemical bath deposition (CBD), and liquid-phase epitaxy can be named under liquid-phase deposition techniques [3].

1.2 Theoretical representation for the fill factor

The concern about the effect of the *FF* on the performance of the CdS/CdTe solar cell began with the theoretical representation of *FF*. The *FF* is commonly described as the combination of the V_{OC}, I_{SC}, and the maximum output power from the device (P_{mp}). Generally, *FF* is defined as the ratio between the P_{mp} and the product of the V_{OC} and I_{SC} (eq:01). The graphical representation of the *FF* is shown in Fig. 2.

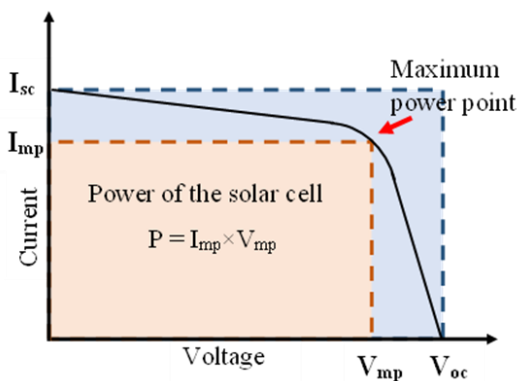$$FF = \frac{P_{mp}}{I_{sc} \times V_{oc}} \tag{01}$$

Fig. 2. Graphical interpretation of the *FF* of the theoretical and practical solar cell

The *FF* is a crucial factor that affects cell performance. Expressions have been developed elsewhere for *FF* that differ from typical expressions interrelating other device parameters, such as shunt resistance (R_{sh}), series resistance (R_s), characteristics resistance (R_{ch}), and diode ideality factor (*n*). The derivation of the empirical expressions for the *FF* of a solar cell elucidates as follows. The eq:02 gives the relationship between the total current with the voltage of a solar cell under illumination conditions in conjunction with R_{sh} and R_s [4].

$$I = I_L - I_o \left\{ exp\left[\frac{q(V + IR_s)}{nkT}\right] - 1 \right\} - \left(\frac{V + IR_s}{R_{sh}}\right) \tag{02}$$

I_L and I_0 are the light-generated current and saturated current of the diode, respectively, *k* is Boltzmann's constant, and *T* is the device temperature. The alternative expression

for the *FF* has derived in the presence of R_{sh}, assuming the effect of the R_s is negligible. The maximum power in the presence of R_{sh} is $P_{mp}{}^{sh}$.

$$P_{mp}{}^{sh} \approx V_{mp}I_{mp} - \frac{V_{mp}^2}{R_{sh}} = V_{mp}I_{mp}\left(1 - \frac{V_{mp}}{I_{mp}R_{sh}}\right)$$
$$= P_{mp}\left(1 - \frac{V_{oc}}{I_{sc}R_{sh}}\right) \tag{03}$$

$$P_{mp}{}^{sh} = P_{mp}\left(1 - \frac{R_{ch}}{R_{sh}}\right)$$
$$FF_{sh} = FF_o\left(1 - \frac{R_{ch}}{R_{sh}}\right)$$
$$FF_{sh} = FF_o\left(1 - \frac{1}{r_{sh}}\right) \tag{04}$$

where $R_{ch} = V_{OC}/I_{SC}$, FF_o is the fill factor of the solar cell neglecting R_{sh}, and R_s, and r_{sh} is the normalized shunt resistance. The eq: 04 shows the *FF* assuming the effect of R_s is negligible and R_{sh} is in considerable value.

Similarly, the *FF* of a solar cell in the presence of R_s, assuming R_{sh} is negligible, is given in eq: 05 [5],

$$P_{mp}{}^s \approx V_{mp}I_{mp} - I_{mp}^2 R_s = V_{mp}I_{mp}\left(1 - \frac{I_{mp}}{V_{mp}}R_s\right)$$
$$= P_{mp}\left(1 - \frac{I_{sc}}{V_{oc}}R_s\right)$$
$$P_{mp}{}^s = P_{mp}\left(1 - \frac{R_s}{R_{ch}}\right)$$
$$FF_s = FF_o\left(1 - \frac{R_s}{R_{ch}}\right)$$
$$FF_s = FF_o(1 - r_s) \tag{05}$$

where r_s is the normalized series resistance, and the FF_{sh} and FF_s defined elsewhere and are labeled as eq (06) and (07) below [4, 5].

$$FF_{sh} = FF_o\left[1 - \frac{(v_{oc} + 0.7)}{v_{oc}}\frac{FF_o}{r_{sh}}\right] \tag{06}$$

$$FF_s = FF_o(1 - 1.1r_s) + \frac{r_s^2}{5.4} \tag{07}$$

The more accurate expression for the *FF* can calculate by substituting eq (06) in (07), which is shown as eq (08).

$$FF = \left(FF_o(1 - 1.1r_s) + \frac{r_s^2}{5.4}\right)\left\{1 - \frac{(v_{oc} + 0.7)}{v_{oc}r_{sh}}\left(FF_o(1 - 1.1r_s) + \frac{r_s^2}{5.4}\right)\right\} \tag{08}$$

