Enhancing Efficiency of Organic-Inorganic Mapbi$_3$ Perovskite Solar Cells Using 1 Sun Solar Simulator

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Abstract

The emerging perovskite solar cells holds all of the qualities required for technology to become commercialized with the exception of some limitations which are hindering, specially their stability. PSCs have exhibited a remarkable improvement in efficiency from 4% to a new high of 25.5 percent in a few years in labscale test devices, marking the fastest performance improvement among all the photovoltaic technologies, however their aging life reduces with increase in efficiency. This research reflects the performance of perovskite solar cells (PSC) employing Methyl Ammonium Lead Iodide as a light harvester to produce perovskite solar cells, and using conventinal method of their production. The efficiency as well as their I-V response is reported when exposed under full sun Solar Simulator. The purpose of this study is to reveal the limitations of perovskite solar cells' efficiency by dispensing technique.

Keywords—Mapbi$_3$, Perovskite solar cell, Photovoltaic, Electron transporting materials, Hole transporting materials, Power Conversion Efficiencies, Renewable energy

1 Introduction

Our sun provides an endless supply of energy to our world. It is capable of meeting all of humanity's energy requirements. The total energy accessible from the 3 trillion barrels of total oil resources identified on Earth thus far is projected to be 1.7 x 1022 J, which is equal to the energy provided to our planet by the sun in 1.5 days [1]. Humans, on the other hand, utilise 4.6 x 1020 J of energy every year, which is a minuscule fraction of the energy we receive from the sun in only one hour.

Thankfully with the advancement of science and technology the solar energy can be converted into electricity through photovoltaic (PV) devices. At present, many competing photovoltaic technologies can convert incident solar energy at various levels of efficiencies based on their configuration and types of semiconductors used to convert solar energy into electricity. Presently, the conversion efficiency of cells of these technologies is varying between 12.6 and 47.1% [2].

Perovskite solar cells (PSCs) are now the most promising PV technology in terms of high efficiency and cost-effective production ingredients and techniques. PSCs have increased their efficiency from 4% to over 25% in the previous few years, which is a remarkable development when compared to other PV devices observed to far. As a result, PSCs were featured in the World Economic Forum's top ten emerging technologies list in 2016. Since then, substantial attempts have been made to commercialise them in order to achieve a big breakthrough in the development of low-cost, long-term solar energy harvesters [2]. Moreover, the material set used to realize the cells are abundant and low-cost processes are utilized for device fabrication. It has therefore been recognized among the top ten emerging technologies in 2016 by the World Economic Forum [3].

In single-junction topologies, solar cell efficiencies employing these materials have risen from 3.8 percent in 2009 to 25.5 percent in 2020, and are comparable to known PV materials such as Silicon, GaAs, and CdTe [1]. The National Renewable Energy Laboratory (NREL) has been keeping track of the best proven conversion efficiencies for research cells in a range of solar systems since 1976 [2].

The technologies are covering a range of semiconductor families including the following 5 main and additional 28 subcategories are also indicated with

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distinctive colored symbols in Figure 1.

- Gallium arsenide cells with a single connection
- Silicon crystal cells
- Cells with many junctions
- New photovoltaic technologies.
- Thin-film technologies

A perovskite solar cell (PSC) functions similarly to a well-known Silicon solar cell, except that instead of Silicon, a hybrid tin halide-based material or inorganic- organic lead is used as the light harvester, and charges (electrons and holes) separate and travel towards respective electrodes through charge selective layers. Because this technology is still in its early phases, the devices are not as long-lasting as silicon solar cells. However, a distinct benefit of PSC over silicon solar cell technology is the possibility of low-cost large-scale solution-processed production [4].

Simplified manufacturing procedures, high light absorption, adjustable bandgaps, and high charge carrier mobilisation are all benefits of perovskite technology over conventional semiconductors. Perovskite solar cells are projected to be the future low-cost photovoltaic technology, according to numerous research analysis studies, and to be a solution to the energy deficit in the current scenario, when the entire globe is battling to satisfy the rising energy demand [5-9]. However, the film absorption edge of perovskites in highly effective perovskite solar cells has been discovered to be approximately 800nm, which has the added benefit of restricting Near Infrared (NIR) solar radiation [10-11].As a result, enormous effort has gone into developing new techniques to increase the absorption of perovskite solar cells. Several novel designs are included with Tin including $FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$ and $MA_{0.5}FA_{0.5}Pb_{0.75}Sn_{0.25}I_3$ in order to control perovskite absorption [12-13]. Alternatively, tandem solar cells can be connected with NIR absorbing solar cells. However, easily oxidised Tin-containing compositions have been discovered to have higher efficiency, which has aided in the advancement of this technology [14].

