Investigation of the Emerging Materials Based High-Efficiency CdTe Solar Cell

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Abstract

Solar light is a renewable source of energy with no bad impact on the environment. It can compensate for energy taken from non-renewable energy sources like petroleum, and fossil fuels. The fabrication of solar cells passed through several steps from 1st generation to modern nano-material-based solar cells. One of the good solar cells is known as the cadmium telluride (CdTe) solar cell which has good efficiency. Thin-film CdTe has been considered the best choice for the development of cost-effective and reliable solar cells. Efficiency has been achieved as high as 23.5% in CdTe cells in the lab in 2020, and the present techniques for CdTe solar cells stepped towards commercialization. This work will investigate the development of the CdTe solar cell in a systematic way that includes its fabrication process, back contact selection, parameters impacts, and structural modification which directly impact improving the efficiency of the solar cell. In the end, this work will discuss a brief comparison of the improved efficiency with other solar cells and its future aspects.

Keywords
Renewable energy, fossil fuels, back-contact, cadmium-telluride, thin-film

1. Introduction
Solar energy with great potential among all renewable energy resources, which can be converted into electricity by photovoltaic (PV) conversion in solar cell technology (Shabir et al, 2022). PV technology is starting to give a significant contribution to the energy sector in many countries (Zaidi et al, 2020). PV technology contributes 4% to 7% in the USA, European Union, and Germany. The working PV power increased at a very high rate (~30-40%) per year in the last 1.5 decades and is growing rapidly worldwide (Zaidi et al, 2019). The efficiency of the solar cells increased, and the cost of photovoltaic modules is reduced (Wu et al, 2001). The motivation of the research is the increasing demand for energy and the increasing efficiency of the solar cell (Bakiri et al, 2021). As shown in Figure 1.

1.1 Objectives
This research focused on the CdTe solar cells efficiency parameters and the comparison of the work with different emerging materials. Work will show simulation-based results and a comparison of this work with different materials in tabular form.

2. Literature Review
The cadmium telluride (CdTe) solar cell become more important in the market for PV technology. Though CdTe holds >7% of the market Si-based solar cells still dominate the market (Kanevce et al, 2013), it is the first in the second generation of thin-film technologies to successfully make the increase to truly mass utilization (Sites and Pan, 2007). It has a direct 1.5 eV bandgap, with the best optical absorption ~1x103 cm-1 (Wu et al, 2001). CdTe has been shown as an eminently scalable technology with simple binary phase chemistry. 22%+ is the efficiency of the modern device in Lab and modules have more than 18% efficiency, more than multi-crystalline silicon modules (Hegedus and Shafarman, 2004).

It is the lowest per watt technology, have the shortest energy payback time, having less carbon-intensive production (Ohyama et al, 1997). CdTe solar cell's efficiency can push closer to the theoretical maximum of >30% (Jackson,

