

An Evolution Review in Solar Photovoltaic Materials

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Abstract—The sensitivity towards the environmental concerns among the humans is picking up the pace. An energy source, which meets the development goals without compromising with this source for the next generation, is the need of the current time. Renewable energy sources are the only solution of this problem. Solar energy is the most abundant form of renewable energy. Since the last decade, the solar energy generation costs have shown a sharp decline. There are many reasons include use of better materials, improved technologies and increased efficiencies of the solar panels. This paper discusses about various solar photovoltaic (SPV) materials being used throughout the globe. A brief description of both, the fully developed and under-developing PV material technologies has been provided. This paper covered the different topics such as the structures of the conventionally used PV cells and their laboratory efficiencies. Various manufacturing processes of each cell have also been highlighted. This paper will provide an overview of current scenario of the PV materials to the industrialists, scientists and manufacturers. Thus, this paper gives the clearer picture in the direction of improvement and innovations in SPV materials as well.

Keywords— *Crystalline Material, Photovoltaic, Silicon materials, Solar cells, Solar energy.*

I. INTRODUCTION

Man is the most intelligent of all the creatures ever existed on this planet. Sadly his greed is the reason for all the problems faced by the environment and eventually him. Air is polluted, fresh water sources are depleting and soon all the land will be covered by the concrete jungle. Evolution requires energy; hence the need for energy's abundant sources is never ending. Today the most abundant usable source of energy on earth is the petroleum and coal, which causes a lot of pollution. According to predictions, coal and petroleum will be completely consumed in next 50 years. Renewable energy sources are the need of the present time for the sake of sustainable development [1]. Out of all non-conventional energy sources, sun is the most abundant source of energy. The light energy of sun can be economically and efficiently converted into electricity. The solar panels used for this purpose affects the environment directly as well as indirectly. They not only provide clean energy but also affect

the local climate by reducing heat is land effect. Solar energy as a non-conventional energy source is a very good option for not only bulk electricity production but also for the off-grid purposes. Rural population contributes to about 80% of the world's population. The use of off-grid plants is very useful in the electrification of the rural areas. They are also helpful in avoiding the long-distance transmission costs [2, 3].

This paper presents the overall evolution review in solar photovoltaic materials. The first half of the paper mainly focused on the structure, efficiencies and manufacturing processes of the conventionally used solar cells. There are many emerging technologies which have been discussed in the later sections of the paper. Evolution & classification in the PV Technology are explained in the section 2 & 3 respectively. Different conventionally used material technologies are described with different structures in section 4. In section-5, modern different emerging PV technologies are clearly explained. Finally, Section-6 concludes this paper.

II. EVOLUTION IN THE PV TECHNOLOGY

Using selenium wafers in 1883 Charles Fritts invented the first photovoltaic cell, in which conversion efficiency is almost 1%. In 1887, Hertz discovered that illuminating a metal surface with light of sufficient intensity and frequency. Due to this electric current is generated. In 1888, Edward Weston received the first patent for PV cell [4]. Although photoelectric effect was observed very early, its theoretical explanation was given by Albert Einstein in 1904. For that he received the Nobel Prize in 1923. Einstein's theory of photovoltaic effect was further advanced by a polish scientist Jan Czochralski. He developed a technique for growing silicon crystals called the Czochralski (CZ) process. This process was very helpful in producing mono crystalline silicon cells of large diameters and has been popularly used in the PV industry since mid 20th century till today [5]. Efficiency and cost are the most important factors which are to be kept in mind while talking about the solar technology. The efficiency mostly depends upon the type of the PV material used. In the beginning, silicon based solar cells are

most popular and dominate in the market due to highest efficiency and developed technology [6]. Although in present scenario, many different types of PV materials are available in the market as shown in Fig. 1, which is recorded by National Center for Photovoltaics (NCPV) research cell.

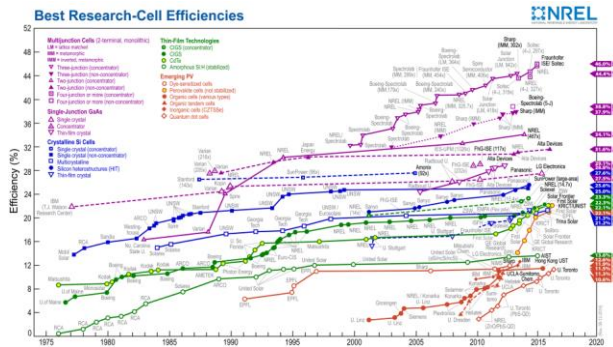


Fig. 1. Best research-cell efficiencies [7].

III. CLASSIFICATION

The solar cell technology can be characterized into three eras. Fig. 2 shows the different types of the PV technologies based on different types of the materials used. First generation cells were based on silicon wafers. Silicon is the second most abundant element present on earth and its non-toxic nature makes it suitable for the widespread use in the PV industry [6].

