Cadmium Telluride/Cadmium Sulfide Thin Films Solar Cells: A Review

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Abstract

The efficiency and steadiness of solar cells are dependent on the experimental conditions during the fabrication of the device. In the present review, development in the last few decades in CdTe/CdS solar cells on different conducting substrates, their characterizations, and their effect on their performances has been illustrated. The variations in the efficiency were observed for the CdTe/CdS solar cells because of not only different deposition methods but also the difference in deposition conditions. In addition to this contact, material plays a significant role in the performance of a solar cell. CdTe/CdS solar cells with cheaper, greater efficiency can be possible soon.

Keywords: Chalcogenides; Thin films; Semiconductors; Heterojunction; Solar cell; CdTe/CdS.

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1. Introduction

In due course of the period, the world may face a problem of an energy crisis. Solar energy is one of the abundant renewable energy sources to resolve the global energy crisis. A solar cell converts solar energy into electrical energy. Historically, the development of solar cells, from the first crystalline silicon solar cell with a 6 % efficiency developed by Bell lab.^[1] The first-generation solar cells are known as a crystalline silicon-based solar cell having power conversion efficiency exceeding 20 % and those of single-crystalline cells have reached up to 26.6 %. The second-generation solar cells are basically thin film solar cells. It comprises various semiconducting materials layers of absorber or active materials. Among this Silicon (Si) GaAs (Gallium Arsenide), CdTe (Cadmium Telluride), and CIGS (Copper Indium Gallium Sulphide) are one of the potential semiconductor materials. They are used to fabricate efficient solar cells. The second-generation solar cells having a power conversion efficiency are 28.8 %, 22.1%, and 22.6% for GaAs, CdTe, and CIGS solar cell, respectively.^[2] Amongst CdTe is one of the potential absorber materials in thin film solar cells.

1.1 Cadmium telluride (CdTe)

CdTe is well studied materials. It is II-VI semiconducting material having direct bandgap of 1.42 eV for polycrystalline

and 1.5 eV for single crystal form.^[3] It shows excellent electrical and optical properties (Table. 1). Since it is used in various optoelectronics devices. Solar cells are one of the potential applications of CdTe thin film. Absorption coefficient of CdTe thin film is 104 cm^{-1} .^[4] Other interesting property of the CdTe material is that we can easily deposited p- and n-type conductivity. CdTe is mostly studied material since 1890, however, last 10 years it used as a polycrystalline thin films and quantum dots.

Conversely, high work function (5.7 eV) and resistivity are some of the major issues of the CdTe thin film. Its effect on the junction of metal and semiconductor. To modify the metal-semiconductor junction, it is essential to find a metal having a metal work function greater than that of the CdTe. The homojunction of CdTe based thin film shows higher recombination speed. A higher recombination rate reduces the properties of optoelectronic devices. Heterojunction thin film is one of the best solutions to resolve this issue. CdS/CdTe heterojunction is one of the best heterojunctions, which is widely used for solar cell application.

1.2 Cadmium sulfide (CdS)

CdS is an II-VI group semiconductor having a bandgap 2.45 eV.^[5] For a long period of time, researchers have attracted towards the CdS thin film due to its interesting optoelectronic properties. It is widely used as a buffer layer in solar cells because of its superior optoelectronic properties. The optical transparency of the film can be easily controlled by thickness variation. The optimized thickness of CdS thin film for solar

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cell applications is 120 nm. This cell achieved higher efficiency of 21%. Various chemical and physical methods were used to deposit CdS thin film. Amongst CBD is one of the potential and low-cost methods for the deposition of the compact thin film. The highest efficiency was obtained by using a CdS prepared by CBD. The choice of the CBD method was probably due to the fact that CBD makes a very compact film that covers perfectly the TCO layer.^[6] Another interesting property of this material is it provides chemical and thermal stability to the CdTe thin film.

Table 1 Properties of CdTe

Semiconductor	CdTe
Crystal structure	Cubic
Band gap	1.42 eV [3]
Lattice Constant	6.482 Å
Electron affinity	4.28 (eV)
absorption coefficient	104 cm ⁻¹ .
Refractive Index	2.76
Density	5.85 g/cm ³
Melting Point	1092 °C
Boiling Point	1130 °C
Young's Modulus	3.7x10 ¹¹ dyne/cm ²
work function	5.7 eV
Hole Mobility	65 cm ² /Vsv
Electron Mobility	700 cm ² /Vs

Fig. 1 Schematic representation (not in scale) of CdTe/CdS solar cell.

1.3 CdTe/CdS

CdTe/CdS thin-film solar cells are an alternative way to harvest sunlight for energy conversion. The polycrystalline CdTe/CdS thin-film solar cell is one of the significant and primary contenders^[7-8] for photovoltaic devices for cost-effective and clean generation of solar electricity for global applications^[9-11] as well environmental friendly energy for the future.^[12] Since 1972 various researchers were fabricated CdTe/CdS solar cell devices. In 1972 Bonnet and Rabenhorst *et al.* reported CdTe/CdS thin-film solar cells with an efficiency of 6 %.^[13] In 1982 Tyan and Perez-Albuern *et al.* fabricated CdTe/CdS thin-film solar cells having efficiency 10 %.^[14] Further in 1993 Ferek-ides *et al.* and Wu *et al.* reported 15.8 % and 16.5 % efficiency for CdTe/CdS thin film solar cells.^[15] They mainly focused on the photoconversion efficiency of the device. The photoconversion efficiency of this device is enhanced from 6 to 16.5 % by modifying the polycrystalline layers of CdS and CdTe from time to time. However, practically, the CdS films should be thin enough to allow high transmission and must be uniform to avoid short-circuit effects.^[16]

CdTe/CdS solar cells are p-n junction hetero-junction device in which a thin film of CdS forms the n-type window layer. The structure of the substrate is in that the transparent conductor and window layer were first deposited onto a transparent substrate such as fluorine-doped tin oxide (FTO) or indium tin oxide (ITO) coated glass. The CdTe absorber layer is deposited over a window layer^[17] as shown in Fig. 1. CdTe/CdS solar cells were non-uniformly doped at the back surface of CdTe with Cu evaporated through a shadow mask. The transparent conducting oxide (TCO), vapor transport CdS, and CdTe layers were treated with annealed CdCl₂ processed for the first solar cell.^[18] The material is first etched for the 30s with 1% Br methanol solution and it dramatically affects device performance^[19] and defect concentrations.^[19-21]

In this article the fabrication technology of CdTe/CdS solar cell on different substrate viz. stainless steel, FTO coated glass substrate, ITO coated glass substrates and polymer substrates were reviewed. Different research groups used different methods for the deposition of CdTe/CdS thin film, metal contacts and top ohmic contact. Various deposition methodologies, fabrication conditions, and the performance of cells, its success, and failures are systematically reviewed in this paper.

