Global Scenario of Solar Photovoltaic (SPV) Materials

Sandeep Gupta(✉) and Abhishek Sharma

Department of Electrical Engineering, JECRC University, Jaipur 303905, Rajasthan, India
{jecsandeep, abheeshek96}@gmail.com

1 Introduction

Since the last decade, the world is developing at a pace like never before. An important factor behind this evolution is the recent advancements in the field of the energy generation technology. With the growing energy demands, the need for technology which must be economically, environmentally, and socially compatible has also increased. The energy-generating technologies can be classified as conventional and nonconventional [1]. The conventional energy sources have been in use since a long time. These include petroleum, coal, wood, etc. These types of sources have proved to be very beneficial for the human race development but still they have many disadvantages. Most of them cause environmental pollution and also are costly as the energy is needed to be transmitted over long distances after conversion into electricity. On the other hand, there are nonconventional energy sources like wind, solar, and thermal energies. These are inexhaustible and environment friendly but still need to be developed more to be conventionally used. Solar energy as a nonconventional energy source is a very good option for not only bulk electricity production but also for the off-grid purposes. They are also helpful in avoiding the long-distance transmission costs [2, 3].

There are many emerging technologies which have been discussed in this paper. Classification in the PV technology is explained in Sect. 2. Different conventionally used material technologies are described with different structures in Sect. 3. In Sect. 4, modern different emerging PV technologies are clearly explained. Finally, Sect. 5 concludes this paper.

2 Classification

The solar cell technology can be characterized into three eras. Figure 1 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 nontoxic nature makes it suitable for the widespread use in the PV industry [4].

S. Bhattacharyya et al. (eds.), *Advanced Computational and Communication Paradigms*, Lecture Notes in Electrical Engineering 475,
https://doi.org/10.1007/978-981-10-8240-5_14

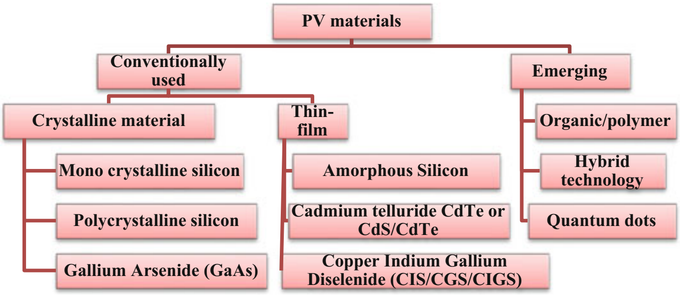

Fig. 1. PV technologies classification

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. The third-generation polymer technology is scotch as well as lightweight. 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 modules [5, 6].

3 Conventionally Used Material Technologies

3.1 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 1000 W/m^2 sunlight intensity) [7].

3.1.1 Monocrystalline Silicon

It is the most prevalent material in PV modules. It utilizes a p–n junction for its course of action. The front of the cell is encrusted with a blanket of micrometer-sized pyramid structures. Solar cells based on this technology have immensely phosphorous-doped n+ section stacked over p-type boron-doped substrate to engender a p–n junction. Immensely doped p+ field (BSF) sections are framed on the back facade of the silicon substrate; its aim is to curtail the recombination of minority carriers. Its structure is shown in Fig. 2. The cells based on this technology are typically 5 inches squares [8, 9].

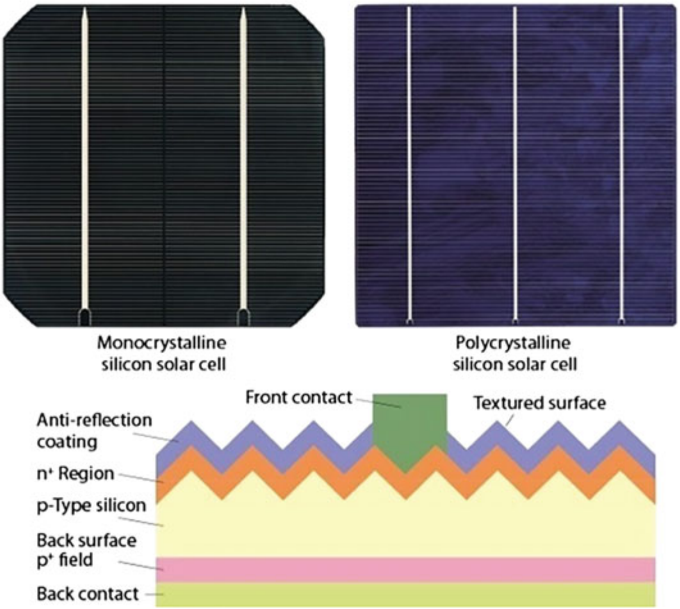

Fig. 2. Structure of crystalline solar cells [8]

