A Review of Perovskite Tandem Solar Cells

Shatrughan Mishra*[,1] and Pooja Lohia

www.RERICProceedings.ait.ac.th

Abstract – *This paper represents a literature review of different research work on Perovskite Tandem solar cells. As the Perovskite solar cells(3rd generation) a thin film device which is transparent in nature hence implement on the upper layer so that the sunlight is penetrate and then incident on the next(lower) Si based solar cells in the bottom layer. The overall efficiency of the Solar cell is the algebraic sum of both the solar cells. The energy band gap(E_g) of Perovskites are larger than that of Si Solar cell. Hence many researchers research work on these Perovskite Tandem solar cells prove that the efficiency(η) is drastically increase to approximate (30%) in a short span of time.*

Keywords – Photovoltaic, Perovskite, Tandem, Energy band gap, efficiency.

1. INTRODUCTION

The non-conventional source of energy is also known as renewable energy because this type of energy cannot be exhausted. The Sun plays a vital role either directly or indirectly in every types of renewable energy like tidal, solar, hydropower, wind, biomass etc.

As far as today's scenario, we are fully dependent on non-renewable source(fossil fuel based) of energy like diesel, petrol, natural gas, coal etc. There are limited reservoirs of these source and as the worldwide population is increasing constantly the energy demand also rises exponentially. They also effect adversely to the environment. To counter this problem. Photovoltaic (PV) energy is a cleanest form of energy resources with a long durability and a high reliability.[4]

On the basis of their structures, year of introduction, features, performance etc. the photovoltaic cells are broadly classified into different generations. The Photovoltaic cell module based generation systems of renewable energy are basically divided into three generations.

Generation-1 The solar cells of this generation are made up of silicon. Due to the easy availability of silicon & cost effective too. The example of this generation are Monocrystalline, Polycrystalline & Amorphous Solar cells.

Generation-2 These PV cells are basically known as thin film Photovoltaic cells because if we compared them with Crystalline silicon based solar cells then these are fabricated by several layers of semiconductor material having a few micrometer thick. Examples are CdTe (Cadmium telluride), CIGS(Copper indium gallium diselenide) etc.

Generation-3 These next generation of PV cells are made-up from various new elements with silicon and also different technology involved in them like Perovskite, Tandem, Organic dyes etc.

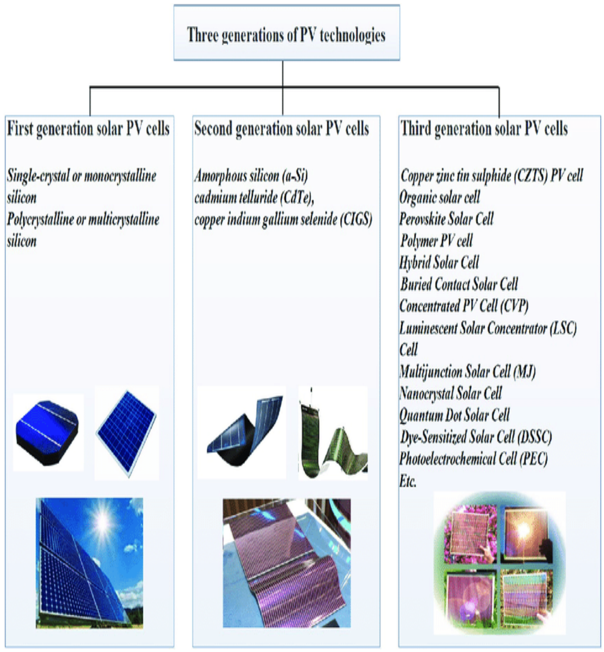

Fig. 1. Generations of PV Technologies

2. PHOTOVOLTAIC (PV) CELL MODEL

2.1 Photovoltaic (Pv) Cell Model

The elementary unit of PV module is PV Cell. These PV cells acts as a PN junction diode[2], where its Shockley current equation is given as

$$I_d = I_s(e^{\frac{Vd}{\eta Vt}} \text{-}1) \tag{1}$$

Thus for the net current of the PV cell is based on the modelling of PV Cell. the difference of the I_i or I_{ph} Photocurrent and I_d, is represent in the given equation

$$I = I_{ph} - I_d \tag{2}$$

Where,
I_{ph}= the current which is generated by the incident light is proportional to the sun's irradiation(s).