2. Structure of CdTe/CdS solar cells

CdTe/CdS solar cells can be generally developed in two fundamental ways as superstrate and substrate depending on the direction of the light incident on the window layer. In Substrate configuration (Fig. 2) light enters through the cell and then reaches the TCO. Conversely, in superstrate (Fig. 3) configuration light enters through the substrate and then reaches the cell. The high-efficiency CdTe solar cells are generally grown in a superstrate configuration where the CdS/CdTe thin films are deposited on TCO coated glass

substrates. According to previous reports, the superstrate configuration achieved the highest efficiency than the substrate configuration. CdTe solar cells based on both configurations consist of four parts:

Substrate: Glass, molybdenum (Mo), polyamide, and stainless steel are widely used as a substrate in CdS /CdTe thin-film solar cells.

A front contact: Highly conducting and transparent metal oxides such as FTO, ITO, AZO are widely used as a front contact in CdS /CdTe thin-film solar cell. Physical as well as chemical deposition techniques such as RF magnetron sputtering,^[22-24] PLD,^[25] CVD,^[26] and spray pyrolysis are widely used deposition techniques for the deposition of a TCOs. Romeo *et al.*^[27] reported a new potential fluorine-doped In₂O₃ which shows excellent properties than other TCOs.

A window layer: CdTe is commonly coupled with thin CdS material. CdS is one of the potential and widely used window material in CdS /CdTe thin-film solar cells. Till date, highest efficiency reported for CdTe/CdS structure-based solar cell.^[28]

An absorber layer: Basically, it is a CdTe layer. It grown on top of the CdS layer.

A back contact: Ag – Au, Cu–Au, ZnO/Al, and NiO are commonly used back contact for CdS /CdTe thin-film solar cells.

Fig. 2 Substrate configuration of CdTe/CdS solar cell

3. Fabrication of CdTe/CdS solar cells

Thin-film solar cells can be generally developed in two fundamental ways as superstrate and substrate depending on the direction of the light incident on the window layer. The high-efficiency CdTe solar cells are generally grown in a superstrate configuration where the CdS/CdTe thin films are deposited on TCO coated glass substrates. The selection of the appropriate substrate is essential for the good solar cell.^[29] Layers of CdTe and CdS for solar cells can be deposited using

a variety of different techniques such as close space sublimation, vapor transport deposition, electrodeposition, chemical bath deposition, magnetron sputtering, high vacuum thermal evaporation, screen printing, chemical vapor deposition.^[30-42]

Fig. 3 Superstrate configuration of CdTe/CdS solar cell

Chemical bath deposition is a popular way to deposit CdS films for the high efficiency of CdS/CdTe solar cells.^[15] The solar cell device fabrication involves the successive deposition of n-type photosensitive CdS thin film. Rose *et al.*^[5] reported that the basic fabrication technique includes low-pressure CVD deposited SnO₂, CBD CdS, and CdS/CdTe with CdCl₂ treatment and an acid contact etch followed by the application of doped graphite paste and the efficiency of the CdS/CdTe solar cell was 15.4%.

Han *et al.*^[43] reported, CdS films prepared by CBD and CdCl₂ annealed under ultrahigh vacuum conditions of about 150nm, and the bath temperature kept 700 °C, for the fabrication of CdS/CdTe solar cell with gold back contact used. Khrypunov *et al.*^[29] reported, that the CdS layer deposited in a high vacuum evaporation chamber at a substrate temperature of 150 °C and annealed at 450 °C for the re-crystalline and then CdTe deposited by the same method at temperature 300 °C, thickness 0.1-0.5 μm for CdS and 3 to 4 μm for CdTe. Influence of the CdS window layer on the performance of 2 μm thick CdS/CdTe solar cells, with a reduction of thickness from 114 to 95 nm, current density (J_{sc}) increases due to an increase in the blue response. While it decreases 85 nm then conversion efficiency mainly decreases due to a decrease in V_{oc} and FF.^[44]

The CBD CdS cells show higher open-circuit voltage and fill factor while the short-circuit current remains with little change as the ratio of S to Cd in CBD solution goes from 1 to 5 and it causes a variation of the thickness of CdS and the performance of the solar cell.^[45] CdTe polycrystalline film deposited by CSS on the CdS layer on TCO/SnO₂: F of thickness 150 nm by CBD method. The thickness of the CdTe thin film was 4-6 microns. The substrate temperature 500 °C and source temperature 620 °C and the deposition time of 4

min and achieved an efficiency of 13.44%.^[46] So, the production of a high-quality integrated cell is hopeful.

Fig. 4 J-V curves of the FTO/CdS/CdTe/ITO solar cell illuminated from (1) the FTO side $V_{oc} = 702$ mV, $J_{sc} = 18.2$ mA/cm², FF = 62, $\eta = 7.9\%$; and (2) the ITO side $V_{oc} = 591$ mV, $J_{sc} = 3.4$ mA/cm², FF = 50, $\eta = 1\%$ under simulated AM1.5 illumination, reproduced with the permission from [9].

When ITO as a back contact for all PVD CdS photovoltaic devices that acts as a free Cu stable back contact and at the same time, allow realizing bifacial CdTe solar cells. When the thickness of CdTe is reduced, it improves the performance at reducing annealing time with 20 % of standard CdCl₂ treatment. The efficiency of the cell was 10.3 % when the CdTe absorber layer 2.5 μ m and it was 8 % when the CdTe absorber layer of 1 μ m.^[47] An efficient and with stable back contacts solar cell of efficiency 12.7 %^[48] obtained by vacuum evaporated Sb or Sb₂Te₃ buffer and Mo layer. It is observed that impurities in CdTe source material may also influence the performance of solar cells. These impurities affect the carrier concentration profile and tend to diffuse across heterojunction; quite often, they are detrimental for the efficiency. Solar cell fabricated without an anti-reflecting coating of area 0.64 cm² and cell efficiency 14.6 % with CdCl₂ treatment in the fabrication of the CdS layer and Sb₂Te₃ back contact. Some mismatch of CdS and CdTe is approximately 10 % but at temperature 500 °C, the mismatch can remove and CdS/CdTe mix very easily with CdTe.^[49] For the heterojunction thin-film solar cell, deposition of n-CdS and p-CdTe by periodic pulse electrodeposition and annealed at 400 °C for 15 min and the ohmic contact were Cu and Au and efficiency was 10.1 %.^[50] From the efficiency, it concludes that maximum efficiency of

10.1 % immediately after fabrication but after 100 days the efficiency decreased slightly up to 9.8 %.