The expression for FF_o is;

$$FF_o = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1} \tag{09}$$

Therefore,

$$FF_s = \left| f_i \left\{ (1 - f_i r_s) + \frac{1}{v_{oc}} ln[1 - f_i(1 - exp(v_{oc}r_s - 1))] \right\} \right|$$

$$FF_{sh} = \left| f_v \left\{ 1 - \left[\frac{(exp(v_{oc}f_v) - 1)\left(1 - \frac{1}{r_{sh}}\right)}{(exp(v_{oc}) - 1)} \right] - \frac{f_v}{r_{sh}} \right\} \right|$$

$$FF_o = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

$$FF_s = FF_o(1 - r_s)$$

2   Improvisation of fill factor

The CdS/CdTe solar cell was first introduced in the 60s and reached a remarkable landmark in 2016 with a recorded highest η of 22.1%, J_{SC} of 31.69 mA/cm^2, V_{OC} of 0.8872 V, and FF of 78.5% by First Solar [6]. In the early 60s, Muller *et al.* observed ~5% power conversion efficiency in the cells prepared by evaporating CdS on single-crystal CdTe [7]. Later, the superstrate configuration was introduced for CdS/CdTe solar cells by Adirovich *et al.* in 1969. The CdTe layer was deposited on the glass/SnO$_2$/CdS substrate using an evaporation technique that delivered η >2% [8].

In 1971, Adieovich *et al.* fabricated the SnO$_2$/n-CdS/p-CdTe/Cu thin-film heterostructure using the vacuum deposition technique. Therein, the cell delivered a J_{SC} of 15 mA/cm^2, V_{OC} of 0.3 V, and η of 1% under the illumination of 100 mW/cm^2 [9]. In 1974, Fahrenbruch *et al.* fabricated p-CdTe/n-CdS with an FF of 54% and η = 3.1% [10]. They have reported two fabrication configurations; first, with close-spaced vapor transport of CdTe onto CdS substrates which are grown in single-crystal form by vapor transport technique, and secondly, by vacuum evaporation of CdS onto CdTe, which is formed in the single crystal form by Bridgman method [11]. Even though the highest FF was recorded for the vacuum evaporation of CdS onto single-crystal CdTe (FF = 54%, J_{SC} = 8.9 mA/cm^2, and V_{OC} = 0.5 V), the cell fabricated by CdTe vapor transport onto single-crystal CdS could achieve the highest η of 4% (FF = 36%, J_{SC} = 14 mA/cm^2 and V_{OC} = 0.610 V).

In 1977, Mitchel *et al.* fabricated ITO/n-CdS/p-CdTe/Au structures by vacuum deposition of CdS on CdTe single-crystals prepared using the Bridgman method. The resistivity of the CdS film has reduced with the heat treatment in H$_2$ ambient. To reduce the resistivity of the CdS layer further, they have co-evaporated indium during the evaporation of CdS. Additionally, CdTe single crystal underwent mechanical polishing with a final (1) polish using alumina and (2) chemical polishing using 1% bromine in methanol (MB). Ultimately CdTe surface was etched with a saturated K$_2$Cr$_2$O$_7$:H$_2$SO$_4$:H$_2$O to improve the efficiency of CdS/CdTe solar cells prior to the Au contact evaporation. Among the CdTe polishing techniques, the MB polished

device has provided much better FF (FF = 55%, J_{SC} = 8.9 mA/cm^2, V_{OC} = 0.5 V, and η = 5.2%). Further, Mitchel *et al.* stated that the deposition of an indium-tin-oxide layer and partially anti-reflection coating have led to significant improvement of photovoltaic properties with the highest FF of 65.8% under the illumination of 85 mW/cm^2 (J_{SC} = 16.1 mA/cm^2, V_{OC} = 0.63 V and η = 7.9%) [12]. Later, in 1977 Yamaguchi *et al.* prepared the CdS/CdTe solar cell by depositing the CdS layer by vapor phase epitaxially on the 1.5 mm thick *p*-CdTe crystal doped with phosphorus by the Bridgman method. The η of that solar cell was 10.5%, with a 59.2% FF under the 68 mW/cm^2 [13]. Yale *et al.* studied the effect of the *n*-CdS annealing in the H$_2$ environment for spray pyrolyzed (SP) *n*-CdS deposited on the *p*-CdTe substrate in 1977. The 1 µm thick CdS film was deposited by spray pyrolysis at 450 °C on the mechanically polished CdTe doped with phosphorus to improve the hole density of the material. Subsequently, SP-CdS mediated the heat treatment in H$_2$ to reduce the resistivity of the material. The annealing in the H$_2$ has led to improving the FF of the In/CdS/CdTe/Au devices measured under 85 mW/cm^2 from 37% to 58%, while η increased from 0.4% to 4.1% (J_{SC} = 9.08 mA/cm^2, V_{OC} = 0.66 V). Further, the device prepared with a highly phosphorus-doped CdTe substrate delivered a η of 6.5% with an FF of 63% under 85 mW/cm^2 (J_{SC} = 16.4 mA/cm^2, V_{OC} = 0.53 V) [14].