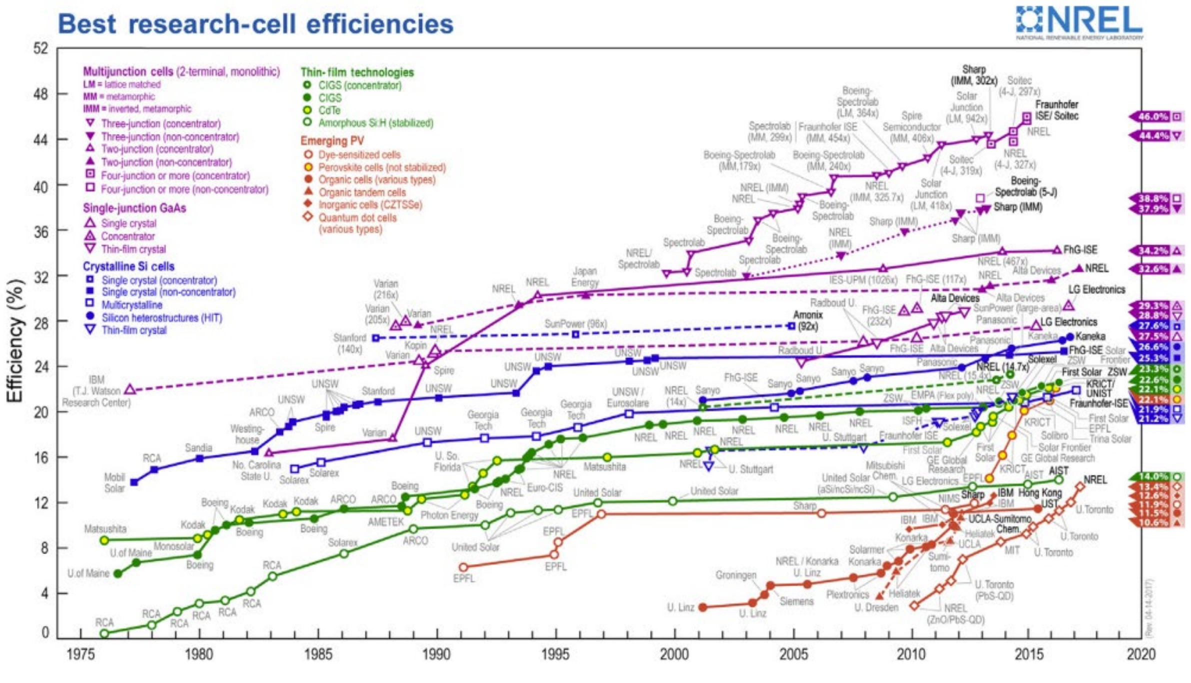

Figure 1. The NREL chart of solar cell efficiencies, Plot COURTESY, National Renewable Energy Laboratory CO, USA

2014). The production costs of CdTe have decreased to such an extent that the device impacts a fraction of the full cost, meanwhile, more than 50% is due to electrical and other components and also its indirect costs including installation and maintenance (Britt et al, 1993). Coming death of fossil fuels and very serious pollution resulting from other fuels solar energy has become a promising solution to the world energy crisis (Bitam et al, 2021). In 2009, solar energy production was 12.3 GW in the last decade that is increased to 20 GW in just one year (Geethika et al, 2019).

Early research focused on CdTe homojunction cells, i.e n-CdTe, in the shape of silicon counterpart, this structure was attractive to have high rates of surface recombination and strong unwanted optical absorption in the CdTe layer. First emerged in 1970 from the work of Bonnet and Rabenhorst (Demtsu et al, 2005). As with CdTe solar cell, it has progressed in the intervening decades with a series of empirically arrived at process improvements such as the chloride treatment, improved back-contacting, window layers, and efficiency of the device by 2020 device 16% to 23%, despite the industrial uptake remained there for over a decade, leading to a great idea so that the technology had reached a high level as shown in Figure.1 (Fonash et al, 2004). This has proven to be a false fear with efficiencies jumping past 22% in recent years with predictions that efficiencies of more than 25% will be reached in the coming years (Gloeckler et al, 2003). Thin-film CdTe is regarded as one leading material for the development of cost-effective PV with a price of less than $1 (Gessert et al, 2002).

3. Working Principle of CdTe Solar Cell

Deep learning techniques are being used in the work as cadmium telluride (CdTe) solar cells consist of thin-film layers of cadmium telluride materials as semiconducting material to absorb sunlight in order to produce energy as shown in Figure 2 (Fritsche et al, 2002). Carbon-doped-Carbon (CDC) paste is used for one electrode and tin oxide or cadmium-based stannous oxide is used for the other electrode (Green et al, 2009). Cadmium sulfide is placed between these two electrodes as shown in Figure 3 (Goswami et al, 2007). CdTe cell technology is a better candidate for the future market after Si-based solar cells (IEA report, 2014).

This technology become a substitute because of its economical design assembling, to the crystalline bulk silicon-based technology (Luque and Hegedus, 2011). The biggest challenge for the researchers is the development of a back contact with the lowest resistance. Device performance improved dramatically when back contact is activated by the rapid thermal processing process (RTPP). Power conversion 19.28 is obtained having V_{oc} = 0.68 V as shown in Table 1.

Figure. 2 The current structure of CdTe solar cell with high efficiency.

