**Solar Cells, The Case for Perovskite Tandem Cells**

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**Perovskite Solar Cells**

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**Introduction to Solar Cells**

Photovoltaic solar cells harvest energy from the sun, the giant power plant millions of miles away, and convert that energy into electricity through the photovoltaic effect to power our buildings and vehicles. And the types of solar cells are great in number. The bigger the size of a solar cell, the lower the rate of efficiency it can achieve. We need to extract more efficiency from solar cells, through better utilization of the sun’s spectrum, and at a lower cost. Improving material quality and optimizing designs are key to unlocking higher efficiencies. New developments are being made every day to increase efficiency and stability of solar cells, utilizing precursors, or substances, such as silicon, perovskite, and kesterite. Silicon is currently the workhorse of solar cells, available in monocrystalline cells, polycrystalline cells, heterojunction (HJT) cells, TOPCON, or PERC cells. Advancements in efficiency, lifetime, and resistance have been achieved with solar panels, including both monocrystalline silicon and perovskite. However, the focus of this paper is on the potential for perovskite solar cells, as perovskite is a mineral with superior absorption properties, albeit stability issues, which can be combined in tandem perovskite-silicon tandem cells to achieve high operating efficiencies.

A tandem cell is a multi-junction cell where multiple solar cells are stacked on each

other in with decreasing energy band-gap, which allows them to capture more energy from the sun. The first material, or top cell, absorbs the high energy photons (light), but transmits photons with lower energies, which then get absorbed in the cell below, bottom cell. There are also triple junction tandem cells, but the focus of this research is on tandem cells with two junctions, often a perovskite top layer, and a silicon bottom layer. Tandem solar cells can be more efficient than single-junction solar cells, with the top efficiency rating for tandem perovskite-silicon cells pegged at 34.5%. Tandem cells can convert a wider range of solar spectra into electricity, and can be more cost-effective than other solar technologies. The materials used in the cells must be compatible with each other over a wide range of temperatures, the thermal expansion coefficients of the materials must be similar, and the bandgaps of the materials must be a good match to the spectrum.

While solar PV avoids the emission of carbon dioxide, it also contributes to landfill waste from the decommissioning of old solar modules, some of which cannot be recycled. Rüther and Blakers (2024B) estimate that each kg of solar panel generates about 0.9 MWh over its lifetime, which allows avoidance of about 900 kg of carbon dioxide from coal burning – a ratio of 900:1, assuming future PV module mass of 25 W/kg (excluding frame), a capacity factor of 16%, and module lifetime of 25 years. The efficiency loss in a photovoltaic module can range from 0.4% to 5% per year, depending on the climate and materials used. Manufacturing technology, aimed at increasing PV module power, is advancing rapidly. Panels are increasing in size and cell efficiency is also increasing. Between 1980 and 2020, a 76% reduction in the weight-to-power ratio of PV modules was achieved. This means that new panels can be mounted on existing support structures or trackers to produce much more power. Currently, the predominant technology in the global market is single crystalline silicon with an approximate module power ranging from 550 W to 750 W, compared with 350 W in 2019, less than 200 W in 2010, and below 100 W before 2000 (Rüther and Blakers, 2024B).

Solar cells can be classified into generations based on the active (sunlight-absorbing) layers used to produce them, with the most well-established or first-generation solar cells being made of single- or multi-crystalline silicon. Second generation includes thin-film technologies, made using thin layers of materials like amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs), and are known as thin-film vapor-deposited semiconductor-based solar cells (Snaith, 2013). Solar cells made with newer, less established materials are classified as third-generation or emerging solar cells, which includes other thin-film technologies, such as perovskite, dye-sensitized, quantum dot, organic, and kesterite (CZTS) thin-film solar cells, and are known as solution-processed solar cells based on organic semiconductors, hybrid composites, or inorganic semiconductors (Snaith, 2013). DSSCs are composed of three main components, mesoporous n-type TiO2 that is sensitized with a light-absorbing dye and filled in with a redox-active electrolyte. With rigid or flexible perovskite solar cells manufactured with absorber layers of 0.2- 0.4 μm, perovskite cells result in even thinner layers than classical thin-film solar cells featuring layers of 0.5-1 μm. First-generation mono- and polycrystalline silicon cells offer high power conversion efficiency (PCE) and stability, though they have a relatively high manufacturing cost. Second-generation thin-film technologies, such as CdTe and CIGS, have lower manufacturing costs, can use flexible substrates for wearable devices, but they have lower efficiency and stability. Third-generation emerging PV technologies, such as CZTS, DSSCs, PSCs, organic photovoltaics, and quantum dot solar cells, are cost-effective and can be fabricated for a variety of applications, but have degradation and scalability issues. Flexible perovskite solar cells (fPSCs) have potential for various niche applications, including portable electronics, wearable power sources, electronic textiles, and large-scale industrial roofing (Mishra et al., 2021).

c-Si PV modules technology features an Al-BSF structure, using monocrystalline c-Si (Mono c-Si) or polycrystalline c-Si (Poly c-Si) for the absorber layer. c-Si and perovskites have different light absorption potential. According to Table 1, crystalline silicon can only absorb wavelengths equal to or superior to 1,100 nm, while perovskites can be tuned wavelengths of 850 nm, which is a wider variety of colors in the solar spectrum. Thin-film solar technology is known for its great performance at different temperatures due to low-temperature coefficients, with perovskite having a temperature coefficient of -0.13%/ºC, only bested by GaAs solar cells with a temperature coefficient of 0.09%/ºC, as shown in Table 1.

A bio-based ultraviolet (UV) protection film made from red onion dye (nanocellulose, a nanoscale biopolymer) has been constructed that has the potential to replace conventional petroleum-derived materials such as polyvinyl fluoride (PVF) and polyethylene terephthalate (PET) in solar cells. The films have been tested on dye-sensitized solar cells, and can be applied to perovskite and organic cells. UV radiation (wavelengths below 400 nm) degradation occurs in solar cells, necessitating protective films to improve UV protection while maintaining transparency of near-infrared light (700 - 1,200 nm) in order to ensure efficient photovoltaic conversion (Nizamov et al., 2025; Sinha, 2025).

**Table 1. Silicon v. Perovskite**

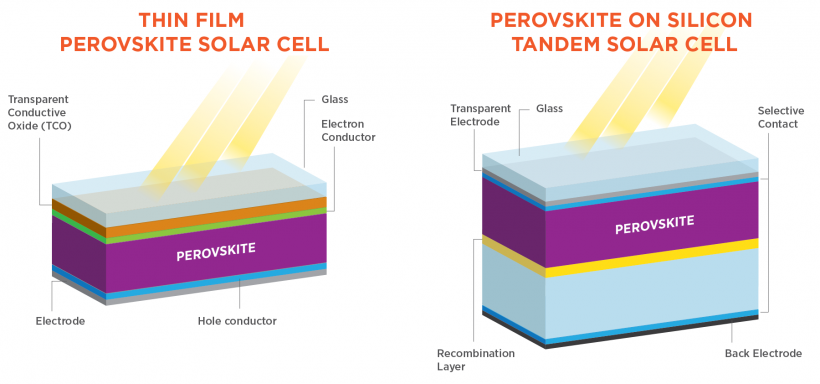
|  | **Monocrystalline Silicon (mono c-Si)** | **Polycrystalline Silicon (poly c-Si)** | **Perovskites** |
| --- | --- | --- | --- |
| **Highest Recorded Efficiency** | 25.4% | 24.4% | 29.15% |
| **Lifespan** | 25-30 years | 25-30 years | 30 months (2.5 years) |
| **Light Absorption Potential** | Wavelengths of of light of 1,100 nm | Wavelengths of of light of 1,100 nm | Wavelengths of light of 850 nm |
| **Temperature Coefficient** | -0.39%/ºC | -0.38%/ºC | -0.13%/ºC |
| **$** | $0.16/W -$0.46/W | $0.24/W | $0.16/W |
| **Applications** | Residential and Industrial | Residential and Industrial | Potential for residential, commercial, industrial, Building Integrated Photovoltaics (BIPV), tactical, and space applications. |

Solar Mag (2022) <https://solarmagazine.com/solar-panels/perovskite-solar-cells/#:~:text=Perovskite%20silicon%20tandem%20solar%20cells,silicon%20(nc%2DSi)>

perovskite film quality optimization, additive engineering, interface engineering, and device structure engineering.

The stability and high performance of PSCs depends on a range of factors from film morphology to encapsulation (Roy et al., 2020; Li et al., 2018; Miah et al., 2024; Zhao et al., 2018A; Ding et al., 2024). Material engineering is a broad field that involves topics such as perovskite absorber layer engineering, interface engineering, device architecture, fabrication techniques, strain engineering, and compositional engineering (Prakash et al., 2018; Bakr et al., 2017). The perovskite absorber layer must be optimized through the selection of the appropriate substrate and precursor solution, with additive engineering playing a role for functional additives and dopants to be mixed with the precursor, and post-treatment techniques such as including thermal annealing (Syed et al., 2022) and solvent engineering (Chao et al., 2021) being employed, to further polish film quality and optimize the perovskite layer for enhancing charge transportation and light harvesting through tuning the bandgap (Liu et al., 2015; Kim et al., 2017A; Dualeh et al., 2014; van Franeker et al., 2017; Vásquez-Montoya et al., 2021; Zhang and Park, 2024). Interface engineering considers the charge transport layers, optimizing the electron transport layer to improve electron injection and extraction and optimizing the hole transport layer to enhance hole extraction and transport (Chen and Park, 2020). The device architecture can be either planar (Soonmin et al., 2023), mesoporous (Ming et al., 2024), or inverted (Li et al., 2024B), and includes the selection of charge transport layers through interface engineering, and passivation strategies to reduce recombination losses and increase the charge extraction efficiency (Krishna et al., 2021; Miah et al., 2023). Fabrication procedures such as solution processing, vapor deposition, and printing methods need to be monitored to create acceptable film morphology, crystallinity, and defect density (Bhattarai et al., 2022; Jamal et al., 2018; Krishna et al., 2021; Dubey et al., 2018). Strain engineering is a method to enhance device performance by modifying electron or hole mobility to reduce microstrain in the perovskite crystal structure (Tao, 2022). Compositional engineering considers modifying the A-site cation such as MA and FA, B-site cation such as tin or lead, and halide X-site anion (Parrott et al., 2016; Shi et al., 2015; Brenner et al., 2016; Liu et al., 2019A). Cell stability and consequently operational lifetime are enhanced with effective encapsulation strategies that shield cells from environmental degradation factors like moisture, oxygen (Miah et al., 2023; Singh et al., 2020).

**Figure 2. Perovskite Cell and Tandem Cell**



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<https://www.solarreviews.com/blog/are-perovskite-solar-cells-the-future-of-solar-power>

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**Perovskite Solar Cells and the Mineral Perovskite**

Solar cells create electricity via the photovoltaic effect, which is the conversion of energy from the sun into electricity (Mohd et al., 2007; McKagan et al., 2009). To create the photoelectric effect, and create electricity, photons must be converted into electrons, and to accomplish this task semiconductor materials, such as silicon or perovskite, are required (Ho, 2016; Koch et al., 2006). Semiconductor materials can be either organic or inorganic (Ho, 2022; Sabah et al., 2020; Costa et al., 2016) substances. Inorganic semiconductors also include: silicon (Si), germanium (Ge), gallium arsenide (GaAs), and cadmium sulfide (CdS). Examples of inorganic perovskites include: (where X = I, Br, Cl), (promising for photoferroelectrics), and (lead-free). Inorganic semiconductors are typically single crystals or thin films, whereas organic semiconductors are often amorphous or polycrystalline. Organic semiconductors (OSCs) are built from organic π-conjugated materials or polymers, typically made of carbon and hydrogen, and sometimes with other elements like nitrogen, sulfur, or oxygen, with good charge transport and/or electroluminescent properties, and widely used in organic and hybrid electronic devices such as organic light emitting diodes (OLEDs), organic photovoltaic cells (OPVs) and organic field-effect transistors (OFETs) (Forrest, 2004; Zhao and Zhan, 2011; Kalyani and Dhoble, 2012; Hains et al., 2010; de Leeuw and Cantatore, 2008; Coropceanu et al., 2007; Pron and Rannou, 2002). Possible organic semiconductor materials include: polycyclic aromatic hydrocarbons (PAHs), metal complexes, and small compounds derived from conductive polymers such as polyacenes, polyphenylamines and polythiophenes (Podeszwa, 2010; Hirose et al., 1996; Norton and Houk, 2005; Shirota, 2000; Yang et al., 2008).

Perovskite solar cells (PSCs) are named for their crystal structure, and are manufactured from a three-dimensional material called perovskite. The name perovskite originates from the structural form of the family of compounds of the original substance, calcium-titanium-oxide , found in the Ural Mountains by German mineralogist Gustav Rose and named for Russian mineralogist Count Lev Alekseyevich von Perovski in 1839 (Miah et al., 2023D). The first perovskites discovered were the mineral composed of calcium titanium oxide , but other perovskites such as methylammonium lead triiodide are being utilized for solar cells. Perovskite can be modified to adopt custom physical, optical, and electrical characteristics. Perovskite solar cells are referred to as thin film cells, because they require much thinner active layers relative to crystalline silicon PV, and commonly use lead-containing perovskite materials, although research is aimed at creating lead-free and thus toxic-free perovskites. Perovskite solar cells are also known as third generation, or emerging technology solar cells, along with organic and dye-sensitized solar cells. Perovskite solar cells, also known as metal-halide perovskites, since they can be made of a combination of organic ions, metals, and halogens, are in demand because of their potential for high performance and low production costs. However, issues remain in developing large-scale manufacturing processes for PSCs, as most experiments create smaller devices, and in improving their durability and stability under real-world conditions such as heat and moisture exposure outside (Garcia, 2024). Perovskite solar cells have increased in efficiency from 3% in 2009 to over 25% in 2025. The theoretical efficiency of perovskite-silicon tandem cells is 43%, which makes them the most feasible alternative to current mono-junction silicon cells (Boyd, 2023).

**Figure 3. Atomic Structure of Lead Halide Perovskite Crystal**

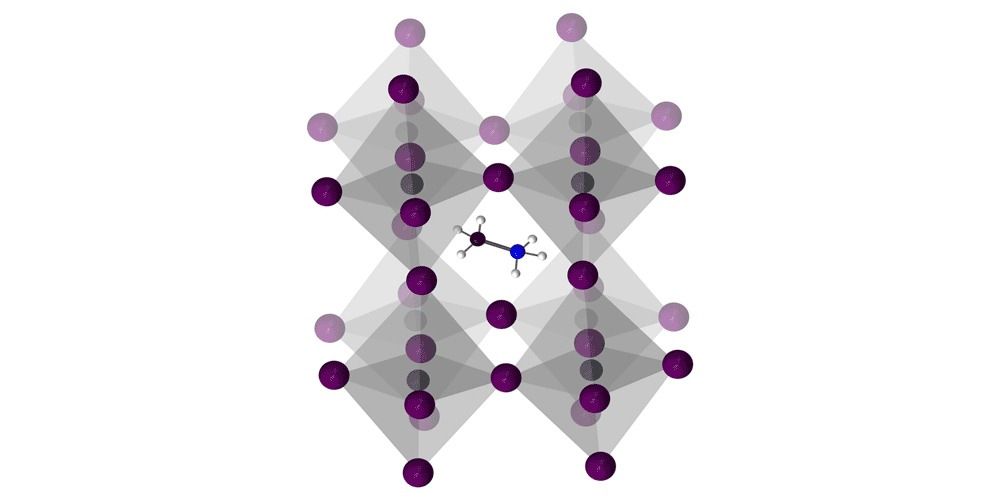


Image: Miyata, K., Atallah, T.L., Zhu, X., et al. (2017) Science Advances, Volume 3, Number 10, <https://www.science.org/doi/10.1126/sciadv.1701469>

Figure 3 shows the atomic structure of a lead halide perovskite crystal, with a grid of 8-sided molecules called lead halides (an atom of lead connected to 6 halogen atoms of either iodine, chlorine, or bromine), surrounding a smaller molecule known as a methylammonium cation.

Perovskite solar cells are thin-film devices built with layers of materials, either printed or coated from liquid inks or vacuum-deposited. Mass manufacturing of perovskites necessitates maintaining the high efficiencies achieved in smaller experiments, while achieving stability in large-area modules. It is important to remember when discussing scaling up small experiments to large modules that the bigger the size of a solar cell, the lower the rate of efficiency it can achieve. PSC cells are easier to produce than silicon and can be made in a single factory, so even with other manufacturing attributes included, the overall cost of production is only half of that of traditional silicon cells. PSCs have lower fabrication cost, low-temperature solution processability, roll-to-roll manufacturing, and wide-bandgap tunability (Bati et al., 2023; Cuthbertson, 2023A). The third-generation perovskite solar cell can convert 50-75% more sunlight into electricity than the traditional silicon photovoltaic cell. Perovskite is also 95% cheaper than the silicon solar cell, for one key raw material, methylammonium lead iodide (Lin et al., 2023; Pao, 2023). Perovskite solar cells are also efficient in harvesting diffuse solar radiation, ambient indirect light, or light at lower light intensities, as when the sun is not shining directly on the perovskite solar cell.

Perovskites are not just used in solar cells. They can be utilized in other energy technologies, such as fuel cells, catalysts, photodetectors, lithium-ion batteries, and even LEDs. Perovskites used in applications other than solar cells may be made of oxygen or nitrides instead of halogens and are usually entirely inorganic. Perovskite LEDs have been described as being cheaper, brighter, and greener than traditional LEDs (Puiu, 2025). Unlike traditional LEDs, which rely on expensive and energy-intensive materials like gallium nitride, perovskite LEDs (PeLEDs) can be manufactured using simpler, less costly processes. A comprehensive life-cycle assessment (LCA) found that the environmental impacts of PeLEDs primarily stem from the inputs of substances and electricity during production. Raw materials, particularly organic cleaning solvents like acetone and isopropanol, are particularly impactful (Puiu, 2025). When used in photodetectors, perovskites can be used to fabricate highly sensitive X-ray detectors, with MAPbI3 PDs having an X-ray sensitivity of . Perovskites can also be used in lithium-ion batteries as electrode materials due to their good ionic conductivity and high diffusion coefficients.

Rethink Energy thinks that by 2026, every mainstream silicon manufacturer will have committed to perovskite products, and expects that perovskites will completely take over solar during the 2030s, regardless of whether the industry reaches 1 TW or 2 TW in scale. There are two minimal reasons for this forecast. First, perovskites will be so disproportionately cost-effective that once the tipping point is reached, they will be adopted quickly. Second, perovskites have the potential for superior performance and price, and thus can enable additional solar demand, such as green hydrogen complexes. Perovskites adoption has the ability to help Europe and the United States reclaim a share of global solar manufacturing, while India, which is still switching from multicrystalline to monocrystalline passivated-emitter rear contact solar (PERC), might be slower to adopt to perovskites (Wantenaar, 2023).

Perovskites with tin or lead are preferable for making organic or inorganic solar cells, however, lead-free perovskites are preferable for environmental concerns. Current research in perovskites is aimed at reducing or eliminating the toxic lead content in perovskite solar cells. Two advantages of perovskite over silicon are that perovskite is easier to manufacture, and perovskite can be tuned to the ideal bandgap. Silicon solar cells are more difficult to make than perovskites, as silicon must first be heated to extremely high temperatures to produce material with the right purity and crystal structure to make electricity. Perovskites have a simpler precursor manufacturing process, known as wet chemistry, where chemicals are mixed in solution and a surface, substrate, is coated with that solution. Perovskites can also be tuned to the ideal bandgap, the amount of energy needed to push an electron to a higher energy level so it can carry an electrical charge across a circuit, by controlling the kinds of molecules that are mixed, or produced, in the precursor manufacturing process (Zientara, 2025).

Perovskite solar cells are a type of thin-film solar cell that use perovskite-structured compounds to harvest light. The perovskite layer needs to be several hundred nanometers thick to harvest light effectively. Perovskite solar cells differ by device architecture or material composition.

**Architecture**

Various structures of perovskite solar cells such as mesoporous n-i-p, p-i-n, planar, and inverted structures have been developed (Kim et al., 2018; Khatoon et al., 2023A). A n-i-p structure is used when the light enters through the electron transport layer deposited on TCO (Transparent Conducting Oxide). Conversely, a p-i-n structure occurs If light enters through the hole transport layer deposited on TCO.

***Thin-film perovskite solar cells***

Thin film perovskite solar cells have perovskite as the only photovoltaic material. There are also thin-film tandem cells with a perovskite layer on top of copper indium gallium selenide (CIGS), which is an already-perfected thin-film solar technology.

***Tandem/Multijunction Cells***

Tandem cells have either multiple layers of perovskite or a thin perovskite layer on top of traditional crystalline silicon. A tandem cell consists of a top cell based on a perovskite absorber and a bottom cell with a silicon structure, including heterojunction (HJT) structure. Tandem solar cells are made by stacking multiple solar devices on top of each other to increase the amount of electrical energy. Tandem cells use a bottom absorber layer, such as silicon, to use the colors of light not absorbed in the perovskite top layer, resulting in a cell that can be theoretically more efficient than cells made of either material on their own.

***Inverted perovskite solar cells***

Inverted perovskite solar cells use a hole-transport layer, such as PEDOT:PSS, PTAA, or P3CT-X. Metal oxides, such as MoO x, GeO 2, and NiO x, can be added to the PEDOT:PSS thin films to improve photovoltaic performance. Inverted are a type of perovskite solar cell structure where the electron-transport layer (ETL) and hole-transport layer (HTL) are reversed compared to conventional structures, and employ a "p-i-n" architecture, where the hole-selective contact (p) is at the bottom, followed by the intrinsic perovskite layer (i), and the electron transport layer (n) at the top.

