MONOGRAPH
METODE SCIENCE STUDIES JOURNAL (2024). University of Valencia.
ISSN: 2174-3487. eISSN: 2174-9221.
Submitted: 01/03/2024. Approved: 09/05/2024.
https://doi.org/10.7203/metode.15.28390

PEROVSKITE SOLAR CELLS

Towards the net zero scenario

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At present, there is an urgent need to reduce greenhouse gas emissions to mitigate the climate change that threatens humanity and our planet's ecosystems. A way to achieve this is by increasing renewable energy production, where solar photovoltaic plays a key role. However, the current commercial crystalline silicon photovoltaic technology might not be enough to achieve the required targets. In this work, we describe the latest advances of an emerging photovoltaic technology known as perovskites. In just ten years of development perovskite solar cells have matched the performance of current commercial crystalline silicon. Here, we outline how to scale and improve the stability of perovskite solar cells as well as examples of applications such as their integration with silicon solar cells, semitransparent solar cells, and their use in outer space.

Keywords: **perovskite solar cells**, **metal halide perovskites**, **solar photovoltaics**, **perovskite-silicon tandem cells**, **net zero emissions**.

THE CURRENT ENVIRONMENTAL CRISIS AND CHALLENGES

It does not matter which indicator we pick, whether it is global average surface temperature, sea temperature, or atmospheric temperature. They are all going up. The ten warmest years since records are kept all occurred since 2010. 2023 was the hottest year on record after an extreme summer in the northern hemisphere. It becomes more urgent than ever to reduce greenhouse gas emissions, one of the main drivers of the steady increase of temperature, to transition to renewable energy sources and, ultimately, to reach a net zero emissions scenario.

In this context, the European Union has put in place the European Green Deal, where a carbon-neutral future is envisioned with the goal of net zero emissions in 2050 and an intermediate target of a 55 % greenhouse gas emissions reduction by 2030. For the energy sector, the Renewable Energy Directive has established a binding target for the share of renewable energy sources in energy consumption for 2030. The latest environmental and geopolitical events have resulted in multiple modifications of this target moving the goal from 32 % to at least 42.5 %, aiming for 45 % in the March 2023 revision. Solar photovoltaic (PV) technology plays a key role in the renewable energy mix and the European Union has acknowledged it in their REPowerEU plan, where they have approved to deploy a total of almost 600 GW of solar PV capacity by 2030.

«Solar photovoltaic technology plays a central role in order to achieve a net zero emission scenario»

However, as much as setting goals and writing them down is an easy task, translating these numbers into

HOW TO CITE:
Tordera, D., & Bolink, H. J. (2025). Perovskite solar cells: Towards the net zero scenario. *Metode Science Studies Journal, 15*, 81–86. https://doi.org/10.7203/metode.15.28390

the real world might turn out to be a little bit more complicated. The current PV capacity in Europe as of 2023 is 260 GW. With the 600 GW goal in mind, 340 GW capacity needs to be added in the upcoming seven years. If we consider that a standard commercial silicon photovoltaic panel has an area of 1.7 m^2 and a power rating of 400 W, this implies that to install PV for 1 GW we need two and half million panels (with a total surface of nearly 5 km^2). Hence, 340 GW requires almost 1 billion panels covering an area of around 1500 km^2. That is a large amount of panels to be produced and it remains unclear if the current supply chain can satisfy this need. Moreover, this would be for Europe only. The rest of the world is also increasing its PV installations and for a global net zero scenario, a staggering installed capacity of 6044 GW is needed by 2030, according to the International Energy Agency (www.iea.org). The global manufacturing capacity of solar PV has increased significantly over the last years and is expected to grow further with a predicted 1TW in 2024, as per the same agency, but as the population and energy needs increase, it might not be enough. The main way to decrease the needed number of solar panels is to increase their efficiency. However, current commercial crystalline silicon solar panels have stagnated in efficiency with values between 15 and 22 %. In this scenario, it seems that novel PV technologies can help reach these goals in a market currently dominated by crystalline silicon (with more than 97 % market share).