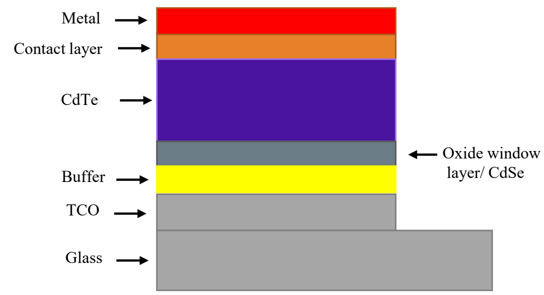

Figure 3. The current structure of CdTe solar cell with emerging materials

Front contact is designed very carefully for CdTe solar cells. TCO used the superstrate structure. TCO makes transparency and conductivity better as it is the 1st layer deposition that needs to be stable during the whole process. There are two kinds of TCO applied in PV thin films (1) SnO_2:In_2O_3 (ITO) and ZnO: AI (AZO), both models have sheet resistance values low as well as optical transparency values high. Some problems may occur due to these layers during the fabrication of CdTe solar cells. The breakdown value of AZO is larger than 400 degrees Celsius, decreasing the conductivity. Breakdown temperature for the FTO is more than 500 degrees Celsius which is highly stable for CdTe solar cells.

4. General Formation Process of CdTe Solar Cell

In the commercial level process, glass-coated TCO is used for the manufacturing of the device for the stability of the device, CdS is deposited with having thickness >200 nm (Kosyachenko et al, 2011), this thickness can be varied according to the deposition process. Chloride treatment is done at the temperature of 300-350 degrees Celsius. This treatment is done in the presence of the back contact to optimize the cell performance tracking. Many processes are available for the treatment having different impacts on the cell performance (Guo, 2018). The scribing process is done many times to improve the front contacts of the cell (Ullah et al, 2014).

4.1 Formation of CdTe Window Layer

The structure of heterojunction solar cells used CdS/p-CdTe as a standard material for its development (Zaidi et al, 2019). In most of the technologies which use thin films CdS used widely as a window layer. It is easily disposable by many routes and has a big bandgap 2,4 eV. Close space sublimation (CSS) and MOCVD (metal-organic chemical vapor deposition) as well as RF sputtering and chemical batch deposition are capable of operating at top of the CdTe superstrate at higher temperatures (Pavlovic et al, 2010). In the cell fabrication of CdTe, deposition parameters i.e temperature of the substrate deposition time CdTe and chloride treatment time as well as temperature are fixed. The amount of Sulfide diffused into CdTe in CdTe solar cell depends on the thickness of the CdTe window layer. The thickness of the CdTe window layer may affect the performance of CdTe/CdS cells by changing value from 0 to 750 nm. The value of the Voc, Fill factor (FF), Jsc, and efficiency (eff) are varied on changing the value of the window layer of CdTe.

4.2 Role of CdTe Absorber Layer in Solar Cell

CdTe is either can be doped as n/p-type due to its polycrystalline property. P-type is used very rarely when chloride treatment of the CdTe is being done for the solar cell or back contact is formed by copper (Li, 2019). The method used for the absorber layer highly impacted the absorber layer, if the deposition is done at higher temperature routes produces bigger grained and high-performance material (Demtsu and Sites, 2006).

4.3 Back-Contacting

One of the biggest challenges in the fabrication of CdTe solar cells is the development of the back contact. CdTe has a high ionization potential with a work function. More than 5.9 eV is needed to construct an ohmic contact. Most of the metals do not owe this work function some of the metals come closer to Platinum and Nickle is not ideal (Zaidi et al, 2019). Schottky junction is created at the CdTe-metal interface to rectify the contact. It is considered a second diode opposing the major junction diode.