* Electronics & Communication Engineering, Madan Mohan Malviya University of Technology, Gorakhpur, Uttar Pradesh, Pin code-273010, India.

[1] Corresponding author;
E-mail: shatru.mishra2013@gmail.com

I_d = Normal current of diode

As the current source is connected in parallel with a diode due to the theoretical modelling of the ideal PV cell. The series and shunt resistance are introduce for improving the PV cell model.

The PV cell can be modeled by various types like one diode model, two diode model etc. In one diode model we use a diode while in two diode model we use two diodes in the equivalent circuit. The two diode model is very complex because of the presence of two diode and the assignment of six parameters. The figure of the simplified one-diode model is given by using the four- parameters which is mostly accepted.

As the current source in connected in parallel with a diode due to the theoretical modelling of the ideal PV cell. The series and shunt resistance are introduce for improving the PV cell model.

The PV cell can be modelled by various types like one diode model, two diode model etc. In one diode model we use a diode while in two diode model we use two diodes in the equivalent circuit. The two diode model is very complex because of the presence of two diode and the assignment of six parameters. The figure of the simplified one-diode model is given by using the four- parameters which is mostly accepted.

2.2 PARAMETERS OF PV CELL

In the figure-2 the current source is connected in parallel with the diode for an ideal PV cell. But as we know that no one PV cell is ideal and hence series and shunt(parallel) resistances are summed up the model [5]-

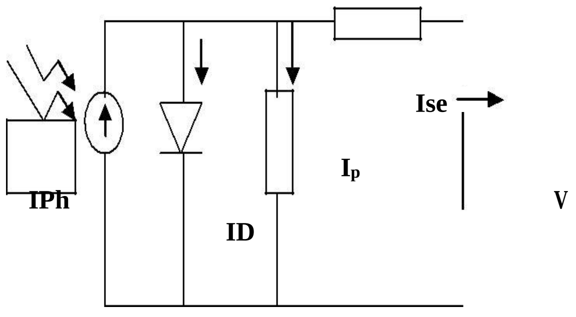

Fig. 2. Single (one) diode model of PV(Solar)cell

In the given figure of electrical equivalent circuit of the solar cell R_{se} is the equivalent resistance in series, the value of this is so small and the Shunt resistance $R_{pl}$is the equivalent resistance in shunt and it's value is very high. [6].

On applying the Kirchhoff's Current law(KCL) law to the junction node where Photo current (I_{ph}), diode current (I_d), R_{pl} and R_{se} meets together, we will get-

$$I_{ph} = I_d + I_p + I_{se} \tag{3}$$

We can find out the resultant current(I_{se}) from the above equation- [2]

$$I \text{ or } I_{se} = I_{ph} - I_d - I_p \tag{4}$$

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_0}\left[e^{\frac{(\mathrm{V+IRse})}{\mathrm{V_T}}} - 1\right] - \left[\frac{(\mathrm{V + IRse})}{\mathrm{Rpl}}\right] \tag{5}$$

here-

I_{ph} : Photocurrent value

I : Cell current value

I_O : Reverse saturation current value

V : Cell voltage value

V_T : Thermal voltage value

T : Temperature in Kelvin value

K : Boltzmann constant value

R_{pl} : Parallel resistance value

R_{se} : Series resistance value

3. RESEARCH REVIEW OF PEROVSKITE TANDEM PV CELLS-

The architecture of Perovskite Solar Cells consist of a material which is Perovskite absorber sandwiched between hole and electron charge transport layers, conducting transparent material and metal contacts[5]-

The general formula for Perovskite is ABX3in which A is the Inorganic and Organic cation, Metal cation is represented by B and Halid anion by X. The different structures of Perovskiteis as follows-

Fig. 3. Representation of different Perovskite structures-

The X-site anion, B-site Cation and A-site Cation with the help of different color bubbles is shown in fig 3.