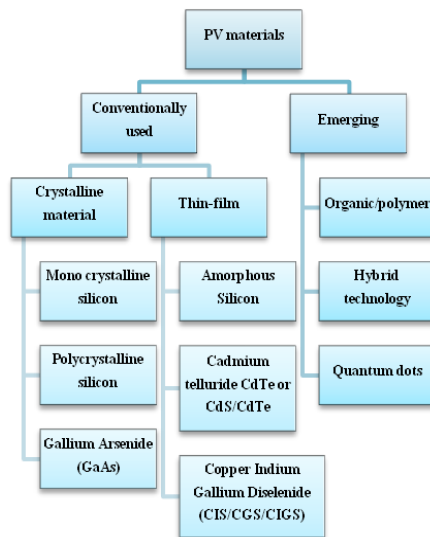


Fig. 2. PV technologies classification

However due to its high cost an alternative path was required, so second generation thin film modules were invented. These modules reduced the material used and hence reduced the cost; but the efficiency was also less as compared to crystalline Si. Scientists are working on

improving the efficiency of thin film modules with the help of amorphous silicon, CdS/CdTe instead of reducing the size of the crystalline module. The third generation polymer technology is scotch as well as light weight. It is helpful in meeting concerns regarding the environmental problems. But even this technology has lower efficiency as compared to Si-based ones. Hybrid technology involves the combination of both the crystalline and thin film module [8, 9].

IV. CONVENTIONALLY USED MATERIAL TECHNOLOGIES

A. Crystalline Material

This technology is considered to be the first generation of photovoltaic technologies. Modules are made by combining different silicon cells or GaAs cells. The crystalline silicon based cells are as yet driving the PV market. The conversion efficiency of single crystal silicon cell has hit the mark of 26.3% at STC (Standard Test conditions i.e. 25°C and 1000W/m² sunlight intensity)[10]. The compound semiconductor GaAs is having the same structure as the silicon. It shows high proficiency and exhibit low weight, yet is costlier than silicon based ones. However, it displays high heat resistance and is accordingly reasonable for space applications and concentrated PV modules.

B. Mono Crystalline Silicon

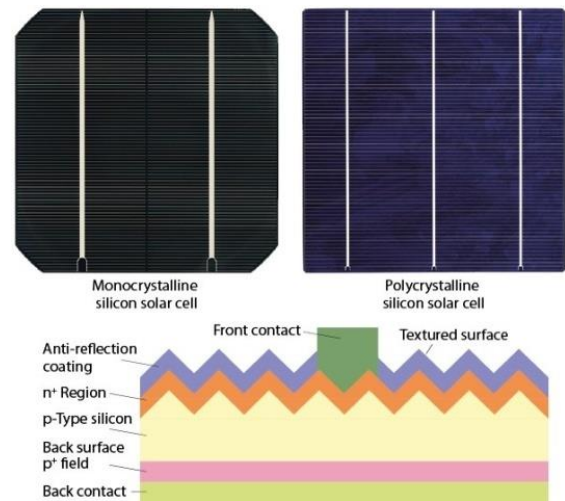


Fig. 3. Structure of crystalline solar cells [11]

It is the most regularly utilized material in PV modules. It employs p-n junction in its course of action. The front surface of the cell is secured with micrometer-sized pyramid structures. It decreases reflection loss of episode light. An anti-reflection coating (ARC) of silicon nitride (SiN_x) or titanium oxide (TiO_x) is overlaid on the finished silicon

surface. It additionally reduces reflection misfortunes. C-Si solar cells have exceptionally phosphorous-doped n^+ locales on the front surface of boron-doped p-type substrates to shape p-n junctions. Back-surface p^+ field (BSF) locales are framed on the back surface of the silicon substrate. Back surface reduces recombination of minority carriers. Its structure is shown in Fig. 3. The cells based on this technology are typically 5 inches squares [11, 12].

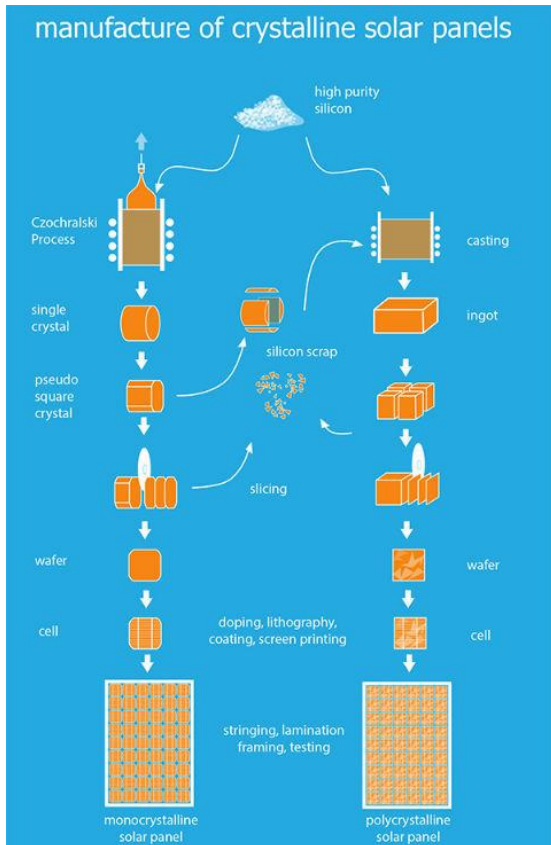


Fig. 4. Manufacturing of crystalline solar panels [14]

These are created by cutting section ingots grown by the Czochralski (CZ) process into pseudo-square silicon wafer substrates. At present no PV manufacturer gets ready silicon source material. Manufacturers purchases off-particular material from microelectronic industry, or sidestep the crystal growth step by acquiring silicon wafers. These wafers are further processed using screen printing technique or Buried contact solar cell technique to produce solar cells [12, 15, 16]. These processes include chemical etching, metal contacts development & grading, doping diffusion, edge isolation, anti-reflection coating. These cells are further interconnected to form a module. Manufacturing of crystalline solar panels is clearly shown in Fig. 4. The state-of-art conversion efficiency of the mono c-Si based modules

by Sun Power Corporation at STC is found to be 24.1% [13].