Table 1. Performance parameters of CdTe with different materials and substrate-thickness

substrate-thickness in um	Voc (V)	Jsc (ma/cm^2)	Fil-Factor (FF)	η (%)
70	0.92	13.84	0.69	8.79
50	0.89	12.85	0.65	7.66
20	0.85	10.00	0.60	5.32

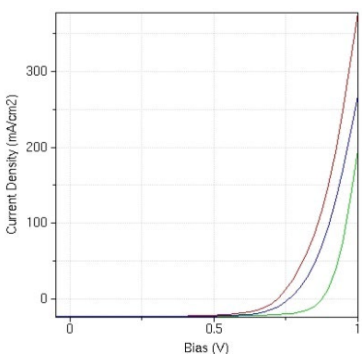

Figure 4. I-V Characteristics of CdTe Solar Cell

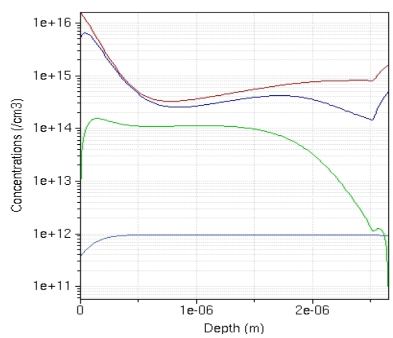

Figure 5. Concentration defect

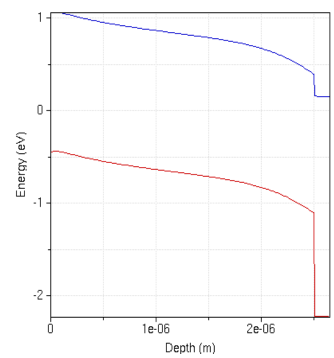

Figure 6. Equilibrium Bandgap energy

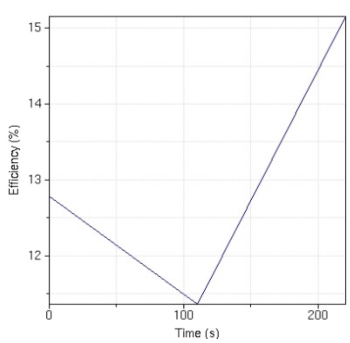

Figure 7. Efficiency vs Time

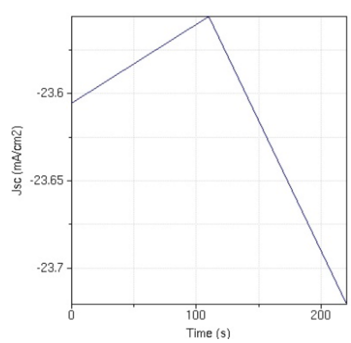

Figure 8. Jsc vs Time

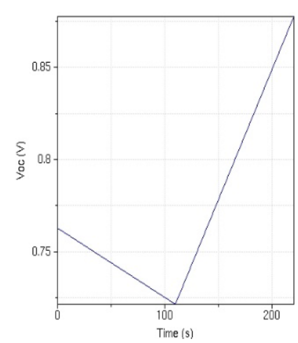

Figure 9. Voc vs Time

Table 1 shows the open circuit voltages variation with different current densities. As the value of the substrate thickness is changing all the other parameters also change and the overall efficiency of the cell is improved.

5. Results and Discussion

This work shows high current density (J_{sc}) which could be varied by using different techniques. Reduction of Jsc losses due to transparent conductive oxides (TCO) absorption process. The CdS absorption losses, as well as the CdTe region's junction recombination, are shown in Table 2 in a summarized way. The I-V characteristics of the CdTe are observed with the different values of the device. Figure 4 shows the I-V characteristics where we can observe that the current value changes in mA as the bias voltage changes. On the other hand, the Concentration defect is shown in

Figure 5 for six different concentration defects, and it is seen that the depth is changing significantly. However, it is important to note that two curves are overlapping with the other curves due to small variations in the process parameters. Besides, Equilibrium bandgap energy is shown in Figure 6 which depicts that more equilibrium can be achieved if the energy band gap is higher. Figure 7 shows efficiency vs time results. It is illustrated that the efficiency goes slow when the device starts working initially. After some period, the efficiency of the device dramatically increased. In Figure 8, Jsc vs Time shows the improvement in the current density. Figure 9 shows Voc vs Time as the open circuit voltages are significantly improved. Figure 10 shows the impact of Ionization defects and doping concentration. It is demonstrated that the device will have fewer defects with more alignment of the doping process. In Figure 11, quantum efficiencies with the value of the thickness of 2.5 um, doping concentration for the device, and electron and hole mobility are observed 1e + 15/cm^3 and 100/ cm^2/Vs respectively. Provided that the electron and hole life is considered as 10 ns, the bandgap of CdTe is 1.5 eV, electron affinity is 4.28 eV, electron mass is 0.095 e $Å^{-3}$, and hole mass is 0.84 e $Å^{-3}$ in the simulation environment. Figure 12 shows the fill factor (FF) of the device which is significantly improved.

