Advances in Solar Photovoltaic Technolgy: A Review

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Abstract - *The work presented analyses the current technology trends in solar cell photovoltaic (PV) industry. The development in solar PV technology has been growing very fast in the recent years due to technological improvement, cost reductions in materials and government support for renewable energy-based electricity production. PV technology is playing an important role to utilize solar energy for electricity production worldwide. At present, the PV market is growing worldwide rapidly with at an annual rate of 35–40%, which makes photovoltaic as one of the fastest growing industries. The efficiency of solar cell has been one of the important parameters in order to establish this technology in the market. Currently, extensive research work is going for efficiency improvement of solar cells for commercial use.*

Key words: Photovoltaic (PV), CdTe, Perovskite, Tandem cells, organic solar cell, dye-sensitized solar cell, quantum dot solar cells

1. INTRODUCTION

Research on semiconductors based solar cells were studied since 1960 and at that time, new technology for polycrystalline Si and thin-film solar cell have been establish in order to lower the material cost and energy input but increase the production capacity. PV is currently a technically and commercially mature technology able to generate and supply short and mid-term electricity using solar energy. Photovoltaics (PV) has advanced at a rate that is astonishing even to experts in the field and now it promises to have a prominent role in the ongoing energy transitions. Therefore, it is time to describe the status of PV technologies and a roadmap of future directions and challenges. PV technology has reduced its unit costs to about one third of where it stood 5 years ago with continuous technical advances and researches for efficiency increase. PV will certainly continue on the fast-growing pace and eventually become one of the important energy suppliers in the world. In the last decade, the global PV industry had been growing at an average compound annual rate of greater than 35%.

At the end of 2019, the world's cumulative PV capacity was about 591 GW with an annual module production capacity of 184 GW and the shipments of approximately 125 GW. It was predicted by a report on the solar photovoltaic electricity empowering the world that PV will be delivering about 345 GW around 4% by 2020 and 1081 GW by 2030. This exponential growth will largely attribute to dramatic cost reductions, solar technology improvement, complementary renewable energy policy and diversified financing.

In this paper, the current global status of the PV technology materials for solar cells such as Copper zinc tin sulfide solar cell (CZTS), Dye-sensitized solar cell, organic solar cell, Perovskite solar cell and Quantum dot solar cell has been reviewed.

2. CdTe

CdTe solar technology has evolved significantly over time. Certified cell efficiencies reached 10% in the 1980s and in the 1990s efficiency exceeded 15% using a glass/SnO2/CdS/CdTe structure and an anneal in a CdCl2 ambient followed by Cu diffusion. In the 2000s, cell efficiency reached 16.7% using sputtered Cd2SnO4 and Zn2SnO4 for the transparent conducting oxide (TCO) layers. In the past decade, First Solar and General Electric exchanged new world-record cell efficiencies, which climbed to 22.1%. Costs has been steadily declined and CdTe solar technology is bankable and scalable. First Solar is forecasting 7.6 GW of annual capacity by the end of 2020 and modules are being installed across the world for multiple applications. Although most installations have been for utility-scale power plants, CdTe technology increasingly has been adopted in the roof-top systems and building-integrated photovoltaics (figure 1).

Fig -1: (a) Residence with CdTe PV tile in Europe; (b) office building with semi-transparent CdTe panels in Europe; (c) exhibition hall with 5556 m2 of standard, semi-transparent, and artistic CdTe panels in Asia; (d)

Topaz solar plant owned by BHE renewables in the United States. (G.M, 2020)

Figure 2 shows a typical CdTe solar cell schematic. The recent performance gains have come in part by nearly maximizing photocurrent through optimizing the cell optical properties, removing parasitically absorbing CdS and introducing lower-bandgap CdSexTe1-x. The CdSexTe1-x grades the absorber bandgap from ~1.4 to 1.5 eV and increases the carrier lifetime, thereby increasing photocurrent collection without a commensurate loss in photovoltage. The adoption of ZnTe in the back contact also significantly improves the contact ohm city therefore improving performance.