***Mesoporous***

Mesoporpus is a type of perovskite solar cell structure where the perovskite material forms a porous network, with the device structure being composed of glass/fluorine-doped tin oxide (FTO)/dense electron transport layer (ETL)/mesoporous oxide layer/perovskite layer (~500 nm)/hole transport layer (HTL)/metal electrode (Ming et al., 2024; Zhao et al., 2014; Burschka et al., 2013; Nadi et al., 2017; Nadi et al., 2021). When mesoporous is used as an ETL material, perovskites can penetrate into the pores to form an interconnected absorbing layer, with titanium dioxide ) preventing the electron-hole recombination in the FTO by blocking the holes. Other oxide materials such as zinc oxide (ZnO), aluminum oxide , and zirconium dioxide have also been used as mesoporous oxide layers, with Spiro-OMeTAD (2,2′,7,7′-Tetrakis [N, N-di(4-methoxyphenyl) amino]-9,9′-spirobifluorene) being the most used HTL and noble metals such as Au, Ag, and Pt used as the counter electrodes (Soonmin et al., 2023). Mesoporous perovskite layers, on the other hand, place the liquid perovskite solution over scaffold materials, with the materials for the mesoporous scaffold layer being conductors like titanium dioxide (TiO2) and Zinc Oxide (ZnO), or insulators like Aluminum Oxide (Al2O3) and Zirconium dioxide (ZrO2). A mesoporous architecture is similar to solid-state DSSC (Hagfeldt et al., 2010), and consists of crystalline organic–inorganic halide perovskite, a mesoporous electron transport layer (generally mesoporous TiO2 and an additional compact TiO2), and a hole transport layer between a TCO and metal contact (Kim et al., 2017B; Ma et al., 2018; Khatoon et al., 2023A). Sintered nanoparticles on the TiO2 layer to make it mesoporous.

However, high-temperature sintering process (usually over 500 °C) required for preparing mesoporous TiO2 films complicates device fabrication and increases energy consumption and thus device cost, which is incompatible with the fabrication of flexible PSCs (Chen et al., 2019).

***Planar***

Planar is a type of perovskite solar cell structure where the perovskite material forms a flat film, and the mesoporous ETL scaffold is removed and only two sharp interfaces are observed between perovskites and two transport layers (ETL and HTL), with a rapid and effective separation of electrons and holes as observed through the ETL and HTL, respectively (Liu and Kelly, 2014). Planar is simply a perovskite absorber layer between the electron transport layer and the hole transport layer (Yang et al., 2016B). As planar heterojunction structures have a minimum number of interfaces, the operating mechanisms of light absorption and electron-hole separation are seen more clearly, which optimizes the structure for the development of highly efficient laminated perovskite photovoltaic cells (Soonmin et al., 2023). Planar architectures are less efficient but industrially preferred over the mesoporous structure, and are more commonly used as they are more compatible with flexible and tandem applications. (Wang et al., 2019; Khatoon et al., 2023A).

***ETL-free and HTL-free***

Configurations that eliminate the need for electron and hole transport layers, respectively. Perovskite solar cells without HTL have advantages of easy and simple device fabrication and high stability (Shi et al., 2014), and the perovskite materials in these cells serve the purpose of both light absorbers and hole transport channels (Soonmin et al., 2023).

**Material**

***3D Lead Halide Perovskites***

3D lead halide perovskites are the most common to date, and have high efficiency but low stability due to sensitivity to environmental factors such as heat and moisture. An example is methylammonium lead halide (MAPbI3).

***2D Perovskites***

2D perovskites are layered structures with perovskite material interleaved with organic molecules, offering improved stability compared to 3D perovskites but with generally lower efficiency.

***Lead-Free Perovskites***

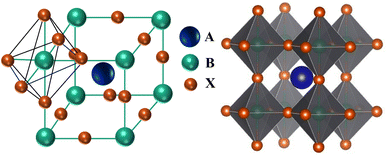
Due to environmental and health concerns, research is ongoing into lead-free perovskites, although lead-free have a lower efficiency than lead-based perovskites. Examples include tin-based, bismuth-based, and antimony-based perovskites.

**Perovskite Chemistry**

The simple cubic structure with (A) ions at the corners of a cube with (B) ions at the body center and (X) ions at the center of the faces is called perovskite, even though, was later determined to be of orthorhombic symmetry at room temperature (Megaw, 1946). Akkerman and Manna (2020) define a perovskite crystal lattice as a network of corner-sharing octahedra that crystallize with a general stoichiometric structure, where in a halide perovskite, A is a monovalent cation (for example, formamidinium, methylammonium, cesium, etc.) located at the center of a cuboctahedral cavity that is surrounded by eight octahedra and coordinated by 12 halide anions. B is a divalent metal cation that occupies the center of the octahedron, and X is a halide anion located at the corner of the BX6 octahedron (Boro et al., 2022). In a non-halide perovskite, A is a cation, B is a metal cation, and X is a non-halide anion (typically oxygen, but also can be sulfide or nitride) (Rahman et al., 2023). The cubic perovskite structure is comprised of corner-sharing octahedra, which form a 3D network with A-site cations in the 12-fold coordinated (cuboctahedral) vacancies to ensure charge neutrality (Figure 4) (Aftab and Ahmad, 2021; Kumar and Naidu, 2021). Conversely, the perovskite material may be viewed as a cubic close-packed sublattice with divalent B-site cations inside six-fold coordinated (octahedral) cavities. Perovskite is perhaps the most adaptable type of crystal lattice, as there are a few natural forming perovskites, such as oxides, with the majority being silicates, but they also exist as fluorides, chlorides, hydroxides, arsenides, and intermetallic compounds. Additionally, synthetic perovskites span across the whole periodic table in terms of elemental composition, and they can exist in many complex formulas, such as metallic perovskites, hybrid organic–inorganic perovskites, metal-free perovskites, and even noble-gas based perovskites (Akkerman and Manna, 2020). Since the A cation must fit between the corner-sharing metal halide octahedra, there is a relatively small size range allowed for it within the metal and halide structure. If the A cation is too large, the 3D perovskite structure is unfavourable, and a lower-dimensional layered or confined perovskites will be formed (Mitzi, 1999; Eperon et al., 2014). If the A cation is too small, the lattice would be too strained to form. The tolerance factor describes the limits on ionic sizes of each component in the perovskite structure.

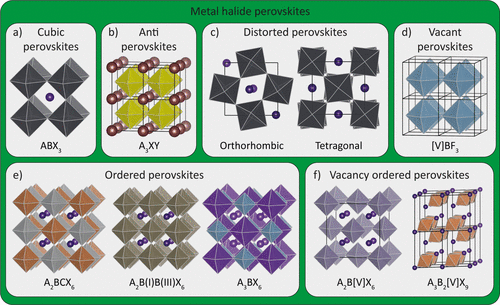
Akkerman and Manna (2020) give a succinct description of what makes a halide perovskite. A halide perovskite has a halide ion (like Cl, Br, or I) at the X-site in the structure. Conversely, a non-halide perovskite has an oxide or other non-halide anion at the X-site. Halide perovskites have superior light absorption and efficiency over non-halides perovskites, however, they suffer from stability issues, including sensitivity to humidity and oxygen, in addition to potential toxicity of some lead-based halide perovskites. Halide perovskites are primarily used in solar cells, whereas non-halide perovskites can be used in various applications beyond solar cells, including catalysts, fuel cells, and electronic devices. In a non-halide perovskite,halogens can be replaced by oxygen, nitrogen, or carbon. For example, A and B are often represented as divalent and tetravalent ions, respectively, when oxygen is utilized instead of halogen for charge neutrality (Park, 2015). Metal halide perovskites consist of lead , methyl-ammonium , an organic cation, and a halide anion such as iodide (I) or bromide (Br). There are a wide variety of unique component combinations which perovskite structures can be built from, and by changing the composition of these substances, perovskite crystals with a variety of properties, including physical, optical, magnetic, and electrical, may be produced. Perovskite compounds are classified into alkaline metal halide perovskites, inorganic oxide perovskites, and organic metal halide perovskites (Chen et al., 2018).

**Figure 4. Schematic Diagrams of Perovskite**



Miah, H., Khandaker, M.U., Rahman, B. (2024) RSC Adv., 14, 15876-15906, <https://pubs.rsc.org/en/content/articlehtml/2024/ra/d4ra01640h>

**Figure 5. Overview of Different Halide Perovskites**

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Akkerman, Quinten A. and Manna, Liberato (2020) ACS Energy Letters, Volume 5, Issue 2, <https://doi.org/10.1021/acsenergylett.0c00039>

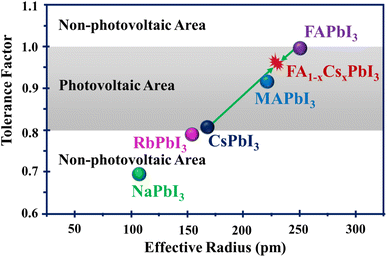
Figure 5. Overview of different halide perovskites. (a) Standard ABX3 cubic halide perovskites. (b) Antiperovskites, with A being a monovalent metal (like Li+ or Ag+), X a halide, and Y a chalcogenide. (c) Common orthorombic and tetragonal disordered perovskites, arising from the tilting of the octahedra. (d) Vacant BX3 perovskites, like AlF3. (e) Ordered perovskites, where two M(II) metals are replaced by a M(I) and M(III) metal. (f) Vacancy-ordered perovskites, where a part of the B-site cations are replaced with a M(III) or M(IV) and vacancies.

Moller (1958) first discovered halide perovskites for cesium lead halides. Shortly after, from the analysis of Goldschimdt’s tolerance factor/octahedral factor, it was observed that small organic molecules with effective radii less than 260 pm could also accommodate the inside of the lead halide octahedrons. Weber (1978) successfully synthesized (X = halogens (I, Br, Cl or mixtures of them) and superhalogen ) for the first time (Weber, 1978). Arend et al. (1978) began work on layered 2D perovskite systems began (commonly, , where the extended inorganic lead halide octahedral cage is separated by large organo-ammonium cations. Snaith (2013) reports that the field of dye-sensitized solar cells (DSSCs) precipitated and lead to solar cells employing perovskite absorbers (Hardin et al., 2012; O’Reagan et al., 1991), by replacing a liquid sensitiser with a solid-state dye. Kojima et al. (2009) began work on 3D hybrid perovskites as absorbers in mesoporous solar cells. Perovskite cells have grown in use as absorber materials in photovoltaic cells since 2009 and have achieved PCE as high as 25.7% in single junction (NREL, 2025) and 29.8% in monolithic perovskite/Si tandem solar cells ([Figure 6](https://www.mdpi.com/2076-3417/13/4/2051#fig_body_display_applsci-13-02051-f006)) (Soonmin et al., 2023).

As crystal-structure changes can impact the stability of perovskite materials, the Goldschmidt tolerance factor is a dimensionless parameter and is used to predict the geometrical distortion and stability of perovskite structures based on the sizes of the cations and anions in , and it plays a critical role in influencing the symmetry and formation of perovskite materials. Goldschmidt (1926) defined the tolerance factor (t) to account for the limits of the size of the cations to form a perovskite structure as , where , and are the effective ionic radii for A, B, and X atoms respectively. The tolerance factor of a given perovskite indicates whether the perovskite will adopt a 3D structure, as tolerance factor values greater than 1 or less than 0.8 tend to result in non-photovoltaic perovskite structures, so it should be within the range of 0.80 < t < 1.0 to sustain the 3D structure (Ramos-Terrón et al., 2020; Mailadil, 2008; Valipour et al., 2020; Stoumpos and Kanatzidis, 2015). Bartel et al. (2019) reports the t should be between 0.825 < t < 1.059, and Tidrow (2014) places it at 0.77 < t < 1.05. Tolerance factors for perovskites also indicate whether the perovskite crystal phases will demonstrate a cubic phase (t ≈ 1), a tetragonal phase (0.9 < t < 1.0), or an orthorhombic phase (0.8 < t < 0.9) (Li et al., 2016A; Gao et al., 2020). Another crucial parameter known as the octahedral factor, μ, is used to forecast the formation of the octahedral and the stability of the perovskite structure. This factor is defined as the ratio of the ionic radius of the divalent cation to the ionic radius of the anion . This octahedral factor needs to be within the range of 0.414 < μ < 0.732 to facilitate the formation of the octahedral (Miah et al., 2025; Wang et al., 2023; Bartel et al., 2019). If t > 1, the A cations have large size and the B cations are small so that B ions have larger room to move. For t < 1, the B cations have large size. In fact, t is related to the packing of ions in the perovskite cell. When t = 1, a perfect cubic cell is formed. When t deviates from 1, the perovskite cell gets deformed and the symmetry is lowered. As for vacancy-ordered double perovskites, a branch of lead-free halide perovskites, Goldschmidt’s tolerance factor and octahedral factor to double perovskites are applicable for A2BX6 double perovskites in analog with ABX3 perovskites (Fedorovskiy et al., 2020). The stability and formation of a perovskite structure is dictated by the Goldschmidt tolerance factor as a general geometric guideline. The tolerance factor has limited the choice of cations (A) in 3D lead iodide perovskites (APbI3) (Fu et al., 2019).

The desired and most stable phase of the perovskite is known as the α-phase, which has a highly symmetrical cubic or tetragonal crystal structure, allowing for effective charge transport. The δ-phase, conversely, possesses less stability and symmetry, does not have the desired perovskite structure, is frequently seen at lower temperatures, and doesn't allow effective charge movement. The two organic cations commonly found in perovskite compounds are methylammonium and formamidinium . The perovskite contains two phases, the photoactive black α-phase with a large tolerance factor at temperatures higher than room temperature, and the non-photoactive yellow of at room temperature, or in a humid environment (Han et al., 2016; Masi et al., 2020; Pool et al., 2017; Zheng et al., 2016). Various complex perovskite compositions have been developed to prevent the formation of the δ-phase, as mixing with a combination of methylammonium , cesium and bromide ions prevents the formation of the δ-phase because the tolerance factor is altered with the combination of the larger ionic radii of and , along with the smaller radii of and stabilizing the α-phase, (JIn-Wook et al., 2015; Yoo et al., 2021; Sabina et al., 2016; Chen et al., 2023). However, mixed perovskites develop an enlarged bandgap and light-induced phase segregation (photoinduced halide phase segregation) which negatively affects cell performance and operational stability and effective charge transport, because segregation leads to the formation of I-rich and Br-rich domains with distinct bandgaps. (Yang et al., 2023; Cui et al., 2022; Draguta et al., 2017; Slotcavage et al., 2016; Brennan et al., 2017).

When exposed to sunlight, films perform better on stability tests, or possess better photostability, than , which expresses phase instability (Yang et al., 2015; Abdelmageed et al., 2018; O’Kane, 2025; Kogo et al., 2018; Ünlü et al., 2020), thus replacing with can improve the thermal stability of the films with the perovskite cell possessing better light absorption and narrower bandgap (Binek et al., 2015). Studies have shown that the absorber layer decomposes during the annealing of the film at 85 °C in an inert atmosphere (Yang et al., 2019; Syed et al., 2022; Lee et al., 2015A; Conings et al., 2015; Han et al., 2015). undergoes a phase transformation from the tetragonal to cubic phase at 54–57 °C, but there is no phase transformation in and in the temperature range (40 °C to 85 °C) (Onoda-Yamamuro et al., 1990; Baikie et al., 2013; Asghar et al., 2017), which leads to issues such as the formation of defects, reduced mobility of charge carriers, shorter diffusion lengths, alterations in the band structure, and increased recombination losses within the absorbing material (Roghabadi et al., 2019; Ball and Petrozza, 2016).



*Miah, H., Khandaker, M.U., Rahman, B. (2024) Band gap tuning of perovskite solar cells for enhancing the efficiency and stability: issues and prospects, RSC Adv., 14, 15876-15906,* [*https://pubs.rsc.org/en/content/articlehtml/2024/ra/d4ra01640h*](https://pubs.rsc.org/en/content/articlehtml/2024/ra/d4ra01640h)

The goal for any solar cell is the combination of high-power-conversion efficiency (PCE), yearlong lifetimes, and ultra-low manufacturing costs.

In order to assess the photovoltaic performance of perovskite devices, their excellent optoelectronic properties can be analyzed, including high absorption coefficients, tunable bandgaps, low exciton binding energy, ambipolar charge transportation, and long carrier diffusion lengths.

***Advantages of Perovskite***

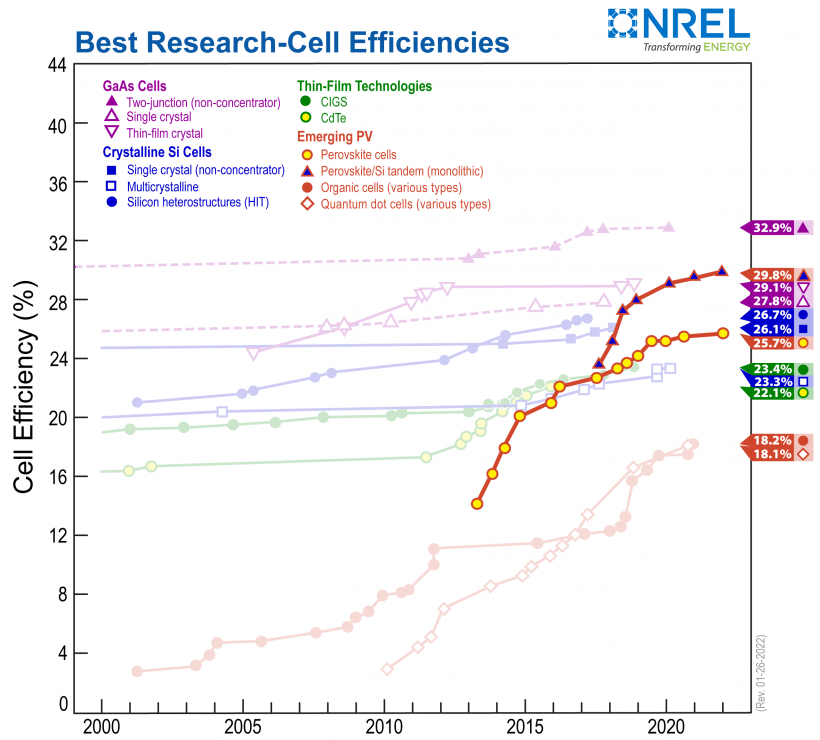
1. ***Simpler fabrication methods at low temperatures-*** Perovskite production methods like low-temperature solution processing do offer theoretical cost advantages, though actual costs remain elevated due to lower yields, challenges in process uniformity, and difficulties scaling up from lab to factory (Miah et al., 2023A; Miah et al., 2023B).
2. ***High power conversion efficiencies- High efficiency, the potential for higher energy conversion efficiencies-*** Perovskite material is able to convert light to electrical power at a similar efficiency to silicon. (Miah et al., 2023A; Barnard, 2025; Kim et al., 2012; Li et al., 2023A; Miah et al., 2023B)
3. ***Lower production/manufacturing costs-*** Perovskite PV cells are made using low-temperature processes and with the potential for ink-based printing of active layers. This may allow for more integrated manufacturing comprising of fewer, less expensive process steps and lower capital expenditure. Perovskite solar cells are cheaper to produce, owing to their inexpensive and naturally abundant materials (lead, iodine, carbon, and hydrogen) (Meng et al., 2018; Miah et al., 2023A).
4. ***Scalable manufacturing-*** Perovskite technology is scalable, and suitable for roll-to-roll printing and high-volume continuous manufacturing, though uniform coating, film homogeneity, and quality control remain persistent challenges.
5. ***High absorption coefficients-*** high optical absorption both in visible and IR regions (Long et al., 2020; Rahman et al., 2023)
6. ***Tunable bandgap, low bandgap with direct nature-*** A material with a low bandgap and a direct nature means the lowest energy transition between the valence and conduction bands occurs without a change in momentum, making it efficient for light emission and absorption. This direct bandgap behavior allows for a significant amount of light emission at room temperature, making it an ideal candidate for optoelectronic devices (Long et al., 2020; Rahman et al., 2023)
7. ***Long spin lifetimes-*** the time a spin-polarized electron maintains its spin orientation (Long et al., 2020)
8. ***Long carrier recombination lifetimes-*** the time a charge carrier (electron or hole) remains free before recombining (Stranks et al., 2013; Chen et al., 2017)
9. ***High carrier charge mobility-*** (Wehrenfennig et al., 2014; Chen et al., 2017; Rahman et al., 2023)
10. ***Large charge carrier diffusion length-*** (Long et al., 2020; Wehrenfennig et al., 2014; Rahman et al., 2023) long charge-carrier diffusion distances require both low recombination rates and/or high charge mobility. Satisfying both requirements simultaneously is generally difficult given the fundamental Langevin limit for kinetic recombination, which typically holds for conductors with charge mobilities below the order of (Pope and Swenberg, 1999)
11. ***Flexible application and design capability-*** ability to be applied to a variety of substrates, from rigid glass to flexible materials. Perovskite has flexibility, such as for wearable electronics or building-integrated photovoltaics (BIPV), however, the thin films are brittle and susceptible to cracks and degradation when repeatedly flexed or exposed to harsh environmental conditions.
12. ***No need for rare earth metals***
13. ***Tandem Cells Use-*** Perovskite absorber material can be stacked on top of a silicon absorber, which can convert light to electrical power more efficiently than either technology separately. Also, by changing the color of light absorbed by the perovskite (band gap), perovskites can be engineered to pair with many other solar materials in tandem solar cells and modules.
14. ***High Defect Tolerance-*** Perovskites appear to be more resilient to imperfections in their crystal structure relative to other conventional semiconductors. These solar cells show better defect tolerance than other solar semiconductors on the market (Ball and Petrozza, 2016), which increases their reusability and lowers production costs. (Yin et al., 2014; Chen et al., 2017)
15. Large and balanced electron-hole mobilities
16. High photoluminescence quantum yield
17. Low surface recombination velocity
18. ***Low exciton binding energy-*** (Soonmin et al., 2023)
19. ***Ambipolar charge transportation, Ambipolar Transport of Electrons and Holes-*** Ambipolar transport refers to the coupled movement of both positive and negative charge carriers (electrons and holes) in a semiconductor, ensuring that internal electric fields remain small. This means the motion of electrons and holes is not independent but rather occurs together as a single entity with a combined mobility and diffusion constant (Oga et al., 2014; Stranks et al., 2013; Lee et al., 2012; Xing et al., 2013; Rahman et al., 2023)
20. ***Great photocurrent generation-*** Due to the high light-absorption coefficient of perovskite solar cells, they possess great photocurrent generation (Meng et al., 2016).
21. ***Solution processability-*** Due to the high light-absorption coefficient of perovskite solar cells, they possess great solution processability (Kim et al., 2021A; Park, 2015; Tablero, 2019; Zhang et al., 2022).
22. ***Large Extinction Coefficient-*** (Xiao et al., 2016; Chen et al., 2017)

