Invited Feature Article

Rise of a Giant: Perovskite Solar Cells and Its Economic Viability

Gaveshana A. Sepalage[1*], T. A. Nirmal Peiris

[1]*Department of Materials Science and Engineering, Monash University, 3800, Clayton, Victoria, Australia.*

Solar energy is plentiful. Over the last decades, a significant portion of the energy market has been acquired by solar power. There are several types of solar cells in the market chosen, dependent on the application (Nayak et al., 2019). Silicon solar panels are commonly found in solar farms, and for domestic use, or in other words, it is the market leader. However, due to the specific processing of the silicon materials and lack of practical applicability due to its rigid and opaque nature, the worldwide deployment of silicon technology is still not at an appreciable level, especially in developing countries. Based on this, alternative approaches have been widely studied, out of which the most relevant technologies to mention here are Dye Sensitized Solar Cells (DSSCs) (Kokkonen et al., 2021) and Organic Photovoltaics (OPV) (Inganäs, 2018). DSSCs and OPV are based on materials that are easily processed compared to silicon and have attractive characteristics such as color variability and transparency, so they can be applied to windows and can be integrated into building aesthetic designs. With the continuous developments in these technologies, scientists were refining them to beat the efficiency and the stability achieved by its rival silicon solar cells.

Perovskites and Sunlight

In 2009, a compound showing a perovskite crystalline structure (Figure 1) was found to possess remarkable absorbance in the visible region of the sunlight (Kojima et al., 2009). Also, it shows compatibility with all the techniques learned from DSSCS and OPVs, making scientists divert their research interest to this direction. Solar power conversion efficiencies (PCE) of perovskite devices, up to 2011, were below 10% (Roy et al., 2020). Surprisingly, in a decade, the efficiency has grown from 12% to 25%, which is itself a record (Li et al., 2022). Digging into deep, why perovskite attracted much attention can be justified by its potential to pass the theoretical efficiency achieved by other solar cell types. The theoretical efficiency means the percentage of power that can be generated compared to the incident power by the sunlight. This is explained by the Shockley–Queisser limit. For an ideal band gap (unique property to a semiconductor) of a material of 1.34 eV, the maximum limit of theoretical percentage power conversion efficiency is 33.7%.

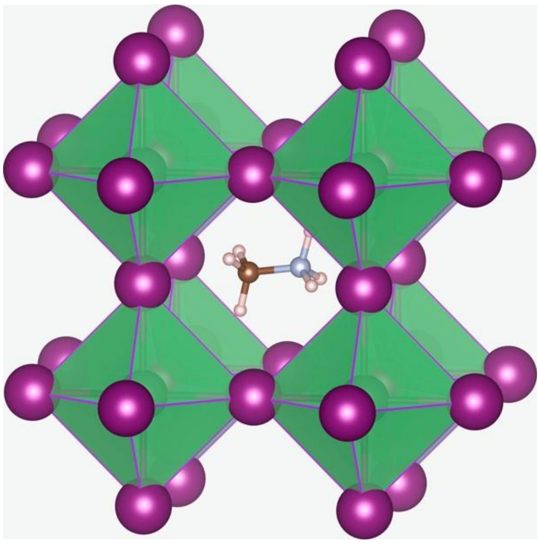

Figure 1, Crystalline structure of perovskite type materials, Methylammonium cation ($CH_3NH_3^+$) occupies the central *A* site surrounded by 12 nearest-neighbour iodide ions in corner-sharing PbI_6 octahedra. *Image Credit: Reproduced under a creative commons license © Eames, C., Frost, J., Barnes, P. et al. Ionic transport in hybrid lead iodide perovskite solar cells. Nature Communications 6, 7497 (2015).*

The question is if any known usable material has this band gap? The answer is no. Silicon has a band gap of 1.2 eV where the maximum theoretical efficiency limit is 32%. The remarkable property of the perovskite material is that it has a variable band gap, including the ideal theoretical band gap of 1.34 eV coupled with strong absorption coeffciencies. Achieving a perovskite with this band gap is up to the material scientists by tuning the composition of the perovskite. Furthermore, multiple perovskite solar cells can be integrated to absorb various parts of the sun's energy and maximise the energy harvest. Also, perovskite devices can be coupled with other types of devices to maximise the absorption of the solar spectrum (Extance, 2019). For example, combining perovskite with the best silicon solar cells can shift the practical conversion efficiencies beyond 30 %. For these reasons, the perovskite technology research has been receiving funding significantly across the globe, and the number of research publications exceeds that of any other competitor technologies.