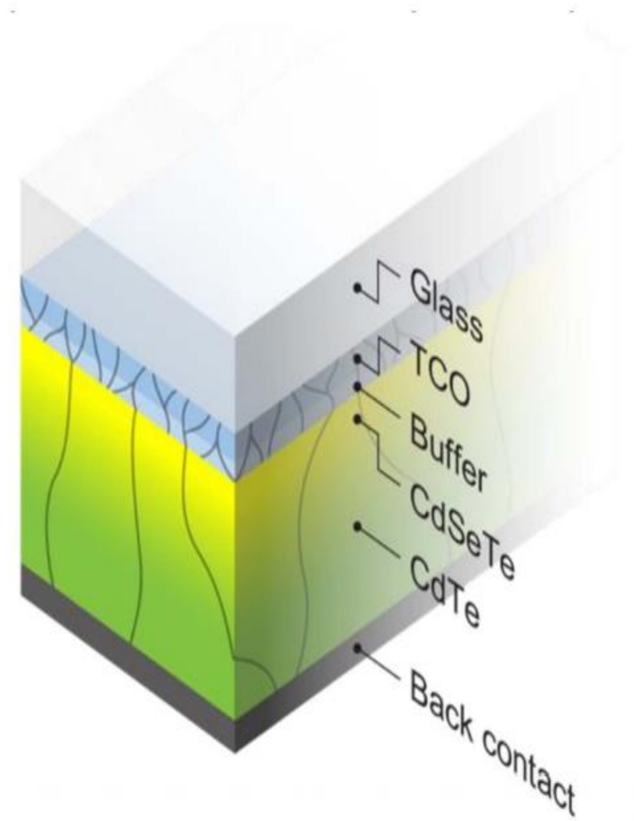

Fig -2: Schematic form of a CdTe solar cell. The TCO layers are typically a few hundred nanometres thick. The buffer may consist of tens of manometers of CdS, MgZnO, or another material. The back contact generally has a layer such as Te or ZnTe followed by metallization. (G.M, 2020)

3. PEROVSKITE

Perovskite solar cells (PSCs) represents an emerging, revolutionary photovoltaic (PV) technology based on metal halide perovskites (MHPs)—e.g., methylammonium or formamidinium lead iodide (MAPbI3 or FAPbI3, respectively). MHPs combines several preferred characteristics for a PV absorber such as direct bandgap with strong absorption coefficient, long carrier lifetime and diffusion length, low defect density and easy tuning of composition and bandgap. In 2009, MHPs were first reported as a sensitizer in a dye cell configuration based on a liquid hole-conducting electrolyte. In 2012, the demonstration of ~10% efficient PSCs based on a solid-state hole conductor has triggered explosive PSC research efforts. Within about a decade of research, the performance of a single-junction PSC has been skyrocketed to a certified 25.2%.