***Disadvantages of Perovskite***

1. ***Stability and Longevity***- Perovskites’ performance declines much more quickly than silicon when they are exposed to moisture, oxygen, heat and even light. The material will break down when exposed to heat, moisture, or snow (Zhao et al., 2018A; Ding et al., 2024; Khatoon et al., 2023)
2. ***Polar Solvents-*** Polar solvents, which can alter the solvated phases of a perovskite and might hydrate a perovskite to produce a monohydrate phase, can be prevented from harming perovskite solar cells by modifying deposition techniques (Askar et al., 2017).
3. ***Cost of Silicon Cells***- Silicon modules have become incredibly cheap and efficient over the past decade, and companies in China continue to expand manufacturing capacity at a startling rate. According to the U.S. National Renewable Energy Laboratory (NREL), current perovskite module manufacturing costs remain closer to $0.38–$0.50 per watt at smaller production scales—still above silicon’s well-established market price of roughly $0.20 per watt or lower.
4. ***Size***- The best perovskite cells made in labs are typically smaller than a postage stamp, the current leader is closer to the size of a sesame seed, and they might operate for only a few days or weeks before their performance degrades
5. ***Manufacturing Process, Scalability for Large-Scale Production***- They’re often made by dropping solutions of materials onto a spinning plate in a process called spin coating, which is impractical for large-scale manufacturing (Zhao et al., 2018A; Ding et al., 2024). complex fabrication processes due to polymer solubility limitations of existing conjugated polymers (Lin et al., 2025; Khatoon et al., 2023)
6. ***Decomposition and Encapsulation***- Although perovskites have a nasty habit of decomposing on contact with air or water, this can be prevented by encapsulating tandem cells in an impermeable coating, a common tactic in the solar industry
7. ***In-built degradation mechanisms that encapsulation cannot solve***- Some of the perovskite’s ions can move around during operation, for example, or escape into adjacent layers. This can create defects that enable electrons and holes to recombine before they can be turned into electricity, wasting the energy that created them. Light and heat tend to exacerbate these degradation mechanisms. To keep the perovskites’ ions in the right places, researchers have fine-tuned their composition and added nanometre-thick protective layers to the cells
8. ***Improved Efficiency-*** The power conversion efficiency of perovskite cells needs to be improved for large scale manufacturing to be cost effective.
9. ***Lead toxicity-*** Potential environmental impacts of perovskite materials, which are primarily lead-based. As such, alternative materials are being studied to evaluate, reduce, mitigate, and potentially eliminate toxicity and environmental concerns. Encapsulation techniques undoubtedly improve lead containment, but the eventual end-of-life handling of perovskite modules remains unresolved, creating a real barrier to their widespread adoption. When thin films use lead, and cracking and leaking of lead on human skin or buildings humans occurs.
10. ***Petroleum-derived polymers-*** environmental concerns about petroleum-derived polymers currently used as photoactive layers (Lin et al., 2025)
11. ***Current-voltage hysteresis between the forward and reverse bias-*** Hysteresis is commonly ascribed to the combination of ion migration with high levels of charge-carrier recombination. Hysteresis behavior in MAPbI3 solar cells (Snaith et al., 2014) is now attributed to both anion and cation (e.g., MA+) migration followed by accumulation at MAPbI3/contact interfaces. (Yuan and Huang, 2016; van Reenen et al., 2015) This leads to the formation of charge injection barriers as well as the screening of built-in fields, degrading device performance (Brennan et al., 2018; Salhi et al., 2018; Snaith et al., 2014; Kim and Park, 2014; Sanchez et al., 2014). Hysteresis in HPSCs denotes the fluctuations in the current-voltage response curves in which the corresponding photovoltaic parameters vary depending on the direction and rate of the scan. Many possible theories elucidating the origin or mechanism of hysteresis in HPSCs have been proposed such as (i) trapping of electronic carriers at the perovskite interface(s) (Shao et al., 2014; Xu et al., 2015); (ii) ionic displacement/ion migration (Tress et al., 2015; De Bastiani et al., 2016; Eames et al., 2015; Azpiroz et al., 2015); (iii) ferroelectric polarization (Wei et al., 2014; Chen et al., 2015; Frost et al., 2014), and (iv) capacitive effects (Almora et al., 2015; Juarez-Perez et al., 2014; Sanchez et al., 2014). A mesoporous layer can also be used to lessen the hysteresis behavior of a PSC. (Soonmin et al., 2023).

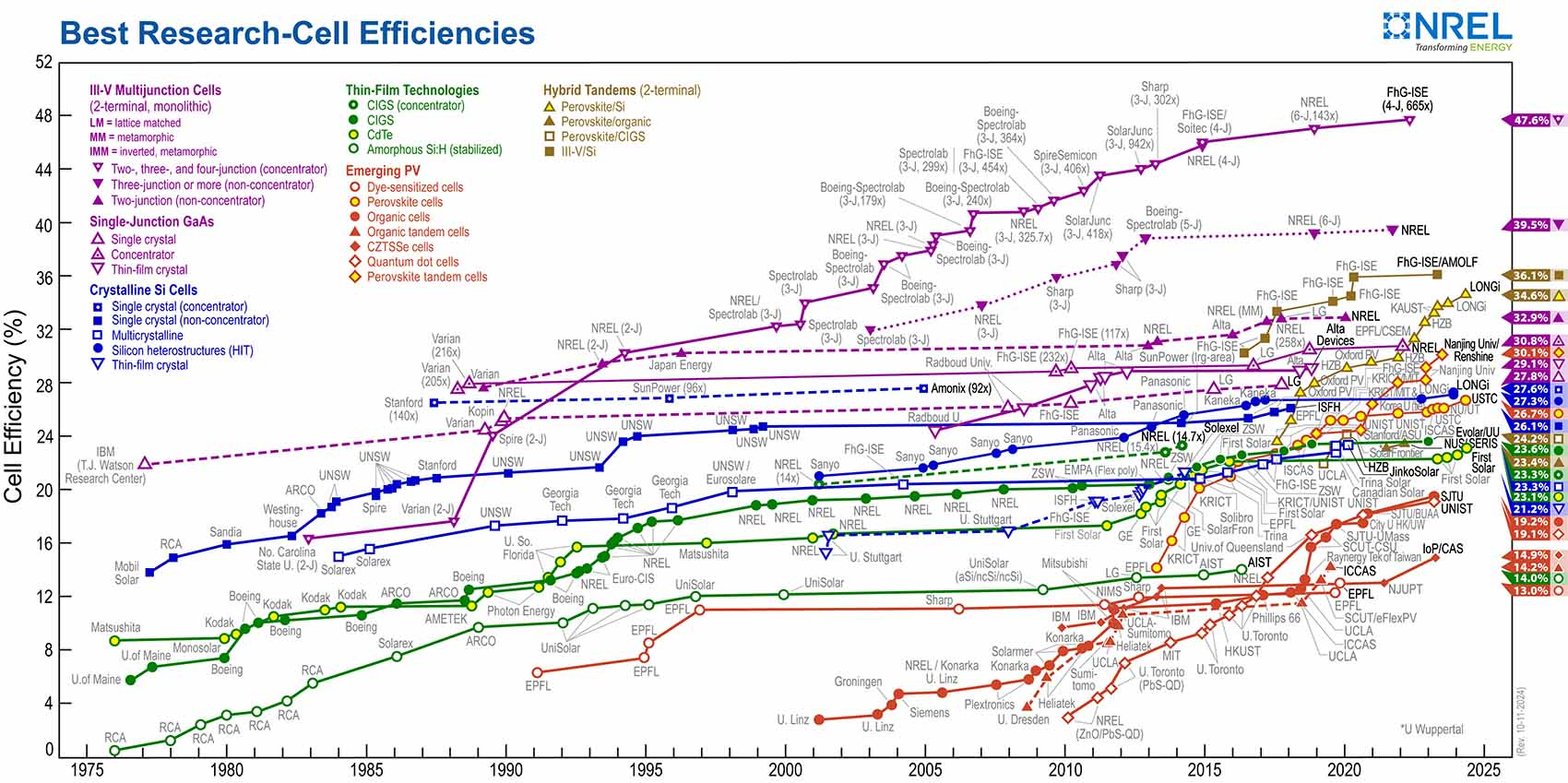
The advantages of these hybrid metal halide perovskites are tunable bandgap, large absorption coefficient, long diffusion length, simple processability, small exciton binding energy, compatible with large-scale solution processing such as roll-to-roll printing, and abundance of ingredients (Unger et al., 2017; Stranks et al., 2013; Lunardi et al., 2017).

The phase transformation affects the optoelectronic properties of PSC and degrades the photovoltaic performance of PSC. The Goldschmidt tolerance factor generally indicates the stability of the 3D perovskite structure

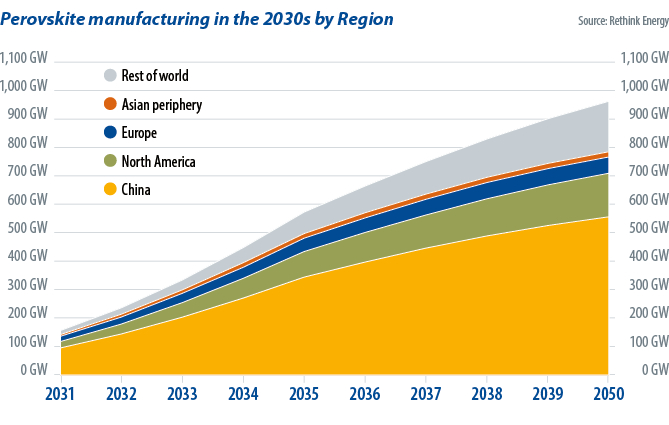


*Chart showing record efficiencies over time of perovskite PV devices compared to other PV technologies. Efficiency records for perovskite PV cells compared to other PV technologies, with current records of 25.7% for single junction perovskite devices and 29.8% for tandem perovskite-silicon devices (as of January 26, 2022).*

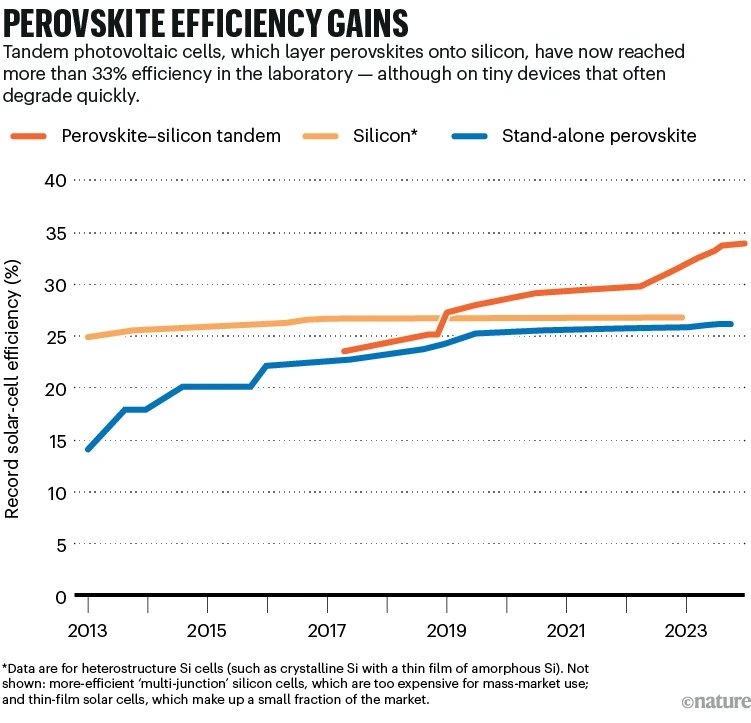
**Figure 6.** The efficiency records for perovskite solar cells and monolithic perovskite/Si tandem solar cells compared with other photovoltaic technologies (NREL, 2025).



<https://www.nrel.gov/pv/cell-efficiency.html>



*Image: PV Magazine,* [*https://www.pv-magazine.com/2023/10/31/commercial-perovskites-imminent/*](https://www.pv-magazine.com/2023/10/31/commercial-perovskites-imminent/)



*Image: US National Renewable Energy Lab,* <https://www.nature.com/articles/d41586-023-03714-y>

***Research Areas for Perovskite Cells***

1. Stability and Durability
2. Power Conversion Efficiency at Scale
3. Manufacturability
4. Technology Validation and Bankability

According to Soonmin et al. (2023), current research areas for perovskite solar cells includes: (i) reduction of halide defect sites through additives and passivation, (ii) the inclusion of 2D perovskites and better-optimized interface materials to increase the efficiency and stability, (iii) the use of inorganic charge-extraction layers rather than organic ones to improve both efficiency and stability, and (iv) proper understanding of charge-carrier transport mechanism.

Optimizing the absorber material to maximize above-bandgap absorption and minimize defect-related sub-gap losses is essential, contact layers are also a major source of transparency losses due to effects such as free charge carrier absorption. The balance between the cell’s optical transparency and electrical conductivity is a critical factor. To relax particularly current-matching constraints, concepts like luminescent coupling, wavelength-selective intermediate reflectors, or bifacial illumination may be considered (Schmid, 2025; Bellini, 2025GG). Furthermore, to make the most of the available solar irradiation, bifacial operation is recommended, as most silicon modules today are already bifacial (Schmid, 2025; Bellini, 2025GG). Bifacial tandem concentrator cells in a three-terminal configuration and combined with spectrum-splitting optics to reduce optical losses and improve adaptability to variable illumination are a future research area (Schmid, 2025; Bellini, 2025GG).

**Cell Stability and Durability**

Perovskites can decompose when they react with moisture and oxygen or when they spend extended time exposed to light, heat, and applied voltage. To increase stability, we must reduce degradation in both the perovskite material itself and the surrounding device layers. Perovskite solar cells presently have limited operational lifetimes, due to degradation from environmental stressors, and as solar cells need to last for up to two decades in the field, perovskite cell stability needs to increase before they can be mass produced. Early perovskite devices degraded rapidly, becoming non-functional within minutes or hours, though recently research groups have demonstrated lifetimes of several months of operation.[[1]](#footnote-0)

**Power Conversion Efficiency at Scale**

Perovskite PV cells have exceeded almost all thin-film technologies, except expensive III-V technologies, in power conversion efficiency, in small-scale single junction lab devices. However, for large-scale manufacturing, we must maintain these high efficiencies while achieving stability in large-area modules.[[2]](#footnote-1)

**Manufacturability**

Perovskite manufacturing processes need to be scalable and reproducible in order to enable commercial production of perovskite solar cells, and to meet or exceed SETO’s (Solar Energy Technology Office) levelized cost of electricity goals for PV. Perovskite solar cells are thin-film devices built with layers of materials, either printed or coated from liquid inks or vacuum-based deposition processed. Producing uniform, high-performance perovskite material in a large-scale manufacturing environment is difficult, which leads to a substantial difference between small-area cell efficiency and large-area module efficiency.[[3]](#footnote-2)

**Technology Validation and Bankability**

Technology validation, performance verification, and bankability includes ensuring the willingness of financial institutions to finance a project or proposal at reasonable interest rates. In order to compare performance across perovskite devices and to develop confidence in long-term operational behavior for real-world failure modes, we need standardized testing protocols, sufficient field data, and replicated results at third-party validation centers. Many perovskite testing protocols were developed from indoor testing protocols for silicon and CdTe cells, which degrade differently from perovskite, which also has rapidly changing material and device compositions. Objective and verified testing protocols are necessary to enable investment in production scale-up and deployment.[[4]](#footnote-3)

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**Perovskite Degradation and Stability Enhancement**

O’Kane, Mary (Retrieved May 21, 2025) Perovskite Solar Cells: Causes of Degradation, Ossila, <https://www.ossila.com/pages/perovskite-solar-cell-degradation-causes>

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***Strategies to Enhance Perovskite Stability***

1. Compositional engineering:
2. Mixed cations: Replacing a single organic cation (like methylammonium) with a mixture of cations (like formamidinium and cesium) can improve stability.
3. Mixed halides: Incorporating different halide ions (like bromine with iodine) can enhance the crystal lattice stability.
4. Surface modification:
5. Hydrophobic coatings: Applying hydrophobic materials on the perovskite surface can prevent water penetration.
6. Passivation layers: Using additives or interfacial layers to passivate surface defects and improve stability.
7. Device architecture:
8. Interface engineering: Optimizing the properties of the electron and hole transport layers to minimize charge carrier recombination at the interfaces.
9. Buffer layers: Adding a stable buffer layer between the perovskite and charge transport layers can protect the perovskite from degradation.
10. Encapsulation techniques:
11. Hermetic sealing: Protecting the perovskite device with a tightly sealed package to prevent exposure to environmental factors.

***Factors affecting perovskite stability:***

1. Moisture: Water molecules can penetrate the perovskite structure, causing degradation.
2. Oxygen: Exposure to oxygen can also lead to perovskite degradation.
3. Temperature: High temperatures can accelerate perovskite decomposition.
4. Light exposure: UV radiation can induce degradation in some perovskite materials.

Solar cells, silicon and perovskite, can be tested for stability by exposing them to different outdoor stressors conditions such as humidity, light and heat and under low temperatures. These individual factors act simultaneously in the real-world conditions to affect solar cell performance. When combined, for example, light and heat significantly accelerate performance degradation or cause new problems that were otherwise absent or occurring at slower rates when testing separately. High temperature and illumination is the most important combination of stressors for determining the performance of a solar cell outdoors. Perovskites can decompose when they react with moisture and oxygen or when they spend extended time exposed to light, heat, or applied voltage. By analyzing and altering the interfaces where the perovskite material meets other components within the cell, and studying degradation in both the perovskite material itself and the surrounding device layers, new strategies for enhancing stability and performance can be developed. Efforts include improved treatments to decrease the reactivity of the perovskite surface, alternative materials and formulations for perovskite materials, alternative surrounding device layers and electrical contacts, advanced encapsulation materials, and approaches that mitigate degradation sources during fabrication and operation. Varied test conditions include different encapsulation approaches, atmospheric compositions, illumination, electrical bias, and other parameters. To improve the stability of perovskites, researchers primarily focus on modifying the perovskite composition by mixing different cations and halides, incorporating additives to strengthen the crystal structure, utilizing hydrophobic coatings, and implementing protective encapsulation techniques to shield the perovskite from environmental factors like moisture, oxygen, and UV light; this can involve adjusting the interface layers and using appropriate electrode materials. Effects of extrinsic factors such as light and humidity must be controlled to evaluate the effect of the intrinsic factors under illumination and load on the solar cell stability test in an inert atmosphere (Shen et al., 2024; Yirka, 2025).

Stability refers to a solar cell’s capability to sustain performance over time under various environmental and internal conditions, and is a multidimensional challenge. To improve the operational lifetime of perovskite solar cells, we must understand and improve cell stability and degradation, and to this effect some current efforts include improved treatments to decrease the reactivity of the perovskite surface, alternative materials and formulations for perovskite materials, alternative contact (non-perovskite) layers and electrical contacts, advanced encapsulation materials, and approaches that counteract degradation sources during fabrication and operation. The stability of PSCs depends on extrinsic factors (temperature, moisture, oxygen, and light) and intrinsic factors (ion migration and trap states) (Boyd et al., 2019).

(Yang et al., 2019) Controlling the crystal growth by adjusting the antisolvent can increase the quality of the morphology in perovskite layer (Yang et al., 2018A; Fu et al., 2018; Jeon et al., 2014; Konstantakou et al., 2017). Doping the perovskite layer with other metals ions has also been shown to increase the stability (Yang et al., 2018B; Niemann et al., 2016; Jin et al., 2017) In addition, modifying the electron or hole blocking layer also can increase the perovskite layers stability (Zhang et al., 2018A; Bi et al., 2016; Yang et al., 2018C; Kundu and Kelly, 2018; Zhang et al., 2018B) Recently, partial substitution of MA+ in MAPbI3 perovskite with a larger organic ammonium cation (i.e., phenylethyl ammonium, butyl ammonium) to obtain 2D/3D hetero structured perovskite can great increase the stability of perovskite layer as the larger organic group has a high stability toward the moisture (Chen et al., 2018; Misra et al., 2017; Qing et al., 2018; Yang et al., 2018D)

Daily temperature variations induce phase transitions and lattice strains in halide perovskites, challenging their stability in solar cells (Li et al., 2023A). External factors such as moisture, oxygen, light, and heat expedite the degradation in perovskite devices and lower performance, which can be slowed by choosing a proper composition of the perovskite material (such as FA0.85MA0.1Cs0.05PbI2.7Br0.3) (Nandi et al., 2021B; Kim et al., 2021B; Nandi et al., 2021C; Nandi et al., 2018; Miah et al., 2023C; Min et al., 2021; Kojima et al., 2009; Green et al., 2024; Chowdhury et al., 2023). Among them, long-term instability in a moist environment, degradation caused by ultraviolet (UV) illumination. The degradation could occur at the grain boundaries or the grain interior due to the effect of various environmental factors, such as light, heat, humidity, etc. (Lu et al., 2019; Kundu et al., 2020). For example, perovskite films may degrade into iodide compounds or by-products when exposed to moisture (Idígoras et al., 2018; Manshor et al., 2016).