In 1980, Nakayama *et al.* introduced the screen-printed thin-film CdS/CdTe heterojunction solar cell, in which the back carbon electrode was replaced with Cu$_2$Te. Here, the CdS/CdTe solar cell was prepared on the borosilicate glass substrates after vacuum evaporation of an In$_2$O$_3$ film on it. The CdS was screen-printed using a CdS paste consisting of CdS powder, CdCl$_2$, and GaCl$_2$ with propylene glycol, and the CdTe film prepared without using dopants was sintered at 630 °C and 720 °C in the N$_2$ environment respectively. After fabricating the back carbon and Cu$_2$Te electrodes, the η of 6.3% and FF of 51% (J_{SC} = 11.4 mA/cm^2, V_{OC} = 0.73 V) were obtained from the device with carbon electrodes, while the η of the device with Cu$_2$Te electrodes was improved up to 8.3% with FF of 58% (J_{SC} = 14.2 mA/cm^2, V_{OC} = 0.67 V) under the illumination of 71 mW/cm^2 [15]. Later, in 1980 Nakayama *et al.* reported the screen-printed CdS/CdTe solar cell, where the screen-printed CdS layer was grown on glass substrates and sintered in the N$_2$ ambient. Herein the CdTe was screen-printed on CdS layer using paste prepared with Cd and Te powder with propylene glycol at a lower temperature than the previously recorded temperatures. Then back carbon electrodes with Cu as impurities were screen-printed on sintered CdTe layer, followed by annealing in N$_2$ ambient. This devices provided a conversion efficiency of 4.7%, and FF was 38% (J_{SC} = 12.7 mA/cm^2, V_{OC} = 0.68 V) under the illumination of 71 mW/cm^2 [16]. The first efficient CdS/CdTe heterojunction solar cell with both ultrathin layers electrodeposited was reported by Basol *et al.* in 1982. CdS (<100 nm) and CdTe (1-2 µm) films were sequentially deposited on the glass/ITO substrate by electrodeposition technique following the deposition conditions reported by Paniker *et al.*, and Au (10

nm) film was deposited to complete the device. The device delivered an efficiency of 7% with an *FF* of 56% (J_{SC} = 18.8 mA/cm², V_{OC} = 0.79 V) [17]. The 8.5% efficiency with 51.9% *FF* was reported for screen-printed CdS/CdTe solar cells prepared on glass substrate by Matsumoto *et al.* in 1983. The screen-printing paste for CdS layer deposition was prepared by mixing CdS and CdCl₂ powder with propylene glycol, and the paste for the CdTe layer deposition was prepared by mixing Cd, Te, and CdCl₂ with propylene glycol. Both CdS and CdTe films were sintered in the N₂ environment at temperatures of 690 °C and 640 °C respectively. The carbon contact electrodes were deposited on CdTe films by screen printing technique and mediated to heat treatment. As per this study, increasing the heating temperature to 400 °C and the O₂ content of 1-2% during the heat treatment of carbon electrodes improved the *FF* of the solar cell. In addition to that, *FF* was reported to be higher for the thick CdS compared to that of a thin CdS [18]. Kuribayashi *et al.* reported a *η* of 12.8% and *FF* of 60.6% (I_{SC} = 0.022A, V_{OC} = 0.754 V) for screen-printed CdS/CdTe solar cells by optimizing the sintering condition of the carbon contact electrode in 1983. The CdS and CdTe films were deposited by screen-printing technique following similar procedures mentioned in earlier studies. In this study, carbon electrodes were prepared with the screen-printing method using a carbon paste consisting of one of the dopants of Cu, Ag, Au, and Sb at different ppm levels and sintered at different temperatures and different O₂ levels. It was identified that the addition of 50 ppm Cu to the carbon paste had improved the efficiency and the *FF* of the device [19]. In glass/ITO/CdS/CdTe solar cells reported by Bulent *et al.* in 1984, the electrodeposition technique has been used to deposit both CdS (60 nm) and CdTe (1.2 - 1.5 µm) layers. The CdTe film was electrodeposited using electrolyte with CdSO₄ and Te in pH ~2 at 90 °C. Subsequently, a glass/CdS/CdTe sample was heated, and Au contact (~10 nm) was formed to complete the device. It was recorded that *η* of 9.35% with *FF* of 64% for the electroplated *n*-CdS and *p*-CdTe solar cell device. Further, the stoichiometric doping of CdTe has improved the performance of the device [20]. In 1984, Matsumoto *et al.* developed screen-printed CdS/CdTe solar cells with different widths of CdTe layer from 2 mm to 8 mm and observed an increase in *FF*, which decreased the CdTe layer's thickness, and the maximum *FF* of 60.6% and efficiency of 12.8% under 100 mW/cm² were obtained from the device with a 2 mm CdTe layer [21].