3.1.2 Polycrystalline Silicon

This technology was introduced to reduce the production cost of silicon ingots. The wafers of these cells are formed by pouring the molten silicon in a cubical mold. The liquid silicon is then allowed to cool down and solidify. The solidified block is sliced to form perfectly square cells [10]. Polycrystalline silicon has high packing factor. 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 [10, 11]. The efficiency of the poly-c-Si-based modules by Trina solar corporation at STC is found to be 19.9% [12, 13].

3.1.3 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, it is not commercially used. It has high-temperature coefficient and hence is suitable for use in the space applications and concentrated PV modules. It possesses lighter weight as compared to c-Si [14]. GaAs can be further alloyed with phosphorous (P), indium (I), aluminum (Al), or antimony (Sb) to improve the efficiency. The efficiency of alloying increases due to the formation of multi-junction structure [15–17].

3.2 Thin-Film Material

This technology is considered to be the second generation of photovoltaic technologies. 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 [18, 19]. Gallium arsenide (GaAs), CdS, and titanium dioxide (TiO_2) are the materials that are most commonly used [20, 21].

3.2.1 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. As shown in Fig. 3, a-Si cells due to high band gap of 1.7 eV absorb very broad range of the light spectrum [22].

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 by about 30 to 40%. This reduction is caused due to Staebler–Wronski effect (SWE) which can be minimized by thermal annealing at or above 150 ºC [22–24].

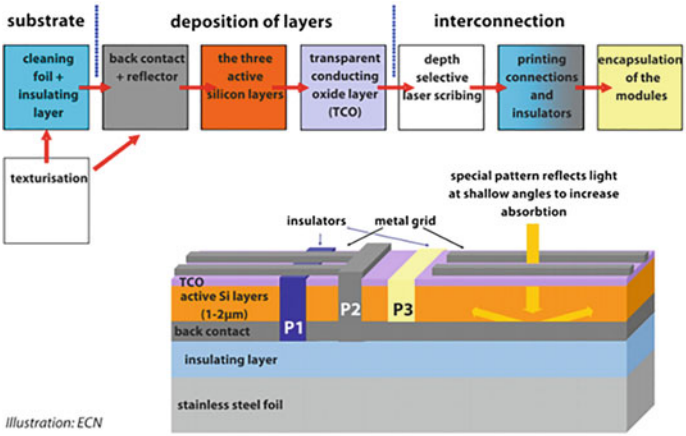

Fig. 3. Structure of a-Si solar cell

3.2.2 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 [25]. Typical CdTe thin-film deposition techniques are shown in Fig. 4.

3.2.3 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 $CuIn_xGa_{(1-x)}Se_2$ [26]. As discussed earlier, the more suitable the band gap, the 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 [27].

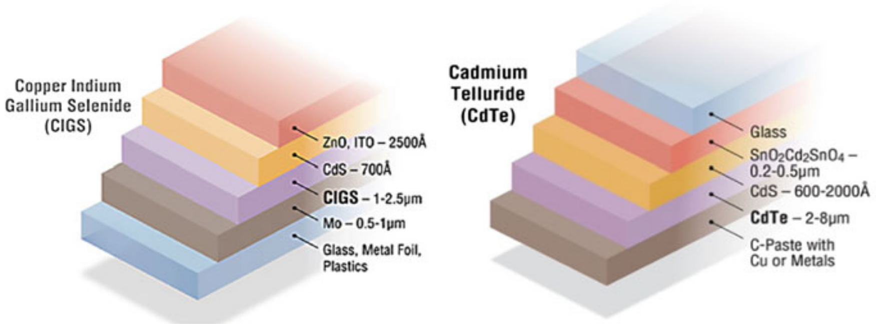

Fig. 4. CIGS and CdTe solar cell diagrams [45]

Photo-degeneration takes place in CIGS modules when subjected to sunlight just like CdTe modules. Additional barrier coating is required to mitigate this problem [28]. CdS layer 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) [29]. The heterojunction is formed between ZnO and CIGS layer [30]. 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 [31].