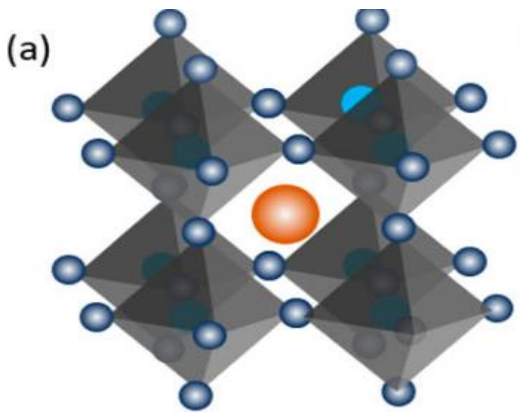

Fig. 3. Structure-a

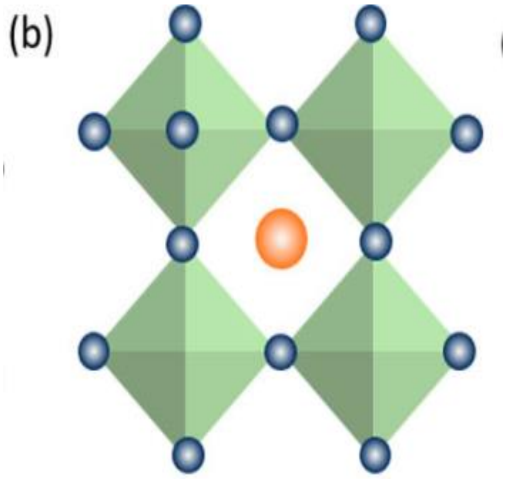

Fig. 4. Structure-b

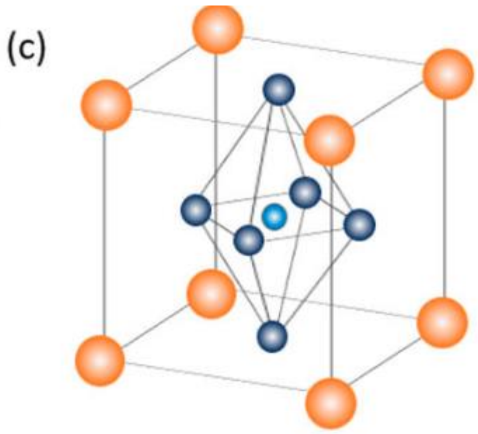

Fig. 5. Structure-c

Tandem Solar Cells are the technical approach of increasing the efficiency limits of the cells of single material. The Tandem Solar cells are a kind of Solar cell that can convert more effectively the solar spectrum into the electric energy than a signal junction solar cells. We use different layers of thin film semiconductors in Tandem solar cells. They limits the two major losses-

a-The excess energy thermalization of photons having high-energy.

b- Low energy photons transparency.

The stack (levels) of p-n junctions in Tandem solar cells in which each stack is formed from a various bandgap energy of semiconductor. Every stack works with a unique section of solar spectrum, Stacking (leveling) the component cells for getting in order to decreasing bandgap. Hence the overall efficiency of the resultant solar cell definitely increases.