The hydrophilic and volatile nature of organic molecules make hybrid perovskite vulnerable to degradation through humidity and heat, which limits the long-term stability of perovskite solar cells for industrial applications. Several fundamental strategies have been adopted to slow down the degradation of the absorber materials and increase device stability: (i) develop a more resilient perovskite absorber via cation substitution/doping; (ii) controlling perovskite crystallization by novel approaches such as solvent engineering and the use of additives or non-halide, (iii) using carbon-based functional materials such as carbon nanotubes (CNT), graphene, or fullerene (C60) between the perovskite absorber and the hole-transport materials, and (iv) developing a protective layer (encapsulation technique) around the absorber material. To date, most perovskite solar cells with high stability are inverted (p-i-n) type (maintaining >90% of the initial power conversion efficiency over 1000 h) (Soonmin, et al., 2023).

For example, when exposed to moisture, air, and temperatures above 55 °C, MAPbI3-based PSCs show a structural phase shift and rapidly deteriorate above 85 °C (Jena et al., 2019). In a moist environment, water molecules form hydrogen bonds with the organic part, thus weakening the bonds between the A-site organic cation and the PbX6 octahedron. Additionally, water molecules protonate iodides resulting in the formation of HI, which further accelerates degradation. Atmospheric oxygen gets adsorbed on the vacant surfaces of perovskite and diffuses mainly through iodide vacancies, resulting in the formation of superoxide when it traps photogenerated electrons (Li et al., 2016). The highly active superoxide starts an acid-base reaction with acidic A-site cation resulting in the degradation of perovskite. Additionally, metallic contacts form metal halides when they react with iodine/iodide species. The reaction occurs as the iodine/iodide species diffuse to the metallic back-contact, or the metallic species diffuse to the perovskite layer. The effects of extrinsic conditions, such as humidity, temperature, UV light, and oxygen can be overcome by proper encapsulation of the PSC device.

The impact of thermal stress cycles on metal-halide perovskite solar cells is important to understand, including strategies to boost resistance to degradation effects of reflecting diurnal cycles or geographical conditions. Thermal stress is the deciding factor in perovskite cell degradation, though encapsulation can effectively protect the cells from moisture and atmospheric oxygen. A thermal stress cycle consisting of cooling to minus 150 C and then heating to plus 150 C allows for observation of changes in the microstructure of the perovskite layer and its interactions with the layers of the cell stack. In their experiment, Wu et al. (2025) noted divergent thermal behaviors of the various materials, and local phase transitions and diffusion of elements into adjacent layers were observed. Enhancing the material crystallinity can make the perovskite and adjacent layers more resilient to thermal stress, or buffer layers could be used to relieve interlayer thermal stress (Wu et al., 2025B; Thompson, 2025G).

D’Souza et al. (2024) designed an experiment to determine why solar cells made with lead halide perovskite, rather than silicon, were failing prematurely, and found that cell performance started to decline with the introduction of humidity. The perovskite formulation was investigated using a synchrotron technique called X-ray diffraction to visualize the 3D structure of the atoms in the material in real time. Possible solutions to address the issue of premature cell failure, including using corrosion-resistant materials for the electrodes, buffer layers to prevent the mobile ions from reaching the electrodes, or fully encapsulating the cell to keep out any moisture (D’Souza et al., 2024; MacPherson, 2024). A one-step method for polydimethylsiloxane encapsulated perovskite solar cells with patterning of the front surface has been created that simultaneously provide anti-reflective light management and shielding from oxygen and moisture-induced degradation (Mousavi et al. 2024; Thompson, 2024H).

Silicon cells can tolerate the high encapsulation temperatures needed to prevent moisture and oxygen from degrading the cell, but perovskite cells have struggled under conditions that exceed 110°C. To solve the issue of high encapsulation temperature with perovskite cells, the conventional additive 4-tert-butylpyridine (tBP) can be replaced with ethylene carbonate (EC). tBP improves efficiency, but also significantly lowers the glass transition temperature (Tg), the point at which the hole transport layer becomes nearly liquid, of the hole transport layer to below 80°C, compromising the stability of the cell in high-temperature environments. Ethylene carbonate uniformly dissolves the lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) dopant, which enhances charge transport performance in the hole transport layer, improving overall solar cell efficiency (Shin et al., 2025; Heo, 2025).

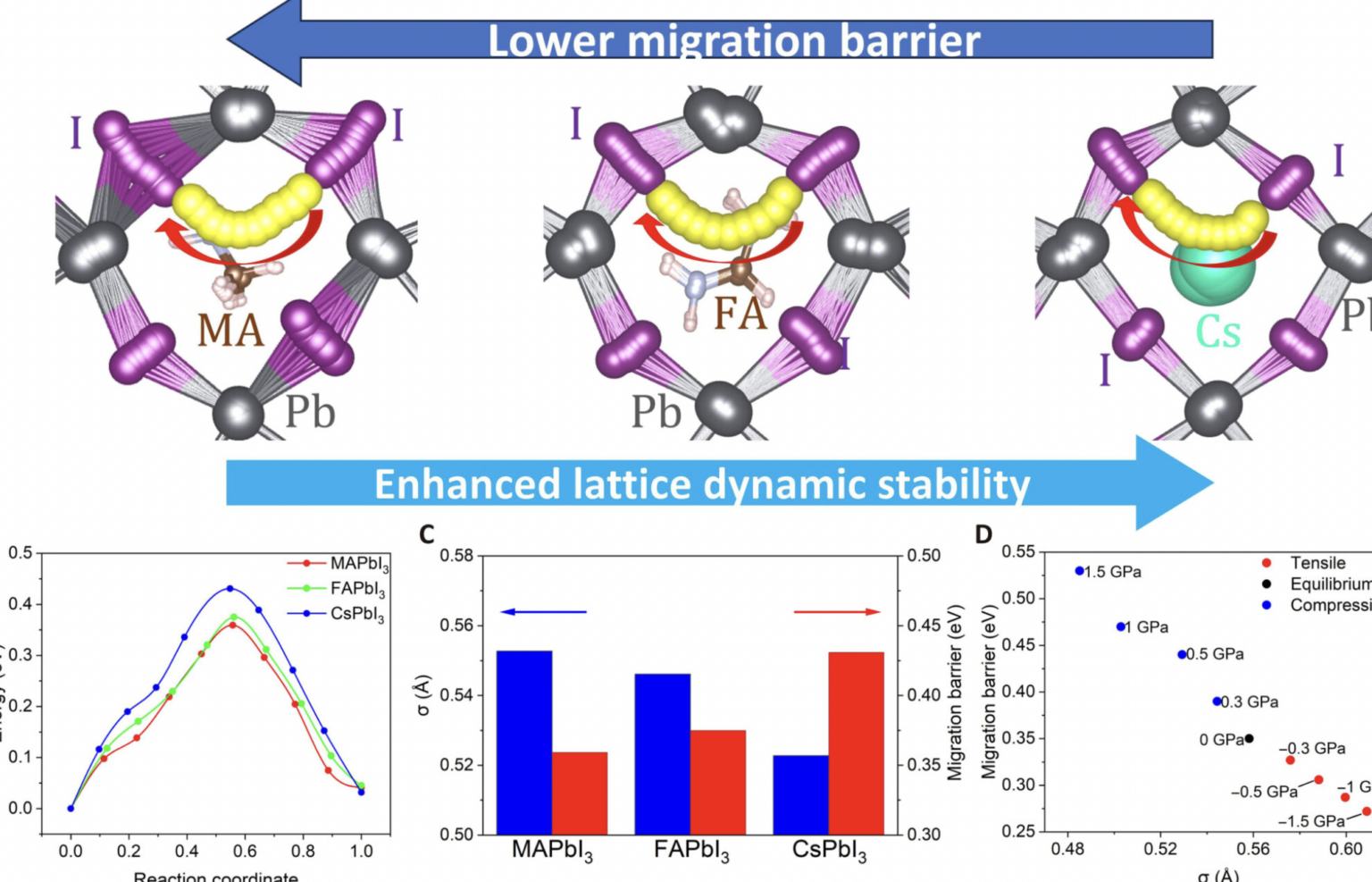
Their performance and stability are also affected by crystal defects (Azpiroz et al., 2015; Pazos-Outon et al., 2018), ion migration (Azpiroz et al., 2015), and hysteresis (Snaith et al., 2014; Azpiroz et al., 2015; Elumalai and Uddin, 2016; Chen et al., 2019). Intrinsic factors leading to instability in perovskite cells, such as ion migration caused during J-V measurement under illumination and the applied external electric field, are unavoidable (DeQuilettes et al., 2016). As for crystal defects, bulky “defect pacifying” molecules can increase perovskite solar cells’ stability and lifespan. In perovskite crystals with lead atoms, there are undercoordinated sites that aren’t fully bound to the other components within the perovskite, and these lead defects hinder the movement of electrons and speed up the decay of the perovskite material. These undercoordinated sites are defects often found on the crystal surfaces and at grain boundaries where there’s a break in the crystal lattice. Mixing defect pacifying molecules into the perovskites can help lock up the undercoordinated lead, in turn preventing other imperfections from forming at high temperatures (Kim et al., 2024).

Incorporating formamidinium cations (FA+) into methylammonium-based (MA+) lead iodide perovskite films increases the stability of perovskite solar cells, as 25% more added formamidinium causes an increase in the size of the grains that make up the crystalline structure of the perovskite, reducing the overall length of the edges. As the edges are the points where moisture accumulates, the perovskite suffers less degradation and the solar cell maintains good performance for longer (Polimante et al., 2025; Jowett, 2025).

**Ion Migration**

Ion migration, induced internal field screening, is a major cause of instability in perovskite solar cells, and occurs when the soft crystal lattice and relatively weak bonds in the perovskite film lead to low formation energies of defects, so heat and light could easily activate ionic defects within the perovskite lattice. The accumulation of ions deforms the local crystal structure and degrades the perovskite film, both the electron transport layer (ETL) and hole transport layer (HTL), as well as the electrodes (Shen et al., 2024; Bellini, 2025H). The mobile ions in the halide perovskite active layer are responsible for issues such as current-voltage hysteresis in the J-V curve depending on the scan rate and direction, slow conductivity response, and efficiency roll-off at high injection currents. The layer-to-layer ion diffusion in the perovskite/doped hole-transport layer (HTL) heterojunction leads to conductivity drop in the HTL and component loss in the perovskite. Holes in solar cells refer to positively charged particles that are generated by light absorption, as they serve as guides toward the anode (Shen et al., 2024; Yirka, 2025).

To solve the issue of ion migration, internal barriers that block the layer-to-layer ion diffusion must be designed, and one method is hole-selective interlayer incorporation in perovskite solar cells inspired by proton exchange membrane (PEM) fuel cells, where the PEM serves as a proton conductor while blocking the diffusion of other chemical species (Shen et al., 2024; Bellini, 2025H). Shen et al. (2024) built a perovskite solar cell that can effectively reduce ion migration through a hole-selective interlayer inhibiting ion diffusion which utilizes an ultrathin membrane made of a polymeric material known as PDTBT2T-FTBDT (D18), which offers conformal coverage on the surface of perovskite film due to its high fluidity (Shen et al., 2024; Bellini, 2025H). Ion migration causes current density–voltage (*J–V*) hysteresis and a decrease in operational stability (Tumen-Ulzii et al., 2020).



Liang, Y., Li, F., Cui, X., et al. (2025) Multiple B-site doping suppresses ion migration in halide perovskites, Science Advances, Volume 11, Number 11, <https://www.science.org/doi/abs/10.1126/sciadv.ads7054>

**Compositional Engineering**

Liang et al. (2025) reports that as the ternary-stoichiometry perovskite structure offers a flexible platform for doping engineering at different atomic sites, strain and compositional engineering have been employed to reduce the migration of halide ions. Although layer-perovskite engineering with large spacer cations effectively blocks ion migration, it disrupts the three-dimensional (3D) phases, leading to reduced charge carrier mobility and narrower absorption bands. Changing atoms and suppressing ion migration at the B-site in halide perovskites can increase stability by strengthening interactions between atoms, reducing structure movement and minimising ion migration (Liang et al., 2025; Foley, 2025). They suggest that adding elements like transition metal ions, alkaline-earth metals such as calcium (Ca), or lanthanides (rare earth metals) such as europium (Eu) and Ytterbium (Yb) to the B-site cation can be helpful in suppressing ion migration. However, B-site doping or alloying has a relatively high formation energy, and research in this area has focused on carbon group elements such as germanium (Ge), tin (Sn), and lead (Pb) (Liang et al., 2025; Foley, 2025).

In PbI2 perovskite cells, iodine loss is a common cause of cell degradation. Huang et al. (2024) built a perovskite solar cell with low non-radiative recombination and defect state density by regulating the secondary growth of lead iodide (PbI2) and utilizing π-π stacking and hydrogen bonding between FBA and and the PBI framework, to stabilize the PBI6 skeleton and enhance photovoltaic efficiency and stability. PbI2 nucleation and crystallization was controlled using 4-fluorobenylamide (FBA), to achieve a porous PbI2 film with low Gibbs free energy (the available energy of a substance that can be used in a chemical transformation or reaction) and high crystallinity for a perovskite absorber with large grains and minimized defect states. π–π stacking interactions is a nondestructive noncovalent interaction strategy that offers advantages such as strong binding force, nondestructive fabrication process, and simple operation (Huang et al., 2024; Bellini, 2024R). Wang et al. (2024A) treated a perovskite solar cell with a molecular passivator based on π-conjugated terpyridine Lewis-base molecules. The treatment worked at high concentrations, which is typically needed to passivate surface defects over time, while improving passivation durability without damaging the perovskite film or diminishing cell performance (Wang et al., 2024A; Thompson, 2024J).

The replacement or doping of some of the A components in the perovskite structure of organic halide perovskites with inorganic Cs or Rb is an effective temperature stabilization method. As perovskite cells are vulnerable to fluctuations in temperature due to the movement of polarons being a significant fraction of current conduction, the method of charge transport within the perovskite crystal structure needs to be improved. A higher energy is required to move the charge through the perovskite crystal than for a normal charge in the conduction band when the effective mass is higher than the actual charge around it in a perovskite cell. Polarons are electrically responsive due to being formed by a free charge becoming coupled to the lattice, with the local electric field-differentiated change in the effect of temperature also playing a role in their movement. The motion of polarons is more influenced by the strength of a strong local electric field than temperature at standard temps (300K). Thermal motions is the damping force likely to prevent the motion of polarons in any direction with a weak electric field. Non-emissive recombination occurs in perovskite cells at higher temperatures, leading to a reduced PCE due to the presence of surface defects. Acting as charge concentrations, surface defects create local fields stronger than the internal field of the intrinsic perovskite layer, thus attracting and becoming traps for free charges such as polarons and preventing them from reaching their charge’s respective CTLs. Bulk material defects, however, are not large enough to maintain charges of significant enough size to alter the intrinsic electric field of the device.[[5]](#footnote-4)

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**Device Architecture Optimization: Interface Engineering**

1. Charge Transport Layer Optimization: Hole Transport Layer
2. Charge Transport Layer Optimization: Electron Transport Layer

Interface engineering refers to the optimization of the interfaces between the perovskite layer and charge transport layers to minimize carrier recombination and enhance charge collection (Chen and Park, 2020). Interface engineering to enhance stability and efficiency should focus on mitigating interfacial non-radiative recombination (NRR) through defect passivation, energy level alignment modulation, and suppression of interfacial reactions. When designing a perovskite cell interface, organic or inorganic charge transport layers (CTLs) must be chosen. CTLs must be tailored to various device structures, perovskite compositions, and deposition methods.

Efficient hole and electron transport materials can be designed to facilitate charge collection by studying the interfacial properties between the perovskite layer and charge transport layers. Currently, the most common CTLs are titanium dioxide (TiO2) or nickel oxide (NiO) for the electron transport layer and Spiro-OMe-TAD or poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA) for the hole transport layer. Selecting the right Hole Transport Material (HTM) and Electron Transport Material (ETM) creates better performance and stability for perovskite devices by ensuring efficient charge transport and separation (Nyiekaa et al., 2024; Bellini, 2025T). To induce charge separation in perovskite devices, an n-type semiconductor such as can be injected with photogenerated electrons, or a p-type material such as spiro-OMeTAD can be injected with holes. To stop holes from reaching the TCO substrate (anode) and short-circuiting the cell, a hole-blocking layer can be utilized between the TCO-conducting substrate and the mesoscopic scaffold and/or perovskite layer (Soonmin et al., 2023). The deposition of a more hydrophobic and UV-stable ETL/HTL, such as replacing TiO2 with SnO2), improves stability of the device and reduces energy loss between layers and degradation of crystal structures (Soonmin et al., 2023). Hossain et al. (2023) noted that a uniform perovskite layer does not form due to the hydrophobicity of Me-4PACz when used as a self-assembled monolayer, though adding a conjugated polyelectrolyte, poly(9,9-bis(3′-(N,N-dimethyl)-N-ethylammonium-propyl-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)) dibromide (PFN-Br), to the Me-4PACz in a specific ratio, defined as Pz:PFN, addresses this hydrophobicity issue. Yu et al. (2023 optimized self-assembly of [4-(3,6-dimethyl-9H-carbazol-9-yl)butyl]phosphonic acid (Me-4PACz) onto nickel oxide (NiOx) nanoparticles as an HTL through treatment with hydrogen peroxide, which created a more uniform dispersion of nanoparticles with high conductivity attributed to the formation of Ni3+ as well as surface hydroxyl groups for bonding.

Photovoltaic conversion requires two successive steps: accumulation of a photogenerated charge and charge separation. When used as a wide bandgap semiconductor mesoporous , its porous morphology provides better infiltration of the perovskite absorber layer on ETL; however, it undergoes high-temperature sintering and degradation in the presence of UV light (Burschka et al., 2013; Prochowicz et al., 2020; Khatoon et al., 2023A; Jeong et al., 2017). Planar PSCs are processed at lower temperatures than mesoporous, but the planar has low electron mobility, which leads to charge accumulation and hysteresis due to the capacitance of solar cells (Kim et al., 2013; Snaith et al., 2014; Tavakoli et al., 2018; Choi et al., 2016). In perovskite-based solar cells moisture resistance is needed at the perovskite HTL interface to prevent moisture from reaching the perovskite absorbing layer through the HTL. Adding hydrophobic additives, such as ammonium (Wu et al., 2018) or 4-Tertbutyl-Pyridine (tBP) (Arias-Ramos et al., 2020) in the HTL could control moisture penetration into the perovskite absorber layer (Nie et al., 2014). Since the HTL and perovskite interface possess better charge transfer and consequently lesser charge accumulation, it is less significant than the ETL and perovskite interface.

*Moreover, interface engineering has been developed to boost interfacial adhesion and regulate perovskite crystallization. For instance, some functional molecules with sticky groups were introduced at the buried interface to enhance the interfacial contact at the fragile ETL/perovskite interface by simultaneously coordinating with upper perovskite and underlying substrate (Xu et al., 2024; Li et al., 2023; Dai et al., 2021). Particularly, hyperbranched polymer with branched three-dimensional molecular structure and anchor groups, which was easy to self-assemble atop metal oxides and strongly coordinate with the perovskite, were incorporated at the SnO2/perovskite interface to enhance the interfacial fracture energy and hence the mechanical resistance of f-PSCs (Li et al., 2023; Dai et al., 2021; Dai et al., 2022). Moreover, the perovskite crystallization can also be modulated from the buried interface. For example, functional molecules, such as proline hydrochloride27 and entinostat12, were introduced at the buried interface as a versatile medium to boost the perovskite crystallinity with eliminated defect states, and f-PSCs with efficiency approaching 25% were ultimately obtained (Ren et al., 2024; Xu et al., 2024; Xu et al., 2023; Zhang et al., 2024).*

Xu, W. et al. Multifunctional entinostat enhances the mechanical robustness and efficiency of flexible perovskite solar cells and minimodules. Nat. Photon. 18, 379–387 (2024).

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Ren, N. et al. 25% - Efficiency flexible perovskite solar cells via controllable growth of SnO2. iEnergy 3, 39–45 (2024).

**Electron Transport Layers**

As an electron transport layer, tungsten disulfide (WS2) has a small, indirect band gap (1.3 eV), a big direct band gap value (2 eV), a high carrier mobility, and excellent conductivity (Ahmad et al., 2022). Nihal et al. (2021) proposed zinc magnesium oxide (ZnMgO) as an electron transport layer.

You et al. (2025) used an ionic salt, 4-(1′,5′-dihydro-1′-me-thyl-2'H-[5,6] fullereno-C60-Ih-[1,9-c]pyrrol-2′-yl)phenyl-methanaminium chloride, synthesized from CPMAC (N-methylglycine, and tert-butyl 4-formylbenzylcarbamate molecules and hydrochloric acid) and buckminsterfullerene (C60), for the electron transport layer (ETL) interface in inverted perovskite solar cells to overcome weak interface encountered in pure buckminsterfullerene (C60) ETLs (You et al., 2025; Thompson, 2025P).

Thompson, Valerie (2025P) PV Magazine, Inverted perovskite solar cell based on ionic salt achieves 26% efficiency,

<https://www.pv-magazine.com/2025/05/05/inverted-perovskite-solar-cell-based-on-ionic-salt-achieves-26-efficiency/?utm_source=Global+%7C+Newsletter&utm_campaign=99d5425626-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-99d5425626-160603208>

You, S., Zhu, H., Shen, Z., et al., (2025) -based ionic salt electron shuttle for high-performance inverted perovskite solar modules.Science, 0,eadv4701, <https://www.science.org/doi/10.1126/science.adv4701>

**Hole Transport Layers**

As a hole transport layer, the homo-polymer poly (3-hexylthiophene), called P3HT, showed a wide band gap, high hole mobility, robust hydrophobicity, high thermal stability, and relatively low cost (Ahmad et al., 2022). Nihal et al. (2021) proposed MASnBr3 as a hole-transport layer. For the hole transport layer, Komal et al. (2021) replaced expensive spiro-OMeTad with cheap ZnTe. In a 2D/3D perovskite cell, spiro-OMeTAD that was not doped with 4-tert-butylpyridine (tBP) and lithium bis(trifluoromethane)sulfonimide (LiTFSI) was used as the hole transport layer (HTLs), in an effort to avoid known causes of degradation problems, especially at higher temperatures (Tan et al., 2025; Thompson, 2025).