CdS/CdTe solar cells were prepared on Corning glass, graphite substrate, and single-crystal CdTe substrates by Antony *et al.* in 1986. The CdTe layer was grown using the close-spaced chemical vapor transport (CSVT) deposition technique under the pressure range from 0.01 Torr to 1 atm, and subsequently, CdS film was deposited by thermal evaporation. It has delivered a *η* of 6.4% with 64% *FF* under 90 mW/cm². Further, it has been reported that increasing the hole density in the CdTe material improved the *FF* of the solar cell device due to the decrement of the series resistance [22].

In 1991, Chu *et al.* reported a *η* of 13.4% with an *FF* of 72.6% for the glass/SnO₂:F/ CBD-CdS/ CSS-CdTe solar cell. In this study, the chemical bath deposited CdS film (55-110 nm) was grown using an aqueous solution consisting of Cd²⁺ ions, NH₄⁺ ions, ammonium hydroxide, and thiourea at a temperature of 50-90 °C on the FTO substrate. Subsequently, a 3-5 µm thick CdTe layer was deposited using the close-spaced sublimation technique. The substrate temperature was maintained at 580-620 °C, and the temperature difference of 50-120 °C was maintained with the source temperature. The separation between the source and substrate was 1-2 mm. The graphite back contact was used, and CdTe film was etched using K₂Cr₂O₇ with H₂SO₄ or HNO₃:H₃PO₄: H₂O to improve the Te richness of the surface and hence reduce the resistivity of the surface [23]. Britt *et al.* reported 15.8% efficiency with an *FF* of 74.5% for CBD CdS and CSS CdTe solar cells in 1993. Further, they suggested that prior to the CdTe deposition, glass/SnO₂: F/CdS sample, annealing at a temperature of 350-425 °C for 5-20 min in an H₂ atmosphere improved the *FF* of the device. There, the CdS film (70 – 100 nm) was deposited by the CBD technique in the bath consisting of cadmium acetate, ammonium acetate, ammonium hydroxide, and thiourea at 90 °C. And a 5 µm CdTe layer was grown using the CSS technique while the substrate temperatures were varied from 500-625 °C and source temperature (600-700 °C) and the pressure (5-30 Torr) was adjusted to maintain the deposition rate between 1-2 µm/min and separation was 2 mm. Prior to the graphite back contact formation, CdTe film was chemically treated using HNO₃:H₃PO₄: H₂O or Br₂ in methanol to form a Te-rich layer. In this study, while changing the substrate temperature, the *FF* of the glass/FTO/CdS/CdTe solar cells varied from 73%-76%. The highest *FF* of 76% with an efficiency of 15.5% was observed from the device with 75 nm CdS with CdTe at the substrate temperature of 620 °C, but the highest efficiency of 15.8% was obtained from 70 nm CdS, and CdTe substrate temperatures were 625 °C [24].

The effect of the CdCl₂ treatment on the electrodeposited CdS layer was discussed by Morris *et al.* in 1993. The CdS (150 nm) was grown with an electrolyte consisting of Cd²⁺ and S₂O₃²⁻ ions in pH 2 at 90 °C. Prior to the CdTe deposition, CdS was treated with saturated CdCl₂ in methanol and annealed at 400 °C for 15 min. The 1.5 µm CdTe film was deposited using Cd²⁺ and HTeO₂⁺ ions solution at a pH of 1.7 and at a temperature of 90 °C. Subsequently, CdS/CdTe samples were annealed at 400 °C for 15 min and etched with acidification in KCl, and Cu (2 nm) and Au (100 nm) back contact was fabricated. The efficiency and *FF* of both electrodeposited glass/ITO/CdS/CdTe solar cells before and after the CdCl₂ treatment were improved from 8.5% to 10.2% and *FF* from 58 % to 66% [25].

A metal-organic chemical vapor deposited (MOCVD) CdS (~50 nm) and close-spaced sublimated CdTe (3.5 µm) based solar cell was prepared on ITO glass following superstrate configuration by Aramoto *et al.* in 1997. The

CSS-CdTe samples grown in the Ar atmosphere were mediated to the post-deposition treatment. Aqueous $CdCl_2$ was spin-coated on CdTe and annealed at 420 °C for 25 min in a furnace. Then the carbon Ag back electrodes were fabricated by screen printing technique. It delivered an efficiency of 16% with a *FF* of 73% [26].

Oladeji *et al.* reported a comparative study of (1) glass/TCO/ZnS (70 nm) /CdS (50 nm) /CdTe, (2) glass/TCO/ZnS-CdS-ZnS (40-30-40 nm) /CdS (35 nm) /CdTe and (3) glass/TCO/CdS/CdTe solar cells in 2000. The CBD-ZnS was grown on the glass/TCO substrate using $ZnSO_4$, $(NH_4)_2SO_4$, $CS(NH_2)_2$, NH_4OH, $N_2H_4.H_2O$, and nitrilotriacetic acid with KOH. Subsequently, dipped in 1% $CdCl_2$ in methanol to improve the conductivity and CBD-CdS deposited using acetate salts of Cd^{2+}, NH_4^+, $CS(NH_2)_2$, NH_4OH to prepare glass/TCO/ZnS/CdS/CdTe device. Glass/TCO/ZnS-CdS-ZnS/CdS/CdTe device was prepared by sandwiching CdS (30 nm) between two ZnS layers (40 nm) and subsequent deposition of another CdS film (35 nm) and then treated with $CdCl_2$ as mentioned above, before CdTe layer was grown by CSS technique at the source and substrate temperatures of 650 °C and 600 °C, respectively. Device glass/TCO/ZnS/CdS/CdTe delivered 10% efficiency with 62% *FF*, device glass/TCO/ZnS-CdS-ZnS/CdS/CdTe provided 8.6% with *FF* 54%, and device glass/TCO/CdS/CdTe delivered the highest efficiency of 11.4% and 67% *FF* over the solar cells with CdZnS [27].