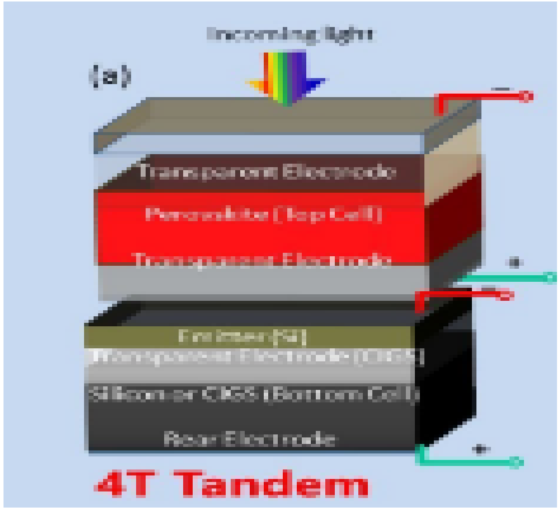

Fig. 6. 4T(4-Terminal) Tandem solar cells-

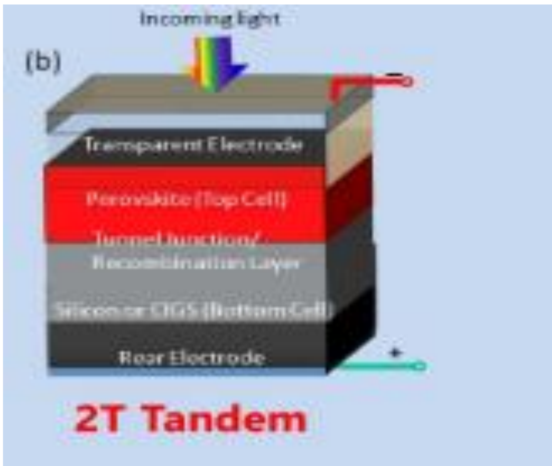

Fig. 7. 2T(2-Terminal) Tandem solar cell.

The graph shows the power conversion efficiency PCE(%) of all perovskite tandem solar cell\s from 2015 to 2024 for Double and Triple junctions

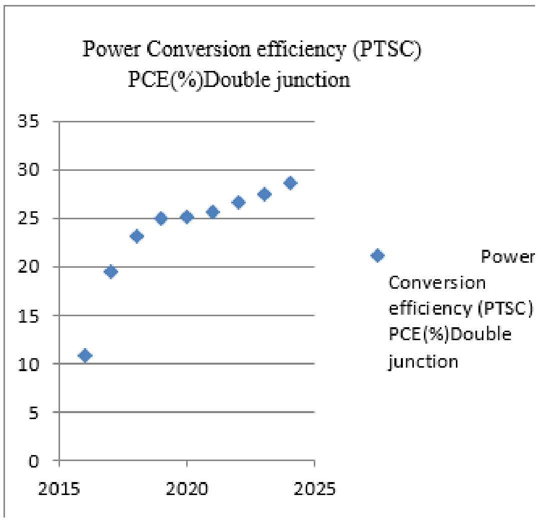

Fig. 8. Power conversion efficiency of Double junction Perovskite tandem solar cell(PTSC) where X-axis represents the time duration in years & Y-axis represents the power conversion efficiency(PCE)%.

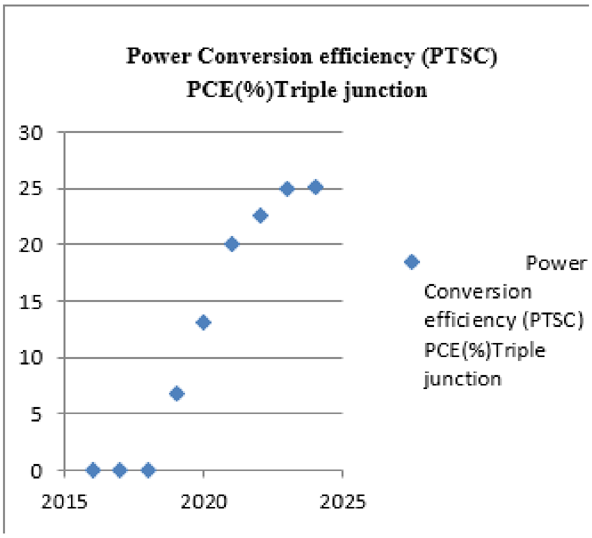

Fig. 9. Power conversion efficiency of Triple junction Perovskite tandem solar cell (PTSC) where X-axis represents the time duration in years & Y-axis represents the power conversion efficiency (PCE)%.

Different types of Perovskite tandem solar cells (PTSC) are shown in fig 10-15.