In a perovskite-silicon tandem cell, HTL cells based on methyl-substituted carbazole and submicron-sized textured silicon bottom heterojunction cells enhances the wettability of the perovskite layer and reduces shunting issues, which are common with conventional HTLs based on a phosphonic acid called methyl-substituted carbazole (Me-4PACz), leading to better film formation while maintaining the very good HTL characteristics of Me-4PACz (Harter et al., 2024; Bellini, 2024F). HTLs used in the top perovskite cells for tandem devices can suffer from defects caused by non-conformal deposition or de-wetting, which can be mitigated by the co-deposition of inorganic CuSCN, copper(I) thiocyanate, and perovskite in the top cell absorber, which demonstrates extraordinary light and damp-heat stabilities (Kan et al., 2024; Bellini, 2024H). Cu2O was chosen as the HTM over other HTMs because it is cheaper than organic-based HTMs, and has a high absorption coefficient, high intrinsic hole mobility, and acceptable energy levels that are aligned with the absorber layer, high photochemical and thermal stability as well as long-term stability in air. ZnO is used as ETM because of its high absorption coefficient, higher electron mobility and aligned energy bandgap with the chosen perovskite when compared to the SnO2 (Nyiekaa et al., 2024; Bellini, 2025T).

Perera et al. (2025A) built a lead-tin narrow bandgap perovskite solar cell with a hole transport layer (HTL) based on PEDOT:PSS with a thiocyanate additive. Utilizing PEDOT:PSS or poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, forms a p-type semiconductor, and is a blend of two distinct polymers: poly(3,4-ethylenedioxythiophene) (PEDOT) and polystyrene sulfonate (PSS). The ratio of PEDOT to PSS can be adjusted to modify the material's conductivity and solubility. PEDOT is highly conductive with impressive mechanical flexibility, while PSS offers stability and allows dispersion in water. Together, they create a material that is transparent in the visible spectrum and exceptionally conductive. Amine-containing organic cations de-dope PEDOT:PSS which can be partially recovered with thiocyanate additives and an iodine reductant. However, cyanogen formation from thiocyanate-iodine interaction decreases device stability, where the organic cations that diffuse into PEDOT:PSS leads to efficiency loss (Perera et al., 2025A; Thompson, 2025E). Shen et al. (2024) developed a perovskite cell utilizing an ultra-thin (~7 nm) p-type polymeric interlayer using a spin coating of PDTBT2T-FTBDT, known as (D18), which produces a hole-selective interlayer inhibiting ion diffusion with excellent ion-blocking ability between perovskite absorber and HTL. The ultra-thin D18 interlayer effectively inhibits the layer-to-layer diffusion of lithium, methylammonium, formamidium, and iodide ions, and improves the energy-level alignment at the perovskite/HTL interface and facilitates efficient hole extraction (Shen et al., 2024; Mishra, 2025B). Holes in solar cells refer to positively charged particles that are generated by light absorption, as they serve as guides toward the anode (Shen et al., 2024; Yirka, 2025).

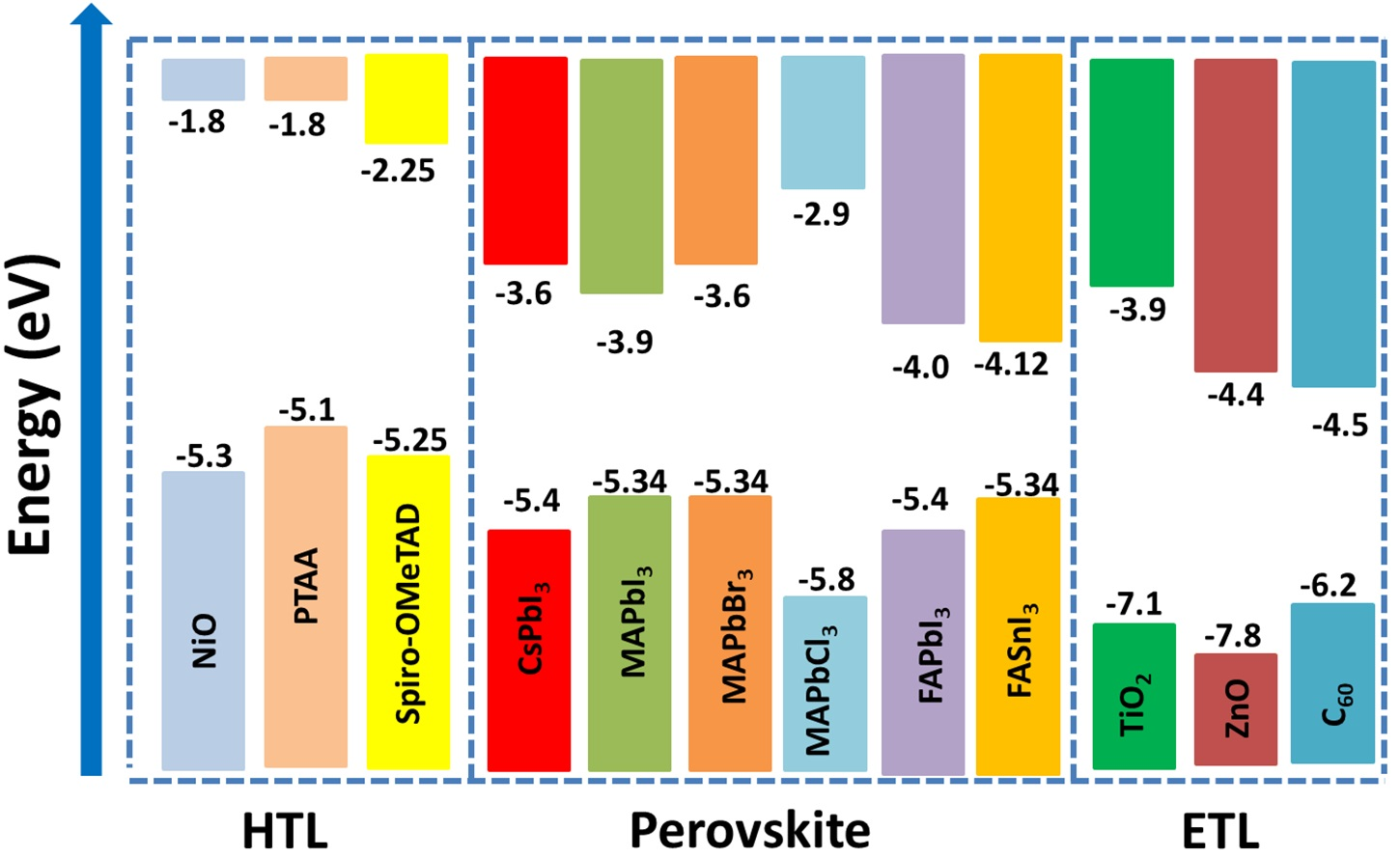
Alumina oxide (Al₂O₃) nanoparticles (NPs) can be used as an interfacial modifier as an nanoengineered interlayer at the hole transport layer (HTL). Perera et al. (2025B) modified an HTL made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz) with PFN–Br and (Al₂O₃), and found that the effect of the alumina oxide nanoparticles at the buried interface was to homogenize the electrical and electronic properties of the perovskite. Utilizing alumina nanoparticles leads to efficient scavenging of iodine and improved bulk electrical and surface electronic homogeneity in fresh films, and the formation of 2D perovskites, which protect against moisture-induced degradation (Perera et al., 2025B; Thompson, 2025N). To ensure efficient collection of the photogenerated carriers, ETL and HTL materials must be aligned with the appropriate energy level of perovskite absorbers (Minemoto et al., 2020). The conduction band of perovskite must be higher than the conduction band of the ETL, whereas the valence band of perovskite must be lower than that of the HTL layer, as shown in Figure XXX. Xing et al. (2013) independently assessed (negative) electron and (positive) hole diffusion lengths and found them well-matched to one another to the ~100-nanometer optical absorption depth.

**Self-Assembled Monolayers (SAM) and Self-Assembled Bilayers (SAB)**

Tumen-Ulzii et al. (2020) introduced an interfacial self-assembled monolayer (SAM) to reduce *J–V* hysteresis. Self-assembled-monolayers (SAMs) can be used as hole transport layers in perovskite-based solar cells, offering low parasitic absorption, rapid charge extraction, and effective passivation of the perovskite’s buried interface. Er-Raji et al. (2025) investigated the impact of the annealing temperature on the self-assembly of a conventional SAM, namely 2PACz, and found that increasing the annealing temperature from the conventional 100 C to 150 C controls the SAM thickness from approximately 5 nm to a monolayer of about 1 nm, while simultaneously enhancing its packing density (Er-Raji et al., 2025; Bellini, 2025R). A self-assembled bilayer (SAB) was used as a hole-selective molecular contact, consisting of a phosphonic acid self-assembled monolayer (SAM-perovskite interface) with an upper layer made of an organic compound known as triphenylamine. Triphenylamine improves the adhesive contact with the perovskite film and also enhances the interface's thermal and mechanical robustness. A basic form of self-assembled multilayers, SABs consist of distinct monolayers with varying constituents interconnected via covalent or ionic bonds, which stabilizes the labile monolayer by introducing rigid components and enables control over film termination (Dong et al., 2025; Bellini, 2025B).

A perovskite-TOPCon solar cell with a top inverted perovskite device utilizing a self-assembled monolayer (SAM) aimed to improve cell thermal stability has been developed. Electron density within the SAMs can be modulated to shift the interfacial energetics between the SAM and perovskite layer, which results in a “more versatile and controlled approach” to optimizing energy alignment in the perovskite solar cell, while also having a “negligible” influence on the phase stability of the wide-bandgap perovskite film (Luo et al., 2025; Bellini, 2025HH).

Figure XXX.



**Figure 1** An energy level diagram showing the conduction and valence band of the perovskite absorber, the electron transport layers, and the hole transport layers.

Minemoto. T., Kawano. Y., Nishimura. T., et al. (2020) Theoretical analysis of band alignment at back junction in Sn-Ge perovskite solar cells with inverted p-i-n structure, Sol Energy Mater Sol Cells, 206, 110268

In addition to the perovskite absorber layer, structures are needed for creating an internal electric field through the intrinsic semiconductor of the perovskite crystal called charge transport layers (CTLs). Current collectors, or contacts, or electrodes, are also needed to connect those transport layers out into the circuits where the devices to be powered are connected. Without charge transport layers (CTLs), perovskites show a significant reduction in PCE. A hole transport layer (HTL) combined with an electron transport layer (ETL) will generate an electric field throughout the perovskite layer capable of promoting charge transport after electron-hole-pair generation, due to perovskites having high carrier mobility and very thin layers. The order the HTL and ETL are placed in relative to the incident light on the solar cell is generally insignificant. In a n-i-p construction, the sunward side of the device is commonly the negative layer (ETL) due to the organic and potentially UV-sensitive nature of Spiro-oMeTAD and PTAA, followed by the intrinsic semiconducting layer (perovskite), and lastly the positive layer (HTL). Charge transport layers (CTLs) can also be used to separate and collect photo-generated charge carriers.[[6]](#footnote-5)

Acting as an uncharged semiconductive material where the incident light can induce charge separation, the perovskite absorber layer between the CTLs boosts valence electrons into the conduction band and leaves behind a hole in the valence band. Similar to in a silicon cell which is dependent on the dopant layers to pull charge carriers out of the depletion zone, a perovskite cell creates an electric field via the charge transport layers (CTLs), which helps to transport the charges to the respective current collectors (metal contacts, or electrodes). To transport their charges CTLs create favourable junctions with the intrinsic semiconductor of the perovskite absorber layer. Similar to how a depletion layer in a traditional pn junction of a silicon solar cell operates, an intrinsic electric field is created by the natural diffusion of free charges from the perovskite absorber into the CTLs that helps to draw more charges to these layers, due to it being energetically favorable for electrons to enter the ETL and holes to enter the HTL.[[7]](#footnote-6)

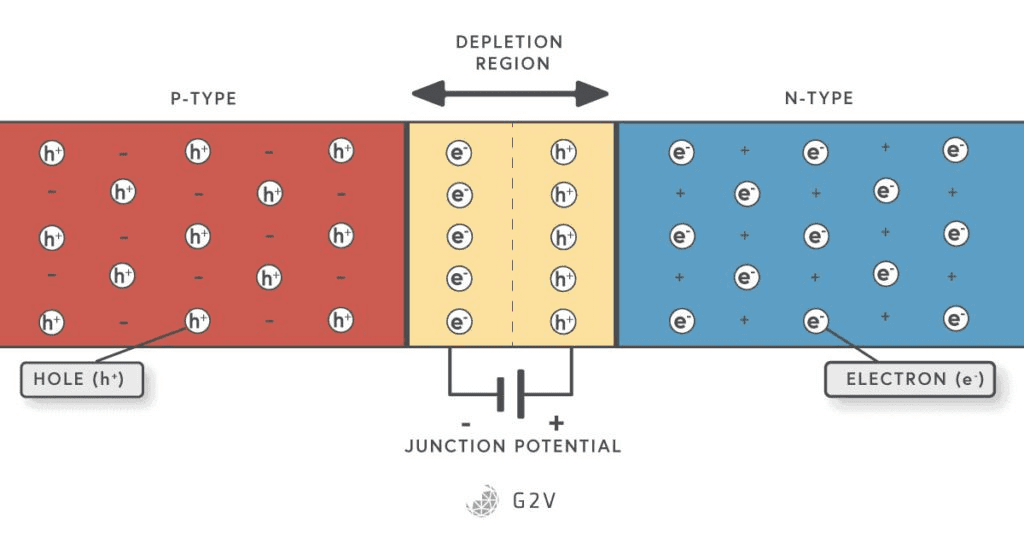
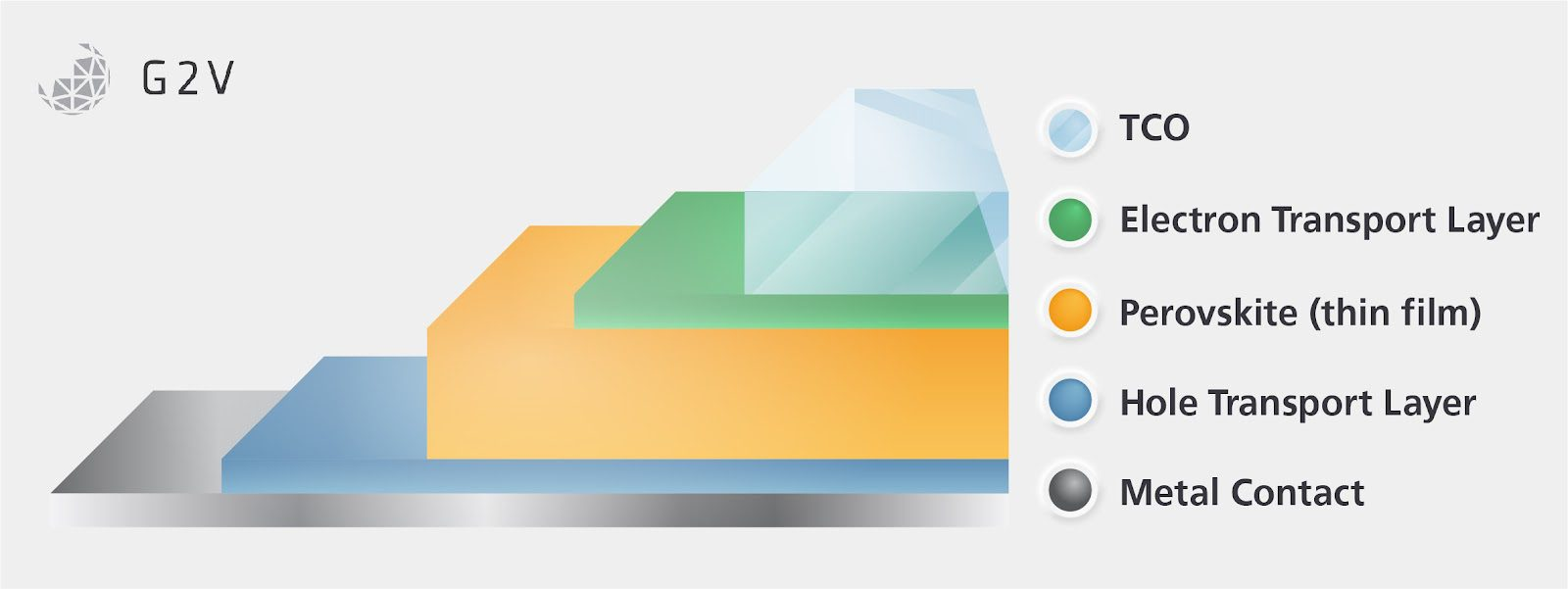


Illustration of a depletion region of a PN junction in a silicon solar cell

G2V, What Are The Advantages And Disadvantages Of Perovskite Solar Cells? <https://g2voptics.com/advantages-of-perovskite-solar-cells/>



N-I-P structure thin film example encapsulated between a Transparent Conducting Oxide (TCO) and a metal electrode.

Elseman, Ahmed & Sajid, Sajid & Shalan, Ahmed & Mohamed, Shaimaa & Rashad, Mohamed. (2019). Recent progress concerning inorganic hole transport layers for efficient perovskite solar cells. Applied Physics A. 125, <https://www.researchgate.net/publication/333997916_Recent_progress_concerning_inorganic_hole_transport_layers_for_efficient>

At the charge-extraction layers and inside the perovskite material nonradiative recombination losses can occur, as electron-hole recombination refers to a condition where the electron-hole pairs are not kept separate and thus the charges do not make it out of the device to do work. Surface defects can arise in the n-i-p construction. In a silicon based p-n junction-based solar cell, the only surface defects are the contact between the silicon and the electrical contacts at the front and back that complete the circuit, which results in a lower number of surfaces on which defects can form. Adhesion between the surfaces of the layers is critical for a properly functioning solar cell, with surfaces referring to the interfaces between the different layers. Issues that can arise which prevent the cell from keeping electron-hole pairs separate include: poor connections from mismatched crystal orientations, different coefficients of thermal expansion, and/or different electrical conductivities can create forces that delaminate the layers from each other.[[8]](#footnote-7)

Excitons (electron-hole pairs) are produced when through the initial light absorption process in a solar device, and a photon activates the active absorber material with an energy higher than its bandgap. To be retrieved, excitons must reach the contacts after being photogenerated in the perovskite, which requires a low exciton binding energy. The perovskite absorber in thin-film solar cells offers effective transport of excitons, which is aided by the material’s outstanding charge-transport properties, including both long charge-carrier diffusion lengths surpassing 5 m and the associated lifetimes of 1 s in both single-crystal and polycrystalline films. Even when thicker films absorb the input light completely, long charge-carrier diffusion lengths ensure that the produced charge can be recovered. Interfacial contacts with the charge extraction layer should provide the least possible voltage, current, and FF loss when extracting the photogenerated charge after absorption and charge transmission. To prevent the reduction of light intensity in the perovskite, the selective contact should not absorb light, should allow only one kind of carrier to be injected, and also need to lower series resistance. Interfacial recombination, energetic losses during the absorber injection, should be eliminated. (Soonmin et al., 2023).