Perovskites Solar cells have a chemical formula of AMX3 (5, 6), which is comprising of metallic cations as “M” and anions as “X” and form MX6 octahedra with “A” cations carrying coordinated holes with 12-folds inside the cavity [15]. These materials have acceptable and controllable bandgaps which supports strong absorption of photons, better carrier diffusion lengths, and improved defect tolerance, all of which are desired optical-electrical features for PV devices. Solution-based manufacturing utilising readily available tools is used to make perovskite films. The most effective devices we must rely on are pricey gold and organic Hole-transport materials, despite the chemicals being abundantly available (HTMs). A TCO (transparent conductive oxide layer), an FTO coated glass substrate, an n-type semiconductor acting as the electron transport layer (ETL), a perovskite absorber layer, a p-type semiconductor acting as the hole-transport layer (HTL), and finally a back-contact layer are all included in the construction of perovskite solar cells (metal, TCO, or carbon). A perovskite layer sandwiched between a planar ETL and a planar HTL is at the heart of planar PSC technology. [for example, compact TiO_2, SnO_2, or C60 and its derivatives] with an HTL [for example, spiro – OMeTAD, poly (triarlyamine) (PTAA), and poly(3, 4 -ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS)] [15-18].

The electrical and optical characteristics of organic-inorganic hybrid perovskites have been good. The efficiency of perovskite photovoltaics in relevance to power conversion has grown to 25.2% as a result of this. They have swiftly increased to a theoretical maximum efficiency of 33%, whereas the efficiency of PSCs with potassium-passivated triple cation has been measured at more than 28%. Their production costs have been shown to be very low since they can be mass-produced utilising inexpensive solution techniques found in nature [5-6]. Perovskite films are being made utilising solution-based manufacturing methods with readily available equipment [16]. Although the chemicals employed in these fabrications are widely accessible and inexpensive, the most efficient devices require rather large hole-transport materials [16-17]. Perovskites, on the other hand, are chemically unstable, and this constraint puts them at a significant disadvantage in terms of commercialisation.

Figure 2 shows a typical perovskite solar cell structure with both electrodes, electron transporting materials (ETMs) in the ETL, hole transporting materials (HTMs) in the HTL, and a light-harvesting perovskite layer. When the perovskite layer absorbs light, PSC’s primary working notion begins. Due to the driving force induced by the energy level difference, photons’ energy is converted into electron and hole pairs, which are produced and selectively removed by electron/hole-transporting materials. These electrons and holes eventually move to the external circuit as a result of potential and photovoltage, generating photocurrent. The current-voltage characteristic is a standard approach to assess the performance of solar cells. Throughout this operation, the bias voltage is swept stepwise, and the resulting photocurrent is monitored at the same time. This test can be used to determine essential characteristics that characterise the device’s performance, such as the short-circuit current (I_{sc})