In 2001, Amin *et al.* studied the effect of the haze ratios of SnO_2: F-TCO in the CdTe solar cell. In that study, thin-film CdS was grown using MOCVD and CdTe film by CSS techniques. Therein, haze 37%, 11%, and 3% TCO with 2000 nm, 1000 nm, and 500 nm thick TCO have been prepared. The conversion efficiency and the *FF* of the CdS (90 nm)/CdTe (1 μm) solar cells grown on the haze ratio of 37%, 11%, 3%, and ITO were 10.1% with 64%, 11.2% with 63%, 10.1% with 62% and 10.7% with 62% respectively. Moreover, the thickness of the CdS film and the CdTe also have been varied. The efficiency of 11.2% and *FF* of 64% were obtained for the optimized thickness of CdS (100 nm)/CdTe (0.6 μm) solar cells grown on SnO_2: F-TCO of 3% haze ratio [28].

Potlog *et al.* have discussed the dipping effect in different saturated chloride solutions of $CdCl_2:H_2O$, $MnCl_2:C_5H_5N$ or CsCl: H_2O before the annealing in air, on the performance of the CdS/CdTe solar cells, in 2003. In that study, both CdS and CdTe films were deposited using the CSS technique. Therein, the efficiency and the *FF* were varied as 0.02% with 21%, 0.4% with 27%, 1.3% with 26%, and 7.4% with 48% for untreated, device and CsCl and $MnCl_2$, and $CdCl_2$ treated devices respectively. Even though the high back-barrier created between Ni back contact and CdTe layer reduced the *FF* of all considered solar cells, Cd atoms delivered from the $CdCl_2$ treatment have reduced the film resistance, unlike the Mn and Cs atoms which have led to the increment of *FF* [29].

Gupta *et al.* reported a 14% efficient CdS/CdTe thin-film solar cell fabricated on an Al-doped ZnO transparent front layer in 2004. In this study, the authors used the RF sputtering technique to deposit Al-doped ZnO, CdS, and CdTe layers at a substrate temperature of 250 °C. Since the maximum processing temperature reached during all the processes is 387 °C, the authors named this a low-temperature process. The Cu/Au back contacts were formed on the $CdCl_2$-treated CdTe layer to fabricate the complete devices. As a reference device, the CdS/CdTe/Cu/Au layer stack was fabricated on SnO_2:F and compared for the best performance. The reference device achieved the highest *FF* of 73.96%, with η of 12.6%, while the highest η of 14% (J_{SC} = 23.6 mA/cm², V_{OC} = 0.814 V, *FF* = 73.25%) was recorded for the device with the proposed transparent conductive layer [30].

In 2005, Vigil-Galán *et al.* fabricated SnO2:F/CdS/CdTe/Cu/Au solar cells by altering the S/Cd ratio of the CBD CdS layer. The $CS(NH_2)_2$ concentration was varied while keeping the $CdCl_2$ concentration fixed to obtain different S/Cd ratios. ~2 μm thick CdTe layer was deposited on the CBD-CdS layer using the close-spaced vapor transport system - hot wall (CSVT-HW) technique in an O_2/Ar ambient. $CdCl_2$ post-heat treatment was performed at 400 °C, followed by Cu/Au back contact deposition and annealing. The highest *FF* of 70.5% (J_{SC} = 23.8 mA/cm², V_{OC} = 0.74 V, η = 12.3%) was obtained for the S/Cd ratio of 5/1 [31]. Later, in 2006 Gupta *et al.* studied the effect of the reduction of the CdTe layer thickness on device performance. The authors used the planar magnetron sputtering to deposit both CdS and CdTe layers. Then the back contacts of either Cu/Au or Au only were deposited on the $CdCl_2$ post-heat-treated CdTe layer, followed by annealing in air. The authors stated that the *FF* of the cells strongly depends on the back-contact processing, while the variation of diffusion time did not have much effect. The lowest *FF* was obtained for the thinnest CdTe (1.04 μm) and 130 nm CdS solar cell with a *FF* of 60.4% and η of 15.1%. The highest η of 11.9% with *FF* of 70.8% was obtained from the CdTe and CdS solar cells having the same thickness with 1.5 nm Cu back contact allowed to diffuse for 18 min. Further, they observed the improvement of the V_{OC} and *FF* of the solar cell after increasing the annealing treatment of the solar cell due to decreasing the shunting [32]. Later in 2006, Matsune *et al.* fabricated CdS/CdTe solar cells by altering metal-organic dopants in the CdS layer.