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Luo, Y., Tian, Y., Zhao, K. et al. (2025) Inductive effects in molecular contacts enable wide-bandgap perovskite cells for efficient perovskite/TOPCon tandems. Nat Commun 16, 4516, <https://doi.org/10.1038/s41467-025-59896-8>

Table 2. Additives in ETL of PSCs (Khatoon et al., 2023A)[[9]](#footnote-8)

| **Additive in ETL** | **Composition** | **Efficiency (%)** | **Voc (V)** | **Jsc(mA/cm2)** | **FF (%)** | **Stability** |
| --- | --- | --- | --- | --- | --- | --- |
| TiO2-Cl | (Tan et al., 2017) | 20.1 | 1.14 | 22.6 | 77 | 90% remain after 500 h at room temperature |
| Er | FTO/cTiO2/Er-TiO2/CH3NH3PbI3/  Spiro-OMeTAD/Au  (Ren et al., 2018) | 14.06 | 1.03 | 20.28 | 67.31 | 90% remain after 500 h under UV radiation |
| Nd | FTO/Nd-TiO2/CH3NH3PbI3/  Spiro-OMeTAD/Au  (Roose et al., 2016) | 18.1 | 1.13 | 22.3 | 71.6 | stabilized efficiency for first 500 s |
| PCBDAN | ITO/PCBM:PCBDAN/CH3NH3PbI3/  Spiro-OMeTAD/Au  (Xie et al., 2017) | 18.1 | 1.08 | 21.7 | 77.3 | 85% efficiency remains after 240 h UV accelerated aging |
| PCBB-2CN-2C8 | ITO/TiO2/PCBB-2CN-2C8/Perovskite/  Spiro-OMeTAD/Au  (Li et al., 2015B) | 17.35 | 1.06 | 20.68 | 79.1 | 200 h |
| GNR | FTO/(m-TiO2/GNRs)/MAPbI3/  Spiro-OMeTAD/Ag  (Meng et al., 2018) | 22.98 | 1.053 | 22.98 | 73.1 | 87% efficiency remains after 1000 h at 25°C in ambient env 30% RH |
| FPA & MLG | FTO/MLG/ZnO/PVK/  Spiro-OMeTAD/Au  (Tavakoli et al., 2019) | 21.03 | 1.15 | 23.42 | 78.1 | 80% efficiency remains after 300 h at continuous illumination at MPP under N2 environment |
| SnO2 at TiO2 | FTO/SnO2/TiO2/CH3N3PbI3/  Spiro-OmeTAD/Au  (Mohammadbeigi et al., 2020) | 11.28 | 0.99 | 19.53 | 60 | 65% efficiency remains after 69d at 25◦C and 30% RH |
| C3N3 at FTO/SnO2. | FTO/SnO2/ C3N3  (Li et al., 2021C) | 19.91 | 1.137 | 22.43 | 78 | power conversion efficiency of the modified device without encapsulation can maintain nearly 90% of its initial value after being stored at 25 °C and 60% relative humidity for 500 h. |
| ZnBr2 | Cs0.05(FA0.83MA0.17)0.95Pb1 − xZnx(I0.83Br0.17)3.  (Jing et al., 2023) | 15.64 | 0.956 | 22.06 | 70.50 | 87 % of its original PCE after aging for 90 days in the ambient condition |
| ZTO-ZnS(ETL) | Cs0.05(FA0.85MA0.15)0.95Pb (Br0.15I0.85)3  (Han et al., 2021) | 21.30 | 1.150 | 23.80 | 77.70 | 1 000 h at 85 °C in air with a relative humidity of 85% |
| NH2-ZnO@SnO2(ETL) | (CsPbI3)0.05(FA0.85MA0.15Pb [I0.85Br0.15]3)0.95  (Zhao et al., 2021) | 78.68 | 1.139 | 25.11 | 22.252 | PCE of NH2-ZnO@SnO2-based PSCs still maintained 86.8% of its initial PCE value beyond approximately 620 h in the ambient conditions |

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Table 3. Additives in HTL of PSCs (Khatoon et al., 2023A)[[10]](#footnote-9)

| **Additive in HTL** | **Composition** | **Efficiency (%)** | **Voc(V)** | **Jsc(mA/cm2)** | **FF(%)** | **Stability** |
| --- | --- | --- | --- | --- | --- | --- |
| Spiro + BuPyIm-TFSI | (Zhang et al., 2014) | 7.91 | 0.87 | 16.26 | 0.56 |  |
| F4TCNQ + BQ | FTO/TiO2/MAPbI3 + BQ/  Spiro-OMeTAD + F4TCNQ/Au  (Yu et al., 2018) | 16.05 | 1.02 | 23.49 | 67 | 95% efficiency remain after 1300 h in open air ar 45–55% RH |
| Mg-TFSI | FTO/C-TiO2/MP-TiO2/PVK/  Spiro-OMeTAD/Au  (Pham et al., 2020A) | 18.6 | 1.096 | 22.44 | 75.65 | 83% efficiency remains after 193d at 55–790% RH without encapsulation |
| Spiro + TFSI | FTO/C-TiO2/MP-TiO2/MAPbI3/  Spiro-OMeTAD/Au  (Liu et al., 2019B) | 19.1 | 1.09 | 23.8 | 74 | 76% efficiency remains after 39d at 26◦C and RH 60% |
| Cu  ] | ITO/Cu:NiOx/perovskite/  (PC61 BM)/C60/Ag  (Kim et al., 2015C) | 15.4 | 1.11 | 18.75 | 72 | 90% efficiency remains after 240 h of storage in air |
|  | ITO/LI:NiO x/perovskite/(PCBM)/Al  (Nie et al., 2018) | 17 | 1.1 | 21.79 | 73.6 | Continuous light soaking under 10-sun without UV filter |
| Cu2O–CuSCN nanocomposite (HTL) | Cs0.05(FA0.85MA0.15)0.95Pb (I0.85Br0.15)3  (Kim et al., 2020D) | 19.20 | 1.054 | 23.23 | 78.40 | PCE over 90% for 720 h under extreme conditions (85 °C/85% of relative humidity, encapsulated). |
| 2,3-bis(4′ -(bis(4-methoxyphenyl)amino)-[1,1′ -biphenyl]-4-yl) fumaronitrile(TPA-BPFN-TPA)  (HTL) | CH3NH3PbI3  (Pham et al., 2020B) | 18.40 | 1.040 | 22.70 | 78.00 | 100 h at RH 70% |
|  |  |  |  | 23.49 | 71.11 |  |
| PdPrPc(HTL) | Cs0.05(MA0.13FA0.87)0.95Pb (I0.87Br0.13)3  (Li et al., 2021D) | 18.09 | 1.083 |  |  |  |

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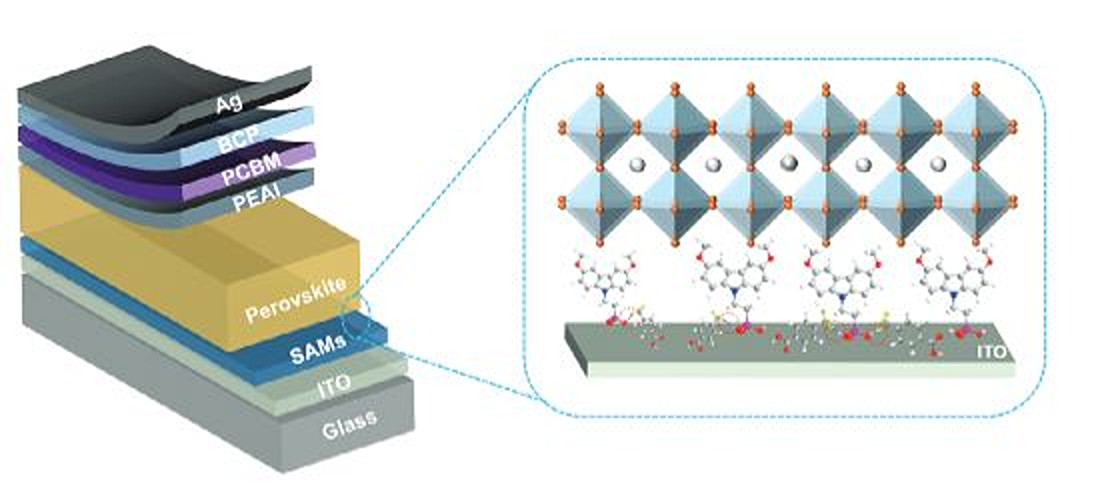
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**Device Architecture Optimization: Inverted Structures**

Inverted perovskite cells have a device structure known as “p-i-n” (positive (p)–intrinsic (i)–negative (n)), in which hole-selective contact (p) is at the bottom of intrinsic perovskite layer (i) with electron transport layer (n) at the top. The conventional halide perovskite cell structure is reversed, an “n-i-p” layout. In an n-i-p architecture, the solar cell is illuminated through the electron-transport layer (ETL) side; in the p-i-n structure, it is illuminated through the hole transport (HTL) surface (Dong et al., 2025; D’Souza et al., 2024; MacPherson, 2024). Jiang et al. (2022) reports that the power conversion efficiency (PCE) and open-circuit voltages of inverted p–i–n PSCs are lower that of n–i–p (or normal) structure counterparts (Li et al., 2022A; Li et al., 2022B; Azmi et al., 2022; Momblona et al., 2016; Zhao et al., 2024).[[11]](#footnote-10)

Utilizing an SAM as an HTL material increases the photoelectric conversion efficiency of inverted perovskite solar cells, but clusters will be formed when SAM exceeds a certain concentration in solution. These clusters lead to weak binding between the phosphate anchoring group at the bottom of SAM and indium tin oxide (ITO), which affects the dispersion of SAM on ITO substrate, resulting in loss of carrier extraction efficiency (Liu et al., 2024A; Bellini, 2024T). Different materials can be placed for the anode/cathode of the layer and different orders for the back sheet and the transparent layer, depending on whether a mesoporous or planar perovskite layer is used and the architecture of the solar cell. An n-i-p perovskite solar cell features a Gold (Au) anode and a Fluorine Doped Tin Oxide (FTO) transparent layer, while p-i-n perovskite solar cells can feature Aluminum (Al) cathodes and Indium Tin Oxide (ITO) anodes.[[12]](#footnote-11)

Inverted perovskite cells can be improved by using a co-adsorbed approach to incorporate self-assembled monolayers (SAM) at the hole transport layer (HTL), in an effort to reduce passivating defects and increase efficiency. SAMs made of PyCA-3F, 2-chloro-5-(trifluoromethyl)isonicotinic acid, and HTL layers made with 2PACz, [2-(9H-Carbazol-9-yl)ethyl]phosphonic acid, were used by Li et al., 2024B). The co-adsorbed approach (CA) for the SAM application consists of growing the perovskite films on 2PACz substrates with and without PyCA-3F (Li et al., 2024B; Thompson, 2024G). Liu et al. (2024A) built an inverted perovskite solar cell based on a hole transport layer (HTL) with a self-assembled monolayer (SAM) using a co-assembled SAM (Co-SAM) strategy, consisting of selecting additive material to be mixed with a common SAM based on a layer of MeO-2PACz, which is also known as [2-(3,6-Dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid (Liu et al., 2024A; Bellini, 2024T). Xing et al. (2025) reports that inverted perovskite solar cells can achieve a greater power conversion efficiency using an optimized buckminsterfullerene (C60) electron transport layer (ETL). However, C60 suffers from significant aggregation in solution, which makes a high-cost and complex thermal evaporation method necessary for its development, of which the C60 ETLs molecules can be stabilized by utilizing an n-type polymeric additive, TPDI-BTI, constructed from the strongly electron-deficient dithienylpyrazinediimide (TPDI) and the imide-functionalized bithiophene (BTI) co-unit. The ETLs can be regulated by controlling the TPDI-BTI addition, including improving film formability and morphological stability, energy levels and electron transport dynamics, and intermolecular interacting behaviors and interfacial contacts (Xing et al., 2025; Bellini, 2025L).



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**Solar Cell Device Components**

1. PV Backsheets
2. Buffer Layer
3. Electrodes and Front and Rear Contacts

**PV Backsheets**

PV backsheets are the protective, outermost layer on the back of solar panels, acting as a barrier against harsh environmental factors like moisture, dust, UV radiation, and extreme temperatures, while also safeguarding against electrical issues. It is the layer of material found at the back of the panel that comes in contact with the mounting surface. PV backsheets shield the internal components of the solar panel (cells, encapsulant, and electrical connections) from water and moisture, which can lead to the corrosion of metal parts, insulation degradation, short-circuiting, and corrosion of electrical connections or components. Electric insulation refers to the resistance to electric flow, as the backsheet insulates electric components of the solar panel, preventing short circuits. The dielectric strength of backsheets prevents its electrical breakdown and it can withstand high voltage. Backsheets provide structural support and mechanical strength to the module, helping it withstand wind, snow, and mechanical pressures like collision, strike from any object, and abrasion. Solar backsheets must have adequate tensile strength to provide a rigid and robust support structure for the PV cells, helping the cell to stay upright and minimizing vibrations and impacts, which helps to minimize the mechanical stress that they may experience. Backsheets protect the cells from overheating by safeguarding photovoltaic cells from adverse and extreme temperatures, thereby preventing the cells from getting exposed to high-energy photons that could cause thermal stress and potentially damage the cells or lower their efficiency. They help to ensure proper adhesion between the encapsulant and the module frame, as inadequate adhesion results in delamination and segregation of the various layers, resulting in a decline in the solar panel’s performance. Backsheet failure can lead to premature degradation of solar panels, reduced power output, and even catastrophic failure. Common signs of backsheet failure include delamination, bubbling, cracking, and discoloration.

Fluoropolymer Backsheets are often made with materials like PVF (polyvinyl fluoride) or PVDF (polyvinylidene fluoride), known for their excellent weather resistance and durability. Many backsheets use a PET (Polyethylene Terephthalate) core for its mechanical strength and insulating properties. Backsheets typically utilize multi-layered laminates, combining different materials to achieve optimal performance. TPT backsheets are a common type, often using a PVF outer layer, a PET core, and a PVF inner layer. KPK backsheets are similar to TPT, but with a different combination of materials. TPE backsheets are a single-sided fluoropolymer laminate. KPE backsheets are similar to TPE, but with a different combination of materials. Some backsheets also incorporate materials like PE (polyethylene) or EVA (ethylene-vinyl acetate). Made from polymer materials such as EVA, polyester, or fluoropolymer, solar backsheets are designed to withstand the effects of exposure to sunlight and temperature changes over time. They may also include additional materials like aluminum or a layer of glass for added protection. Common types of airside layer backsheet materials include: Poly(vinylidene fluoride) (PVDF); acrylic PVDF; poly(tetrafluoroethylene-co-hexafluoropropylene-co-vinylidene fluoride) (THV); poly(vinyl fluoride) (PVF); poly(ethylene terephthalate) (PET); fluoroethylene vinyl ether (FEVE); polyethylene naphthalate (PEN); and glass (Wieser et al., 2025; Bellini, 2025X).

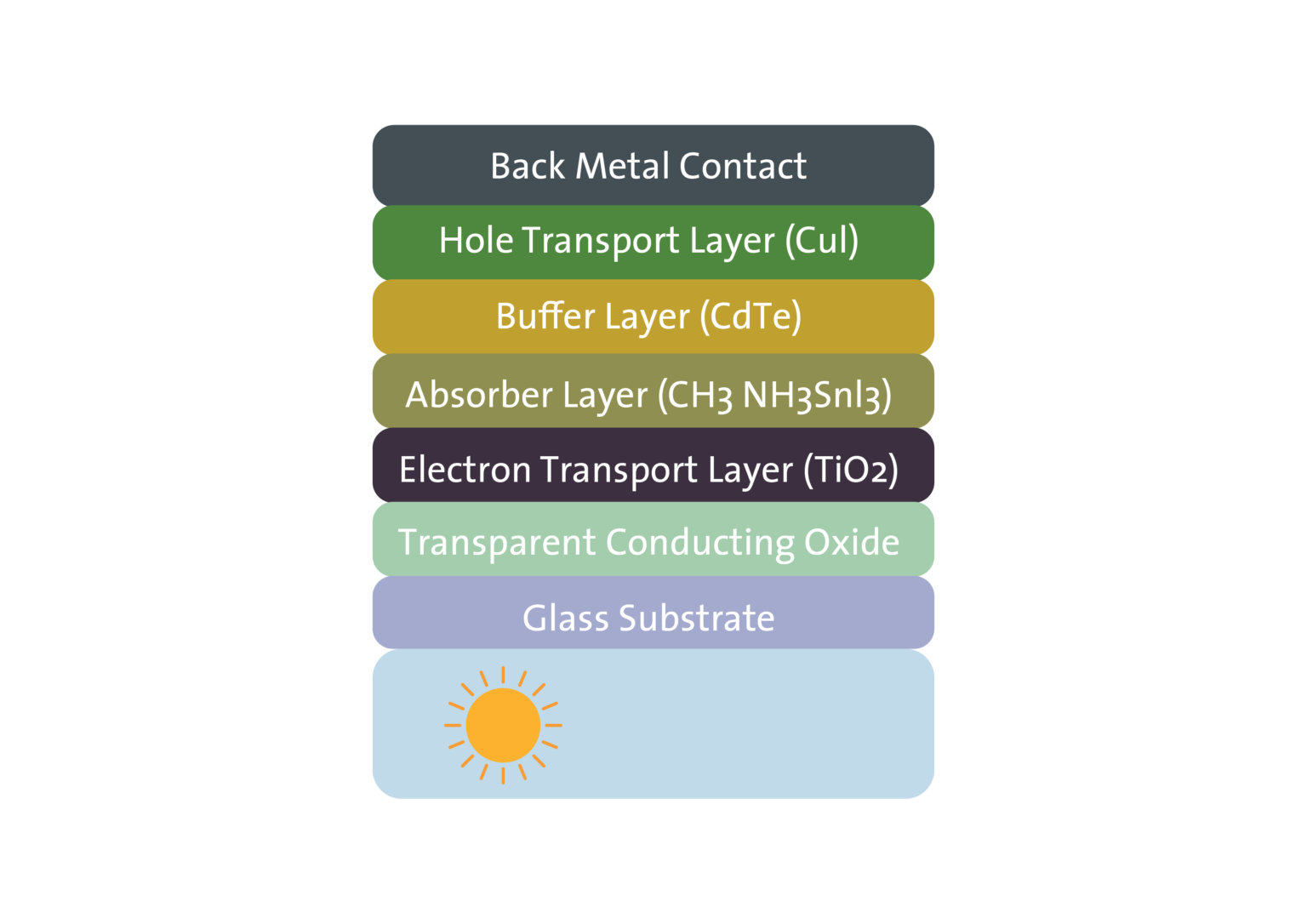
Around 2025, with 45% of modules produced still using backsheets, Chinese solar manufacturers switched from laminated multilayer polymer backsheets with a core PET layer laminated with polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF), to a coated single layer of polyethylene terephthalate (PET), with a protective coating on both sides of their modules, known as “CPC.” They switched for cost reasons, although it is unknown whether CPC backsheets can withstand 30 years-plus of outdoor use. Concerns about durability and limited transparent polymer options for polymer backsheets have led module makers to instead use glass on both sides. The additional adhesives and films which laminated backsheets require are susceptible to price increases and import restrictions, though the fluorocarbon coatings which coated backsheets use as raw materials have a wide range of sourcing channels and are cost-controllable. Coated backsheets also have a simpler production process, with lower investment costs for coating equipment and less energy consumption (Hutchins, 2025).

As cracking can allow moisture to affect the inner workings of a solar module, the adhesives used in lamination for laminated multilayer backsheets can be a weak point, as they can soften or debond under high temperature or humidity conditions. While a properly applied and cured coating can form a dense structure on the surface of the backsheet, lamination can leave gaps between the two film layers, potentially allowing moisture and oxygen to reach a module’s inner workings. Flexible CPC backsheets utilize coating formulas that can be adjusted to develop backsheets with performance characteristics to suit different climatic conditions and installation environments, such as by adjusting parameters including coating thickness, hardness, and color. CPC backsheets are also environmentally sustainable, since separating and recycling a coating and base polymer is much simpler than pulling apart laminated layers, while they also offer a reduction in the use of adhesives and solvents, and their thin coating consumes less material, and less toxic fluoropolymers, than a full additional layer laminated on top of a core layer (Hutchins, 2025).

Wieser’s et al. (2025) backsheet degradation field assessment protocol utilizes the Köppen Geiger Climatic Zone (KGCZ) standardized guide as the approximate indicator of local climates, and uses an inexpensive colorimeter to monitor the PV systems, as opposed to the commonly used hand-held Fourier transform infrared (FTIR) spectroscopy instruments, which are more expensive. According to Wieser’s study, backsheet degradation has a non-uniform spatial and temporal distribution, with elevated edge degradation being observed for all materials and climatic zones. There is a less significant difference observed for edge molecules than center modules, which is known as anisotropy, due to the combined effect of elevated junction box temperature and the ‘Edge Effect,’ which refers to increased rear-side irradiance. The property of a material where its characteristics vary depending on the direction of measurement, meaning it has different properties along different axes, is known as anisotropy, unlike isotropic materials which have uniform properties in all directions. Degradation rates can vary within different parts of the same site, block, row, sub-row, or module depending on the local microclimate around the material (Wieser et al., 2025; Bellini, 2025X).

**Buffer Layer**

In solar cells, a buffer layer, typically an n-type material, forms a p-n heterojunction with a p-type absorber layer, facilitating charge separation and improving efficiency by optimizing band alignment and reducing recombination losses. The primary role of the buffer layer in a solar cell is to enhance the efficiency of the device by facilitating charge separation and improving the overall performance of the solar cell. The buffer layer's bandgap should be wide enough to allow light to pass through to the absorber layer, while also ensuring proper band alignment to facilitate electron transport. The buffer layer helps in the separation of photo-generated electrons and holes, preventing them from recombining and improving the overall efficiency of the solar cell. Common materials used as buffer layers include CdS, CdTe, ZnO, PbS, , , and . The properties of the buffer layer, such as its thickness, doping concentration, and bandgap, significantly affect the performance of the solar cell, including its open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and overall efficiency (η). BUffer layers physically block ion migration of perovskite into carrier transport layers and chemically stabilize the formamidinium lead iodide phase through strong coordination interaction (Zai et al., 2025). A buffer layer offers a porous structure that aids in forming the upper hole-transporting layer (HTL), while also preventing the leakage of corrosive additives from the HTL material, to promote efficient hole transfer and conduction and also restrict charge recombination (Islam et al., 2024; Bellini, 2024S).



*Islam, A., Haider, S.Z., Wang, M., Ismail, A.G., and Anwar, H. (2024) Interface engineering for improved performance of perovskite solar cells using CdTe buffer layer, Results in Engineering, Volume 23, 102618,* [*https://doi.org/10.1016/j.rineng.2024.102618*](https://doi.org/10.1016/j.rineng.2024.102618)

Adding a buffer layer (BL) made of cadmium telluride (CdTe) to perovskite solar cells enhances extraction of charge carriers while reducing device defects. CdTe was chosen since the hydrophobic nature of CdTe could protect the absorber from moisture and corrosion, and that its high UV resistance could minimize UV-induced degradation, enhancing cell stability. They used the SCAPS-1D solar cell capacitance software, developed by the University of Ghent, to simulate the cell configuration (Islam et al., 2024; Bellini, 2024S). The e-beam evaporation technique was used to fabricate the buffer layer, whereby the optical and electrical properties of the film exhibited a strong dependence on the deposition rate, as a higher deposition rate resulted in In-rich films with poor transmittance and increased parasitic absorption (Du et al., 2025; Bellini, 2024G).