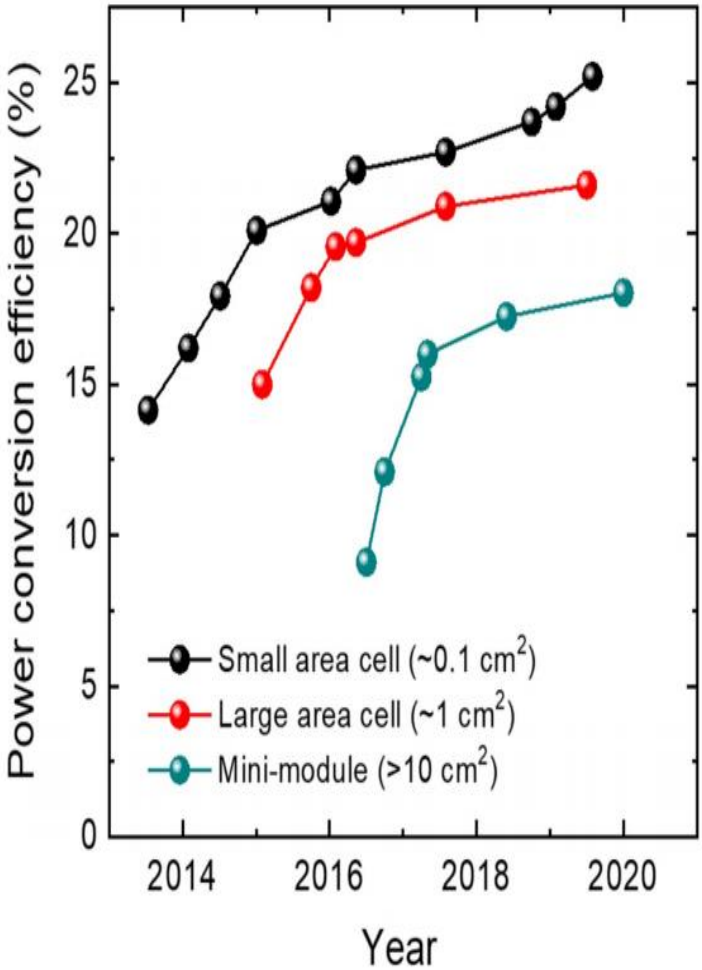

Fig -3: Significant power conversion efficiency progress for perovskite solar cells and mini-modules with different active device areas. (G.M, 2020)

Figure 3 summarizes the efficiency progress for the PSCs ranging from lab cells (~0.1 to 1 cm^2) to mini-modules (>10 cm^2). Strikingly, the most high-efficiency PSCs to date are fabricated by solution processing which makes PSCs attractive as a potentially high-performance and low-cost PV technology. Various deposition approaches have been developed to scale up PSCs, leading to recent demonstration of a 802 cm^2 perovskite solar module with a certified 16.1% efficiency. This module performance is rapidly approaching to that of established thin-film PV technologies (e.g, CdTe and CIGS). During the past few years, PSC stability has also been drastically improved via various efforts to optimize the perovskite absorbers and device structures along with encapsulation strategies.

Although there are still many unanswered technical and scientific questions to address the high performance and scalable fabrication of PSCs coupled with low production and CapEx costs have already positioned PSCs as a potential PV technology to address terawatt-scale energy demand. Among all the polycrystalline thin-film PV technologies, PSCs are uniquely capable of producing >20%-efficient devices with a bandgap near 1.7 eV or higher. These wide bandgap PSCs can be paired with low-bandgap PSCs and other PV technologies (e.g., Si and CIGS) to form an ultrahigh efficiency tandem device to break the thermodynamic efficiency limits of single-junction cells set by the Shockley-Queisser detailed balance theory. Thus, the PSCs have multiple potential pathways to terawatt-scale energy production.

4. TANDEM CELLS

Record efficiency single junction photovoltaics are nearing their practical limits but tandem cells offer headroom to reach significantly higher efficiencies. This in turn gives the potential for decreased cost as area-related balance-of-systems costs now dominates the cost of photovoltaic systems. Tandem cells have historically been used for space and concentrator applications but the emergence of new materials and processing techniques means that they are now of interest as a direct competitor to single junction cells. Efficiencies of up to 47.1% have been achieved using III–V based multi-junction cells under concentration. Typical module efficiencies are ~20% while bifacial design can achieve an additional energy yield of ~10%–20%.

High-efficiency tandem solar cells using Si as the bottom junction have been demonstrated by being partnered with III– V semiconductors with high efficiencies reaching 32.8% for two junctions and 34.1%–35.9% for three junctions (two and four terminals, respectively). Perovskite materials have the advantage of much lower cost and rapid strides have been made in their performance leading to the highest perovskite/Si tandem efficiency of 29.15% in only a few years of development. The latest reported tandem efficiency, 17% is less than commercial CdTe module efficiencies today. Several all-thin film options that do not use Si as a bottom cell have also been demonstrated including all-perovskite tandems and perovskite/CIGS tandems with efficiencies over 24%.