Wu *et al.*^[51] fabricated CdTe devices with Zinc stannate (Zn₂SnO₄ or ZTO) buffer layer. CdS/CdTe preliminary solar cells demonstrate high performance. Also, these films were chemically stable and exhibit higher resistivity that are roughly matched with the CdS window layer in the device structure. ZTO buffer layer in both SnO₂ based and Cd₂SnO₄ CTO based CdS/CdTe devices, enhances significantly performance and reproducibility of solar cell. The behavior of the CdS/CdTe interface is highly sensitive to the chemical and thermal state interfaces. When CdTe diffused into CdS, the blue spectral response is reduced, whereas, for CdS diffusion into CdTe, the CdS film is consumed,^[52] reducing its thickness and lowering the absorber bandgap.^[53-54]

CdS/CdTe heterojunction have has been prepared by depositing 3-5 μ m of p-CdTe films on CdS films of 500-1000 Å. Typical dark current-voltage characterization of CdTe/CdS heterojunction solar cell at forwarding bias up to 1 V. Above higher voltages 1.5 V, the current-voltage characterization becomes linear due to the predominance of series resistance and efficiency of the cell of 13.4%.^[55] CdTe thin-film solar cells with Sb-Te back contacts before and after annealing, V_{oc} , and FF of solar cells with as-deposited Sb-Te thin films do not change drastically for cells with/without back contact layer, but J_{sc} increases by about 10 %. After annealing J_{sc} and FF increase and efficiency rises to 13.1%.^[56]

Britt *et al.*^[41] reported that the high temperatures used during the deposition of CdTe by CSS may cause the formation of inter diffused regions between CdS and CdTe. The presence of the CdS/CdTe region would shift the electrical junction away from the metallurgical junction and improve the electrical and PV characteristics. Oman *et al.*^[57] reported that the sharp drop in quantum efficiency was seen at the CdS bandgap of 510 and 600 nm, but it shows better performance at 510 nm which was interpreted as an indication that mixing between CdS and CdTe during processing reduces the amount of recombination current at the interface.

Lin *et al.*^[58] reported that the effect of MoOx thickness, when it is around 40 nm with which the highest cell efficiency of 12.2%, obtained along with excellent FF and V_{oc} , it was with the thickness of 100 nm for CBD CdS and 4 μ m of CSS CdTe with CdCl₂ treatment at temperature 575 and 635 °C for substrate and source temperature, respectively. The CdTe growth rate was about 1 μ m per second. Pookpanratana *et al.*^[59] reported that the CdCl₂ treatment induces S atoms to migrate from the CdS layer towards back contact but no S atoms reach the back surface. Furthermore, CdCl₂ treatment affects the morphology and chemical structure of subsequently deposited Au/Cu layer. The back contact treatment alone leaves the back surface dominated by Au and Cu with Cu being driven towards the back surface and Au towards CdTe absorber.

Bai *et al.*^[60] reported that efficiency of 7.9 % was obtained for 1 μ m thick CdTe solar cells and it absorbs 99 % solar spectrum with photon energy above the bandgap. When the

absorber layer thickness was reduced to below $\sim 1 \mu\text{m}$, a shunting path could be relatively easily induced due to the structural and electrical non-uniformity in the micro-scale. The density of recombination centers within the space charge region was increased due to the not well-formed CdS/ CdTe junction and in the diffusion of Cu from back contact. Unlike most semiconductor devices, the sudden interfaces lead to the lower CdTe solar cell conversion efficiency. It is due to the slow interface due to inter-diffusion represents reduced lattice mismatch and lower interface defect density, resulting in improved cell efficiency. Secondly, tunneling is undesirable in CdTe devices because it increases the leakage current and the smooth interface decreases the amount of tunneling and interfaces recombination due to reduced interface states. The highest efficiency of cell 10 % due to Cd and Te ratio much less than 1 or 0.85 i.e. high-efficiency cell tends to have a Te-rich surface.^[61-62]

Rakhshani^[63] reported that solar cells of p-CdTe and n-CdS structure with a conversion efficiency of 10 (± 1) % were prepared by electrodeposition of CdTe on CBD CdS coated conducting glass. The annealing assisted diffusion of S yields an interfacial region in CdTe in which 6 % of tellurium atom replaced by sulfur and cell performance of efficiency of 9.3%. Batzner *et al.*^[64] reported CdTe/CdS deposited by CSS on TCO coated soda-lime glass with Au/Sb on a back contact. The average efficiency of 12.5 % was by etched CdTe layer i.e. short etching times were sufficient for good efficiency. The etching with a mixture of concentrated nitric and phosphoric acid produces a low resistive Te rich surface on the CdTe absorber layer. All solar cells with Sb/Au and Cu/Au back contact on nitric-phosphoric acid-etched CdTe do not require annealing. However, it is not possible to get rid of the rollover in I-V characteristics through annealing unlike for the solar cells with Cu/Au back contacts on Br MeOH etched absorber layers.

Proskuryakov *et al.*^[65] reported different efficiencies for CdTe/CdS solar cells. The devices consist of ITO glass and ZnO of 60 nm deposited followed by 240 nm of CdS and further by 4 μm of CdTe doped with metal-organic chemical vapor deposition and CdCl₂ layer of 600 nm thick, annealed at 400 °C for 10 min. under hydrogen. To create Te rich layer at the back surface, its efficiencies were maximum with Au/CdTe and Au/As doped /CdTe as 8 and 10.5 %, respectively. But with the ZnO layer for films and as doping were small resulting lower efficiency as 6.5 %.