Zai et al. (2025) integrated wafer-scale continuous monolayer buffers at the top and bottom of a perovskite layer through a transfer process. Effective chemical passivation results from the formation of Pb-S bonds, and minority carriers are blocked through a type-I band alignment (Zai et al., 2025). In perovskite solar cells, a type-I band alignment, also known as a step-down band alignment, is used to efficiently block minority carriers and promote charge separation. This alignment ensures that the minority carriers (e.g., electrons in an n-type material) are blocked at the interface between different layers, preventing them from recombining and increasing the overall efficiency of the solar cell. In a solar cell, minority carriers are the charge carriers that are not in the majority (e.g., electrons in an n-type material or holes in a p-type material). In a type-I band alignment, the conduction band of one material is lower in energy than the conduction band of another material, and similarly, the valence band of one material is lower in energy than the valence band of another material. This creates a "step-down" in the energy levels at the interface. Because of this "step-down," when a minority carrier reaches the interface between two materials with a type-I band alignment, it is blocked from moving into the other material. This is because it would require too much energy to overcome the potential barrier. By blocking minority carriers, the type-I band alignment helps to promote the separation of charge carriers (e.g., electrons and holes) in the perovskite solar cell, which are then extracted as current. This leads to higher efficiency in converting light into electricity.

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**Solar Cell Electrodes**

Solar cell electrodes are essential components that facilitate the conversion of sunlight into usable electrical energy by collecting and conducting the generated current. Solar cell electrodes, which facilitate the flow of electricity, are commonly made from materials like transparent conductive oxides (TCOs) for front electrodes, carbon materials, and metal nanowires. Transparent conductive oxides (TCOs) include: indium tin oxide (ITO), fluorine-doped tin oxide (FTO), zinc oxide (IZO), aluminum-doped zinc oxide (AZO), and tungsten-doped indium oxide (IWO). Carbon Materials include: carbon nanotubes (CNTs), graphene, carbon black, graphite, and carbon Pastes. Metal nanowires include metals such as silver, gold and copper. While not transparent, metals like silver, copper, and gold can be used as metal electrodes in some solar cell designs.

When sunlight strikes a solar cell, it excites electrons, creating electron-hole pairs. The electrodes act as contact points to collect these generated charges (electrons and holes), for charge collection and transport. The electrodes are made of conductive materials that allow the flow of electrical current out of the solar cell to an external circuit. At least one electrode needs to be transparent to allow sunlight to reach the active material, and the electrode material must have high electrical conductivity to minimize energy loss during current transport. The contact between the electrode and the semiconductor or active layer should have low resistance to ensure efficient charge collection. Using materials like spiro-OMeTA or P3HT for the hole transport layer can improve the interface between the electrode and the perovskite layer. The front electrodes (anode), are typically made of transparent conductive oxides like ITO or FTO, as they need to be transparent to allow sunlight to reach the perovskite layer.

The rear electrodes (cathode) can be made of various materials, including gold, silver, and carbon.

In solar cells, both front and rear contacts play crucial roles in collecting and conducting the generated electricity, with back contact designs potentially offering higher efficiency by reducing shading on the front surface. In traditional solar cells, front contacts, often in the form of a metal grid, are used to collect the electrical current generated by the solar cell. The presence of these grids on the front surface can block some sunlight, reducing the overall efficiency of the cell. Back contact solar cells, like interdigitated back contact (IBC) cells, move the alternating contacts for electrons and holes to the rear side of the cell, allowing the entire front surface to collect sunlight by eliminating shading on the front surface. Back contact designs are particularly useful in high-current applications like concentrator PVs. There are also EWT (Emitter Wrap-Through) and MWT (Metalization Wrap-Through) configurations of back contact solar cells. The alternating contacts in IBC cells are fabricated using masked diffusion, masked ion-implantation, or laser doping, followed by metallization.

Graphene electrode technology can be used to replace silver and other metals used as rear contacts. Graphene material offers chemical stability and cost-effectiveness, is compatible with typical industry processes, such as screen printing, doctor blading, and slot die coating processes, and is similar to inkjet printing (piezo-electric dispensers) (Thompson, 2025L). A robust single-walled carbon nanotube (CNT) electrode was integrated into a perovskite solar cell to improve durability by not accelerating the decomposition of the perovskite material as much as metal electrodes, and to enable dual-sided light absorption. Metal electrodes currently used in solar cells can suffer from oxidation and corrosion, diminishing long-term stability. CNT electrodes are more chemically stable, more resistant to oxidation, and due to their high electronic conductivity allow efficient charge transport. Even though CNT-PSCs have a lower power conversion efficiency than that of traditional gold electrode perovskite solar cells, they are transparent and thus have dual sided light absorption which increases energy output (Jeon et al., 2025; Publicover, 2025).

**Tandem (Multijunction) Perovskite Cells**

1. Perovskite-Silicon Tandem Cells
2. Perovskite-Perovskite Tandem Cells and Other Configurations
3. Heterojunction Engineering of Perovskite Solar Cells
4. Exploring 2D/3D Layered Perovskites for Enhanced Stability

Tandem solar cells: HJT + perovskite - the future of solar power - [hjtpv.com](http://hjtpv.com/) <https://hjtpv.com/tandem-solar-cells-hjt-perovskite-the-future-of-solar-power/>

Tandem cells can capture a wider range of the solar spectrum and generate more electricity than single-junction cells. Perovskite-based tandem solar cells combine perovskite cells with other photovoltaic technologies like silicon to achieve higher efficiencies. Efficient charge transfer mechanisms between different layers must be designed, such as the top perovskite absorber layer, bottom silicon absorber layer, hole transport layer, electron transport layer, buffer layer, and electrode contacts. The absorber layer is attached to other materials, which force electric current to flow in a single direction through the absorber layer and into the metal contacts to be collected as electric current. In a perovskite-silicon tandem cell, two or more different photovoltaic materials are combined in a single device, with the top wide bandgap perovskite sub-cell absorbing the short wavelength high energy incident photons, and the remaining low energy photons transmitting through it and falling on the silicon, cadmium telluride, or copper indium gallium selenide bottom sub-cell. This arrangement of perovskite top cell and silicon bottom cell thereby serves to maximize the light absorption, with the different cells capturing different light wavelengths. In a tandem cell, the component cells must be stacked in order of decreasing bandgap, so the light is automatically filtered as each cell extracts photons which exceed its bandgap. Compatible materials must be used in the various junctions over a wide temperature range (defined by the fabrication temperatures), and specifically, the thermal expansion coefficients should be similar and the bandgaps should be a good match to the spectrum (Corkish, 2004).

By changing the material composition, perovskites have flexibility and can be tuned to respond to different colors in the solar spectrum, which allows perovskites to be combined with another, differently tuned absorber material to deliver more power from the same device in a tandem device architecture. The theoretical limit of a single junction PV cell in full sunlight at room temperature is 33% power conversion efficiency, which can be overcome with tandem devices. Perovskite and silicon make promising hybrid-tandem partners, because perovskite can be tuned to take advantage of the parts of the solar spectrum that silicon PV cells can’t use very efficiently. A perovskite-perovskite tandem cell combines two perovskite solar cells of different composition, and could be useful in the mobile, disaster response, and defense operations sectors, as they can be made into flexible, lightweight devices with high power-to-weight ratios.

The main commercial challenge in constructing tandem cells lies in balancing cost, aesthetics, and efficiency, as top-cell transparency and performance must be improved for tandem devices to be commercialized. In a current-matched device, imperfect transmission not only impacts the bottom cell but also the top cell itself, so the top perovskite cell must achieve higher single-cell efficiency to compensate for reduced transparency. Schmid (2025) recommends the rule for tandem cell transparency is that if the top cell fully transmits photons below its bandgap and the solar spectrum is evenly split between the top and bottom cells, then the top cell needs to reach at least 50% of the bottom cell’s efficiency for the tandem to match the performance of a bottom cell alone. However, in the case where the transparency is reduced to 35%, the top cell must be even more efficient, as if the tandem is to outperform the single bottom cell by 30%, an 85% top-to-bottom single-cell efficiency ratio is required. Spectrum splitting, utilizing up-conversion and down-conversion of photons, is a promising route along with optimizing transparency, when used to replace transmission losses with the anticipated lower losses of spectrum-splitting optics. Tandems have a material efficiency disadvantage, particularly in the top perovskite cell, which can be mitigated by combining them with light concentration techniques which concentrate more light on the solar panel (Schmid, 2025; Bellini, 2025GG).

Figure XXX.

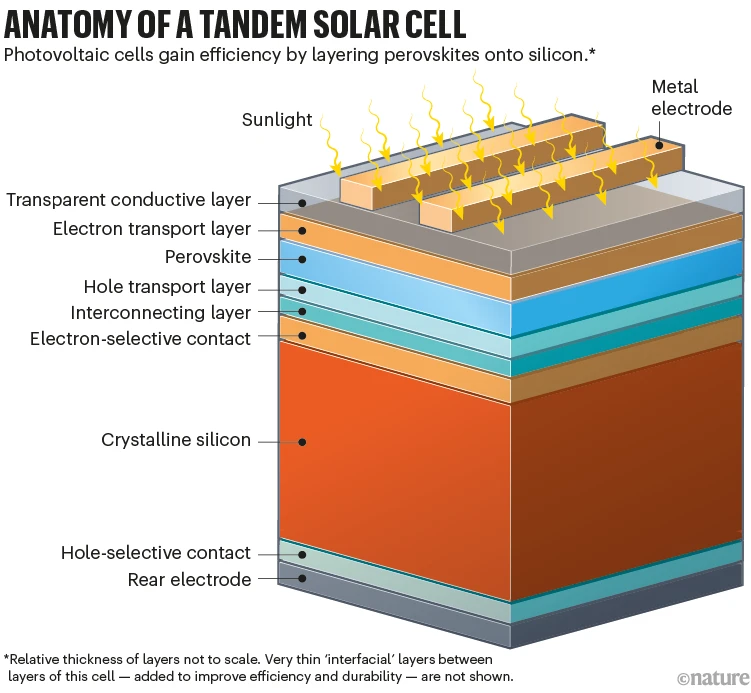


Image: Nature, <https://www.nature.com/articles/d41586-023-03714-y>

Power-conversion efficiencies (PCE) of 33.89% with a fill factor of 83.0% and an open-circuit voltage of nearly 1.97 V (Liu et al., 2024B) and 30.73%, with the top and bottom cells contributing 23.34 % and 7.39 % to the overall efficiency (Moeini et al., 2025), have been achieved in monolithic 2T and 4T perovskite/silicon tandem solar cells, where perovskite was used as the top sub-cell and silicon as the bottom cells, respectively. Other than the above, various perovskite-based tandem cells such as perovskite/CZTSSe (PCE~14.2%), perovskite/CIGS (PCE~26.8%), perovskite-DSSC (PCE~17.5%), and perovskite-perovskite (PCE~25.9%) have been widely developed in recent years and will be ready for commercialization within a couple of years (Soonmin et al., 2023). Where single-junction silicon has a theoretical efficiency limit of 29.4%, a perovskite-perovskite tandem could reach 43% (Wantenaar, 2023). As more junctions are added, the technical potential grows: the theoretical limit for a triple-junction perovskite is 50%.

Ahmad et al. (2022) describes a methylammonium tin iodide (CH3NH3SnI3) solar cell made from glass/ITO (as an electron-transport layer)/n-type WS2/CH3NH3SnI3/p-type P3HT (as a hole-transporting layer)/Au.

1. Substrate- substrate made of glass and: 1) indium tin oxide (ITO) 2) transparent fluorine-doped tin oxide (FTO). ITO (Indium Tin Oxide) functions as the transparent conducting electrode and acts as an electron-transport layer (ETL).
2. Transparent conductive oxide (TCO). TCOs are transparent electrodes that allow light to enter while simultaneously collecting and transporting the generated electricity. An IZO layer refers to a thin film made of Indium Zinc Oxide (In2O3−ZnO), and is a type of transparent conducting oxide (TCO). A transparent conductive oxide (TCO) layer serves as the top cell’s electrode that passes the light from the top cell into the bottom one and a 150 nm thick tin oxide (SnO2) layer is located at the interfaces of two sub-cells and top cell’s electrode to prevent electrical connections.
3. Perovskite absorber (e.g., MAPbI3)- The main light-absorbing layer, often made of metal-halide perovskites (e.g., MAPbI3, CsFAPbI3). Methylammonium tin iodide (CH3NH3SnI3). a wide-bandgap perovskite absorber treated with 1,2-diaminopropane (DAP). gas quenched perovskite. PZ (pyrrodiazole) additive inverted perovskite film. perovskite-FP1-H. a perovskite absorber doped with 2-phenylethylammonium iodide (PEAI).
4. Hole transport layer (HTL, like PEDOT:PSS, or spiro-OLED)- Facilitates the transport of holes (positive charges) from the perovskite absorber to the electrode. 2PACz [2-(9H-Carbazol-9-yl)ethyl]phosphonic acid HTL layer. MeO-2PACz HTL layer. a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz). a hole transport layer (HTL) relying on spiro-OMeTAD. an HTL made of Copper(I) iodide (Cul). a hole transport layer (HTL) made of nickel(II) oxide (NiOx). polymer hole transport layer made of poly(triarylamine) (PTAA). a sputtered nickel(II) oxide (NiOx) film. Copper (cuprous) oxide (Cu2O) HTL. a methyl-substituted carbazole (Me-4PACz) hole transport layer. a hole transport layer (HTL) relying on spiro-OMeTAD and molybdenum oxide (MoOx). a hole transport layer (HTL) with a self-assembled monolayer (SAM) based on [2-(3,6-Dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid (MeO-2PACz). a hole transport layer (HTL) made of nickel(II) oxide (NiOx), the MeO-2PACz SAM. a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz). p-type P3HT. (Poly(3-hexylthiophene-2,5-diyl)). regioregular poly (3-hexylthiophene) (P3HT) polymer. spiro-OMeTAD that was not doped with 4-tert-butylpyridine (tBP) and lithium bis(trifluoromethane)sulfonimide (LiTFSI) was used as the hole transport layer (HTLs).
5. Electron transport layer (ETL, such as ITO)- Facilitates the transport of electrons from the perovskite absorber to the electrode, often employing materials like ITO (Indium Tin Oxide). an electron transport layer (ETL) made of buckminsterfullerene (C60). an ETL based on phenyl-C61-butyric acid methyl ester (PCBM). an electron transport layer (ETL) made of tin oxide (SnO2). an electron transport layer (ETL) made of titanium oxide (TiO2). an electron transport layer (ETL) based on phenyl-C61-butyric acid methyl ester (PCBM) and molybdenum trioxide (MoO3). zinc oxide (ZnO) for the ETL. tin(IV) oxide (SnO2) electron transport layer (ETL). an electron transport layer (ETL) made of tin oxide (SnO2) and buckminsterfullerene (C60). n-type WS2 tungsten sulfide.
6. Buffer Layer- a tin oxide (SnOx) buffer layer, an ITO buffer layer. Four-terminal (4T) semi-transparent perovskite-silicon tandem solar cells can be manufactured with an indium oxide () sputtering buffer layer (SBL) to protect the top layer perovskite absorber and the electron transport layer (ETL) from bombardment arising from the indium tin oxide (ITO) transparent electrode deposition process. a bathocuproine (BCP) buffer layer. a tin oxide (SnOx) buffer layer. a spacer based phenyl-C61-butyric acid methyl ester (PCBM). the CdTe buffer layer. an Rh101 buffer layer. CdS, CdTe, ZnO, PbS, , , and
7. Electrode, Contact- silver (Ag) metal contact. copper metal contact. aluminum (Al) back contact. a transparent back contact made of indium zinc oxide (IZO), and a silver (Ag) metal contact, an ITO electrode, then Al2O3 or PFN–Br, (Au) rear contacts, front contact of fluorine-doped tin oxide (FTO).
8. 3D perovskite- The 3D perovskite was a FAPbI3-based composition (FA, formamidinium) with added MACl and MAPbBr3 (MA, methylammonium) for improved crystallization as well as excess lead iodide (PbI2),
9. ultrathin lithium fluoride (LiF) interlayer. a dense and uniform ultrathin lithium fluoride (LiF) protective coating on the Li metal surface by vacuum evaporation.
10. The silicon subcell can be a crystalline silicon (c-Si) device, often with a silicon heterojunction (SHJ) structure using amorphous silicon (a-Si:H) layers. Crystalline Silicon (c-Si) Core: The main light-absorbing material, often an n-type silicon wafer.
11. Silicon Heterojunction (SHJ) Structure: A common configuration for c-Si subcells, using thin layers of amorphous silicon (a-Si:H) at the front and rear of the silicon wafer.
12. Silicon Passivation: Layers are used to improve the performance of the silicon subcell by reducing recombination losses, such as the AlOx/SiNx rear passivation layer in PERC (Passivated Emitter and Rear Cell) cells. Bilayer interface passivation strategy is a method used to improve the efficiency and stability of the cell to maximize both electron transport and hole blocking, by addressing issues at the interface between different materials, and involves using two layers to effectively passivate the interface between different materials, often a thin lithium fluoride (LiF) layer followed by a short-chain ethylenediammonium diiodide (EDAI) molecule, between perovskite and silicon in a tandem solar cell, or within the perovskite material itself. The thicker LiF layer may help improve the passivation, but comes with a considerable undesirable resistive loss. Likewise, the EDAI molecule can chemically passivate the unpassivated areas that are not contacted by the LiF layer, forming nanoscale localized contacts at perovskite/C60 interface, which can provide an optimal tradeoff between passivation and charge extraction (Mishra, 2025C).
13. Self Assembled Monolayer- 2PACz, PyCA-3F (2-chloro-5-(trifluoromethyl)isonicotinic acid)
14. Surface passivation layer- a layer based on phenethylammonium iodide (PEAI).
15. A recombination layer or interconnect layer (e.g., nanocrystalline silicon (nc-Si:H)) is also used to connect the two subcells. To connect the perovskite and silicon subcells electrically, allowing for the flow of electrons and holes between the two. Nanocrystalline silicon (nc-Si:H), amorphous silicon (a-Si:H), or tunnel junctions (e.g., nc-Si:H(n+)/nc-Si:H(p+)) can be used. Kan et al. (2024) deposited the perovskite precursor ink with CuSCN directly on the recombination layer made of indium tin oxide (ITO).
16. 2D/3D- a 2D perovskite layer made of PeDAMA4Pb5I16, a 3D layer of CsGeI3-xBrx
17. Anti-reflective coating- anti-reflective coating based on magnesium fluoride (MgF2). anti-reflecting coating doped with lithium fluoride (LiF).
18. monolithic perovskite-PERC tandem solar cell that utilizes a new type of tunnel recombination junction (TRJ) based on indium tin oxide (ITO), nickel(II) oxide (NiO), and carbazole (2PACz). They explained that usually TRJs are based on ITO and 2PACz alone, and that the addition of the NiO layer is intended to reduce electrical shunts in the perovskite top cell, due to the inhomogeneity of the 2PACz layer on ITO.

**Perovskite Cells**

The conventional perovskite solar cell consists of an anode, an ETL, a perovskite absorbing layer, an HTL, and a cathode. Perovskites can absorb certain colors of light very effectively, which means that they can efficiently process smaller wavelengths of the sun’s spectrum. Perovskites possess a tunable absorption spectra, or bandgap, meaning that perovskites can be combined with every other PV semiconductor, including other perovskites. Perovskite cells have a lower energy and material footprint than silicon cells, because perovskite cells require very thin light-absorbing layers, consisting of low cost and abundant materials.

The structure of perovskite solar cell (PSC) devices mainly consists of a transparent conductive oxide (ITO/FTO) as the top electrode, an n-type semiconducting electron transport layer (ETL) such as or [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), a perovskite absorber layer, a p-type semiconducting hole transport layer (HTL) like PEDOT:PSS, or spiro-OLED, a back-contact electrode (Au, Ag, copper, or carbon), with regular n-i-p and inverted p-i-n configurations. In the n-i-p configuration, the ETL is a planar or mesoporous structure where perovskite is sandwiched between an n-type material (TiO2, [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), etc.) at the bottom and a p-type layer (for example, 2,2’,7,7'-Tetrakis [N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (spiro-OMeTAD) at the top, while in the p-i-n configuration, it is the opposite (Boro et al., 2022). Perovskite solar cell manufacturers place a perovskite absorber layer between ETL and HTL, with both of these layers being sandwiched between electrodes, and the transparent layer is then covered with glass. The most widely used method uses deposition with a One-Step Method, but there are different manufacturing methods using Two-Step depositions, Vapor-Assistance, or Thermal Vapor Deposition.

Perovskite solar cells can have a conventional (normal) structure, using and n-type semiconductors, or an inverted PSC structure, using p-type poly (3,4-ethylene dioxythiophene)-poly(styrene sulfonate) (PEDOT: PSS). Typical mesoscopic perovskite solar cell structures consist of a glass surface with a transparent conducting oxide (TCO), such as in FTO , in which an anode is deposited on the glass substrate, a dense (compact) layer of is a hole-blocking layer, and a mesoporous layer of serves as an electron-transporting layer (ETL). Mesoscopic perovskite solar cells (PSCs) refer to a type of perovskite solar cell where the perovskite material is structured at a mesoscopic scale, meaning it has a porous or interconnected structure with pores ranging from 2 to 50 nanometers in size. Moreover, a layer of the perovskite material is used for light absorption, followed by a hole-transporting layer, followed by metal contacts to complete the device’s structure. This type of solar cell has an organic material with a perovskite structure in its absorbing layer, most typically a lead–metal hybrid (Methylammonium lead iodide perovskite, ). Methylammonium lead iodide is an ambipolar semiconductor that may transmit both electrons and holes to the collecting electrodes. Because of this, perovskite solar cells can operate without a hole or electron conductor. The Spiro-OMeTAD polymer composition is the HTL material most frequently utilized in perovskite solar cells (Soonmin et al., 2023).