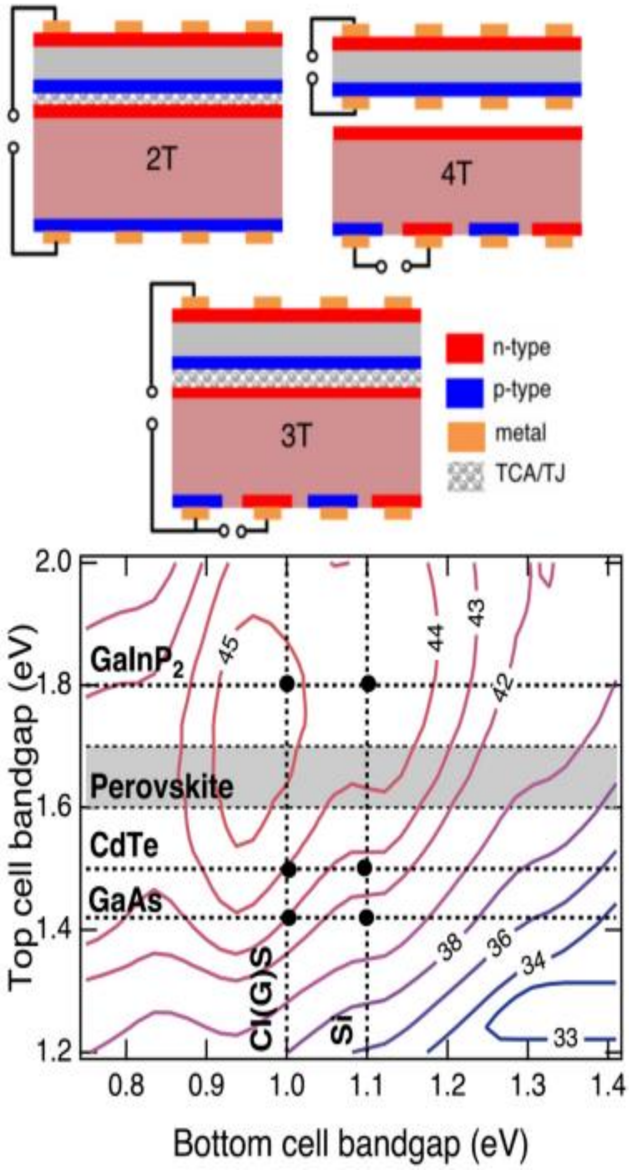

Fig - 4: Top: example configurations for tandem solar cells. 2 T and 3 T cells have an electrical interconnection that can be provided by a tunnel junction (TJ, e.g., by monolithic growth), recombination layer, metal interconnect, or transparent conductive adhesive (TCA). Reproduced with permission from The Royal Society of Chemistry. Bottom: there are many different possible cell material combinations that can be used in tandems; this image shows the detailed balance efficiency for different band gap combinations for 3 T or 4 T designs. Reproduced with permission from Dan Friedman and Emily Warren, NREL. (G.M, 2020)

One of the most significant factors in tandem cell designs is the choice of monolithic (e.g., materials deposited directly on each other) or stacked (e.g., cells fabricated separately and then combined) designs. Important considerations include processing compatibility of cell materials and number of terminals ultimately desired. Two main tandem architectures have been investigated that are 4-terminal (4 T typically stacked) and 2- terminal (2 T typically monolithic). 4 T tandems are easier to prototype due to the absence of the electrical coupling between the sub cells, hence permitting the independent development of the sub cells. 4 T's also do not require any processing compatibility or current matching between individual sub cells which results in higher efficiency and energy yield. 2 T tandems may reach lower LCOE as a result of the usage of fewer substrates and the transparent contacts. An alternative is the three terminal tandems which can be either monolithic or stacked but require a more nuanced understanding of device physics.