CBD CdS and CSS CdTe under dry CdCl₂ annealing process with nitric phosphoric etch, it creates a highly p-type region near back contact for improving contact quality. The best device without an anti-reflecting coating exhibited an NREL verified efficiency of 15.3% and the buffer layer has been crucial for good results.^[66] Oladegi *et al.*^[67] reported that CBD and CSS were used to grow the window and absorber

layers Cd_{1-x}Zn_xS/CdS/CdTe and solar cell structures at 80 and 600 °C, respectively with CdCl₂ treatment. The thickness of CdS film was 0.035 μm and the efficiency of 8.6 % while CdS/CdTe solar cell further annealed in the CSS reactor chamber in H₂ ambient for about 15 min and the efficiency of 11.4% with increasing V_{oc}. Romeo^[68] reported in his Ph.D. thesis about CdS layers were grown in an ultra-high vacuum evaporation chamber at a substrate temperature of 150 °C and annealed at 450 °C for recrystallization then without breaking vacuum CdTe is deposited at 300 °C. The thickness of CdS and CdTe films was about 0.5 μm and 3 to 4 μm respectively with CdCl₂ treatment on CdTe with different thicknesses. Solar cell performance depends on the amount of CdCl₂ and type of TCO. For FTO solar cell, 60 nm CdCl₂ have low V_{oc} (730 mV) and low FF (50) while for 600 nm treated cells have V_{oc} in the range of 800-836 mV and FF in the range of 64 to 70%. While on ITO solar cells, 60nm CdCl₂ has high V_{oc} (810-838 mV) and FF of 60% compared to the CdCl₂ of 600 nm with V_{oc} 710-770 mV and FF 50 % and this may be due to enhanced migration of Cu in CdTe. The efficiency of the solar cells does not depend only on the grain size of CdTe but also influenced by CdTe-CdS intermixing. After CdCl₂ treatment ~ 150 nm thickness of the CBD CdS layer having a low-efficiency range of 5 to 6% and V_{oc}= 720 mV. The poor performance of CBD CdS with 5-6 % efficiency is attributed to the presence of pinholes and excessive intermixing.

Ferekids *et al.*^[69] reported that CBD CdS deposited to a thickness of 600-1000 Å annealing in H₂ and CSS CdTe deposited to a thickness of 4-8 μm after a post-deposition heat treatment at 400 °C. The surface structure was chemically treated to achieve a Te-rich CdTe surface and back contact with the CdTe was formed by applying doped graphite paste. The effect of a substrate temperature decreases (from 625 to 570 °C) and the thickness of CdS increased, the efficiency of solar cells continuously decreases (from 15.8 to 14.5 %) with slightly changing V_{oc}. CdTe/CdS films were deposited at ~ 260 °C on FTO by using magnetron sputtering. The optimized thickness of the CdS and CdTe layer were 0.13 μm and 2.3 μm respectively. CdTe thickness varied from 0.6 to 1.28 μm and the cell structure was treated in the vapor of CdCl₂ ~ 390 °C in dry air. The performance of the solar cell changes with changing the thickness of CdTe and CdS thin films.^[70] The J_{sc} of cells almost remains the same, the V_{oc} decreased as the CdTe thickness decreases. The FF of cells depends strongly on back contact processing and the minimum efficiency of the cell were 4.3 % for 0.08 μm thickness of CdS and 0.6 μm of CdTe and the maximum efficiency 13 % for 0.13 μm thickness of CdS and 2.3 μm thickness for CdTe.

Bosio^[71] reported that solar cells fabricated by the conditions of sputtering CdS on ITO of thickness 70-120 nm, CSS CdTe of thickness 4-7 μm . With heat treatment at 380-

Fig. 5 Cross-sectional SEM images of the CdTe/CdS solar cells with: (a) as-deposited CdS; (c) air- annealed CdS and (e) CdCl₂-annealed CdS. The corresponding cell J-V curves (b), (d) and (f) are shown besides the SEM images, respectively, reproduced with permission from [73].

420 °C with Cl₂ and it recrystallizes the nano-grains and the typical parameters with an efficiency 15.8% can be measured and they conclude that for obtaining high efficiency to deposit CdTe by CSS in presence of O₂. Flores *et al.*^[72] reported the efficiency of CdTe/CdS solar cells more than 14

% activated with HCF₂Cl gas on ITO. CdTe was deposited by CSS at low substrate temperature, and CdS was deposited by sputtering at substrate temperature 250 °C.

Baier *et al.*^[73] reported that the good crystalline quality of both the CdTe/CdS junction and the absorption layer ensured a high short circuit current and this type of CdTe solar cell showed the lowest series resistance of 4.61 Ωcm^2 and the highest efficiency of 12.4% with a high short circuit current of 25.4 mA/cm² in Fig. 5. The CdTe solar cell, which used an air-annealed CdS window layer, showed the worst cell performance with an efficiency of only 5.12 %. Somewhere the CdTe/CdS interface, large pin-holes with a diameter of about 100 nm formed. Such a solar cell had the largest series resistance and the smallest fill factor due to the formation of

oxides on the CdS surface. The CdTe solar cell efficiency of 6.48%, a value almost half of the solar cell which used the CdCl₂-annealed CdS as the window layer. So, the results demonstrate that CdCl₂ heat treatment is very important to improve the performance of the solar cell.

Gretener *et al.*^[74] grows CdS/CdTe solar cells on borosilicate glass substrates. Different metallic back contacts were tested for the efficiency of CdS/CdTe solar cell. Cu, Sb, Te, and MoO₃ were evaporated by the high vacuum system and ZnO/ZnO: Al bilayer with thickness 100 and 800 nm respectively for the front contact by r-f magnetron sputtering. The efficiency of the single-treated cells (CdCl₂ treatment) increases with higher Cu with Cu is harmful to double treated cells. The stability and efficiency of CdS/CdTe solar cells tested with the different buffer layers and was maximum (η = 11.3 %) for Cu/Te/MoO₃ and minimum (η = 6.1%) for Cu/Sb it is due to Cu containing always tend to degrade faster than Cu free cells.

Fig. 6 SEM images of the CdTe film deposited at substrate temperatures of 340 and 520 °C, reproduced with permission from [79]

Asher *et al.*^[75] discussed that the diffusion of Cu and its unfavorable effect were studied extensively in the CdS but Zhou *et al.*^[76] reported that a small amount of Cu for the back contact enhanced the cell efficiency. Mohamed *et al.*^[77] reported that the reflection losses in the interfaces between glass-ITO-CdS-CdTe decrease short circuit current from 31.2 to 28.2 mA/cm². For the thickness of 100 nm for both CdS and ITO, the optical and recombination processes lead into loss of the efficiency of CdS/CdTe solar cells in the range of 12–16%.