SCAPS-1D was used to detect compatible electron transport layers (ETL) and hole transport layers (HTL) for the mixed perovskite layer FA0.85Cs0.15Pb (I0.85Br0.15)3 (MPL), employing diver ETLs such as SnO2, PCBM, TiO2, ZnO, CdS, WO3 and WS2, and HTLs such as Spiro-OMeTAD, P3HT, CuO, Cu2O, CuI, and MoO3. They settled on FTO/SnO2/FA0.85Cs0.15Pb (I0.85Br0.15)3/Spiro-OMeTAD/Au and (FTO/WS2/FA0.85Cs0.15Pb (I0.85Br0.15)3/MoO3/Au). WS2 and MoO3 were chosen as ETL and HTL, respectively, for designing the proposed novel structure of FA0.85Cs0.15Pb (I0.85Br0.15)3-based perovskite solar cells. With the inspection of several parameters such as variation of the thickness of FA0.85Cs0.15Pb (I0.85Br0.15)3, WS2, and MoO3 including different defect densities, the novel proposed structure has been optimized, and a noteworthy efficiency of 23.39% was achieved with the photovoltaic parameters of VOC = 1.07 V, JSC = 21.83 mA cm−2, and FF = 73.41%. The dark J–V analysis unraveled the reasons for the excellent photovoltaic parameters of our optimized structure. Furthermore, the scrutinizing of QE, C–V, Mott–Schottky plot, and the impact of the hysteresis of the optimized structure was executed for further investigation (Rahman et al., 2023).

Tandem Cells- inefficient photon harvesting. Here we increase the optical path length in perovskite films by preserving smooth morphology while increasing thickness using a method we term boosted solvent extraction. Carrier collection in these films – as made – is limited by an insufficient electron diffusion length; however, we further find that adding a Lewis base reduces the trap density and enhances the electron-diffusion length to 2.3 µm, enabling a 19% PCE for 1.63 eV semi-transparent perovskite cells having an average near-infrared transmittance of 85%. these devices usually employ materials having a bandgap of 1.5–1.7 eV, they are also particularly attractive as top cells in tandem devices (Chen et al., 2020).

The group built the black perovskite cesium lead triiode cell with a substrate made of fluorine-doped tin oxide (FTO), a titanium dioxide (TiO2) electron transfer layer (ETL), the CsPbI3 absorber, a hole transport layer (HTL) relying on a regioregular poly (3-hexylthiophene) (P3HT) polymer, and a gold (AU) metal contact (Li et al., 2023B; Bellini, 2023C, Jia, 2023).

In this direction for A site Cs gives promising results while for B site Sn based devices and carbon as HTL provides the future of the all inorganic Pb-free stable PSCs. Although the efficiencies of such devices are still low at experimental level. Also using DFT (density functional theory) study in combination with the simulation tool various groups are reporting exciting results (Sebastian and Kurian, 2021). Also for increasing efficiency along with the stability some groups reported heterojunction devices based on inorganic materials. Various heterojunction structures such as bilayer and triple layer solar cell are reported in the literature using SCAPS-1D simulation tool employing caesium based inorganic material providing the direction for the stability along with efficiency to the scientific community (Khatoon et al., 2022; Khatoon et al., 2023B; Khatoon et al., 2023A).

Placing a 0.5 mm thick aluminum (Al) foil inside PV modules, between the solar cell and the EVA, and between the EVA and the glass layer, may enhance its in-plane thermal conductivity and cool it from within, to dissipate heat from the transversal direction and simultaneously increase the in-plane temperature uniformity of the PV module. Passive cooling methods such as phase change cooling and radiation cooling dissipate heat from the surface of the PV module (Sun et al., 2025; Kahana, 2025A). An encapsulant EVA (Ethylene Vinyl Acetate) is a key component in the production of photovoltaic (PV) modules. It offers excellent optical, electrical, and mechanical properties, making it ideal for use in solar panels. It works as a layer that covers and protects the solar cells, providing a durable and long-lasting barrier that shields the cells from environmental factors such as moisture, dust, and physical damage. The encapsulant is applied to the top and bottom of the solar cells to retain their efficiency at the module level. The Solar cells are sandwiched between encapsulants which forms a hermetic seal that protects the solar cells from moisture and other environmental factors.

A polymer-based n-type conductive ink that has the electrical conductivity and energetics required for indoor and outdoor PV has been developed that can be used in the charge-extracting layer of organic solar cells (OPV), as well as in transport layers of perovskite solar cells. n-type polymers have traditionally not been able to reach the performance and scaling reached with p-type polymers. The N-ink material has several advantages, including performance and handling benefits, flexibility, reduced manufacturing costs, and enables a fully printed PV process. It is alcohol or water-based, halogen-free, and an environmentally-friendly precursor. (Yang et al., 2021; Thompson, 2025D).

in situ gettering during the application of asymmetric configuration of n-type and p-type tunnel oxide passivating contact (TOPCon) layers increases the material quality of n-type epitaxially grown silicon wafers sufficiently to fabricate perovskites silicon tandem solar cells with a high energy conversion efficiency and with low carbon footprint. Gettering is a process widely used in the PV manufacturing industry during crystal growth to remove impurities and defects in wafers. Epitaxially grown wafers (EpiWafers) are fabricated in a direct gas-to-wafer process as a low-carbon material for solar cells (Rittman et al., 2025; Thompson, 2025P).

**Cell Structures**

The academics built the tandem cell with a top inverted perovskite device based on an indium tin oxide (ITO) substrate, the 2PACz layer, a perovskite absorber, an electron transport layer (ETL) made of buckminsterfullerene (C60), a tin oxide (SnOx) buffer layer, an ITO buffer layer, a silver (Ag) metal contact, and an anti-reflective coating based on magnesium fluoride (MgF2). The bottom cell was based on a heterojunction (HJT) architecture (Er-Raji et al., 2025; Bellini, 2025R). The 2PACz layer, specifically [2-(9H-carbazol-9-yl)ethyl]phosphonic acid, is a self-assembled monolayer (SAM) used as a hole-selective layer (HSC) in inverted perovskite solar cells (PSCs). It's a popular choice due to its ability to enhance charge extraction and transport, leading to improved device performance and stability.

The inverted cell was built with a substrate made of indium tin oxide (ITO), the 2PACz HTL, a perovskite absorber, an electron transport layer (ETL) relying on buckminsterfullerene (C60), a bathocuproine (BCP) buffer layer, and a copper metal contact (Li et al., 2024B; Thompson, 2024G). The inverted cell was produced with a substrate made of glass and indium tin oxide (ITO), the MeO-2PACz layer, the perovskite absorber, a layer based on phenethylammonium iodide (PEAI), an ETL based on phenyl-C61-butyric acid methyl ester (PCBM), a bathocuproine (BCP) buffer layer, and a silver (Ag) metal contact (Liu et al., 2024A; Bellini, 2024T). After calibrating the new ETLs, the research team built an inverted solar cell with a substrate made of indium tin oxide (ITO), a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz), a perovskite absorber, the optimized C60 ETL, a tin oxide (SnOx) buffer layer, a bathocuproine (BCP) buffer layer, and a silver (Ag) metal contact (Xing et al., 2025; Bellini, 2025L).

The π–π stacked perovskitecell was built with a substrate made of indium tin oxide (ITO), an electron transport layer (ETL) made of tin oxide (SnO2), the perovksite absorber, a hole transport layer (HTL) relying on spiro-OMeTAD, a spacer based phenyl-C61-butyric acid methyl ester (PCBM), and a silver (Ag) metal contact (Huang et al., 2024; Bellini, 2024R).

The device was based on a substrate made of glass, a transparent conductive oxide (TCO), an electron transport layer (ETL) made of titanium oxide (TiO2), an absorber made of a perovskite material known as CH3NH3SnI3, the CdTe buffer layer, an HTL made of Copper(I) iodide (Cul), and a back metal contacts (Islam et al., 2024; Bellini, 2024S).

In 2023, an international research team fabricated a four-junction (4T) tandem solar cell based on perovskite and copper/indium/selenium (CIS) thin-film with a power conversion efficiency of up to 29.9%. The researchers used methyldiammonium diiodide (MDADI) to reduce open-circuit voltage losses in the top perovskite cell. The scientists said they used halide salt methyldiammonium diiodide (MDADI) for surface defect passivation, which they said reduced the open-circuit voltage loss in the device's top cell based on perovskite while improving the overall tandem cell efficiency and near-infrared (NIR) transmittance. The scientists grew the top cell through a multi-stage co-evaporation process. The device was based on a substrate made of glass and indium tin oxide (ITO), a hole transport layer (HTL) made of nickel(II) oxide (NiOx), a perovskite absorber, a buckminsterfullerene () electron transport layer (ETL), a tin oxide (SnOx) layer, an ITO layer, and an ultrathin lithium fluoride (LiF) interlayer (Zhang et al., 2024C). a dense and uniform ultrathin lithium fluoride (LiF) protective coating on the Li metal surface by vacuum evaporation.

Li et al. (2024) built a tandem device with a substrate made of glass and indium tin oxide (ITO), a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz), a wide-bandgap perovskite absorber treated with 1,2-diaminopropane (DAP), an electron transport layer (ETL) based on buckminsterfullerene (C60), a gold (AU) metal contact, a PEDOT-PSS layer, a low bandgap perovskite absorber, another ETL made of C60, a tin oxide (SnO2) buffer layer, and a metal electrode (Li et al., 2024A; Bellini, 2024L).

The devices used in the argon and helium quenching experiment were inverted p-i-n type devices with glass substrates measuring 9 cm2, and based on a formamidinium-cesium (FA-Cs) dual cation perovskite recipe with a 1.6 eV bandgap. In an n-i-p solar cell, the device is illuminated through the electron-transport layer (ETL) side, while a p-i-n structure is illuminated through the hole transport (HTL) surface. The stack was as follows: indium tin oxide (ITO), polymer hole transport layer made of poly(triarylamine) (PTAA), gas quenched perovskite, buckminsterfullerene (C60) electron transport layer (ETL), a bathocuproine (BCP) buffer layer, and silver (AG) electrode (Hadipour, 2025; Thompson, 2025I).

The cell stack for the PZ (pyrrodiazole) additive inverted perovskite film was: transparent fluorine-doped tin oxide (FTO) coated glass substrate, a sputtered nickel(II) oxide (NiOx) film, the methyl-substituted carbazole (Me-4PACz) layer, perovskite, buckminsterfullerene (C60) electron transport layer (ETL), a bathocuproine (BCP) buffer layer, copper (Cu) contact (Yuan et al., 2025; Thompson, 2025J).

Using PEDOT:PSS, an HHSC cell was fabricated with a silver (Ag) metal contact, a textured n-type silicon (n-Si) absorber coated with PEDOT:PSS, and an indium gallium (In:Ga) interface. The textured surface of the n-Si absorber is claimed to reduce surface reflectance while providing saw and damage-free smooth surface and increased junction area, which is crucial for high quality and efficient PEDOT:PSS/n-Si junction formation. The addition of ethylene glycol in the PEDOT:PSS enhances its electrical conductivity and induces a strong inversion layer at PEDOT:PSS/n-Si interface near the n-Si surface. The top perovskite device was constructed with a transparent fluorine-doped tin oxide (FTO) substrate, a hole transport layer (HTL) made of nickel(II) oxide (NiOx), a perovskite absorber, an electron transport layer (ETL) based on phenyl-C61-butyric acid methyl ester (PCBM) and molybdenum trioxide (MoO3), an Rh101 buffer layer, a silver (Ag) metal contact. The energy bandgap and transparency of the top perovskite cell is gauged to increase light absorption and power conversion efficiency. The wide bandgap light absorber layer of the top cell was based on a perovskite material known as Cs0.1FA0.9PbI2Br (Afroz et al., 2025; Bellini, 2025S).

Nyiekaa et al. (2024) built an n-type heterojunction planar inverted perovskite solar cell with all-inorganic transport materials and a lead-free perovskite absorber without using transparent conducting oxides (TCOs) for the passivate contacts. For the cell absorber, a lead-free perovskite material known as methylammonium tin triiodide (CH3NH3SnI3) was used, which has an energy bandgap of 1.3 eV. Copper oxide (Cu2O) was used for the HTL and zinc oxide (ZnO) for the ETL. The cell utilizes a glass substrate and an aluminum (Al) back contact (Nyiekaa et al., 2024; Bellini, 2025T).

On the front side, the TOPCon devices featured a boron-diffused emitter, passivated by a multilayer stack of aluminum oxide (AlOx), a SiNx layer, and a silicon oxynitride (SiOyNz) layer as an antireflection coating (ARC). On the rear side, the cells had a tunneling silicon oxide (SiO2) layer, a phosphorus-doped polycrystalline silicon (poly-Si) layer, and an additional SiNx ARC layer. Furthermore, the front side was treated with silver (Ag) and aluminum (Al), while the rear-side contact was formed using a screen-printed Ag paste (Tong et al., 2025; Bellini, 2025U).

The stacks under comparison for the aluminum oxide nanoparticles hole transport layer were as follows: glass substrate coated with indium tin oxide (ITO), a methyl-substituted carbazole (Me-4PACz) hole transport layer, then Al2O3 or PFN–Br, the perovskite absorber, a buckminsterfulleriene (C60) electron transport layer (ETL), a bathocuproine (BCP) buffer layer, and copper electrodes (Perera et al., 2025B; Thompson, 2025N).

They used caesium ions to improve the microstructure and reduce defects in the THP film. The 2D/3D tin halide perovskite cell was fabricated with a substrate made of indium tin oxide (ITO) and glass, a PEDOT:PSS hole transport layer, the perovskite absorber, a bathocuproine (BCP) buffer layer, and a silver (Ag) metal contact (He et al., 2025; Bellini, 2025EE).

Lin et al. (2025) examined a hexane-soluble fraction that they labeled FP1-H and a chloroform-soluble fraction, labeled FP1-C, to test the furan material. The FP1-H was used by the team in an HPSC based on a stack as follows: indium tin oxide (ITO) glass, tin(IV) oxide (SnO2) electron transport layer (ETL), perovskite-FP1-H, Spiro-OMeTAD layer and silver (Au) electrode contacts (Lin et al., 2025; Thompson, 2025F). Using x-ray diffraction, scanning electron microscopy, and transmission electron microscopy to analyze samples, the team noted that the PBDF-DFC accumulates at grain boundaries, improving film crystallization and reducing defects (Lin et al., 2025; Thompson, 2025F). The biomass-derived polymer for hybrid organic-inorganic perovskite solar cells (HPSC) is known as PBDF-DFC.

The bifacial perovskite cell was designed to have a transparent fluorine-doped tin oxide (FTO) substrate, an electron transport layer (ETL) made of tin oxide (SnO2), a perovskite absorber, a hole transport layer (HTL) relying on spiro-OMeTAD and molybdenum oxide (MoOx), the IZO layer, a molybdenum oxide (MoOx) (Paul et al., 2024; Bellini, 2024U).

The optimized 3D/2D cell design is based on silver (Au) rear contacts, a cuprous oxide (Cu2O) hole transport layer (HTL), a 2D perovskite layer made of PeDAMA4Pb5I16, a 3D layer of CsGeI3-xBrx, an electron transport layer (ETL) based on phenyl-C61-butyric acid methyl ester (PCBM), and a front contact of fluorine-doped tin oxide (FTO) (Verma et al., 2025; Thompson, 2025H). The research team built the 3D/2D solar cell with a substrate made of glass and indium tin oxide (ITO), a hole transport layer (HTL) based on 2PACz, a 3D perovskite absorber, a 2D perovskite layer, an electron transport layer (ETL) based on buckminsterfullerene (C60), a bathocuproine (BCP) buffer layer, and a silver (Ag) metal contact (Chang et al., 2025; Bellini, 2025K).

The 2D/3D solar cell stack included gold (Au), spiro-MeOTAD, 2D perovskite, 3D perovskite, tin dioxide, and fluorine-doped tin oxide (FTO). The 3D perovskite was a FAPbI3-based composition (FA, formamidinium) with added MACl and MAPbBr3 (MA, methylammonium) for improved crystallization as well as excess lead iodide (PbI2) (Tan et al., 2025; Thompson, 2025). The team built the top perovskite cell with an indium tin oxide (ITO) layer, the SAM, a nickel oxide (NiO) layer, a perovskite absorber with an energy bandgap of 1.68 eV, a lithium fluoride (Lif) layer, an electron transport layer (ETL) based on buckminsterfullerene (C60) and tin oxide (SnO2), a transparent back contact made of indium zinc oxide (IZO), and a silver (Ag) metal contact (Luo et al., 2025; Bellini, 2025HH).

**Bottom Cell**

By using submicron-sized textured silicon bottom cells, the Harter et al. (2024) cell overcomes the challenges associated with traditional micrometer-sized textures, enabling better integration of solution-processed perovskite films, reducing reflection losses and enhancing light in-coupling, while maintaining compatibility with industrial production methods. Optimizing the perovskite layer’s thickness and spin-coating parameters allows for efficient film formation on the submicron-textured surface (Harter et al., 2024; Bellini, 2024F). Harter et al. (2024) fabricated a silicon bottom cell was fabricated with an a-Si:H(i)/nc-SiOx:H(n) layer stack on the front side and an a-Si:H(i)/a-Si:H(p) layer stack on the rear side deposited using plasma-enhanced chemical vapor deposition (PECVD) (Harter et al., 2024, Bellini, 2024K). Canadian researchers have fabricated an all-perovskite tandem solar cell with a wide-band-gap bottom cell based on tin-lead (Pb-Sn) perovskite with a limited amount of passivating defects and reduced interface recombination, by using diamine chelation chemistry targeting tin-containing perovskite, where a metal ion forms a stable bond with a molecule that has two nitrogen atoms holding the metal in place. To improve the perovskite solar cell’s surface, the scientists created partially non-conductive and non-functional areas that protect the perovskite area underneath from becoming defective. The addition of diamine to the surface allowed extra tin to be removed and the tin-to-lead ratio to be more balanced, and also created a stable barrier layer that helps protect the surface from atmospheric oxygen and heat (Li et al., 2024A; Bellini, 2024L).

**Top Cell**

South Korean company Qcells has developed a solar cell that uses perovskite technology for the top cell and proprietary Q.ANTUM technology for the bottom cell, which boosts performance by letting the top cell capture high-energy light more efficiently while the bottom cell captures transmitted low-energy light (Jowett, 2024C). Harter et al. (2024) developed a perovskite top cell with a hole transport layer (HTL) with a self-assembled monolayer (SAM) based on [2-(3,6-Dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid (MeO-2PACz), a perovskite absorber, an electron transport layer (ETL) made of tin oxide (SnO2) and buckminsterfullerene (C60), a transparent back contact made of indium zinc oxide (IZO), and a silver (Ag) metal contact (Harter et al., 2024, Bellini, 2024K). Using a bottom silicon heterojunction device and a top inverted perovskite solar cell integrating the ICLs, the perovskite layer was designed with a substrate made of indium tin oxide (ITO), a hole transport layer (HTL) made of nickel(II) oxide (NiOx), the MeO-2PACz SAM, a perovskite absorber doped with 2-phenylethylammonium iodide (PEAI), an electron transport layer (ETL) based on a buckminsterfullerene (C60), a transparent back contact made of indium zinc oxide (IZO), and a silver (Ag) metal contact (Zheng et al., 2024; Bellini, 2024J).

Taiwan's Academia Sinica created a two-terminal (2T) perovskite-silicon tandem solar cell that utilizes a heterojunction crystalline device as the bottom cell and a perovskite top cell made of indium tin oxide (ITO), integrating a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and phosphonic acid called methyl-substituted carbazole (Me-4PACz), a perovskite absorber, a buckminsterfullerene (C60) electron transport layer (ETL), a tin oxide (SnOx) buffer layer, a transparent back contact made of indium zinc oxide (IZO), a silver (Ag) metal contact, and an anti-reflective coating based on magnesium fluoride (MgF2) (Bellini, 2025D).

The research group built the top perovskite cell with a substrate made of indium tin oxide (ITO) and glass, an electron transport layer (ETL) based on tin oxide (SnO2), the optimized perovskite absorber, a Spiro-OMeTAD hole transport layer (HTL), a molybdenum oxide (MoOx) layer, and a semi-transparent back contact made of indium zinc oxide (IZO) (Chen et al., 2025; Bellini, 2025I).

A 4-terminal (4T) bifacial perovskite-silicon tandem solar cell was developed with interdigitated back contact (IBC) configurations for both the top perovskite cell and bottom silicon heterojunction cell. The top perovskite cell was designed with a substrate made of indium tin oxide (ITO), an electron transport layer (ETL) made of tin oxide (SnO2), a perovskite absorber, and a hole transport layer (HTL) made of nickel(II) oxide (NiOx) and an anti-reflecting coating doped with lithium fluoride (LiF). A transparent conductive oxide (TCO) layer serves as the top cell’s electrode that passes the light from the top cell into the bottom one and a 150 nm thick tin oxide (SnO2) layer is located at the interfaces of two sub-cells and top cell’s electrode to prevent electrical connections (Abbasiyan and Golmohammadi, 2025; Bellini, 2025Y).

The top perovskite cell was fabricated with a self-assembled monolayer made of MeO-2PACz, which is also known as [2-(3,6-Dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid, a glass substrate coated with indium tin oxide (ITO), a perovskite absorber with an energy bandgap of 1.68 eV, an electron transport layer (ETL) made of buckminsterfullerene (C60), a tin oxide (SnO2), another ITO layer, an anti-reflective coating based on magnesium fluoride (MgF2), and a silver (Ag) metal contact (Shishido et al., 2025; Bellini, 2025CC).

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Spanish researchers have developed a post-deposition in situ passivation strategy to reduce surface defects in silver bismuth sulfide cells, using a layer-by-layer solid-state ligand exchange process that, however, is not suitable for large-area high-volume manufacturing needed for PV deployment. Silver bismuth sulfide (AgBiS2) nanocrystals (NCs), a promising ternary semiconductor that is free of toxic heavy metals and has been shown to possess extraordinary optical properties including the highest optical absorption amongst any other photovoltaic absorber, are an earth-abundant material that has been used in recent years as a promising PV material, often in combination with cadmium sulfide in the development of several kinds of ultra-thin solar cells. AgBiS2 NCs can be fabricated in air at low temperatures using low-cost solution processing techniques and inexpensive production equipment, and have very low toxicity compared to other materials used for thin-film solar cells, such as cadmium telluride and cadmium sulfide (Oh et al., 2024; Bellini, 2024P).

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