C. Polycrystalline Silicon

This technology was introduced to reduce the production cost of silicon ingots. The wafers for these cells are formed by pouring the molten silicon in a cubical mould. During this process a seed silicon crystal of desired crystal structure is introduced in it. The liquid silicon is then allowed to cool down and solidify. The solidified block is sliced to form perfectly square cells. Although this process requires less material and cells produced have lower cost; efficiency is also low as compared to c-Si cells [17]. Polycrystalline silicon have high packing factor. Due to this poly c-Si PV modules have conversion efficiency approximately equal to mono c-Si PV modules. Nowadays, new sorts of back-contact polycrystalline cells are created by different organizations. Among these, metal wrap through (MWT) cells and emitter wrap through (EWT) cells are mostly used for PV cells [17, 18]. The EWT cell structure incorporates laser drilled holes which interfaces rear n-type contact with the emitter. The front contacts are removed resulting in whole cross sectional area to be used for trapping solar radiation; thereby improving the conversion efficiency of the PV unit. The state-of-art conversion efficiency of the poly c-Si based modules by Trina solar corporation at STC is found to be 19.9% [19, 20].

D. Gallium Arsenide (GaAs)

GaAs cells are having high energy conversion efficiency as compared to mono c-Si and poly c-Si cells. But due to high cost is not commercially used. It has high temperature coefficient and hence is suitable for use in the space applications and concentrated PV modules. It possess lighter weight as compared to c-Si [21]. GaAs can be further alloyed with phosphorous (P), Indium (I), Aluminum (Al) or Antimony (Sb) to improve the efficiency. The efficiency on alloying increases due to the formation of multi-junction structure [22-24].

E. Thin-film Material

This technology is considered to be the second generation of photovoltaic technologies. In this technology, the solid backing materials are used with thin layers of semiconductors based thin film solar cells. Thin-film technology extensively reduces amount of semiconductor material used and hence reduces the production costs. But due to high radiation capture losses, its efficiency is lower than c-Si cells[25, 26]. Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Cadmium Sulphide (CdS), Copper

indium Selenide (CIS), Copper Indium Gallium Selenide (CIGS), Titanium Dioxide (TiO_2) are the materials that are most commonly used [27, 28].

F. Amorphous Silicon

This material is having about 40 times superior absorptive rate of light as comparison to mono c-Si. Due to high efficiency it is most commonly used material in the thin film cells. a-Si cells due to high band gap of 1.7eV absorbs very broad range of the light spectrum. a-Si contains defects due to its random orientation. More stable structure is produced by reacting the a-Si with hydrogen to produce amorphous silicon hydride (a-Si:H) [29].

Amorphous silicon can be consolidated with layers of other allotropic types of silicon to produce a multi-junction solar cell. At the point when two layers are joined, it is called a tandem-cell. By stacking these layers together, range of the light spectra absorbed increases, improving the cell's efficiency. The Tel solar corporation a-Si solar cell at STC is found to have 12.3% efficient. But when exposed to sunlight, its efficiency decreases to about by about 30 to 40 percent. This reduction is caused due to Staebler-Wronski effect (SWE) which can be minimized by thermal annealing at or above 150°C [29, 31, 32]. Structure of a-Si solar cell is shown in Fig. 5.

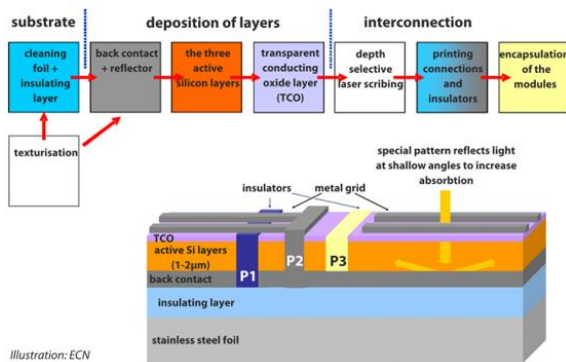


Fig. 5. Structure of a-Si solar cell

The cell manufacturing process can be divided into three major steps:

- 1.) Backing material preparation: which includes shaping and cleaning of backing material such as metal, glass or plastic and deposition of transparent conducting oxide on it.
- 2.) Cell fabrication: it includes depositing thin layer of amorphous silicon on the backing material substrate. Plasma-enhanced chemical vapor deposition technique (PECVD) is commonly used technique for silicon layer deposition. Further zinc and silver layers are deposited on the cells [33].
- 3.) Module assembly process: it includes the final testing and lamination of the cells [34, 35].