N. Romeo's research group deposits ZnO, CdS, and back contact layer by sputtering, and CdTe layer is deposited by close space sublimation process without Freon and CdCl₂ treatment. Reported that the effect of CdTe film drying in the air the efficiency of the solar cell is 13.82% which is slightly greater than before annealing in air efficiency is 12%.^[78] Schaffner J. *et al.* study the effect of annealing temperature on the performance of CdTe/ CdS thin-film solar cells having efficiency up to 12%. Morphological study (Fig. 6) shows that the CdTe film deposited at a substrate temperature of 340 °C shows smaller grain size and lower roughness are observed for CdTe films deposited than samples deposited with a higher substrate temperature.^[79]

The standard CBD method is also important for the deposition of CdS thin film for CdTe solar cells achieve 8.31% efficiency.^[80] Pulsed Laser Deposition (PLD) is also the best method for the deposition of thin films like CSS, CBD, and sputter deposition. Li B *et al.* demonstrate the PLD method for CdS/CdTe thin-film solar cells achieving 6.68% efficiency.^[81] Chengdu O. K *et al.* report high short circuit current in the

range of 38.5 to 47.8 mA/cm² for CdS/ CdTe and ZnS/ CdTe thin films respectively, deposited by electrodeposition method.^[82]

A Romeo *et al.*^[83] discussed a new simplified method of deposition of CdTe/CdS on a soda-lime glass substrate, in this work CdS layer is deposited by RF sputtering in an Ar⁺CHF₃ atmosphere. CdTe layer is at room temperature and without using any nontoxic gas and step of treatment CdCl₂ is removed. In this work As₂Te³⁺Cu, stable back contact is used. I-V characteristics of cells show 15.8 % conversion efficiency and short circuit current are 27 mA/cm². Christina *et al.* report the different back contact buffer layer such as Cu, Te, Sb, and MoO₃ and their effect on the performance of the solar cell. Cu/Te/MoO₃ buffer layer shows 11.3 % efficiency, which is best as compared to other buffer layers because the cell containing Cu always tends to degrade faster than Cu free cell. Buffer layer MoO₃ /Te which is without Cu was investigated and showed 10 % efficiency.^[84]

Paul NR. *et al.* studied various thickness CdTe/ CdS films in the range of 0.25 to 2.1 μm deposited by the magnetron sputtering method. The film deposited by RF magnetron sputtering having optimum control of the grain and grain boundary morphology needed for the good performance of the device. As thickness increases efficiency of the film is slightly improved in the range of 7 to 12.6%.^[85]

GS Khyrpunov *et al.* and Echendu *et al.* discussed the impact of chloride treatment and Freon gas treatment on the CdTe base layer. Chloride treated solar cells show maximum efficiency i.e. (11.07) and Freon gas treated solar cell with 7.2 % efficiency.^[86,87] As mentioned earlier, annealing of CdS/CdTe

film strongly affects on performance, annealing of CdS film in the presence of H₂ gas removes the oxygen compounds from the grain boundaries and opens them for the formation of shortcircuiting through the CdS layer, efficiency of the cell, in this case, is 4.5%. But when CdS film is annealed in the presence of air performance of CdS/CdTe is 11.4 % which is drastically higher than the previous case main reason for this improvement is an oxide which resides on the grain surface and penetrates grain boundaries of CdS.^[88] Ojo *et al.* highlight the effect the inclusion of Ga to the regular CdCl₂ post-growth treatment on the material and doping of Ga improves the electronic properties.^[89]

Shen *et al.* reports the performance of CdTe thin-film solar under low light intensity, this results demonstrate that polycrystalline CdTe thin-film solar cell is intrinsically suitable for electric power generation at weak light intensity irradiance. This study provides constructive guidelines for the future design and fabrication of CdTe based solar cells.^[90]

4. Strategies for Improving Efficiencies:

Selection of suitable methods for the deposition of CdTe and CdS thin film for CdTe/CdS solar cell for the good result also thinner layer of CdS is important for higher efficiency and spectral response. CdS thin layer is deposited by CBD by most of the researchers, so the CBD method is very important for maintaining the thickness of the film. Different methods are used for the deposition of the CdTe layer as CSS, ED, sputtering, etc by different researchers. For larger grain-sized of CdTe layer deposited by CSS method with higher temperatures for better performance and stability. ED deposition method is one of the simplest methods for the deposition of CdTe films with low temperatures with cost-effective for deposition on TCO and metallic foils.

In addition to this, the back contact method is very important for CdTe/CdS solar cells, so better techniques used for doping resulted in better ohmic contacts for the achievements of higher carrier concentrations. Substrate selection is also important for the good performance of CdTe/CdS solar cells. Generally, TCO's (ITO/FTO) of the smoother surface was preferred for the CdTe/CdS solar cells. Optimization in the thickness of the window layer is an essential task for improvement in device efficiency and photocurrent. Improvement in V_{oc} can be achieved by the removal of pinholes and better layer coverage. Values of open-circuit voltage, current density, and conversion efficiency of the photovoltaic device can be better by controlling the pressure inside the growth chamber which helps to reduce the coast of the device. Chemical and thermal treatment can help to improve conversion efficiency.^[91]

5. Conclusion

This review summarized different techniques used for the deposition of CdS and CdTe thin films to improve the grain size on the different substrates. For improving the performance of CdTe/CdS solar cell, back contact issue is

important for the performance. To avoid the diffusion in the development of an appropriate buffer layer between the CdTe substrates. The low efficiency of CdTe/CdS is due to poor back contact, appropriate choice of deposition method, and substrates. Till CdTe/CdS solar cells will be a very strong candidate to resolve the global issues regarding energy crises and low-cost solar cells in the future.

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Conflict of Interest

There are no conflicts to declare.