The metal-organic components such as $(CH_3)_2SnCl_2$, $(C_6H_5)_3GeCl$, $(CH_3CO_2)_3In$ or $[(C_2H_5)_2NCS_2]_2Zn$ were mixed into the MO source of CdS and deposited on ITO substrates using the MOCVD technique. 2.5-2.9 μm thick CdTe layer was deposited on the CdS layer using the CSS technique. The highest *FF* of 72% (J_{SC} = 25.5 mA/cm², V_{OC} = 0.82 V, η = 15.1%) was obtained for the CdS layer doped with 1wt% $(CH_3)_2SnCl_2$ [33]. In 2007, Wu *et al.* studied the effect of the Cu_xTe phase in CdS/CdTe solar cells, which forms during the Cu back contact post-heat treatments. In this study, they have fabricated CdS/CdTe solar cells with

glass/CdSnO$_4$/ZnSnO$_x$/nano-CdS:O/CdTe structure. The structure was chemically etched using NP etchant to form a Te-rich CdTe layer, and a Cu layer was deposited with different thicknesses using an E-beam evaporator. Post-heat treatments with different temperatures were performed in He ambient to promote different levels of Cu diffusion. Then, pure carbon and silver pastes were subsequently applied to form secondary contacts. The highest *FF* of 71.3% (J_{SC} = 22.7 mA/cm^2, V_{OC} = 0.797 V, η = 12.9%) was obtained for the 10 nm thick Cu layer deposited sample, consisting of both CuTe and Cu$_{1.4}$Te dominant phases, while the increment of Cu layer thickness has reduced the *FF* [34]. Vasko *et al.* fabricated CdS/CdTe solar cells on polyimide substrates using the sputter deposition technique in 2009. In this study, aluminium-doped zinc oxide was used as the TCO layer, which was deposited using the sputter deposition technique. A CdS layer (90 nm) and CdTe layer (2.4 μm) were also deposited using the same technique. Cu/Au back contacts for the solar cells were deposited on the CdCl$_2$ treated CdTe layer. The highest *FF* of 70.2% (J_{SC} = 13.4 mA/cm^2, V_{OC} = 0.765 V, η = 7.2%) was obtained for the brand A polyimide, while the highest η of 10.5% (J_{SC} = 19.5 mA/cm^2, V_{OC} = 0.768 V, *FF* = 69.8%) was recorded for type B polyimide [35].

In 2011, Kephart *et al.* reported the effect of oxygenated CdS on the device performance. In that study, the CdS layer (100 nm) was grown using RF magnetic sputtering under Ar and O$_2$ gas flow. The oxygenated CdS was deposited under 2.5% O$_2$ flow was delivered an efficiency of 10.7% with a *FF* of 61.5% (J_{SC} = 24.4 mA/cm^2 and V_{OC} = 0.712 V) [36]. Jaber *et al.* studied the influence of the substrate temperature of thermal evaporated CdS on the performance of the CdS/CdTe solar cell devices in 2012. The thermal evaporated CdS layer was grown on glass/FTO substrate in a 10^{-5} Torr environment, and the substrate temperature varied from ambient to 300 °C. Subsequently, the CdTe layer was deposited using CSS technique followed by CdCl$_2$ treatment and annealed at 400 °C for 15 min in air. After the etching with Br-MeOH solution, Cu (30 nm) and Au (60 nm) back contacts were fabricated. According to the results, the substrate temperatures of 200 °C and 300 °C delivered a η of 9.89 % with *FF* of 55.24% and η of 10.56%, with *FF* of 61.55%, respectively [37]. In 2013, Paudel *et al.* fabricated a CdS/CdTe solar cell using a 60-100 nm thick CdS layer deposited by RF magnetron sputtering and 4-5 μm CdTe grown using a homebuilt CSS system. During the CdS deposition, the substrate temperature was maintained at 270 °C and pressure of 10 mTorr in (0 to 5)% O$_2$ flow variation, while CdTe deposition proceeded at the substrate temperature range of 550 °C - 630 °C and sublimation pressure of 1 Torr - 200 Torr. Subsequently, samples were activated with CdCl$_2$ treatment at 390 °C for 30 min, and the Cu (4 nm) and Au (40 nm) back contacts were fabricated by thermal evaporation without any chemical etching treatment. In that study, it was observed that η of 8.0% with *FF* of 61.8% for the as-prepared device, and after the CdCl$_2$ treatment, it was improved to η of 14.0% with *FF* of 74.2%. And also, the authors studied the effect of the O$_2$