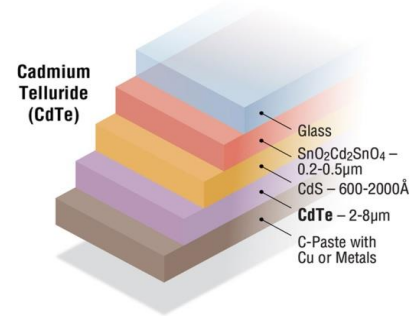


Fig. 6. CdTe solar cell diagram

G. Cadmium telluride (CdTe or CdS/CdTe)

Photovoltaic solar cells based on CdTe contribute to the major part (about 5.1%) of commercial thin-film module production worldwide. CdTe based solar cells are the second most normal PV innovation on the planet. The United States is the leading manufacturer of CdTe PV. In addition to high efficiency these cells can be quickly manufactured and also costs low [36]. It is a direct-bandgap material having a bandgap E_g of 1.5eV and absorption coefficient is high. This coefficient value is less than $5 \times 10^5/\text{cm}$. This bandgap is about ideally coordinated to the solar spectrum for sunlight to electricity conversion with one joint [37]. Generally, CdTe solar cells involve a straight forward simple p-n heterojunction structure containing an n-doped cadmium sulfide (CdS) layer stacked over a p-doped CdTe layer [38].

Typical CdTe thin-film deposition techniques are shown in Fig. 6. These can be divided into 3 basic techniques:

- 1.) Condensation/reaction of Cd and Te vapors on a surface: close-spaced sublimation (CSS) [40], vapor-transport deposition (VTD), physical-vapor deposition (PVD), sputter deposition [41]
- 2.) Cd and Te ions based galvanic reduction on the surface: electrodeposition [42].
- 3.) Precursor reaction on a surface: metal-organic chemical-vapor deposition (MOCVD), spray deposition and screen-print deposition [43, 44].

In 2016 First Solar Corporation held world record for highest efficient CdTe laboratory solar cell with 22.1% efficiency. The average commercial module efficiency was reported to be 16.1% [45].

H. Copper Indium Gallium Diselenide (CIS/CGS/CIGS)

It is fabricated by storing a thin layer of copper, indium, gallium and selenide on plastic or glass backing. CIGS is a strong arrangement of copper indium selenide (CIS) and copper gallium selenide (CGS), having chemical composition as $\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$. The estimation of x can shift from 1 (pure CIS) to 0 (pure CGS). The bandgap varies continuously with x from about 1.0 eV (for CIS) to about 1.7

eV (for CGS) [46]. As discussed earlier, the more suitable the bandgap, more is the range of the wavelength to be absorbed from the solar radiation. CIGS-based solar panels are the most elevated performing thin film solar panels till date. These cells contain less of the toxic material cadmium as compared to CdTe cells [47]. Typical CIGS solar cell diagram is explained in Fig. 7.

The issue with the CIGS is failure to balance the manufacturing process for high output keeping with low cost. Indium is also scarce. Photo degeneration also takes place in CIGS modules when subjected to sunlight just like CdTe modules. Additional barrier coating is required to mitigate this problem [49].

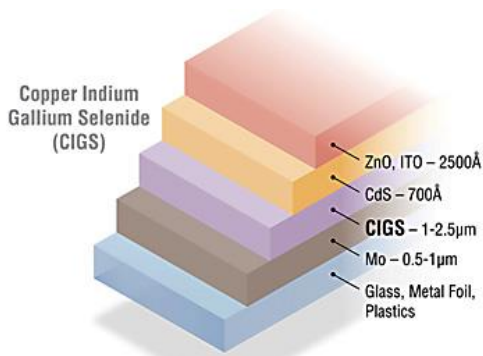


Fig. 7. CIGS solar cell diagram [48]

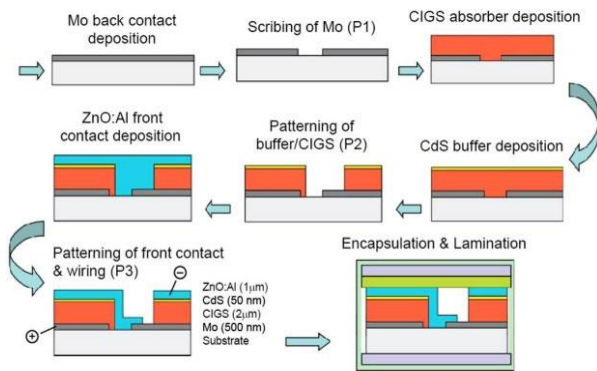


Fig. 8. CIGS solar cell manufacturing [50]

The CIGS solar cell manufacturing is shown in Fig. 8. The substrate is coated with Mo layer and then p-type CIGS layer is grown on it. After deposition of every layer, the cell is patterned with the help of Computer numerical control(CNC) machine. The CIGS thin films can be grown using three techniques: 1.) Co-evaporation process [51] 2.) Selenization (Sequential process) which can be a.) Selenization from Se vapor b.) Annealing of stacked elemental layers [52]. 3.) Roll to roll deposition. Then a buffer layer of CdS is deposited with the help of Chemical bath decomposition (CBD) method [53]. CdS layer avoids

lattice misfit between CIGS and zinc oxide (ZnO) layer. It also protects the CIGS layer from further processes. Further the ZnO layer as the transparent front contact is deposited by Radio frequency sputtering or Atomic layer deposition (ALD) [54]. The heterojunction is formed between ZnO and CIGS layer. After final patterning metallization and deposition of anti reflection coating is done [55]. In June 2016 The Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) held world record for highest efficient CIGS laboratory-sized (0.5 square centimeter) solar cell with 22.6% efficiency [56].