Support information

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References:

- [1] D. M. Chapin, C. S. Fuller and G. L. Pearson, *J. Appl. Phys.*, 1954, **25**, 676-677, doi: 10.1063/1.1721711.
- [2] T. K. Todorov, D. M. Bishop and Y. S. Lee, *Sol. Energ. Mat. Sol. C.*, 2018, **180**, 350-357, doi: 10.1016/j.solmat.2017.07.033.
- [3] Y. Zhao, M. Boccard, S. Liu, J. Becker, X. H. Zhao, C. M. Campbell, E. Suarez, M. B. Lassise, Z. Holman and Y. H. Zhang, *Nat. Energy*, 2016, **1**, 16067, doi: 10.1038/nenergy.2016.67.
- [4] R. Cardenas, Jesus, and H. Sobral, *Materials*, 2017, **10**, 607, doi: 10.3390/ma10060607.
- [5] A. I. Oliva, O. Solis-Canto, R. Castro-Rodriguez and P. Quintana, *Thin Solid Films*, 2001, **391**, 28-35, doi: 10.1016/S0040-6090(01)00830-6.
- [6] C. Ferekides, J. Britt, Y. Ma and L. Killian, *Proceedings of Twenty-Third-Photovoltaic-Specialists-Conference IEEE*, New York, USA, 1993, 389-393. doi: 10.1109/PVSC.1993.347151.
- [7] D. H. Rose, F. S. Hasoon, D. S. Albin, R. M. Ribelin, X. S. Li, Y. Mahathongdy, T. A. Gessert and P. Sheldon, *Progress in Photovoltaic: Research and Applications*, 1999, **7**, 331-340, doi: 10.1002/(SICI)1099-159X(199909/10)7:53.O.CO;2-P.
- [8] K. Zweibel, *Int. J. Solar Energy*, 1992, **12**, 285-292, doi: 10.1080/01425919208909768.
- [9] M. M. Aliyu, M. A. Islam, N. R. Hamzah, M. R. Karim, M. A. Matin, K. Sopian and N. Amin, *Int. J. Photoenergy*, 2012, 351381, doi: 10.1155/2012/351381.
- [10] S. K. Das and G. C. Morris, *J. Appl. Phys.*, 1993, **73**, 782-786, doi: 10.1063/1.353338.
- [11] O. Savadogo, *Sol. Energ. Mat. Sol. C.*, 1998, **52**, 361-388, doi: 10.1016/S0927-0248(97)00247-X.
- [12] H. R. Motinho, D. Albin, Y. Yaan, R. G. Dhere, X. Li, C. Perkins, C. S. Jiang and M. M. Al Jassi, *Thin Solid Films*, 2003, **436**, 175-180, doi: 10.1016/S0040-6090(03)00646-1.
- [13] D. Bonnet and H. Rabenhorst, *Proceedings of the 9th Photovoltaic Specialists Conference*, 1972, 129-131.