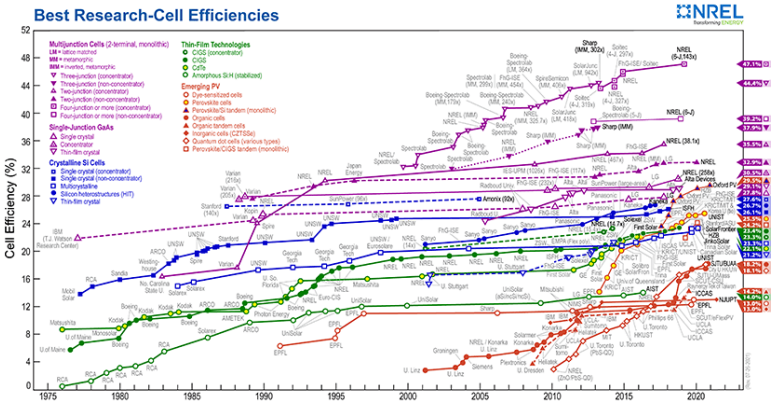

Fig. 1: Research solar cell efficiencies from NREL

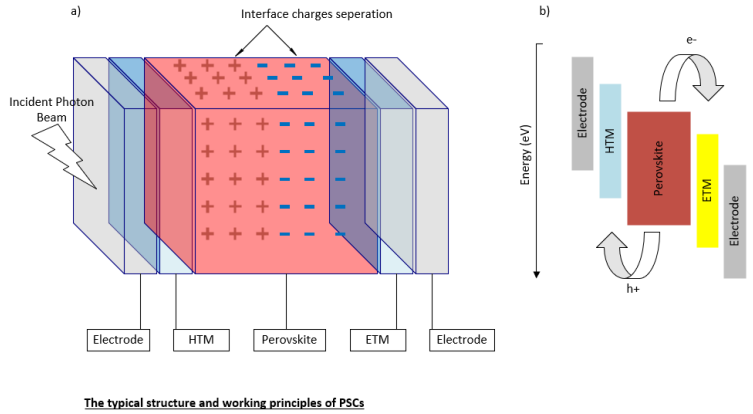

Fig. 2: Type structure and working principle of PSCs

or current density (J_{sc}), open-circuit voltage (V_{sc}), fill factor (FF), and power conversion efficiency (η), which are related in the equation below [11].

$$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}A_{aperture}} = \frac{J_{sc}V_{oc}FF}{P_{in}}$$

Equation 1: where Pin is the incident photon irradiance and Pm is the maximum output power of the test cell, and Aaperture is the exposed/aperture area exposed to incident light.

Current-voltage curves and spectrum responsivity wave-length curves can be used to evaluate the performance of solar cells. The most generally used performance statistic for PV cells is PV power conversion efficiency, which is defined as a ratio of maximum output (electric) to total irradiance [1] and provided by Equation 2.

$$Efficiency(\eta) = \frac{Max.Power \times 100}{Incident\ Irradiance \times DeviceArea}$$

$$\eta = \frac{P_{max}}{E_{tot} * A} \times 100 \qquad (1)$$

IEC 61215 (2005), IEC 60904 (2006), IEC 61646 (2008), IEC 60891 version 2.0 (2009), and IEC 61853 (2011) are examples of standards developed by the International Electrotechnical Commission (IEC) for reliable measurement of solar cells [19-20]. These standards with guidelines have outlined stringent requirements for irradiance, series resistance for conduction, operating temperatures, etc. during testing in photovoltaic technologies.

Solar energy can be converted into two different types of energy. The first is photovoltaic (PV) technology, which uses the PV effect with regular solar radiation or a concentrated beam utilising lenses to project multiple Sun photons on the same area of PV Cells to convert solar radiation directly into electrical energy. The second is CSP technology, which concentrates solar energy to produce heat, which is then used to generate electricity via a power cycle similar to that used in industrial power plants. Both technologies have advantages and disadvantages [1]. Global CSP installed capacity will reach 261 GW by 2030, according to the International Energy Agency

(IEA), while global PV installed capacity will reach 1721 GW [18].

CSP installations with solar multiples of 3–5 and thermal energy storage periods of more than 10 hours include the Gemasolar solar tower plant (19.9 MW) in Spain and the Crescent Dunes sun tower plant (100 MW) in the United States [20].

PV cells can gather up to 80% of solar energy, but only a small fraction of it is turned into electricity, which is governed by the PV cell's efficiency, also known as conversion efficiency [21]. The remaining absorbed energy is released as heat, which is dissipated on the cell surface and results in a temperature increase. The rest of the energy is released as heat, which can reach levels of up to 40 degrees Celsius higher than the ambient temperature. This is because PV cells only convert a fraction of the incoming irradiation into energy, while the remainder is lost as heat [22].

Unfortunately, one of the most important factors influencing PV cell performance and efficiency is temperature increase. They also promote cell deterioration and limit their lifespan. For Perovskite bases, this impact becomes much more important. Solar cells are more sensitive to environmental variables during their lifetime since they are organic-inorganic hybrids.

Due to greater inherent carrier concentrations, which tend to boost the p–n junction's dark saturation current, the performance of silicon-based photovoltaics is proven to be inversely related to temperature. The band gap narrows significantly as a result of high doping, allowing the inherent carrier concentration to rise. This produces an increase in dark saturation current, which causes the open-circuit voltage to linearly fall, with the open-circuit voltage for silicon being determined to be 2.3 mV/oC at 300 K [23].