It is reported that the defect diffusion value for the CdTe solar cell is ~40,000 $cm^2·s^{-}1$ with an activation energy of 0.57 eV. However, the diffusion coefficient is 6.65e-9 with the first ionization energy of -0.01 eV. Six defect reactions with different values are observed. Left-hand side reactants are (1,4) and right-hand side reactants are (2,5). Forward and backward barrier energy is 0.1 eV and 1.5 eV respectively. The left boundary is Schottky with values of bias voltage (Vb) and Subthreshold voltage (Vs) 0.45 eV and 1eV respectively.

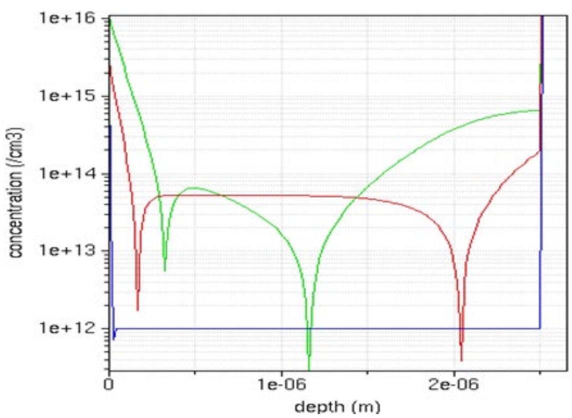

Figure 10. Ionization Defect and doping concentration

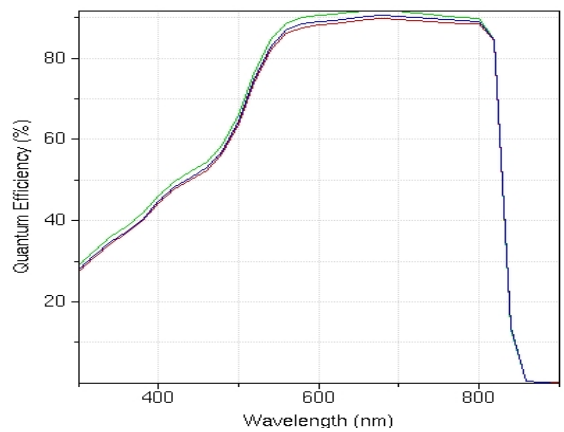

Figure 11. Quantum Efficiencies

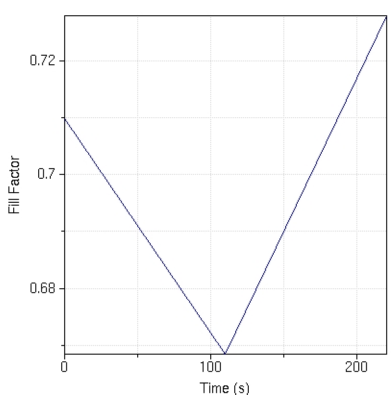

Figure 12. Fill Factor Vs Time

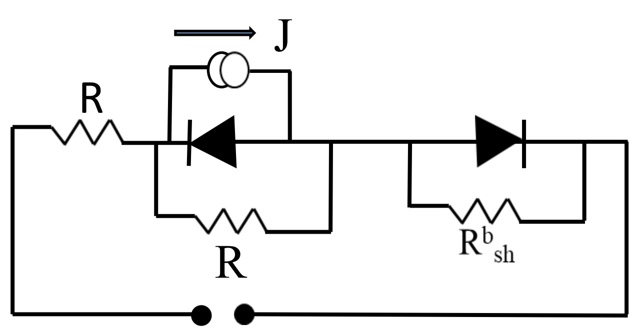

Figure 13. Circuit for evaluating Current density

The working temperature for the device is 200°C and the annealing model is used for the simulation shown in Figure 13 (Tursun et al, 2020). If the front contact and back contacts distance is larger the value of the FF is decreased Shown in Figure 12. The device is also simulated for different materials in 2D to get the different results with the length 1