> **«The main way to decrease the needed number of solar panels is to increase their efficiency»**

PEROVSKITE PHOTOVOLTAIC TECHNOLOGY

An emerging technology known as perovskite is in the PV spotlight. After merely ten years of development, this novel thin-film PV technology has already surpassed all other competing thin-film technologies with a certified power-conversion efficiency of 26.1 % on single-junction cells, a value that matches that of lab-scale single crystal silicon (Liang et al., 2023). This technology is based on a metal halide perovskite absorber. Metal halide perovskites (henceforth, perovskites) are a class of compounds with the chemical structure of ABX_3, where A is a monovalent (organic or inorganic) cation, B is a divalent metal, and X is a halide (Figure 1) (Manser et al., 2016). In particular, perovskites incorporating Pb^{2+} in the divalent site have shown outstanding optoelectronic properties (Fakharuddin et al., 2022; Zhang et al., 2022).

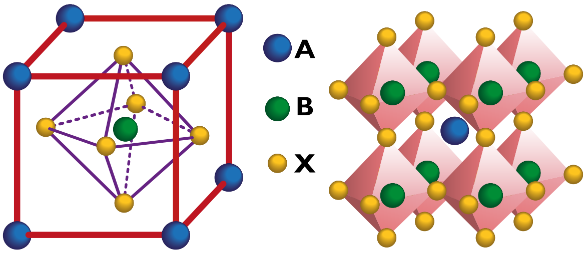

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Figure 1. Schematic presentation of the crystal structure of a perovskite with the chemical formula ABX_3, where the A cation is usually $CH_3NH_3^+$, $NH_2CHNH_2^+$, Cs^+; the B cation is Pb^{2+}, Sn^{2+}; and the X anion is a halide: I^-, Cl^-, Br^-. It is worth noting that this structure is common to a myriad of materials, but due to their electrical properties, the halide perovskites are the ones used for photovoltaics.

Perovskites have large light absorption coefficients, allowing them to efficiently absorb incoming light, long diffusion lengths and high carrier mobilities, required for efficient charge extraction, and doping-free bandgap (the difference between the valence and conduction band) tunability, so they can be engineered to absorb in the different visible and near-infrared regions of the electromagnetic spectrum (Adinolfi et al., 2018; Herz, 2017). Moreover, they have shown to have a very high defect tolerance, maintaining their desirable optoelectronic properties. This opens the possibility to be processed using simple and inexpensive coating methods such as solution process and dry vacuum deposition. Perovskite PV can be processed using high speed manufacturing techniques, allowing for low-cost final products. Finally, it is worth noting that the raw materials for perovskites are cheap and abundant.

A perovskite solar cell consists of a stack of multiple layers. The total thickness of the solar cell is commonly below 1 µm, resulting in a lightweight easily integrable device that uses a low quantity of material (Basumatary & Agarwal, 2022). In the stack the active metal halide perovskite layer is sandwiched between two charge transport layers (electron and hole transport layers) whose roles are to facilitate the transport and extraction of the photogenerated charge carriers, and to act as an energy barrier to block undesirable charge carrier injection (holes or electrons, respectively) and prevent charge recombination. They are essential for an efficient functioning of the solar cell. Two electrodes top the device on each side, so the generated charges can be extracted. At least one of these electrodes should be semitransparent, to allow