In the laboratory, Cadmium Telluride CdTe films have attained a 16% efficiency [24]. Similarly, solar cells based on Copper Indium Gallium Selenide (CIGS) continue to attract widespread interest for solar power generation. They are thin-film PV cells with a 22.8% efficiency that is comparable to Crystalline Silicon wafer-based solar cells [25]. Other PV technologies that failed to attain high efficiencies in the past but prepared the path for the development of perovskite solar cells include dye sensitised solar cells (DSC) and organic photovoltaics (OPV). Because of its constant rise in power conversion efficiency (PCE), low-cost materials constituents, and simple solution fabrication procedure, perovskite solar cells (PSCs) are an emerging technology that has gotten a lot of interest. PSCs have now surpassed the performance of commercially produced Copper Indium Gallium Selenide (CIGS), multi-crystalline silicon solar cells, and Cadmium Telluride (CdTe) thin-film photovoltaic cells in the lab, with a power conversion efficiency of 25.5 percent. They were first presented in 2009, with a 3.8 percent efficiency. Because of its newness as a technology, perovskite's stability had been an open question until recently. Under 1 sun (1 kW/m^2) lighting with a UV filter at a stable temperature of 55°C under short-circuit conditions, printed triple mesoscopic PSCs have recently achieved lifetimes of 10,000 hours.

Perovskite solar cells have a greater coefficient of light absorption than their competitors, as well as the benefit of being thin and light, allowing them to be employed in flexible and portable devices [19-20]. However, due of the limited gadget lifetime, their commercialization is hampered (LT). In a variety of situations, halide perovskite materials can quickly deteriorate [7].

To reduce environmental consequences, it is critical to extend the lifetime (LT) of PSCs. When the LT is just one year, the energy pay-back time (EPBT) is the time it takes to create enough energy to pay back the energy used in the production of PSCs. It is now 16.54 years. When the LT is extended to 15 years, however, the EPBT is lowered to 1.10 years. PSCs' environmental implications on climate, human health, and freshwater ecotoxicity would be directly reduced with such a drop in EPBT from extended LT [8]. Since a result, establishing a long LT of PSCs is significant at this time, as it is important for both commercialization and environmental impact reduction. A solar cell must be thermally and chemically robust to endure temperatures ranging from -40 to +85 degrees Celsius and prevent interactions with air molecules like oxygen and water. As one might expect, degradation occurs as a result of a number of interconnected processes that come from various degradation causes (e.g., thermal energy, water, illumination, oxygen, and electric bias). PSC degradation mechanisms are complicated and varied, with several degradation causes producing a wide range of degradation responses. This establishes a number of links between degradation sources and the phenomena that result, helping researchers to gain a better understanding of how they are maintained at Perovskites' interfaces [21]. Thermodynamic energy is a primary contributor to PSC deterioration. Mechanical shocks, as well as heat and irradiation, wreak havoc on the stability of PSCs. Perovskites have a low fracture energy and a thermal expansion coefficient that is more than ten times higher than glass and TCOs. This mechanism induces delamination during temperature cycling with weather changes. Nonetheless, one of the key causes is phase transition in perovskites. Because

the perovskite materials used in PSCs are organic-inorganic hybrid halide perovskites with an ABX3 general structure [26]. A is a monovalent cation like Methyl Ammonium (MA) or Formamidinium (FA). In some cases Cesium, Rubidium, or both in combination. B is a divalent metal cation (like Pb, Sn, Ge etc) X is an anion from halogen group (like I, Cl, Br, or their combinations). The Goldschmidt tolerance factor t is used to assess the stability and distortion of perovskite crystal formations.

$$t = \frac{R_A + R}{\sqrt{2(R_X + R_B)}} \tag{2}$$

where Rx is radius of the X anion, RA is radius of the monovalent cation and RB is radius of the divalent metal ion.