4 Emerging PV Technologies

4.1 Organic/Polymer Material

This underdeveloped technology is the part of the third generation of photovoltaic technologies. The organic polymers have high light absorption coefficient, and hence more light can be absorbed using less material [32]. The demerits of this technology include very low conversion efficiency and less stability due to photochemical degradation [32, 33]. Based on the junction types, these cells can be divided into three basic categories: (1) Single layer [34–36], (2) Discrete heterojunction [35–37], and (3) Bulk heterojunction (BHJ) [38].

4.2 Hybrid Technology

A hybrid solar cell can be a 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. Following are some common hybrid technologies:

- Perovskite-based cells: This solar cell uses a perovskite-structured compound as active layer for light absorption. The problem with this technology is low sunlight stability of the perovskite material [39]. Shin et al. [40] using methylammonium lead iodide ($MAPbI_3$) perovskite as active layer and lanthanum (La)-doped $BaSnO_3$ (LBSO) as photoelectrode materials achieved photo-conversion efficiency of 22.1% and high photostability of about 1000 h.
- Multi-junction solar cells: These cells contain three 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 [41]. Frank et al. [42] developed a 44.7% efficient four-junction GaInP/GaAs//GaInAsP/GaInAs tandem cell.

4.3 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 [43]. These cells are easy to synthesize and less costly. The highest conversion efficiency shown by quantum dots based solar cells till date is 11.3% only [44].

5 Conclusion

Various state-of-the-art solar photovoltaic materials have been discussed in this paper. The first half of the paper is mainly focused on the structure, efficiencies, and manufacturing processes of the conventionally used solar cells. Si-based solar cells still rule the PV industry. There are many emerging technologies which have been discussed in the later sections of the paper. These emerging technologies may prove to be competing with the conventionally used technologies in the near future. But currently the challenges for these emerging technologies are increasing conversion efficiencies and stability under direct solar radiation exposure. 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. Sen PK, Awtar K, Bohidar SK (2015) A review of major non-conventional energy sources. IJSTM 4(01):20–25
2. Tazvinga H, Thopil M, Numbi PB, Adefarati T (2017) Distributed renewable energy technologies. Handbook of distributed generation. Springer International Publishing, pp 3–67
3. Gupta S, Singh R (2011) Investigation of steady state performance of static synchronous compensator on transmission line. ELEKTRIKA J 13(1):42–46
4. An X et al (2016) Empirical and Quokka simulated evidence for enhanced VOC due to limited junction area for high efficiency silicon solar cells. In: 2016 IEEE 43rd photovoltaic specialists conference (PVSC)
5. De Azevedo Dias CL, Branco DAC et al (2017) Performance estimation of photovoltaic technologies in Brazil. Renew Energy 114:367–375
6. Goetzberger A, Knobloch J, Voss B (1998) Crystalline silicon solar cells. Wiley
7. Green MA et al (2015) Solar cell efficiency tables (Version 45). Prog Photovolt Res Appl 23 (1):1–9
8. Green MA, Emery K (1993) Solar cell efficiency tables. Prog Photovolt Res Appl 1(1):25–29
9. Saga T (2010) Advances in crystalline silicon solar cell technology for industrial mass production. NPG Asia Mater 2(3):96–102
10. Chu TL, Singh KN (1976) Polycrystalline silicon solar cells on metallurgical silicon substrates. Solid State Electron 19(10):837–838
11. Van Kerschaver E, Beaucarne G (2006) Back-contact solar cells: a review. Prog Photovolt Res Appl 14(2):107–123
12. Fabre E, Baudet Y (1978) Polycrystalline silicon solar cells. In: Photovoltaic solar energy conference, pp 178–186
13. Pandey AK et al (2017) Solar photovoltaics (PV): a sustainable solution to solve energy crisis. Green technologies and environmental sustainability. Springer International Publishing, pp 157–178
14. Knechtli RC, Loo RY, Kamath GS (1984) High-efficiency GaAs solar cells. IEEE Trans Electron Devices 31(5):577–588
15. Khanna V et al (2016) Statistical analysis and engineering fit models for two-diode model parameters of large area silicon solar cells. Sol Energy 136:401–411
16. Sivananthan S, Carmody M, Bower RW, Mallick S, Garland J (2016) Tunnel homojunctions in group IV/group II-VI multijunction solar cells. U.S. Patent 9,455,364, 27 Sept 2016
17. Kurtz SR et al (2001) InGaAsN/GaAs heterojunction for multi-junction solar cells. U.S. Patent No. 6,252,287, 26 June 2001
18. Dezfooli AS et al (2017) Solar pavement: a new emerging technology. Sol Energy 149:272–284
19. Chopra KL, Das SR (1983) Why thin film solar cells? In: Thin film solar cells. Springer, US, pp 1–18
20. Coutts Timothy J et al (2003) Critical issues in the design of polycrystalline, thin-film tandem solar cells. Prog Photovolt Res Appl 11(6):359–375
21. Aberle AG (2009) Thin-film solar cells. Thin Solid Films 517(17):4706–4710
22. Galloni R (1996) Amorphous silicon solar cells. Renew Energy 8(1):400–404
23. Kołodziej A (2004) Staebler-Wronski effect in amorphous silicon and its alloys. Opto-Electr Rev 12(1):21–32