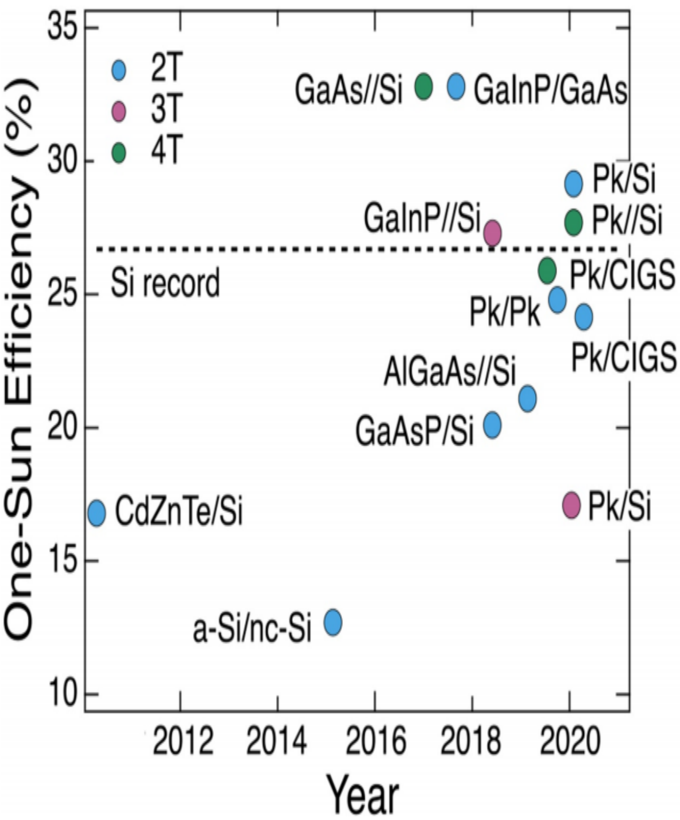

Fig - 5: Highest reported efficiencies for two-junction tandem cells. Materials separated by a single slash (/) represent monolithic growth/deposition, while a double slash (//) represented bonded or stacked approached. 'Pk' refers to perovskites. (G.M, 2020)

5. ORGANIC AND POLYMER CELLS

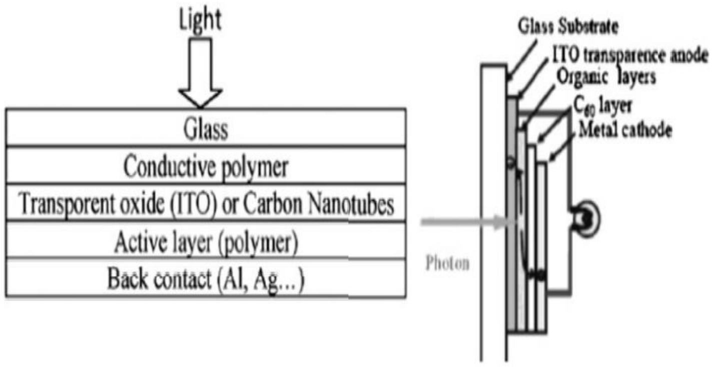

Fig - 6: Organic solar cell (Tyagi V.V., 2013)

An organic solar cell is a new emerging technology and is still in its developing phase like CIS/CIGS. Even though it has a very low efficiency which is around 4–5% but the other advantages like mechanical flexibility, disposability and cost efficient has brought much interest in this material. An experiment by Gorter was to evaluate the performance of 15 polymers for application in PV modules in PV-powered boats. The focus of experiment was on material properties of the polymers such as density, strength, thickness, UV stability, temperature and etc. They concluded that some of the polymers showed the high potential to replace the silicon PV modules in the future by considering cost and weight reduction. Most of the organic materials has very low open circuit voltages. The highest open circuit voltage for organic cells was achieved by the Molecular Solar Ltd Company which was 4 V. Due to that, Peumans suggested that in order to increase the output voltage of organic material, broad absorption band material needs to be found and produced.

6. DYE SENSITIZED SOLAR CELLS

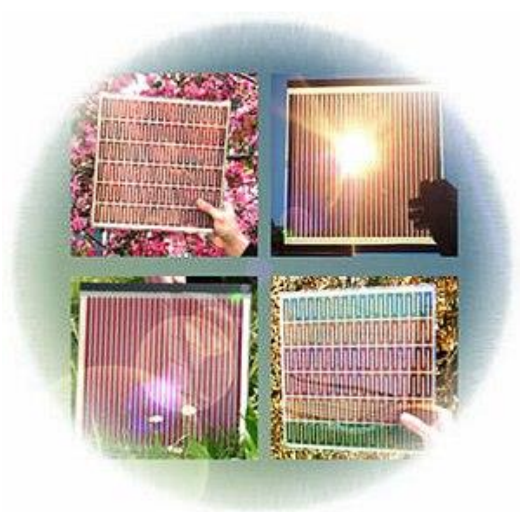

Fig - 7: Dye sensitized solar cells

A dye-sensitized solar cell is a low-cost solar cell belonging to the group of thin film solar cells that are based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photoelectrochemical system.