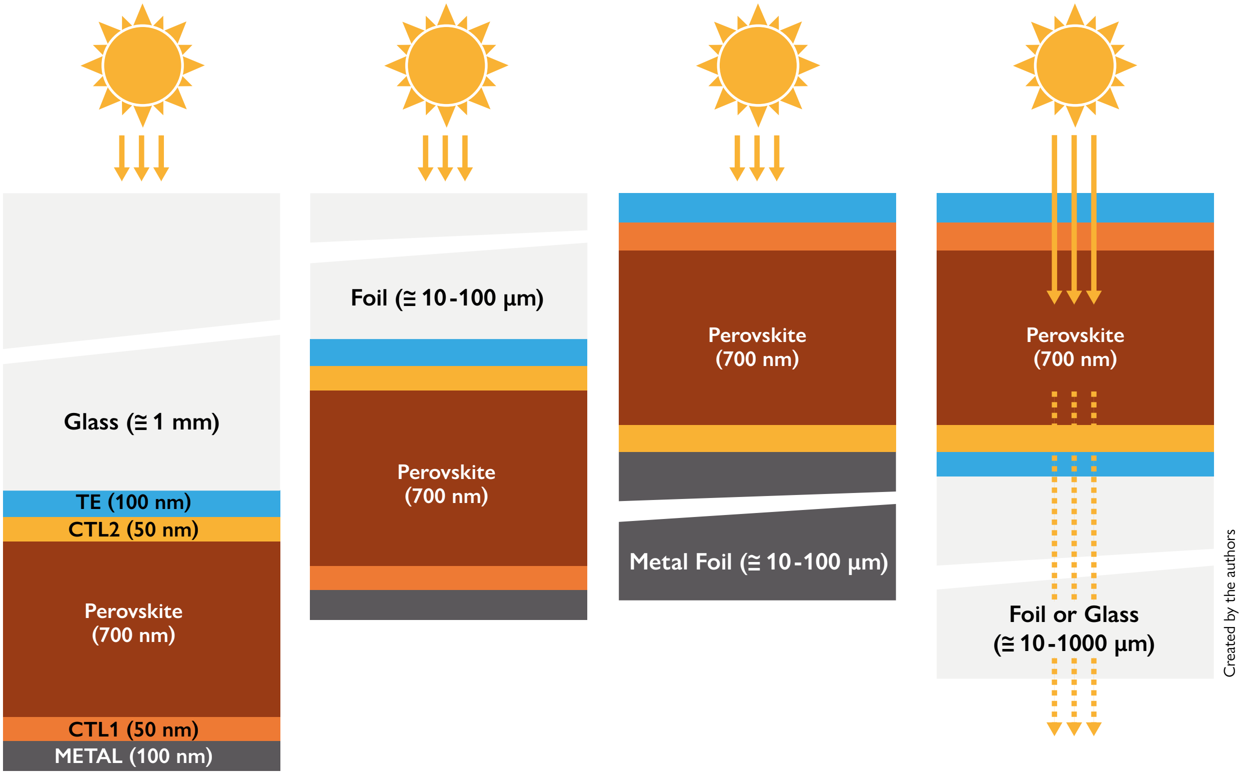

Figure 2. Different perovskite solar cell architectures. Glass (type 1), foil based (type 2a), metal or metal-coated foil (type 2b), and semitransparent devices (type 3). TE: transparent electrode, CTL1 and CTL2 = charge transport layers with opposite carriers (holes or electrons). Credit: Created by the authors.

sunlight to penetrate into the active perovskite layer. The other electrode can be a metal, acting as a mirror to reflect back light into the active perovskite layer, therefore increasing the total absorption, or another semitransparent electrode, for applications where transparency is needed. The full perovskite solar cell can be integrated into different types of substrates: rigid glass, metal foil, or flexible plastics. Figure 2 shows different examples of perovskite solar cell architectures.

More importantly, the perovskite solar cell can be integrated on top of a commercial silicon solar cell in a so-called multi-junction or tandem solar cell (Raza & Ahmad, 2022). This is possible due to the aforementioned tunability of the perovskite bandgap. In other words, the perovskite solar cell can be engineered to absorb high energy (short wavelength) photons while the silicon cell absorbs low energy (high wavelength) photons, thus each subcell responds to different wavelengths of light. This results in a larger power per area generation, therefore a smaller area is required, which minimizes the impact on the natural environment and urban design. Indeed, perovskite-silicon tandem cells have achieved efficiencies of 33.9 % (Longi, 2023). As silicon requires to have a textured surface (1-4 µm) to be highly efficient, the top perovskite needs to be conformally coated, which is not an easy task. Recent studies have shown that the perovskite-silicon tandem PV cells can compete with current commercial solutions, with a reduction of 11 % of the levelized cost of energy (the minimum price at which energy must be sold for an energy project to break even) (Messmer et al., 2021).