The short shelf and operating lifetime of perovskite were important barriers in the development of this technology [22]. The exact process of perovskites deterioration in the presence of water is currently being debated. At the same time, oxygen has been discovered to have a minute influence on the deterioration of perovskite devices [23]. Several approaches have been used, including cross-linking perovskite grains with phosphonic acid ammonium derivatives, which further minimises perovskite device moisture sensitivity [24]. Moisture ingress is additionally delayed by the use of hydrophobic carbon nanotube/poly(methyl methacrylate) composites and Teflon, which have been demonstrated to be effective barriers, resulting in an increased lifespan of perovskite cells [25]. Unpackaged cells retain 80% of their initial Power Conversion Efficiency (PCE) after 500 hours and around 60% of their initial PCE after 1000 hours when projected with white light under ambient conditions keeping the temperature below 30 °C. Furthermore, unsealed perovskite devices can retain 92 percent of their original PCE after 1900 hours under ambient and dark conditions (shelf lifetime).

According to a study , Oxo- G1 based solar cells retain 74 percent of their initial PCE after 670 hours, but PEDOT: PSS based devices only retain 54 percent. The most significant difference in lifetime is found at ambient environmental conditions (temperature of roughly 20-30 °C, RH of 30-50%) and light of approximately 0.5 suns equivalents given by a white LED. Unsealed oxo-G1devices retain 60% of their initial PCE after 1000 cycles.

Different approaches have been established to increase efficiency and stability in perovskite solar cells, which remains a significant difficulty in this technology with plenty of potential for development. Methodologies used to achieve over 20% efficiency in PSCs in both standard (n-i-p) and inverted (p-i-n) designs have opened new doors in terms of obtaining improvement and comprehending the difficulties related to PSC performance and stability [26].

In the same way, synthesis, and characterization in PSCs is achieved with the perovskite materials, APbX3 A = methylammonium (MA) or formamidinium(FA) X = Br, I or their combination

They're employed in photovoltaics and have impressive qualities such as long carrier diffusion length, good panchromatic absorption with an adjustable bandgap from 1.1 3.1 eV, and low nonradiative recombination rates. These are the physical features that drew researchers to perovskites for a variety of applications, including lasing, light-emitting devices, and photodetection, as well as tandem applications [27].

Thanks to the methodology adopted with the incorporation of Rubidium cations in PSCs with MAFA exhibited considerable improvement in efficiency and stability with 19% PCE with 0.5cm^2 of maximum power point tracking area [28]. When all the technical problems with the Perovskite Solar cells can be solved, this could become a very important technology in the future because of its high efficiency and low production cost. We used a solar simulator to carryout our tests after producing perovskite solar cells. The solar simulator is used to expose a PV with an environment similar to expose it under sun with same quantity of photons. There are solar simulators which can project photons in a quantity equivalent to multiple suns so as to evaluate power conversion efficiency of same PV under multiple suns and to asses the factors like heat and stability of that PV in an unsual environment. It can be used for standard applications like PV devices test, chemical batteries, testing cosmetic products, thermal power generators, consumable electronics goods (like Cell phones, camera), testing building materials like paints, testing of textiles and their life and for cancer and bioscience analysis.

2 Experimental Setup

Spin Coater, Hotplate, Glovebox, dispensing pipette, Solar Simulator (Model Oriel by Newport) , I-V response measurement Keithley 2400

3 Chemicals

FTO glass substrates 5x5mm (2.2mm TEC15, TiO2 (Sigma Aldrich) Spiro-OMeTAD (Merck) Precursor solution with PbI2 (1.1 M) and PbBr2 (0.22 M) TCI Dyenamo products. Solvents ethanol (Sigma Aldrich), Spiro-OMeTAD (Merck) Deionized water (DI, 2%, Hellmanex).

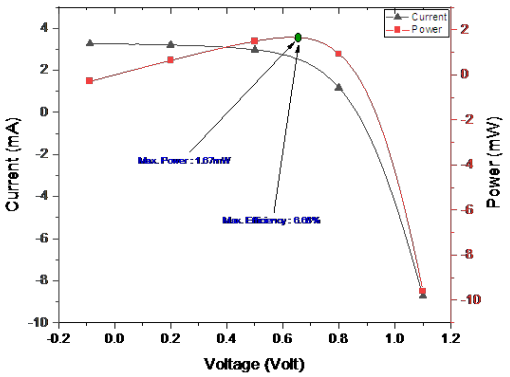

Fig. 3: I-V, P-V Characteristics of $MAPbI_3$ PSCwith maximum attained efficiency of 6.68%