The DSSC has a number of attractive features like it is simple to make using conventional roll-printing techniques, is semi-flexible and semi-transparent which offers a variety of uses not applicable to glass-based systems and most of the materials used are low-cost. In practice it is difficult to eliminate a number of expensive materials, notably platinum and ruthenium, and the liquid electrolyte presents a serious challenge to making a cell suitable for use in all weather. Although its conversion efficiency is less than the thin-film cells, in theory its price/performance ratio should be good enough to allow them to compete with fossil fuel electrical generation by achieving grid parity.

7. QUANTUM DOT SOLAR CELLS

Fig - 8: Quantum dot solar cells

These cell uses quantum dots as the absorbing photovoltaic material. It has bulk materials such as silicon, copper indium gallium selenide (CIGS) or cadmium telluride (CdTe). Quantum dots have large bandgaps that are tunable across a wide range of energy levels by changing their size. In bulk materials, the bandgap is fixed by choice of the material. This property makes quantum dots attractive for multi-junction solar cells where a variety of materials are used to improve the efficiency by harvesting multiple portions of the solar spectrum. As of 2019, efficiency has exceed 16.5%.

8. SUMMARY TABLE

Sr. No.	RESEARCH PAPER / YEAR OF PUBLICATION	AREA OF RESEARCH
1	The 2020 photovoltaic technologies roadmap [2020]	Current trend in PV technology
2	Progress in solar PV technology: Research and achievement [2013]	Progress in solar PV technology
3	Advances in solar photovoltaics: Technology review and patent trends [2019]	Review on advances in solar photovoltaics
4	Recent advances and remaining challenges in thin-film silicon photovoltaic technology [2015]	Advances in thin-film silicon photovoltaic technology
5	Advances in Solar Photovoltaic Technology: An Applications Perspective [2005]	Applications of Solar Photovoltaic Technology
6	Current and future trends in photovoltaic technology [2019]	Current trends in photovoltaic technology
7	Technology advances needed for photovoltaics to achieve widespread grid price parity [2016]	Technology advances for photovoltaics to achieve widespread grid price parity
8	Enhanced performance of photovoltaic–thermoelectric coupling devices with thermal interface materials [2020]	Performance of photovoltaic thermoelectric coupling devices
9	Recent Developments and Future Advancements in Solar Panels Technology [2019]	Advancements in Solar Panels Technology
10	Review on recent trend of solar photovoltaic technology [2016]	Recent trend of solar photovoltaic technology
11	A Review on Solar Photovoltaic Technology and Future Trends [2018]	Solar Photovoltaic Technology and Future Trends

9. CONCLUSION

The promising environmental and political benefits from implementing the renewable energy has driven PV research for many years and recently PV electricity is also becoming the economic choice for utilities providers. This makes it an exciting time to expand the PV characterization efforts and build comprehensive understanding of PV performance and reliability from modules to atoms. Multi-scale characterization drives the deeper understanding and targeted improvement of PV systems where the use of complementary methods is essential to identify performance implications arising from specific device layers, components, defects, interfaces, additives, and so on. For further elucidating structure-function relationships between micro-nanoscale composition and semiconductor performance, additional improvements in chemical sensitivity paired with high spatial resolutions would be beneficial to the community. Enabling more facile access of these characterization capabilities to a wider range of non-specialists is also critical for achieving the broad understanding through greater statistics. In addition, continued development of non-traditional and outdoor-compatible instrumentations is essential for decreasing the cost of PV electricity while filling the needs of additional users through varied materials and technologies.

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