V. EMERGING PV TECHNOLOGIES

A. Organic/polymer material

This under-developed technology is the part of the third generation of photovoltaic technologies. Organic materials such as a conjugated molecules or polymer are used for light absorption. The organic polymers have high light absorption coefficient and hence more light can be absorbed using less material [57]. These materials are produced through solutions. Hence they are light weight, flexible, provides molecular level customization and their manufacturing is inexpensive. The demerits of this technology include very low conversion efficiency and less stability due to photochemical degradation [57, 58]. Based on the junction types these cells can be divided into three basic categories:

1.) Single layer: A layer of organic electronic materials is sandwiched between two metal contacts having dissimilar work functions as shown in Fig. 9. Usually a coating of Indium Tin Oxide (ITO) having high intensity and a low work function metal based thin coating (such as Magnesium, Aluminum or Calcium) is used. These are found to have conversion efficiency <0.01% [59-61].

2.) Discrete heterojunction: These cells are made by sandwiching two or more layers of organic electronic materials between the electrodes. One of them is the electron donor (P3HT, F8T2, and PPDFV) and the other is acceptor, which is usually a derivative of buckminsterfullerene (PCBM-60, dKMC60s and bis-PCBM)[60-62].

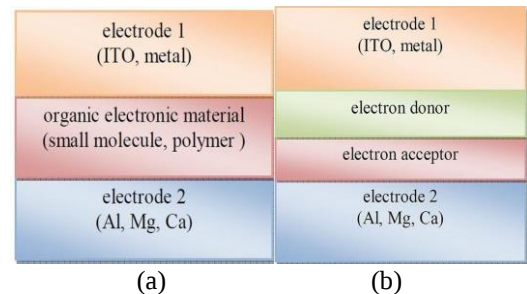


Fig.9. (a) Single layer and (b) bi-layer solar cell diagram

3.) Bulk heterojunction (BHJ): It is the most commonly used polymer technology. The interface between both components is all over the bulk as shown in Fig. 10. Till date the highest efficient BHJ cell has conversion efficiency of 10.6% [63].

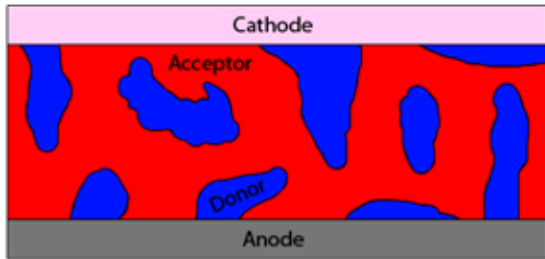


Fig. 10. Single layer BHJ solar cell diagram [63]

In 2016 He Yan et al. [64] developed a record holding organic solar cell. The conversion efficiency of 11.5% was recorded by National Renewable Energy Laboratory of the United States (NREL). Performing better than hazardous solvent based organic cells despite of using non-toxic solvent is what makes this approach unique. Combination of low cost hydrocarbon solvent readily obtained from petroleum and polymers with specially-tailored side chains was used. Polymer used was PffBT4T-C₉C₁₃ along with the solvent 1, 2, 4-trimethylbenzene (TMB) and a novel additive 1-phenylnaphthalene (PN).

Step used in fabrication: 1.) ITO coated glass was cleaned using ultrasonication and ultraviolet O₃ cleaner. 2.) ZnO layer was spin coated on the substrate. 3.) Active layer containing polymer solvent and additive blend was spin coated on the ITO substrate. 4.) Substrate is annealed in glove box and sent for thermal evaporation. 5.) V₂O₅ and Al thin films were deposited. 6.) Finally cells were encapsulated using epoxy inside the glove box [64,65].

B. Hybrid technology

A hybrid solar cell can be combination of organic and inorganic materials. Due to combination of high charge carrier mobility of the inorganic material and high light absorption capability of organic materials this technology got much attention in the recent year. It can also be totally made up of inorganic materials with multi-layers or organic materials with multi-layers. Following are some common hybrid technologies:

- Perovskite based cells: This solar cell use a perovskite structured compound as active layer for light absorption. The problem with this technology is low sunlight stability of the perovskite material [66]. Seong et al. [67] using methyl ammonium lead iodide (MAPbI₃) perovskite as active layer and Lanthanum (La)-doped BaSnO₃ (LBSO) as photo-

electrode materials achieved photo conversion efficiency of 22.1% and high photostability of about 1000hrs.

- Multijunction solar cells: These cells contain 3 or more p-n junctions using materials having different band gaps. The use of different semiconductors with different band-gaps increases the range of the light spectrum absorbed by the cell. This results in increased cell's sunlight to electricity conversion efficiency [68]. The most efficient multi-junction cells till date are four-junction (Tandem) cells. Tandem cells are used for concentrated photo voltaic (CPV) applications only. Frank et al. [69] developed a 44.7% efficient four-junction GaInP/GaAs//GaInAsP/GaInAs tandem cell.

C. Quantum dots

A quantum dot is a semiconductor crystal having size in nanometers. The band gap of these dots can be changed by changing their size. The change of the band gap changes the range of the solar spectrum radiation absorbed by the material. Hence it is an attractive technology to be used in multilayer PV cells [70]. It was found that decreasing the band-gap increased the output current while increasing the band-gap increased the output voltage. These cells are easy to synthesis and less costly. The highest conversion efficiency shown by quantum dots based solar cells till date is 11.3% only [71].