«An emerging technology known as perovskite is in the photovoltaic spotlight»

Most of the current research effort in perovskite solar cells is done using solution-process fabrication methods. These methods are convenient on the lab scale as they are cheap and straightforward. However, they are not easily transferable to the industry, which relies on dry vacuum processing. Vacuum processing is a readily scalable technique that allows for high reproducibility, large-area substrates and, at the same time, miniaturization of every single cell (Lee et al., 2022). Moreover, dry processing does not require the use of solvents, which need to be carefully handled and recycled, due to their inherent toxicity. Finally, these deposition methods are more suitable for coating a conformable layer of perovskite over the textured silicon in the multi-junction perovskite-silicon cells. On the other hand, vacuum processing often relies on the sublimation of perovskites by co-deposition from multiple precursor sources or by sequential methods, a process that needs to be tuned and optimized to obtain efficient perovskite solar cells (Ávila et al., 2017). It becomes clear that the route to market perovskite solar cells must be achieved by fully processing them using dry vacuum techniques (Paliwal et al., 2023).

LATEST DEVELOPMENTS ON VACUUM-DEPOSITED PEROVSKITE SOLAR CELLS

As high efficiency perovskite solar cells have been reached on single junction and tandem cells, the focus is now mainly on increasing the stability of these cells and on scalable production methods that can produce larger area cells and modules while maintaining the high efficiencies. More and more research groups and also companies focus their attention on vacuum-based processing methods for the deposition of the perovskites. For example, the research group Molecular Opto-Electronic Devices[1] directed by Dr. Bolink at the University of Valencia (Spain) has published over 130 scientific publications since their first paper in *Nature Photonics* in early 2014 on perovskite films and solar cells prepared using vacuum-based processing methods (Malinkiewicz et al., 2014). Some of the latest achievements are listed below.

«Perovskite photovoltaics can be processed using high speed manufacturing techniques, allowing for low-cost final products»

Upscaling and industrialization of the deposition method

So far almost all vacuum-deposited perovskites are deposited in high vacuum chambers using co-sublimation of the precursors. This enables the control of the perovskite composition and purity but it is a rather slow progress, taking some two hours to complete a film. Using this method, we have achieved very high performing solar cells, reaching power conversion efficiencies of 21 %. To enable perovskite-based semiconductors to reach the next level, it is important to develop deposition processes that are compatible with upscaling and industrial speeds, while maintaining the high performances of the solar cells. For example, our group is working in a proof of concept project to advance new techniques to deposited perovskite films for photovoltaic applications. We designed and built a lab-scale close-space sublimation (CSS) tool and developed a process to make perovskite solar cells with power conversion efficiency of > 18 %. CSS is compatible with industrial deposition tools (it is used to produce thin film CdTe solar cells on very large scale by the company First Solar). CSS works with a simple roughing pump at pressures of 0.01 mbar, which is much easier to reach than the usually employed high vacuum $1 \cdot 10^{-6}$ mbar for conventional sublimation (Rodkey et al., 2024).

Improved stabilities of the perovskite films and solar cells

Using vacuum deposited perovskites we demonstrated the stability of solar cells for more than 2000 hours when kept at 85°C. Currently in the framework of the Horizon Europe project Valhalla[2] we are investigating how 2000 hours at 85°C can be extrapolated to outdoor conditions, with varying sunlight intensities (clouds, day and night cycles) and temperatures. We also intend to identify the degradation mechanism that occur upon prolonged stressing of the cells. For this we combine extensive photophysical and chemical analysis combined with device modeling and quantum chemical modeling. Ultimately, via this knowledge we intend to design more stable perovskites and solar cells so that they can also operate for 25 years in outdoor conditions.