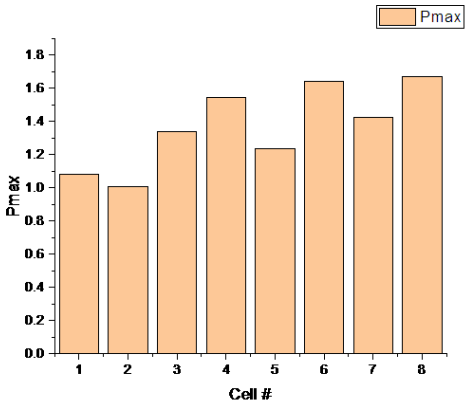

Fig. 4: Efficiencies of 8 different PSCs tested under 1 Sun simulator

4 Results & Discussion

Organic-inorganic hybrid perovskite, methylammonium lead iodide (CH3NH3PbI3), is a game-changing semiconductor for solar cells and light-emitting devices due to its defect tolerance and extraordinarily extended carrier lifetimes and diffusion lengths.

The current-voltage characteristics of the perovskite solar devices were used to investigate their photovoltaic activity. The bias voltage was swept in tiny increments during the experiments, and the resultant photocurrent was observed at the same time. These readings may be used to derive a number of important metrics about the device's performance. These examples include Open circuit voltage, Short-circuit current, current density, fill factor, and power conversion efficiency. The following equation describes the connection between these variables.

$$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}A_{aperture}} = \frac{J_{sc}V_{oc}FF}{P_{in}} \qquad (3)$$

Where Pin is the incident light irradiance on the test cell, Pm is the maximum power output, and Aaperture is the area of aperture that has been exposed to the incident light.

It has been observed that the efficiency achieved after production of PSCs was 6.68% without using any quality improvement techniques like Gold evaporation of terminals as show in Figure 3. Whle all analyzed parameters to asses the performance of different PSCs are well elaborated in Figure 7. Figure 3 shows the maximum achieved efficiency of 6.68% with a max obtained power of 1.27mW. The power drawn from Solar cell using a resistive load for all types of produced solar cells is shown in Figure 4 , while their standard deviation with error bars is in Figure 5. When comparing the performance efficiency of solar

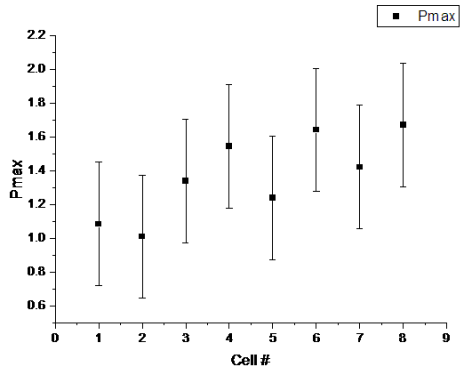

Fig. 5: Error bars with standard devitation of power achieved from 8 different PSCs tested under 1 Sun simulator

cells, the Fill Factor, which is the ratio of the highest possible power to the product of short circuit current and circuit voltage, is usually utilized. It is calculated with quite repeatable performance as in Figure 6. To calculate the ratio, use the formula below.

$$Fill\ Factor(FF) = \frac{P_{max}}{I_{sc} \times V_{oc}} \qquad (4)$$

It has been noticed in figure 6, that the FF and Pmax achieved for all produced PSCs are with narrow error bars showing good repeatability of results. The error bars reveal that the dispensing process has been performed with perfection to avoid shortening of layers.

5 Conclusion

Perovskite Solar cell is an unstable type of solar cell and the performance we achieved in first hour was different from the very next. We produced 8 PSC