VI. CONCLUSIONS

Various conventionally and emerging PV material technologies have been discussed in the paper. The conventionally based technologies section covers crystalline materials including mono-crystalline silicon, polycrystalline silicon, gallium arsenide (GaAs) based solar cells and thin-film materials including amorphous silicon, cadmium telluride and copper indium gallium diselenide (CIS/CGS/CIGS) based solar cells. In these materials, Polycrystalline silicon is introduced to reduce the production cost of silicon ingots. Mono-crystalline silicon is the most regularly utilized material in PV modules. Gallium arsenide is having high efficiency but higher cost too. Thin-film PV cells uses less materials, costs less but shows low efficiency too. Amorphous Silicon have high absorption rate and is most commonly used thin-film technology followed by cadmium telluride. CIGS based solar cells contain less of the toxic material cadmium as compared to CdTe cells. In this paper, the evolving technologies section covers Organic/polymer, Hybrid technology and Quantum dots based solar cells. Organic/polymer and Quantum dots based solar cells are only laboratory tested and can't be used conventionally. Finally, we can say that hybrid technology based PV cells are the most efficient solar cells till date but are costly. Thus, the race to develop highly efficient solar

cells with low manufacturing cost is never ending. Therefore, further improvements are expected in the near future in the PV technologies.

REFERENCES

- [1] Prakash Kumar Sen, Krishna Awtar and Shailendra Kumar Bohidar: A Review of Major Non-Conventional Energy Sources. *International Journal of Science, Technology & Management*, 4(01), 2015, 20-25.
- [2] Panwar, N. L., S. C. Kaushik, and Surendra Kothari: Role of renewable energy sources in environmental protection: a review. *Renewable and Sustainable Energy Reviews*, 15(3), 2011, 1513-1524.
- [3] Nema, P., Nema, R. K., & Rangnekar, S.: A current and future state of art development of hybrid energy system using wind and PV-solar: A review. *Renewable and Sustainable Energy Reviews*, 13(8), 2009, 2096-2103.
- [4] Green, Martin A.: *Solar cells: operating principles, technology, and system applications*, Prentice-Hall, United States, 1982.
- [5] Rogiros Dimitris Tapakis, Alexandros George Charalambides: Performance evaluation of a photovoltaic park in Cyprus using irradiance sensors. *Journal of Power Technologies*, 94(4), 2014, 296–305.
- [6] Wenham, S. R., and M. A. Green: *Silicon solar cells. Progress in Photovoltaics: Research and Applications*, 4(1), 1996, 3-33.
- [7] National Center for Photovoltaics (NCPV) Homepage, <https://www.nrel.gov/pv/>
- [8] Akinyele, D. O., R. K. Rayudu, and N. K. C. Nair: Global progress in photovoltaic technologies and the scenario of development of solar panel plant and module performance estimation– Application in Nigeria. *Renewable and Sustainable Energy Reviews*, 48, 2015, 112-139.
- [9] Goetzberger, Adolf, Joachim Knobloch, and Bernhard Voss: *Crystalline silicon solar cells*. editorial John Wiley & Sons Ltd 1, 1998.
- [10] Green, Martin A., et al.: *Solar cell efficiency tables (Version 45). Progress in photovoltaics: research and applications*, 23.1, 2015, 1-9.
- [11] Green, Martin A., and Keith Emery: *Solar cell efficiency tables. Progress in Photovoltaics: Research and Applications*, 1.1, 1993, 25-29.
- [12] Saga, Tatsuo: Advances in crystalline silicon solar cell technology for industrial mass production. *NPG Asia Materials*, 2.3, 2010, 96-102.
- [13] Tyagi, V. V., et al.: Progress in solar PV technology: research and achievement. *Renewable and sustainable energy reviews*, 20, 2013, 443-461.
- [14] 14. Stutenbaeumer, Ulrich, and Belayneh Mesfin: Equivalent model of monocrystalline, polycrystalline and amorphous silicon solar cells. *Renewable Energy*, 18.4, 1999, 501-512.
- [15] Simon, John, et al.: Upright and Inverted Single-Junction GaAs Solar Cells Grown by Hydride Vapor Phase Epitaxy. *IEEE Journal of Photovoltaics*, 7.1, 2017, 157-161.
- [16] Richards, B. S.: Comparison of TiO₂ and other dielectric coatings for buried-contact solar cells: a review. *Progress in photovoltaics: research and applications*, 12.4, 2004, 253-281.
- [17] Chu, T. L., and K. N. Singh: Polycrystalline silicon solar cells on metallurgical silicon substrates. *Solid-State Electronics*, 19(10), 1976, 837-838.
- [18] Kerschaver, Emmanuel Van, and Guy Beaucarne. "Back-contact solar cells: A review." *Progress in Photovoltaics: Research and Applications* 14.2, 2006, 107-123.
- [19] Fabre, E., & Baudet, Y. : Polycrystalline silicon solar cells. In *Photovoltaic Solar Energy Conference*, 1978, pp. 178-186.
- [20] Pandey, A. K., et al.: Recent advances in solar photovoltaic systems for emerging trends and advanced applications. *Renewable and Sustainable Energy Reviews*, 53, 2016, 859-884.
- [21] Knechtli, R. C., Loo, R. Y., & Kamath, G. S.: High-efficiency GaAs solar cells. *IEEE Transactions on Electron Devices*, 31(5), 1984, 577-588.
- [22] Cotfas, D. T., P. A. Cotfas, and S. Kaplanis: Methods and techniques to determine the dynamic parameters of solar cells: Review. *Renewable and Sustainable Energy Reviews* 61, 2016, 213-221.
- [23] Sivananthan, Sivalingam, Michael Carmody, Robert W. Bower, Shubhrangshu Mallick, and James Garland: Tunnel homojunctions in group IV/group II-VI multijunction solar cells. U.S. Patent 9,455,364, issued September 27, 2016.
- [24] Kurtz, Steven R.,: InGaAsN/GaAs heterojunction for multi-junction solar cells. U.S. Patent No. 6,252,287. 26 Jun. 2001.
- [25] Chopra, K. L., Paulson, P. D., & Dutta, V.: Thin-film solar cells: an overview. *Progress in Photovoltaics: Research and Applications*, 12(2.3), 2004, 69-92.
- [26] Chopra, Kasturi Lal, and Suhit Ranjan Das: Why thin film solar cells?. *Thin film solar cells*. Springer US, 1-18, 1983.
- [27] Coutts, Timothy J., et al.: Critical issues in the design of polycrystalline, thin-film tandem solar cells. *Progress in Photovoltaics: Research and Applications*, 11(6), 2003, 359-375.
- [28] Aberle, A. G.: Thin-film solar cells. *Thin solid films*, 517(17), 2009, 4706-4710.
- [29] Galloni, R.: Amorphous silicon solar cells. *Renewable*