- [14] Y.S.Tyan and E.A. Perez-Albuern, *Proceedings of 16th IEEE Photovoltaic Specialists Conference*, IEEE Publishing, New York, 1982, 794-800.
- [15] X. Wu, J. C. Keane, R. G. Dhere, C. DeHart, D. S. Albin, A. Duda, T. A. Gessert, S. Asher, D. H. Levi and P. Sheldon, *Proceedings of the 17th European Photov. Solar Energy Conf., Munich, Germany, II*, 2001, 995.
- [16] K. Durose, P. R. Edwards and D. P. Halliday, *J. Cryst. Growth*, 1999, **197**, 733-742, doi: 10.1016/S0022-0248(98)00962-2.
- [17] R. K. Sharma, K. Jain and A. C. Rastogi, *Current Appl. Phys.*, 2003, **3**, 199-204, doi: 10.1016/S1567-1739(02)00201-8.
- [18] D. Rose, R. Powell, U. Jayamaha and M. Maltby, *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2002, 555-558, doi: 10.1109/PVSC.2002.1190625.
- [19] B. E. McCandless and J. R. Sites, *Handbook of PV Science and Engineering*, Edited by Legue A and Hegudus S (Wiley West Sussex, England), 2003, 633.
- [20] A. S. Gilmore, V. Kaydanov and T. R. Ohno, *Mater. Res. Soc. Symp. Proc.*, 2003, **763**, 453-458, doi: 10.1557/proc-763-b9.6.
- [21] S. D. Feldman, R. T. Collins, V. Kaydanov and T. R. Ohno, *Appl. Phys. Lett.*, 2004, **85**, 1529-1531, doi: 10.1063/1.1787596.
- [22] Pankaj K. Bhujbal, Habib M. Pathan and Nandu B. Chaure, *Eng. Sci.*, 2020, **10**, 58-67, doi: 10.30919/es8d1003.
- [23] V. Sittinger, F. Ruske, W. Werner, C. Jacobs, B. Szyszka and D. J. Christie, *Thin Solid Films*, 2008, **516**, 5847-5859, doi: 10.1016/j.tsf.2007.10.031.
- [24] P. K. Bhujbal, H. M. Pathan and N. B. Chaure, *ES Energy Environ.*, 2019, **4**, 15-18, doi: 10.30919/esec8c188.
- [25] H. Ohta, M. Orita, M. Hirano, H. Tanji, H. Kawazoe and H. Hosono, *Appl. Phys. Lett.*, 2000, **76**, 2740-2742, doi: 10.1063/1.126461.
- [26] R. Groenen, J. Löffler, P. M. Sommeling, J. L. Linden, E. A. G. Hamers, R. E. I. Schropp, M. C. M. van de Sanden, *Thin Solid Films*, 2001, 392, 226-230, doi: 10.1016/S0040-6090(01)01032-X.
- [27] N. Romeo, A. Bosio, V. Canevari and A. Podesta, *Sol. Energy*, 2004, **77**, 795-801, doi: 10.1016/j.solener.2004.07.011.
- [28] A. Bosio, G. Rosa and N. Romeo, *Sol. Energy*, 2018, **175**, 31-43, doi: 10.1016/j.solener.2018.01.018.
- [29] G. Khrypunov, A. Romeo, F. Kurdesau, D. L. Batzner, H. Zogg and A. N. Tiwari, *Sol. Energy Mat. Sol. C.*, 2006, **90**, 664-677, doi: 10.1016/j.solmat.2005.04.003.
- [30] D. M. Oman, K. M. Dugan, J. L. Killian, V. Ceekala, C. S. Farekids and D. L. Morel, *Appl. Phys. Lett.*, 1995, **67**, 1896-1898, doi: 10.1063/1.114369.
- [31] N. Romeo, A. Bosio, V. Canevari, M. Terheggen and L. Vaillant Roca, *Thin Solid Films*, 2003, **431-432**, 364-368, doi: 10.1016/S0040-6090(03)00239-6.
- [32] E. Bertran, J. L. Morenja, J. Esteve and J. M. Codina, *J. Phys. D*, 1984, **17**, 1679-1685, doi: 10.1088/0022-3727/17/8/021.
- [33] R. R. Chamberlin and J. S. Skarman, *J. Electrochem. Soc.*, 1959, **113**, 86-89, doi: 10.1149/1.2423871.
- [34] G. Hodes, J. Manassen and D. Cahen, *Nature*, 1976, **261**, 403-404, doi: 10.1038/261403a0.
- [35] T. W. F. Russell, B. N. Baron and R. E. Rocheleau, *J. Vac. Sci. Technol. B*, 1984, **2**, 840-844, doi: 10.1116/1.582904.
- [36] I. Kaur, D. K. Pandya and K. L. Chopra, *J. Electrochem. Soc.*, 1980, **127**, 943-948, doi: 10.1149/1.2129792.
- [37] W. J. Dananer, L. E. Lyons and G. C. Morris, *Sol. Energy Mat.*, 1985, **12**, 137-148, doi: 10.1016/0165-1633(85)90029-2.
- [38] G. C. Morris and S. K. Das, *Int. J. Solar Energy*, 1992, **12**, 95-108, doi: 10.1080/01425919208909753.
- [39] S. Ikegami, *Solar Cells*, 1988, **23**, 89-105, doi: 10.1016/0379-6787(88)90009-9.
- [40] N. Romeo, A. Bosio, R. Tedeschi, A. Romeo and V. Canevari, *Sol. Energy Mat. Sol. C.*, 1999, **58**, 209-218, doi: 10.1016/S0927-0248(98)00204-9.
- [41] J. Britt and C. Ferekides, *Appl. Phys. Lett.*, 1993, **62**, 2851-2852, doi: 10.1063/1.109629.
- [42] T. L. Chu and S. S. Chu, *Int. J. Solar Energy*, 1992, **12**, 121-132, doi: 10.1080/01425919208909755.
- [43] J. Han, C. Spanheimer, G. Haindal, G. Fu, V. Krishnakumar, J. Schaffner, C. Fan, K. Zhao, A. Klein and W. Jaegermann, *Sol. Energy Mat. Sol. C.*, 2011, **95**, 816-820, doi: 10.1016/j.solmat.2010.10.027.
- [44] K. Nakamura, M. Gotoh, T. Fujihara, T. Toyama and H. Okamoto, *Sol. Energy Mat. Sol. C.*, 2003, **75**, 185-192, doi: 10.1016/S0927-0248(02)00154-X.
- [45] R. M. Perez, G. S. Rodriguez, J. S. Hernandez, A. M. Acevedo, A. A. Carbajal, O. V. Galan and J. C. Alonso and G. C. Puente, *Thin Solid Films*, 2005, **480-481**, 173-176, doi: 10.1016/j.tsf.2004.11.060.
- [46] H. Zheng, J. Zhang, L. Feng, J. Zheng, W. Cai, B. Li and Y. Cai, *J. Wuhan Univ. Technol.*, 2006, **21**, 65-68, doi: 10.1007/BF02840882.
- [47] A. Romeo, G. Khrypunov, S. Galassini, H. Zogg and A. N. Tiwari, *Sol. Energy Mat. Sol. C.*, 2007, **91**, 1388-1391, doi: 10.1016/j.solmat.2007.03.010.
- [48] D. Batzner, A. Romeo, H. Zogg and A. N. Tiwari, (2001) The CdTe thin film solar cell improve back contact, *Energy Research: Active Solar Energy PV prog.* Swiss Federal Office 1-8.
- [49] N. Romeo, A. Bosio, R. Tedeschi and V. Canevari, *Mater. Chem. Phys.*, 2000, **66**, 201-206, doi: 10.1016/S0254-0584(00)00316-3.
- [50] G. C. Morris and R. J. Vanderveen, *Appl. Surf. Sci.*, 1996, **92**, 630-634, doi: 10.1016/0169-4332(95)00307-X.
- [51] X. Wu, P. Sheldon, Y. Mahathongdy, R. Ribelin, A. Mason, H. R. Moitinno and T. J. Coutts, *AIP Conference Proceedings*, 1999, **462**, 37, doi: 10.1063/1.57910.
- [52] B. E. McCandless and S. S. Hegedus, *Conference Record of the IEEE Photovoltaic Specialists Conference*, 1992, **2**, 967-972.
- [53] B. E. McCandless, *Mater. Res. Soc. Symp. Proc.*, 2001, **668**, H161-H1612, doi: 10.1557/proc-668-h1.6.
- [54] J. D. Beach and B. E. McCandless, *MRS Bulletin*, 2007, **32**, 225-229, doi: 10.1557/mrs2007.26.
- [55] T. L. Chu, S. S. Chu, C. Ferekides, C. Q. Wu, J. Britt and C. Wang, *J. Appl. Phys.*, 1992, **70**, 7608-7612, doi: 10.1063/1.349717.