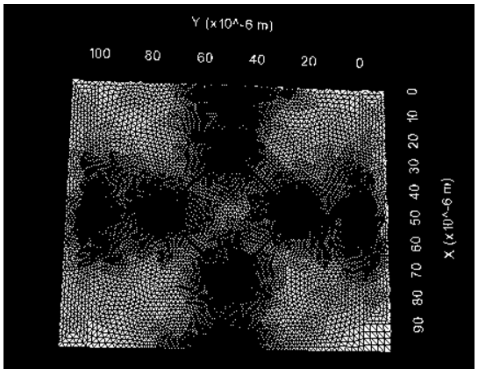

Figure 14. Material concentration in CdTe solar cell substrate

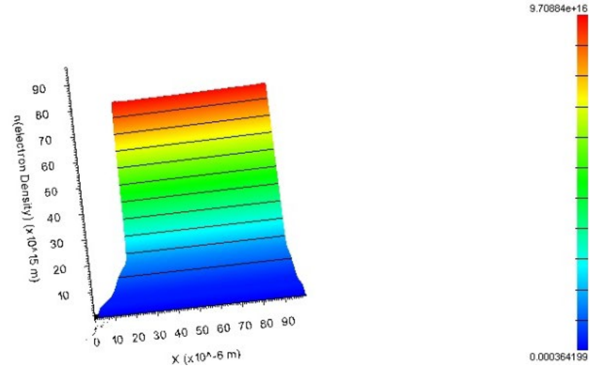

Figure 15. n-electron density

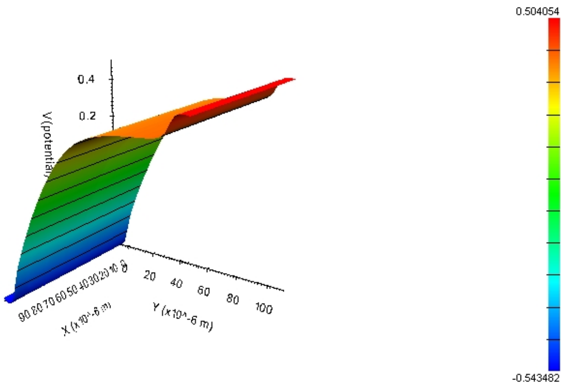

Figure 16. V (potential)

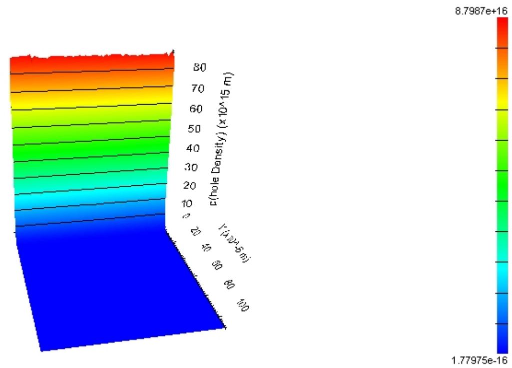

Figure 17. p-hole density

Table 2. Comparison of different materials with the existing work

TCO	R_s (ohm/sq)	J_{sc} (losses due to TCO absorption)
SnO_2 ($SnCl_4$)	8-10	2.8
SnO_2 (TMT)	7-8	1.3
SnO_2 SnO_4	7-8	0.62
CTO/ZTO	7-8/~ 10^6-10^6	0.68
CdTe/CDS	7-9	0.60

nm, CdTe and ZnTe = 1 nm, and CdS= 1 um, CdS, ZnTe, CdTe, CdTeGrain is used to get the output for the device with different parameters using Figure 13.

The concentration of materials is shown in Figure 14, the value of n-electron density is illustrated in Figure 15 which is significantly improved by using these CdS, ZnTe, CdTe, and CdTeGrain materials in the cell model formation. The value of the voltage in figure 16 is increased significantly on the x and y-axis, with limits of - 0/453482 to 0.504054. Work also showed significant improvement in the density of the p-hole as shown in Figure 17. Besides, a comparison of different materials is shown in Table 2.