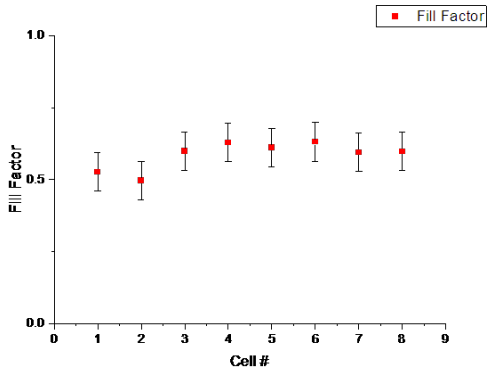

Fig. 6: Fill factor of 8 PSCs with error bars & standard deviation

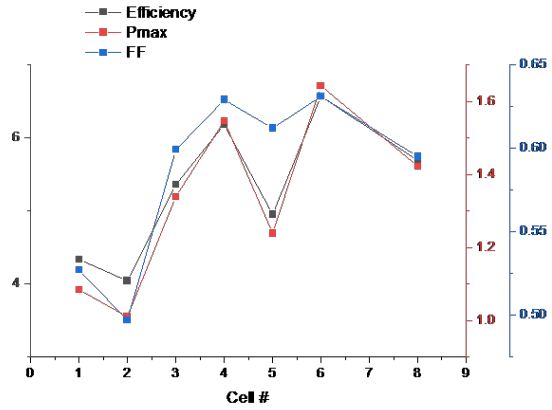

Fig. 7: Consolidated results to optimize performance of 8 PSCs with their Efficiency, Obtained power and Fill Factor

with 0.25cm^2 of active area and analyzed that after around 500hrs of time, there was a drastic decrease of efficiency tempting to produce PSCs encapsulated but it incurs costs making it exorbitant. This approach can be further improved and adopted commercially to overcome the present limitations associated with the conventional fabrication techniques and methodologies of perovskite solar cells.

References

[1] Hayat, M.B., Ali, D., Monyake, K.C., Alagha, L. and Ahmed N., "Solar energy—A look into power generation, challenges, and a solar-powered future." International Journal of Energy Research, Vol. 43, No. 3, pp. 1049-67, 2019.

[2] NREL BR-CEC, https://www.nrel.gov/pv/cell-efficiency.html. 2021.

[3] Agenda, G., "Top 10 Emerging Technologies of 2016." 2016.

[4] Saki, Z., Byranvand, M.M., Taghavinia, N., Kedia, M. and Saliba, M., :Solution-processed perovskite thin-films: the journey from lab-to large-scale solar cells.: Energy Environmental Science, 2021.

[5] Jeon, N.J., Noh, J.H., Kim, Y.C., Yang, W.S., Ryu, S. and Seok, S.I., "Solvent engineering for high-performance inorganic–organic hybrid perovskite solar cells." Nature Materials, Vol. 13, No. 9, pp. 897-903, 2014.

[6] Zhou, H., Chen, Q., Li, G., Luo, S., Song, T.-B., Duan, H.-S., et al., "Interface engineering of highly efficient perovskite solar cells." Science, Vol. 345, No. 6196, pp. 542-6, 2014.

[7] Kaltenbrunner, M., Adam, G., Głowacki, E.D., Drack, M., Schwödiauer, R., Leonat, L., et al., "Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air." Nature Materials, Vol. 14, No. 10, pp. 1032-9, 2015.

[8] Leijtens, T., Eperon, G.E., Noel, N.K., Habisreutinger, S.N., Petrozza, A. and Snaith, H.J., "Stability of metal halide perovskite solar cells." Advanced Energy Materials, Vol. 5, No. 20, pp. 1500963, 2015.

[9] Espinosa, N., Serrano-Luján, L., Urbina, A. and Krebs, F.C., "Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective.: Solar Energy Materials and Solar Cells, Vol. 137, pp. 303-10, 2015.

[10] Li, Y., Arumugam, S., Krishnan, C., Charlton, M. and Beeby, S., "Encapsulated textile organic solar cells fabricated by spray coating." Chemistry Select, Vol. 4, pp. 407-12, 2019.

[11] Wang, Y., Liu, X., Zhou, Z., Ru, P., Chen, H., Yang, X., et al., "Reliable measurement of perovskite solar cells." Advanced Materials Vol. 31, No. 47, pp. 1803231, 2019.

[12] Yang, Z., Rajagopal, A., Chueh, C.C., Jo, S.B., Liu, B., Zhao, T., et al., "Stable Low-Bandgap Pb–Sn Binary Perovskites for Tandem Solar Cells." Advanced Materials, Vol. 28, No. 40, pp. 8990-7, 2016.

[13] Eperon, G.E., Leijtens, T., Bush, K.A., Prasanna, R., Green, T., Wang, J.T.-W., et al., "Perovskite-perovskite tandem photovoltaics with optimized band gaps." Science, Vol. 354, No. 6314, pp. 861-5, 2016.