PEDOT:PSS electrode
Spiro-OMeTAD
Perovskite
PCBM:PEI
PEI
PEDOT:PSS
Spiro-OMeTAD
Perovskite
m-TiO_2
c-TiO_2
FTO
Glass

Fig. 10. sequence of the bi-facial PTSC configuration 2022 Springer nature where all rights are reserved

Au
Spiro-OMeTAD
Narrow-Eg Perovskite
C_{60}
PEDOT:PSS
Spiro-OMeTAD
Wide-Eg Perovskite
TiO_2
FTO
Glass

Fig 11- Figure shows next type of bi-facial configuration by American society where all right are reserved

Au
TaTm:Fe.TCNNQ
T_aT_m
Narrow-Eg Perovskite
C_{60}
C_{60}:Phlm
TaTm:Fe.TCNNQ
T_aT_m
Wide-Eg Perovskite
IPH
TiO_2
ITO
Glass

Fig. 12. scattering function as increasing photon length of path for the band-gap perovskite film, 2022 American association of the advancement of science where all right are reserve.

Ag
BCP
C_{60}
Ps
Narrow-Eg perovskite
PEDOT:PSS
Ultrathin metal
BCP
C_{60}
FSIP
Wide-Eg perovskite
NiO
FTO
Glass

Fig. 13. Figure shows the full solution processed triple junction of PTSC structure

Cu
BCP
C_{60}
Narrow Eg Perovskite
PTAA
ITO
(n)SnO_2
(n^+) C_{60}
Wide-Eg perovskite
PTAA
ITO
Glass

Fig. 14. other type of PTSC configuration of solution-processed triple junction, 2020 by American Society where all rights are reserve.

Cu
BCP
C_{60}
Narrow Eg Perovskite
(n)SnO_2
(n^+) C_{60}
Wide-Eg perovskite
PTAA
ITO
Glass

Fig. 15. other type of PTSC configuration of solution-processed triple junction, 2020 by American Society where all rights are reserve.

The table below represents the chronological data of Perovskite Tandem Solar cells [7]. These are 12 reference papers which are research papers. Hence the date of submission is used in place of the date of acceptance-
.

Structure of cell	Junction	Technique	Wband (PCE) (%)	Wband (ev)	Nband (PCE) (%)	Nband (eV)	Tan (PCE)	Active area (mm^2)	Terminal	Substrate	Accepted Date (Ref.)
Glass/ITO/WB/PVK/C_{60}/ALD/SnO_2/Au/PEDOT-Pss/NB PVK /C_{60}/BCP/Cu	Double	VNP as Hole transport layer	16.71	1.78	15.91	1.16	24.92	4.90	2T	Glass	June-2021
Glass-ITO- NiO-VNPB- WB PVK-C60/ ALD-SnO2/ Au- PEDOT:PSS-NBPVK-C60-BCP- Cu	(Double)	Passivation	17.3	1.76	22.2	1.22	26.7	4.9	2T	Glass	Dec-2021
Glass-ITO- NiO-VNPB- WB PVK-C60/ AL-SnO2-Au-PEDOT:PSS-NBPVK- C60-ALD-SnO2-Ag	(Double)	Blade Coating and Cs additive	17.2	1.8	19	1.22	25.1	4.9	2T	Glass	Apr-2022
Glass- MeO-2PACz/ WB PVK-LiF-C60/ SnOx-Au- PEDOT:PSS/-NBPVK- C60-BCP/-Ag(silver)	(Double)	Quasi-2D	16.6	1.75	22.2	1.25	25.5	9	2T	Glass	May-2022
Glass/ITO/NiO/SAM/WB PVK/$C_{(60)}$/SnO_2/Au/PEDOT-Pss/NbPvK/$C_{(60)}$/SnO_2/ITO	Double	Bifacial Tandem	15.11	1.77	NA	1.22	28.51	9	2Terminal	Glass	Sept-2022
Glass- ITO-PTAA- PFMBr-WB PVK-C60-SnO2- ITO-PEDOT:PSS-NBPVK- C60-BCP- Cu	Double	$PbCl_2$ and PMAC additive	20.22	1.73	21.97	1.25	26.68	9	2T	Glass	Mar-2023
Glass-ITO-2PACz- WB PVK-C60-SnO2-ITO-PEDOT:PSS-CysHCl D&P NB PVK- C60- BCP-Cu	Double	Passivation	17.48	1.77	22.15	1.27	25.7	5.76	2T	Glass	Mar-2023
WB: ITO- MeO-2PACz- WB PVK-C60-LD-SnO2-ITO NB: ITO-PEDOT:PSS- NB PVK-C60/ BCP-Cu	Double	Antimony potassium tartrate additive	20.35	1.67	20.3	1.24	26.3	11.88	4T	Glass	Mar-2023
Glass- ITO- novel HTL- WB PVK-C60- SnO2- IZO-NB PVK/ C60-SnO2-Cu	Double	New hole-selective layer	18.22	1.77	21.27	1.25	27	104.4	2T	Glass	Mar-2023