concentration in the CdS deposition environment on the device performance. As a result, *FF* and η were increased (*FF* = 73.6% to 76.6%, η = 14.8% to 15.5%) when O$_2$ flow in the sputtering gas in 0% to 1% (*FF* = 75.8% to 68%, η = 13.5% to 10.7%) and it declined when was O$_2$ 2% to 5%. Among them, the highest *FF* of 76.6% and the highest η of 15.5% were obtained from the device with a CdS layer grown in 1% O$_2$ ambient [38]. In 2014, Korevaar *et al.* prepared sputtered CdS and CSS CdTe solar cells treated with CdCl$_2$ and CuCl$_2$. That study discussed the device's performance with respect to the O$_2$ concentration during the CdTe deposition and the thickness of the CdS layer. The CdTe layer was grown under He and O$_2$ ambient, and the partial pressure of O$_2$ was varied. Therein, the cell with CdTe grown in 6% O$_2$ delivered efficiency of 14.7% and 15.6% for 80 nm and 50 nm thick CdS, respectively, while the *FF* remained at 75.3% in both cases. At 100% O$_2$ ambient, both η and *FF* for 80 nm and 50 nm thick CdS were improved up to 15.3% with *FF* of 77.8% and 16.1% with *FF* of 77.2%, respectively [39]. In 2014, Meysing *et al.* also carried out a study on the impact of the RF magnetron sputtered oxygenated CdS (CdS:O) and CdS/CSS-CdTe solar cells. The CdS layer (100 nm) was deposited in O$_2$/Ar ambient at 15 mTorr, and a CSS-CdTe layer (4 μm) was grown at 660 °C and 600 °C as the source and substrate temperatures respectively. Prior to the Cu (5 nm) and Au (150 nm) back contact evaporation, samples were treated with CdCl$_2$ and chemically etched in Br/MeOH for 20 s. Solar cell devices consisted of CdS:O from 0% to 6% O$_2$, the J_{SC}, V_{OC}, *FF*, and efficiency were increased from 22.4 to 25.6 mA/cm^2, 806 to 830 mV, 60.4% to 68.0%, and 10.8% to 14.5% respectively [40].

Islam *et al.* (2015) reported the influence of RF power in the deposition of the CdS:O by RF magnetron sputtering on the device performance. The CdS:O (80-100 nm) was deposited on the glass/FTO/ZnO:Sn substrate at a pressure of 18 mTorr (O$_2$:Ar = 1:99) by varying the RF power from 1.5 W/cm^2 - 2.15 W/cm^2. Subsequently, ~2 μm CdTe layer was grown by sputtering at 300 °C in Ar ambient at 8 mTorr pressure, and C:Cu/Ag back contact was fabricated using screen printing after the CdCl$_2$ treatment. The solar cells with CdS:O grown at RF power of 1.5 W/cm^2 and 2.0 W/cm^2 were delivered a η of 6.72% with *FF* of 59% (V_{OC}=0.71 V, J_{SC}=19.05 mA/cm^2) and η of 10.27% with *FF* of 68% (V_{OC}=0.68 V, J_{SC}=22.55 mA/cm^2) respectively [41]. Diso *et al.* studied the influence of the CdTe electrodeposition voltage and CdCl$_2$ + CdF$_2$ annealing in 2016. The CdS layer was electrodeposited using a two-electrode configuration on FTO glass substrates. Then the CdTe layer was cathodically deposited on the glass/FTO/CdS layer stack using two electrodes configuration by varying cathodic voltage. Then the glass/FTO/CdS/CdTe layer stacks were treated with CdCl$_2$ and/or CdF$_2$ and annealed at 450 °C for 15 min. The results showed that the highest *FF* of 49% and η of 3.7% were obtained for the CdTe layer deposited at the cathodic voltage of 1.576 V and treated with CdCl$_2$. The efficiency of the solar cells in which the CdTe layer was deposited at cathodic voltage 1.576 V was further improved by the CdCl$_2$

+ CdF$_2$ treatment up to η = 10.1% (V_{OC} = 0.60 V, J_{SC} = 36.7 mA/cm^2 and *FF* = 46%) [42]. In 2017, Vásquez *et al.* studied the influence of the CdCl$_2$ treatment and a Te-rich layer on the performance of the device. The CdS layer (60 nm) was deposited by CBD technique using CdCl$_2$, SC(NH$_2$)$_2$, NH$_4$Cl, and NH$_4$OH at 76 °C for 8 min. While 4 μm CdTe layer was grown using the CSVT technique, maintaining the source and substrate temperatures at 630 °C and 530 °C, respectively, in 50% Ar and 50% O$_2$ ambient for 3 min. Later, samples were thermally annealed with CdCl$_2$ using the CSVT technique in an Ar environment. Prior to the Cu (2 nm)/Au (8 nm) back contact fabrication, Te film was deposited over the thermally treated CdTe layer by the CSVT method in an Ar ambient for 20 min and 30 min. The η of 4.5%, *FF* of 48% (V_{OC}=0.418 V, J_{SC}=22.4 mA/cm^2) was obtained for the untreated CdS/CdTe solar cell while the CdS/CdTe device with Te region grown for 30 min and treated with CdCl$_2$ rinse process was improved the η up to 12% with *FF* of 60% (V_{OC}=0.730 V, J_{SC}=28 mA/cm^2) [43]. In 2019, Artegiani *et al.* compared the suitability of magnesium zinc oxide (MZO) instead of CdS in CdTe solar cell devices. The MZO layer was RF magnetron sputtered with 11% MgO and 89% ZnO wt% in Ar and O$_2$ ambient, and the 7 μm CdTe layer was vacuum evaporated with a substrate temperature of 340 °C on the MZO layer. The best efficiency of the FTO/MZO/CdTe solar cell obtained was 12.9% with *FF* of 53.9% (V_{OC} = 0.888 V, J_{SC} = 26.9 mA/cm^2), while the ITO/ZnO/CdS/CdTe efficiency was 15.6% with *FF* of 72% (V_{OC} = 0.852 V, J_{SC} = 25.4 mA/cm^2). The thickness of the MZO layer and the CdS layers were 65 nm and 150 nm, respectively. According to the results, the best *FF* can be obtained from the CdS/CdTe rather than MZO/CdTe solar cell [44].