Integration of perovskite front cells on silicon bottom cells for increased efficiencies

One of the unique features of sublimation of perovskites is the ability to conformally coat these films on virtually any substrate. This is important for perovskite-Si tandem cells as silicon is a so-called indirect semiconductor which means it is not a very good absorber of light. This may seem surprising as almost all solar cells are made of Si, but it is true. To ensure that all the available photons where the

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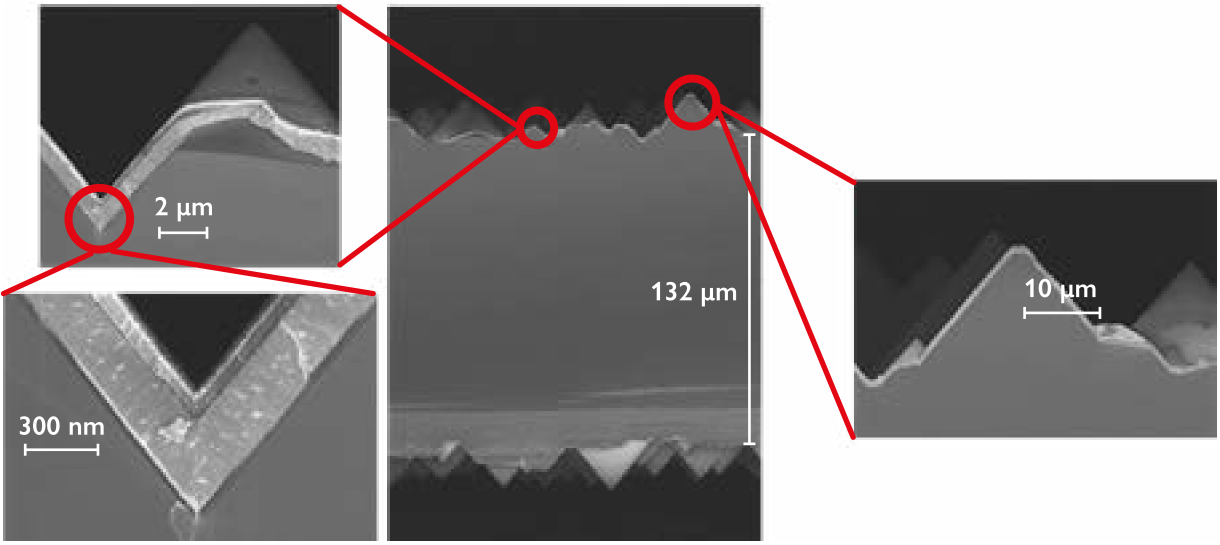
[1] www.moed.es

[2] https://valhalla-solar.eu



Nexus project

Figure 3. Scanning electron microscope images of the cross section of a 2 terminal perovskite-silicon solar cell. A full wafer (center, 132 µm) with three magnifications shows the perfect conformal coating of the perovskite top cell (only 1 µm).

silicon absorbs are in fact absorbed, Si-cells use light incoupling structures. These structures are small, usually below 10 µm, so not visible by the human eye, and appear as pyramids on the top and bottom of the cells. But by using a scanning electron microscope they can be visualized (Figure 3). To make a good tandem cell it is important that the top perovskite cell is perfectly coated on the silicon cell. State of the art Si wafers have a thickness in the range of 130 µm, whereas the perovskite top cell is in the µm range, which is much less than the height of the pyramids on the Si wafers. When zooming in using a scanning electron microscope on cross sections, it is possible to visualize the conformally coated perovskite top cell prepared by the MOED group. This is the work we are doing as part of Horizon Europe's Nexus project.[3]

> **«The full perovskite solar cell can be integrated into different types of substrates: rigid glass, metal foil, or flexible plastics»**

Semi-transparent solar cells

As mentioned, the solar cell market is dominated by silicon. Due to economy of scale it is not easy to compete with Si solar cells, even if in theory perovskites can be prepared more easily. But silicon is not transparent, as rather thick wafers need to be used. Perovskite, however, can be made semi-transparent simply by making the perovskite film thinner and by depositing transparent electrodes on both sides. By making the perovskite film thinner, part of the light is transmitted, which means it is not absorbed and thus the efficiency is somewhat lower than for the thicker films. Hence there is a trade-off between efficiency and transparency. This is of interest for applications on buildings, in particular on windows. We have achieved cells with an average visible transmittance of 50 % while still obtaining power conversion efficiency above 8 %.