Glass- ITO- NiO-SAM- WB PVK-C60- ALD-SnO2-Au- PEDOT:PSS-NBPVK- full-lead WB- C60- BCP or ALDSnO2- Cu	(Double)	33D/3D bi-layer	18.61	1.78	23.81	1.25	28.50	4.90	2T	Glass	May/2023
WB: Glass- ITO-NiOx- Me-4PACz-WB PVK- C60-SnO2- ITONB: Glass- ITO-PEDOT:PSS-NBPVK-C60-BCP- Cu	(Double)	octane-1,8-diamine dihydroiodide add. in WB perovskite soln	20.06	1.67	22.75	1.25	28.35	100	4T	Glass	Mar/2023
WB: glass- ITO-MeO-2PACz-WBPVK- PDAI2-C60- ALD-SnO2-ITO-Ag-NB: glass-ITO-PEDOT:PSS/-NBPVK-C60-BCP-Cu	(Double)	1&3 PDAI for WB PVK using Surface Passivation Technique	20.11	1.68	21.26	1.21	28.07	11.88	4T	Glass	Apr-2024

4. CONCLUSION

The given Table represents the different Cell structures, number of junctions, Technique used, the narrow band, Wide band and Tandem (Combined structure) power conversion efficiency (PCE), number of terminals, types of substrate and finally the acceptance date. All parameters cover the information about the progressive behavior of Perovskite tandem solar cells.

REFERENCES

[1] IEE-Europe programme, Renewable Electricity make the switch –Project report analysis, Executive Agency for the competitiveness& Innovation of the European.

[2] Alex Dev. and S. Berclin., 2013- Modelling and Simulation of Photovolatic module using Matlab

[3] Domineque Bonk. and Zecharie Koallasgs, Amrch 2013. Modelling and Simulation of Photovoltaic module considering single-diode equivalent circuit model using Matlab.

[4] Niraj. N. Lal., Yasmina. Dkhissi. Wei., May 2017. Perovskite Tandem Solar Cell.

[5] Xueyu. Tian., Samuel. D. Stranks, 2020. Life Cycle energy uses and Environmental implications of High performance Perovskite tandem Solar Cells.

[6] Jaekeun. Lima., Nam. Gyu. Park., Sang. Il Seokd., and Michael Saliba., 2024.All-perovskite tandem solar cells from fundamentals to technological progress, Energy and environmental science a review article.

[7] Marko Jošt., Lukas Kegelmann., Lars Korte, and Steve Albrecht. 2020. Monolithic Perovskite Tandem Solar Cells: A Review of the Present Status and Advanced Characterization Methods Toward 30% Efficiency by advance energy materials.

[8] Park J., Kim J., Yun H. S., Paik M. J., Noh E., Mun H. J., Kim M. G., Shin T. J. and Seok S., J. 2023 *Nature journal*, 616, 724–730.

[9] Research-Cell Efficiency Chart, Photovoltaic Research, accessed 11 January 2024 NREL ,https://www.nrel.gov/pv/cell-efficiency.html,

[10] Todorov T., Gershon T., Gunawan O., Sturdevant C. and Guha S. 2023, *Appl Phys Lett*, ,DOI:10.1063/1.4899275.

[11] Liu S., Lu C., Yu C., Li J., Luo R., Guo R., Liang H., Wang S., Sui M., Müller-Buschbaum P., and Hou Y., 2023 *Nature journal*, DOI:10.1038/s41586-024-07226-1.