- [56] S. Hu, Z. Zhu, W. Li, L. Feng, L. Wu, J. Zhang and J. Gao, *AIP Adv.*, 2011, **1**, 042152, doi: 10.1063/1.3663613.
- [57] D. M. Oman, K. M. Dugan, J. L. Killian, V. Ceekala, C. S. Ferekides and D. L. Morel, *Appl. Phys. Lett.*, 1995, **67**, 1896-1897, doi: 10.1063/1.114369.
- [58] H. Lin, W. Xia, H. N. Wu and C. W. Tana, *Appl. Phys. Lett.*, 2010, **97**, 123504, doi: 10.1063/1.3489414.
- [59] S. Pookpanratana, X. Liu, N. R. Paudel, L. Weinhardt, M. Bar, Y. Zhang, A. Ranasinghe, F. Khan, M. Blum, W. Yang, A. D. Compaan and C. Heske, *Appl. Phys. Lett.*, 2010, **97**, 172109, doi: 10.1063/1.3505155.
- [60] Z. Bai, J. Yang and D. Wang, *Appl. Phys. Lett.*, 2011, **99**, 143502, doi: 10.1063/1.3644160.
- [61] R. W. Birkmire, B. E. McCandless and S. S. Hegedus, *Int. Solar Energy*, 1992, **12**, 145-154, doi: 10.1080/01425919208909758.
- [62] M. E. Ozsan, D. R. Johnson, D. W. Lane and K. D. Rogers, *In Proc of 12th European PV Solar Energy Conf.* Amsterdam, Ed by R. Hill, W. Palz, P. Helm, 1994, 1600.
- [63] A. E. Rakhshani, *J. Appl. Phys.*, 2001, **90**, 4265-4271, doi: 10.1063/1.1397279.
- [64] D. Batzner, R. Wendt, A. Romeo, H. Zogg and A. N. Tiwari, *Thin Solid Films*, 2000, **361**, 463-467, doi: 10.1016/S0040-6090(99)00842-1.
- [65] Y. Y. Proskuryakov, K. Durose, M. K. Al Tuekestani, I. M. Sero, G. G. Belmonte, F. F. Santiago, J. Bisquert, V. Barrioz, D. Lamb, S. J. C. Irvine and E. W. Jones, *J. Appl. Phys.*, 2009, **106**, 044507, doi: 10.1063/1.3204484.
- [66] E. Colegrove, R. Banai, C. Blissett, C. Buurma, J. Ellsworth, M. Morley, S. Barnes, C. Gilmore, J. D. Bergeson, R. Dhere, M. Scott, T. Gessert and S. Sivanathan, *J. Electron. Mater.*, 2012, **41**, 2833-2837, doi: 10.1007/s11664-012-2100-z.
- [67] I. O. Oladeji, L. Chow, C. S. Ferekides, V. Vishwanathan and Z. Zhao, *Sol. Energ. Mat. Sol. C.*, 2000, **61**, 203-211.
- [68] R. Alessandro, Ph. D. thesis, Growth and Characterization of high efficiency CdTe/CdS solar cell, Swiss Federal Institute of Techn. Zurich, 2002.
- [69] C. Ferekides and J. Britt, *Sol. Energ. Mat. Sol. C.*, 1994, **35**, 255-262, doi: 10.1016/0927-0248(94)90148-1.
- [70] A. Gupta, V. Parikh and A. D. Compaan, *Sol. Energ. Mat. Sol. C.*, 2006, **90**, 2263-2271, doi: 10.1016/j.solmat.2006.02.029.
- [71] A. Bosio, N. Romeo, S. Mazzamuto and V. Canevari, *Prog. Cryst. Growth Ch.*, 2006, **52**, 247-279, doi: 10.1016/j.pcrysgrow.2006.09.001.
- [72] A. R. Flores, O. Ares, J. M. Camacho, V. Rejon and J. L. Pena, *Sol. Energy*, 2012, **86**, 780-785, doi: 10.1016/j.solener.2011.12.002.
- [73] Z. Bai, L. Wan, Z. Hou and D. Wang, *Phys. Status Solid C*, 2011, **82**, 628-630, doi: 10.1002/pssc.201000445.
- [74] C. Gretener, J. Perrenoud, L. Kranz, L. Kneer, R. Schmitt, S. Buechler and A. N. Tiwari, *Progressing Photovoltaic: Research and Applications*, 2013, **21**, 1580-1586, doi: 10.1002/pip.2233.
- [75] S. E. Asher, F. S. Hasoon, T. A. Gessert, M. R. Young, P. Sheldon, J. Hiltner and J. Sites, *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2000, 2000, 479-482, doi: 10.1109/PVSC.2000.915876.
- [76] J. Zhou, X. Wu, A. Duda, G. Teeter and S. H. Dematsu, *Thin Solid Films*, 2007, **515**, 7364-7369, doi: 10.1016/j.tsf.2007.03.032.
- [77] H. A. Mohamed, *J. Appl. Phys.*, 2013, **113**, 093105, doi: 10.1063/1.4794201.
- [78] N. Romeo, A. Bosio, D. Menossi, A. Romeo and M. Aramini, *Energy Procedia*, 2014, **57**, 65-72, doi: 10.1016/j.egypro.2014.10.009.
- [79] J. Schaffner, M. Motzko, A. Tueschen, A. Swirschuk, H. J. Schimper, A. Klein, T. Modes, O. Zywitzki and W. Jaegermann, *J. Appl. Phys.*, 2011, **110**, 064508, doi: 10.1063/1.3639291.
- [80] J. Han, C. Spanheimer, G. Haindl, G. Fu, V. Krishnakumar, J. Schaffner, C. Fan, K. Zhao, A. Klein and W. Jaegermann, *Sol. Energ. Mat. Sol. C.*, 2011, **95**, 816-820, doi: 10.1016/j.solmat.2010.10.027.
- [81] B. Li, J. Liu, G. Xu, R. Lu, L. Feng and J. Wu, *Appl. Phys. Lett.*, 2012, **101**, 153903, doi: 10.1063/1.4759116.
- [82] O. K. Echendu, F. Fauzi, A. R. Weerasinghe and I. M. Dharmadasa, *Thin Solid Films*, 2014, **556**, 529-534, doi: 10.1016/j.tsf.2014.01.071.
- [83] N. Romeo, A. Bosio and A. Romeo, *Sol. Energ. Mat. Sol. C.*, 2010, **94**, 2-7, doi: 10.1016/j.solmat.2009.06.001.
- [84] C. Gretener, J. Perrenoud, L. Kranz, L. Kneer, R. Schmitt, S. Buechler and A. Tiwari, *Progress in Photovoltaics: Research and Applications*, 2013, **21**, 1580-1586, doi: 10.1002/pip.2233.
- [85] N. R. Paudel, K. A. Wieland and A. D. Compaan, *Sol. Energ. Mat. Sol. C.*, 2012, **105**, 109-112, doi: 10.1016/j.solmat.2012.05.035.
- [86] G. S. Khrypunov, T. N. Shelest, T. N. Li, A. V. Meriuts, N. A. Kovtu, A. V. Makarov and L. V. Avksentyeva, *Se. Phy., Q. Ele. & Opt.*, 2011, **14**, 122-126, doi: 10.15407/spqe14.01.122.
- [87] O. K. Echendu and I. M. Dharmadasa, *Mater. Chem. Phys.*, 2015, **157**, 39-44, doi: 10.1016/j.matchemphys.2015.03.010.
- [88] N. Maticic, N. Spalatu, V. Mikli and J. Hiie, *Appl. Surf. Sci.*, 2015, **350**, 14-18, doi: 10.1016/j.apsusc.2015.01.172.
- [89] A. A. Ojo, O. Olusola and I. M. Dharmadasa, *Mater. Chem. Phys.*, 2017, **196**, 229-236, doi: 10.1016/j.matchemphys.2017.04.053.
- [90] K. Shen, Q. Li, D. Wang, R. Yang, Y. Deng and M. J. Jeng, *Sol. Energ. Mat. Sol. C.*, 2016, **144**, 472-480, doi: 10.1016/j.solmat.2015.09.043.
- [91] T. Sinha, D. Lihare and A. Khare, *J. Mater. Sci.*, 2019, **54**, 12189-12205, doi: 10.1007/s10853-019-03651-0.

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