5.1 Improvements and Challenges of CdTe Solar Cell

The easy manufacturing process makes the CdTe solar cell a very strong candidate for the new technologies of renewable energy (Heath, 2004). The necessary electric field, which converts sunlight into electricity, can be done by

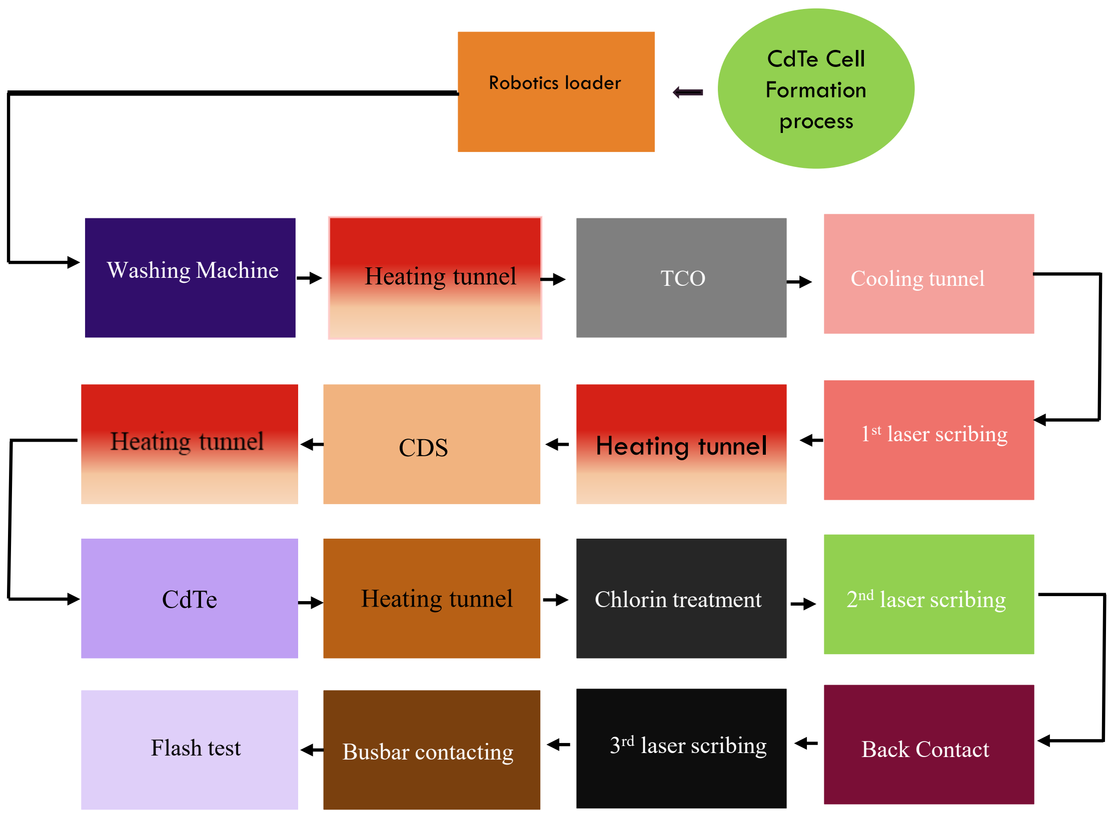

Figure 18. CdTe formation - A brief explanation of the CdTe solar cell manufacturing

two types of cadmium molecules, (1) cadmium sulfide and (2) cadmium telluride. On the contrary, to get maximum energy, the simple mixture of these molecules with emerging materials can be used with Si doping to improve efficiency (Geethika, 2019). It can absorb more light due to having matching wavelengths with solar light (Li, 2019). It is a big advantage of the CdTe which has an ideal solar spectrum range (Luque, 2011). The other thing that makes this technology more interesting is the abundance and production of elements as a by-product of zinc, as a result, it has low prices as compared to other materials used in solar cell technologies (Green 2007).