Space application of perovskite solar cells

As already mentioned, the perovskite solar cells is extremely thin, which means it has almost no weight. The weight is determined by the substrate. Hence if we use a thin plastic or a metallic foil it is possible to make solar cells with very high power per weight. This is of interest for mobile applications, such as vehicle integrated PV but also for high altitude and space applications. We collaborate with Airbus Defense and Space with the aim to design thin perovskite solar cells films and launch them to space on a mini-satellite (Figure 4).

■ CONCLUSIONS

Solar photovoltaic technology plays a central role in order to achieve a net zero emission scenario. However, the current commercial technology based on silicon might fall short. Perovskite is a thin-film

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[3] **https://nexus-pv.eu**

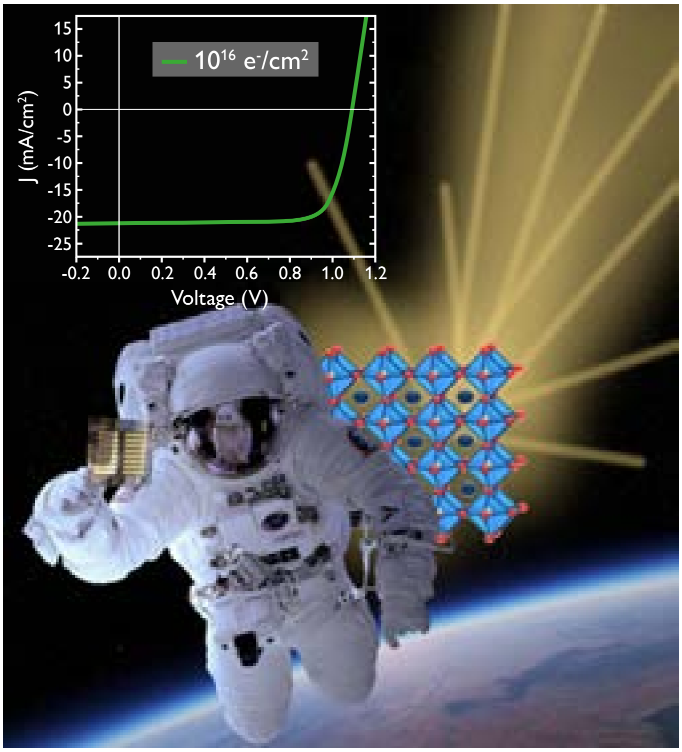

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Figure 4. Artistic impression of a perovskite solar cell in outer space, with the perovskite crystal structure and a solar cell J-V curve.

> **«Perovskite is a thin-film PV technology that has already shown high efficiency, as well as many desirable functional properties, and can also be combined with silico»**

PV technology that has already shown high efficiency, as well as many desirable functional properties, and can also be combined with silicon. Here we show how this perovskite technology can be scaled up and industrialized using a near space sublimation fabrication technology, as well as means to improve its stability under different conditions. The processing conditions of perovskites allow them to be coated on top of silicon, to combine their efficiencies, and due to their thickness (below 1 µm) they can be made into semitransparent devices or integrated in applications where weight is a key factor, such as vehicles and space.

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ACKNOWLEDGMENTS

Daniel Tordera acknowledges the support of the Ministry of Science and Innovation (MCIN) and the Spanish State Research Agency (AEI): Project PID2022-139910NB-I00, funded by MCIN/AEI/10.13039/501100011033 and by FEDER, a way to make Europe.

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