- Energy, 8(1), 1996, 400-404.
- [30] <https://www.ecn.nl/news/newsletter-en/2010/june-2010/solar-cells-on-foil/>
- [31] Kolodziej, A.: Staebler-Wronski effect in amorphous silicon and its alloys. *Opto-electronics review*, 12(1), 21-32 (2004).
- [32] Kakkad, R., Smith, J., Lau, W. S., Fonash, S. J., & Kerns, R.: Crystallized Si films by low-temperature rapid thermal annealing of amorphous silicon. *Journal of applied physics*, 65(5), 1989, 2069-2072.
- [33] Guo, L., Kondo, M., Fukawa, M., Saitoh, K., & Matsuda, A.: High rate deposition of microcrystalline silicon using conventional plasma-enhanced chemical vapor deposition. *Japanese journal of applied physics*, 37(10A), 1998, L1116.
- [34] Liu, X., Fang, J., Liu, Y., & Lin, T.: Progress in nanostructured photoanodes for dye-sensitized solar cells. *Frontiers of materials science*, 10(3), 2016, 225-237.
- [35] Fritzsche, H.: Photo-induced structural changes associated with the Staebler-Wronski effect in hydrogenated amorphous silicon. *Solid state communications*, 94(12), 1995, 953-955.
- [36] Wu, X.: High-efficiency polycrystalline CdTe thin-film solar cells. *Solar energy*, 77(6), 2004, 803-814.
- [37] Energy Efficiency and Renewable Energy Homepage, <https://www.energy.gov/eere/sunshot/cadmiu-m-telluride>
- [38] McCandless, Brian E., and James R. Sites.: Cadmium telluride solar cells. *Handbook of Photovoltaic Science and Engineering*, 2, 2003.
- [39] Morales-Acevedo, A.: Thin film CdS/CdTe solar cells: research perspectives. *Solar Energy*, 80(6), 2006, 675-681.
- [40] Ferekides, C. S., Britt, J., Ma, Y., & Killian, L.: High efficiency CdTe solar cells by close spaced sublimation. In *IEEE Twenty Third Photovoltaic Specialists Conference*, 1993, pp. 389-393.
- [41] Compaan, A. D., Gupta, A., Lee, S., Wang, S., & Drayton, J.: High efficiency, magnetron sputtered CdS/CdTe solar cells. *Solar Energy*, 77(6), 2004, 815-822.
- [42] Diso, D. G., Muftah, G. E. A., Patel, V., & Dharmadasa, I. M.: Growth of CdS layers to develop all-electrodeposited CdS/CdTe thin-film solar cells. *Journal of the electrochemical society*, 157(6), 2010, H647-H651.
- [43] McEvoy, Augustin Joseph, Luis Castaner, and Tom Markvart. *Solar cells: materials, manufacture and operation*. Academic Press, 2012.
- [44] Kumar, S. G., & Rao, K. K.: Physics and chemistry of CdTe/CdS thin film heterojunction photovoltaic devices: fundamental and critical aspects. *Energy & Environmental Science*, 7(1), 2014, 45-102.
- [45] Chevrier, Michèle : Vers des nouveaux systèmes pi-conjugués pour des applications photovoltaïques. PhD dissertation, université montpellier; Université de Mons, Belgique, 2016.
- [46] Wieting, Robert D., et al.: Single Junction CIGS/CIS Solar Module." U.S. Patent Application No. 13/086,135, 2011.
- [47] Pollock, Gary A., Kim W. Mitchell, and James H. Ermer: Thin film solar cell and method of making. U.S. Patent No. 4,915,745. 10 Apr. (1990).
- [48] Abou-Ras D, Kirchartz T, Rau U, editors: *Advanced characterization techniques for thin film solar cells*. Weinheim, Germany: Wiley-VCH, 2011.
- [49] Brun, N. R., Wehrli, B., & Fent, K.: Ecotoxicological assessment of solar cell leachates: Copper indium gallium selenide (CIGS) cells show higher activity than organic photovoltaic (OPV) cells. *Science of the Total Environment*, 543, 2016, 703-714.
- [50] International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) Homepage, <https://www.arci.res.in>
- [51] Gwak, Jihye, et al.: Method of fabricating copper indium gallium selenide (CIGS) thin film for solar cell using simplified co-vacuum evaporation and copper indium gallium selenide (CIGS) thin film for solar cell fabricated by the same. U.S. Patent No. 9,472,708, 18 Oct. 2016.
- [52] Harvey, T. B., et al. : Copper indium gallium selenide (CIGS) photovoltaic devices made using multistep selenization of nanocrystal films. *ACS applied materials & interfaces*, 5(18), 2013, 9134-9140.
- [53] Cruz, J. S., Cruz, D. S., Arenas-Aroccena, M. C., DE, F., FLORES, M., & HERNÁNDEZ, S. M.: Green Synthesis of ZnS thin films by chemical bath deposition. *Chalcogenide Letters*, 12(5), 2015, 277-285.
- [54] Lee, Sang Woon, et al.: Improved Cu₂O-Based Solar Cells Using Atomic Layer Deposition to Control the Cu Oxidation State at the p-n Junction. *Advanced Energy Materials*, 4(11), 2014.
- [55] Metin, Burak, Deepak Nayak, and Mustafa Pinarbasi: Cigs based thin film solar cells having shared bypass diodes. U.S. Patent Application 13/163,485, filed June 17, 2011.
- [56] OSBORNE M. ZSW achieves world record CIGS lab cell efficiency of 22.6%. 2016-06-15. <http://www.pv-teeh.org/news/zsw-achieves-world-record-cigs-lab-eell-e-fficiency-of-22.6.>, 2016.
- [57] Duan, C., Furlan, A., van Franeker, J. J., Willems, R. E., Wienk, M. M., & Janssen, R. A.: Wide Bandgap Benzodithiophene-Benzothiadiazole Copolymers for Highly Efficient Multijunction Polymer Solar Cells. *Advanced Materials*, Wiley Online Library, 27(30), 2015, 4461-4468.
- [58] Chiechi, R. C., Havenith, R. W., Hummelen, J. C.,