In 2021, Hu *et al.* discussed the effect of post-annealing on ultra-thin CdS:O/CdTe solar cells. Both 20-40 nm thick MgZnO buffer layer and a 0-60 nm CdS:O layers were deposited by RF magnetron sputtering sequentially on glass/FTO substrate in Ar/O$_2$ mixed ambient at RF power of 300 W and 100 W, respectively. The 3-5 μm CdTe layer was deposited by CSS technique while the source temperature was maintained at 640 - 680 °C in an O$_2$:N$_2$ (2: 98 ~ 10: 90) ambient at 6 - 15 Torr. Then samples were mediated to the CdCl$_2$ treatment, and the back contact of carbon paste with Cu and Mo/Al/Cr layers was also sputtered as the back electrode. After the annealing process, the *FF* of the 35 nm and 40 nm CdS:O solar cells were improved due to the reduction of the series resistance. The performances before and after the annealing of the 35 nm and 40 nm CdS:O were varied as η =15.9%, *FF* =73.9% to η =16.6%, *FF* =76.3% and η =15.2%, *FF* =71.3% to η =16.5%, *FF* =73.9% respectively. And also, they reported the highest efficiency of 18.05%, with *FF* of 78.2% (J_{SC} = 26.8 mA/cm^2 and V_{OC} = 862.5 mV) for the device with 30 nm CdS:O layer, new TCO from AGC, and the anti-reflection (AR) coating prepared by a liquid process [45].

Table 01: Summary of the maximum fill factors obtained by considered studies and corresponding efficiencies.

Author(s)	Year	η (%)	*FF* (%)	Ref. #
Fahrenbruch et al.	1974	3.1	54	[10]
Mitchel et al.	1977	7.9	65.8	[12]
Yamaguchi et al.	1977	10.5	59.2	[13]
Yale et al.	1977	6.5	63	[14]
Nakayama et al.	1980	8.3	58	[15]
Nakayama et al.	1980	4.7	38	[16]
Basol et al.	1982	7.0	56	[17]
Matsumoto et al.	1983	8.5	51.9	[18]
Kuribayashi et al.	1983	12.8	60.6	[19]
Bulent et al.	1984	9.35	64	[20]
Matsumoto et al.	1984	12.8	60.6	[21]
Antony et al.	1986	6.4	64	[22]
Chu et al.	1991	13.4	72.6	[23]
Britt et al.	1993	15.5	76	[24]
Morris et al.	1993	10.2	66	[25]
Aramoto et al.	1997	16	73	[26]
Oladeji et al.	2000	11.4	67	[27]
Amin et al.	2001	11.2	64	[28]
Potlog et al.	2003	7.4	48	[29]
Gupta et al.	2004	12.6	73.96	[30]
Vigil-Galán et al.	2005	12.3	70.5	[31]
Gupta et al.	2006	11.9	70.8	[32]

Matsune et al.	2006	15.1	72	[33]
Wu et al.	2007	12.9	71.3	[34]
Vasko et al.	2009	7.2	70.2	[35]
Kephart et al.	2011	10.7	61.5	[36]
Jaber et al.	2012	10.56	61.55	[37]
Paudel et al.	2013	15.5	76.6	[38]
Korevaar et al.	2014	15.3	77.8	[39]
Meysing et al.	2014	14.5	68	[40]
Islam et al.	2015	10.27	68	[41]
Diso et al.	2016	10.1	46	[42]
Vásquez et al.	2017	12	60	[43]
Artegiani et al.	2019	15.6	72	[44]
Hu et al.	2021	18.05	78.2	[45]

Conclusion

This paper has reviewed the improvisation of *FF* by different fabrication techniques of CdS/CdTe-based solar cells and different layer treatments employed by researchers since the 1960s. This review illustrates that the improvement of *FF* will not always lead to maximum efficiency. The *FF* can be improved by selecting the proper deposition technique for a particular layer in the layer stack of CdS/CdTe solar cells. The introduction of buffer layers and interfacial layers will lead to a higher *FF*. As a result of the solar cell performance, the CdS layer annealing in the H_2 environment, Cu doping of the back carbon electrode, increasing the hole density in the CdTe material, introduction of the post-deposition treatments of $CdCl_2$ treatment, etching treatments, and introduction of the anti-reflection coatings can improve the *FF* of the CdS/CdTe solar cell devices.

Conflicts of Interest

There are no conflicts to declare.

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