How is it made?

Though there are various types of perovskite device structures, herein describes three of the simplest types. They are made with lab-scale techniques (Type A), a printable technique (Type B) and by integration into another device (Type C) (Figure 2).

**Correspondence: gaveshana.sepalage@monash.edu*

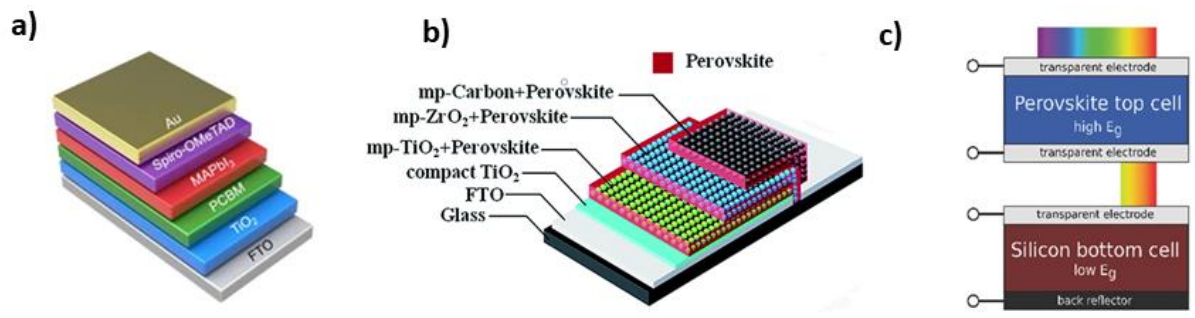

Figure 2, Device structures made by lab-scale techniques (Type A (a)), a printable technique (Type B (b)) and integration to other device (Type C (c)). Type A: Image Credit: *Reproduced under a creative commons license* © Wei, H., Zhao, X., Wei, Y. *et al.* Flash-evaporation printing methodology for perovskite thin films. *NPG Asia Mater* 9, e395 (2017), Type B: Image Credit: *Reproduced under a creative commons license* © Y. Zhang, J. Wang, X. Liu, W. Li, F. Huang, Y. Peng, J. Zhong, Y. Cheng and Z. Ku, *RSC Adv.*, 2017, 7, 48958 Type C: Image Credit: *Reproduced under WILEY-VCH Verlag GmbH & Co. KGaA licence* © Christophe Ballif, Bjoern Niesen, Jérémie Werner, *Adv. Mater. Interfaces* 2017, 5, 1, 1700731.

In Type A, the device fabrication starts with a glass substrate that is modified to be electrically conductive by applying a transparent conductive oxide layer (TCO) which is commercially available. Next, solution chemistry comes into play, where the electron transport materials, perovskite precursors (light absorber), and hole transporters are deposited by spin coating of each layer, followed by annealing or drying steps after each deposition. Finally, the metal electrode is deposited via a vacuum evaporation method. These types of devices have passed the PCE of 25% and have been reported by several laboratories around the world. In type B, every layer is printable and scalable. The electron transport layer and electrodes are printed on top of each with subsequent annealing after each deposition. Afterwards, the perovskite material solution is infiltrated into the device and dried, making a complete device. Type C is the next level of this technology, where a perovskite device has been integrated into a silicon solar cell and called a tandem device. In this case, the process started with a silicon solar cell, and various other layers are deposited by evaporation and solution processing to make the perovskite solar cell on it. The device structures discussed above show how versatile the perovskite solar cells can be.