- Koster, L. J. A., & Loi, M. A.: Modern plastic solar cells: materials, mechanisms and modeling. *Materials Today*, 16(7), 2013, 281-289.
- [59] Günes, S., Neugebauer, H., & Sariciftci, N. S.: Conjugated polymer-based organic solar cells. *Chemical reviews*, 107(4), 2007, 1324-1338.
- [60] Chen, Jing-De, et al.: Single-junction polymer solar cells exceeding 10% power conversion efficiency. *Advanced Materials*, 27(6), 2015, 1035-1041.
- [61] Snaith, H. J.: Perovskites: the emergence of a new era for low-cost, high-efficiency solar cells. *The Journal of Physical Chemistry Letters*, 4(21), 2013, 3623-3630.
- [62] Bagher, A. M., Introduction to Organic Solar Cells. *Sustainable Energy*, 2(3), 2014, 85-90.
- [63] Mayer, A. C., Scully, S. R., Hardin, B. E., Rowell, M. W., & McGehee, M. D.: Polymer-based solar cells. *Materials today*, 10(11), 2007, 28-33.
- [64] Zhao, Jingbo, et al.: Efficient organic solar cells processed from hydrocarbon solvents. *Nature Energy*, 1, 2016, 15027.
- [65] Zhao, W., Qian, D., Zhang, S., Li, S., Inganäs, O., Gao, F., & Hou, J.: Fullerene-Free Polymer Solar Cells with over 11% Efficiency and Excellent Thermal Stability. *Advanced Materials*, 28(23), 2016, 4734-4739.
- [66] Burschka, Julian, et al.: Sequential deposition as a route to high-performance perovskite-sensitized solar cells. *Nature* 499(7458), 2013, 316-319.
- [67] Shin, Seong Sik, et al.: Colloidally prepared La-doped BaSnO₃ electrodes for efficient, photostable perovskite solar cells. *Science*, 356(6334), 2017, 167-171.
- [68] Yamaguchi, M., Takamoto, T., Araki, K., & Ekins-Daukes, N.: Multi-junction III-V solar cells: current status and future potential. *Solar Energy*, 79(1), 2005, 78-85.
- [69] Dimroth, F., Grave, M., Beutel, P., Fiedeler, U., Karcher, C., Tibbits, T. N., & Bett, A. W.: Wafer bonded four-junction GaInP/GaAs/GaInAsP/ GaInAs concentrator solar cells with 44.7% efficiency. *Progress in Photovoltaics: Research and Applications*, 22(3), 2014, 277-282.
- [70] Kamat, Prashant V.: Quantum dot solar cells. The next big thing in photovoltaics. *The journal of physical chemistry letters*, 4(6), 2013, 908-918.
- [71] Zheng, Z., Ji, H., Yu, P., & Wang, Z.: Recent progress towards quantum dot solar cells with enhanced optical absorption. *Nanoscale research letters*, 11(1), 2016, 1-8.