[14] Gao, K., Zhu, Z., Xu, B., Jo, S.B., Kan, Y., Peng, X., et al., "Highly efficient porphyrin-based OPV/perovskite hybrid solar cells with extended photoresponse and high fill factor." Advanced Materials, Vol. 29, No. 47, pp. 1703980, 2017.

[15] Rong, Y., Hu, Y., Mei, A., Tan, H., Saidaminov, M., Seok, S., et al., "Challenges for commercializing perovskite solar cells." Science, Vol. 361, pp. eaat8235, 2018.

[16] Dubey, A., Adhikari, N., Mabrouk, S., Wu, F., Chen, K., Yang, S., et al., "A strategic review on processing routes towards highly efficient perovskite solar cells." Journal of Materials Chemistry A, Vol. 6, No. 6, pp. 2406-31, 2018.

[17] Salado, M., Kokal, R.K., Calio, L., Kazim, S., Deepa, M. and Ahmad, S., "Identifying the charge generation dynamics in Cs+-based triple cation mixed perovskite solar cells." Physical Chemistry Chemical Physics Vol. 19, No. 34, pp. 22905-14, 2017.

[18] Technology roadmap: solar photovoltaic energy - 2014 edition i, International Energy Agency (IEA) report, 2014. Technology roadmap: solar photovoltaic energy - 2014 edition, in, International Energy Agency (IEA) report, 2014. 2014.

[19] Jiang, Q. Wang, H.-L., Yang, X.-L., Meng, J.-H., Liu, H., Yin, Z.-G., Wu, J.-L., Zhang, X.-W. and You, J.-B., "Enhanced electron extraction using SnO_2 for high-efficiency planar-structure HC (NH2) 2PbI3-based perovskite solar cells [J]." Nature Energy, Vol. 2, No. 1, pp. 1-7, 2016.

[20]] Zheng, X., Chen, B., Dai, J., Fang, Y., Bai, Y., Lin, Y., et al., Zeng; Xiao, C.; Huang. J Nat Energy, Vol. 2, pp. 17102, 2017.

[21] Lim, K.G., Ji, S.G., Kim, J.Y. and Lee, T.W., "Effect of Interfacial Layers on the Device Lifetime of Perovskite Solar Cells." Small Methods, Vol. 4, No. 8, pp. 2000065, 2020.
[22] Chen, H. and Yang, S., "Methods and strategies for achieving high-performance carbon-based perovskite solar cells without hole transport materials." Journal of Materials Chemistry A, Vol. 7, No. 26, pp. 15476-90, 2019.
[23] Yang, J., Siempelkamp, B.D., Liu, D. and Kelly, T.L., "Investigation of CH3NH3PbI3 degradation rates and mechanisms in controlled humidity environments using in situ techniques." ACS Nano Vol. 9, No. 2, pp. 1955-63, 2015.
[24] Li, X., Dar, M.I., Yi, C., Luo, J., Tschumi, M., Zakeeruddin, S.M., et al., "Improved performance and stability of perovskite solar cells by crystal crosslinking with alkylphosphonic acid ω-ammonium chlorides." Nature Chemistry, Vol. 7, No. 9, pp. 703-11, 2015.
[25] Habisreutinger, S.N., Leijtens, T., Eperon, G.E., Stranks, S.D., Nicholas, R.J. and Snaith, H.J., "Carbon nanotube/polymer composites as a highly stable hole collection layer in perovskite solar cells." Nano Letters, Vol. 14, No. 10, pp. 5561-8, 2014.
[26] Saliba, M., Correa-Baena, J.-P., Wolff, C.M., Stolterfoht, M., Phung, N., Albrecht, S., et al., "How to Make over 20% Efficient Perovskite Solar Cells in Regular (n–i–p) and Inverted (p–i–n) Architectures." Chemistry of Materials, Vol. 30, No. 13, pp. 4193-201, 2018.
[27] Saliba, M., Orlandi, S., Matsui, T., Aghazada, S., Cavazzini, M., Correa-Baena, J.-P., et al., "A molecularly engineered hole-transporting material for efficient perovskite solar cells." Nature Energy Vol. 1, No. 2, pp. 1-7, 2016.
[28] Saliba, M., Matsui, T., Domanski, K., Seo, J.-Y., Ummadisingu, A., Zakeeruddin, S.M., et al., "Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance." Science, Vol. 354, No. 6309, pp. 206-9, 2016.