Where are perovskites in the energy market?

Can we buy a perovskite solar cell in the market? The answer is no. The technology is still young to go to the end user. Though we discussed the remarkable qualities of material and the technology, there is a certain requirement that the technology needs to meet for it to come into the market, which is called levelized cost of the electricity (LCOE, which means how much the customer need to pay for a kWh. This parameter includes a wide range of costs, i.e. making solar cells, acquiring the local permits, installation, and device lifespan. Though the perovskite technology has proven to be efficient and versatile, some aspects still need to be improved. Figure 3 shows the calculation of LCOE assuming the device show 25 years lifetime. For the utility purpose, the perovskite solar cells need to demonstrate 17% efficiency, and tandem cells need 28% to beat the current Si utility level energy market.

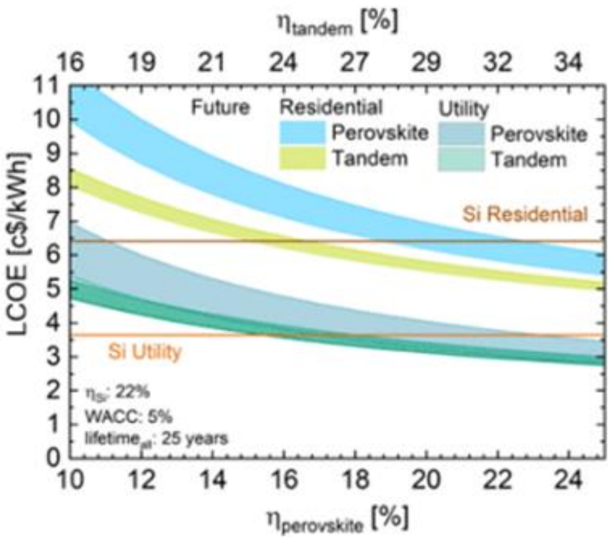

Figure 3, LCOE comparison graph of different device technologies. Image credit: *Reproduced under a creative commons license* © L. A. Zafoschnig, S. Nold and J. C. Goldschmidt, "The Race for Lowest Costs of Electricity Production: Techno-Economic Analysis of Silicon, Perovskite and Tandem Solar Cells," in *IEEE Journal of Photovoltaics*, vol. 10, no. 6, pp. 1632-1641.

It is quite clear that efficiency is not a hurdle. Two main obstacles are the toxicity of lead materials in perovskite and the stability of devices (Zientara., 2021). Lead, which is the base metal ion of the perovskite, is known to be neurotoxic; hence the application of this will not be easy without lead tight encapsulation that is a hundred percent guaranteed for the lifespan of the device. Alternative approaches with other metals are being investigated and reported to be promising (Wang et al., 2021). The stability of the device varies depending on device structures and the materials chosen. Some studies have shown a still comparatively low standard stability and experimental large-scale production of modules (Dipta and Uddin, 2021) (Liu et al., 2022). In this context, the technology has to go through more refining at the research level before it hits the market in terms of stability and eco-friendliness.

Perspectives on deployment

As outlined earlier, the perovskite solar cell technology is versatile in device structures, printable on to different types of materials and has less technological requirements making the technology establishment feasible even in the developing countries. The basic components such as lead iodide and methyl ammonium iodide are relatively cheap to synthesize, while carbon, titanium dioxide, and zirconium oxide are also easily accessible. When considering device structure B, in particular to Sri Lanka, materials like carbon are plentiful, and the production technologies are available. Furthermore, titanium dioxide is available, and process techniques can be introduced, while aluminium oxide and lead iodide are accessible. Though unavailable at the initiation, transparent conductive oxide coated glass can either be purchased or can be developed at a reasonable cost. However, the payback to the economy of home harvested energy is tremendous as it will relieve the country from being solely dependent on fossil fuel imports. Hence, the perovskite technology can be readily deployable across the globe compared to many other solar technologies.

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**Correspondence: gaveshana.sepalage@monash.edu*

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