24. Watahiki T et al (2016) Analysis of short circuit current loss in rear emitter crystalline Si solar cell. J Appl Phys 119–129
25. Wu X (2004) High-efficiency polycrystalline CdTe thin-film solar cells. Sol Energy 77 (6):803–814
26. Wieting RD et al (2011) Single junction CIGS/CIS solar module. U.S. Patent Application No. 13/086,135
27. Pollock GA, Mitchell KW, Ermer JH (1990) Thin film solar cell and method of making. U.S. Patent No. 4,915,745, 10 Apr 1990
28. Gwak J et al (2016) 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
29. Lee SW et al (2014) Improved Cu2O-based solar cells using atomic layer deposition to control the Cu oxidation state at the p-n junction. Adv Energy Mater 4(11)
30. Metin B, Nayak D, Pinarbasi M (2011) Cigs based thin film solar cells having shared bypass diodes. U.S. Patent Application 13/163,485, 17 June 2011
31. Osborne M (2016) 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-efficiency-of-22.6
32. Duan C et al (2015) Wide-bandgap Benzodithiophene-Benzothiadiazole copolymers for highly efficient multijunction polymer solar cells. Adv Mater (Wiley Online Library) 27 (30):4461–4468
33. Gupta S, Tripathi RK (2015) Transient stability assessment of two-area power system with LQR based CSC-STATCOM. Automatika 56(1):21–32
34. Günes S, Neugebauer H, Sariciftci NS (2007) Conjugated polymer-based organic solar cells. Chem Rev 107(4):1324–1338
35. Chen J-D et al (2015) Single-junction polymer solar cells exceeding 10% power conversion efficiency. Adv Mater 27(6):1035–1041
36. Peng J et al (2017) Interface passivation using ultrathin polymer-fullerene films for high-efficiency perovskite solar cells with negligible hysteresis. Energy Environ Sci
37. Bagher AM (2014) Introduction to organic solar cells. Sustain Energy 2(3):85–90
38. Gupta S, Sharma AK (2010) STATCOM-Its control algorthim. I-Manager's J Electr Eng 3 (4):41–48
39. Burschka J et al (2013) Sequential deposition as a route to high-performance perovskite-sensitized solar cells. Nature 499(7458):316–319
40. Shin SS et al (2017) Colloidally prepared La-doped BaSnO3 electrodes for efficient, photostable perovskite solar cells. Science 356(6334):167–171
41. Dimroth F (2017) III–V solar cells–materials, multi-junction cells–cell design. In: Photovoltaic solar energy: from fundamentals to applications (Book Chapter), pp 373–382
42. Dai P et al (2017) Electron irradiation study of room-temperature wafer-bonded four-junction solar cell grown by MBE. Sol Energy Mater Sol Cells 171:118–122
43. Kamat PV (2013) Quantum dot solar cells. The next big thing in photovoltaics. J Phys Chem Lett 4(6):908–918
44. Gupta S, Tripathi RK (2014) Improved performance of LQR controller in CSC based STATCOM using genetic optimization. In: 6th IEEE power india international conference (PIICON), pp 1–6, Dec 2014
45. Abou-Ras D, Kirchartz T, Rau U (eds) (2011) Advanced characterization techniques for thin film solar cells. Wiley-VCH, Weinheim, Germany