Despite these challenges, it also has some challenges (1) Lower efficiency of the CdTe cell is a big concern for the researchers (Wu, 2001), and (2) the abundancy of the cadmium and non-abundance of the telluride is another concern that needs to be addressed, the availability of the Te is like 1/5 parts per billion in the crust of the earth. USGS, global tellurium production reported in 2017 it was 135 metric tons (Funash 2004). Most of it comes as a copper by-product. 93 metric tons requires for the production of one gigawatt. The toxicity of the cadmium is another big challenge for the CdTe solar cell since the cadmium lies in the top six toxic and deadliest known materials (Jackson, 2014). However, the CdTe is less toxic than the element cadmium in terms of acute exposure (pavlovi, 2011). CdTe solar cell is the major leading thin-film Photovoltaic (PV) material used in CdTe solar cell due to its near-ideal band gap of 1.45eV. CdTe has a high optical absorption coefficient for solar light which make it a good competitor for the Si, Ge, and many other materials used in the solar cell technologies.

6. Conclusion

CdTe solar cell progress is significant for years, and improvement of the device performance set a breakthrough in the last decade with the design of new device structure and process. The emergence of absorber bandgap, with window layers with emerging materials and breaking the 1V with a single crystal is a great achievement. As doping results are shown in the paper that it will remain a technology under development, even after decades. Although it has set firmly itself as a competitor with silicon. However, more work needs to be done in the development of new compositions of the materials for CdTe solar cells. Through many ways like cost-effectiveness, high performance, and refinement process, the overall module economy can be tremendously reduced by new methodologies. The busbar connecting and the flash test are done as a final step (Green et al, 2007) in Figure 18. The whole general manufacturing process is shown in Figure 18. Consequently, there is a large scope that CdTe can be a technology that will remain at the forefront of photovoltaic research to make renewable more efficient for foreseeable future.

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Biography

Aamar Shabir joined Florida Polytechnic University in January 2021 as a student of master’s in electrical engineering. He served as the trainee engineer in the AJK Electricity department in 2017-2019 and served INPRO Pakistan in 2019-2020 as a site engineer. Aamar did his undergraduate project on Induction Motors. Which covered the automated monitoring of induction motors parameters. He is a member of IEOM Society International and IEEE. He is the director of membership at the IEOM Chapter at Florida Polytechnic University. Aamar is working on emerging materials carbon nanotubes to improve solar cell efficiency under the supervision of Dr. Muhammad Ullah. He worked on LabVIEW, Power world simulator in Power system analysis to improve the power factor of power system, and R-studio to design an adaptive cruise control system.

Dr. Muhammad Ullah, Ph.D. Dr. Muhammad S. Ullah is an assistant professor of electrical and computer engineering at Florida Polytechnic University. His research focuses are the modeling of RLC interconnects in high density integrated circuits and energy-efficient electronic devices (TFET) for logic applications based on emerging 2-D nanomaterials (MoS2, Graphene, and CNT). He also worked on a neural network-based classification of deceptive and stress speech using non-linear spectral and cepstral features during his master’s study. In his Ph.D. dissertation, he investigated the high-speed very-large-scale integration (VLSI)interconnect and energy-efficient electronic devices for emerging post-MOSFET and beyond silicon technologies. Before joining Florida Poly, Ullah worked as a full-time lecturer from 2008 to 2011 at the Chittagong University of Engineering & Technology (CUET), Bangladesh. From 2011 to 2013, he worked as a teaching assistant at Purdue University Northwest. He began working as a full instructor at the University of Missouri-Kansas City while he pursued his doctoral degree. He has taught undergraduate courses in electrical circuits, digital logic designs, signals and systems, and graduate courses in advanced digital signal processing, introduction to VLSI designs, advanced VLSI designs, and emerging nanotechnology, including hands-on experience in MATLAB, Cadence Virtuoso, and HSPICE. Ullah has served as a regular reviewer of many journals and conferences, including IEEE Transactions on very large scale integration systems, IEEE International Symposium on Circuits and Systems, IEEE Midwest Symposium on Circuits and Systems, Microelectronics Journal-Elsevier and Circuits, Systems and Signal Processing-Springer, and ASP Journal of Low Power Electronics.