**Perovskite-Perovskite Tandem Cells**

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Yang, Z. et al. (2019) Enhancing electron diffusion length in narrow-bandgap perovskites for efficient monolithic perovskite tandem solar cells. Nat. Commun. 10, 4498 (good simulation)

Liang, H., Feng, J., Rodríguez-Gallegos, C.D. et al. (2023) 29.9%-efficient, commercially viable perovskite/CuInSe2 thin-film tandem solar cells, Joule, Volume 7, Issue 12, Pages 2859-2872, <https://doi.org/10.1016/j.joule.2023.10.007>

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Choi, H. ∙ Jeong, J. ∙ Kim, H.-B. (2014) Cesium-doped methylammonium lead iodide perovskite light absorber for hybrid solar cells, Nano Energy., 7:80

These cells utilize two perovskite subcells with different bandgaps, offering a high degree of flexibility in designing the subcells. This configuration is potentially cost-effective and scalable, but it may face challenges in optimizing the materials and device structure. Perovskite-perovskite-based tandem solar cells have also been studied by various groups (Yang et al., 2019) (Zhao et al., 2017; Tong et al., 2019).

To date, both four-terminal and monolithic perovskite–perovskite tandem solar cells have been successfully developed. Im and coworkers reported the first monolithic perovskite–perovskite tandem cell with PCE of 10.4%, and the PCE has been gradually increased to 21.0% (Eperon et al., 2016; Forgács et al., 2017; Rajagopal et al., 2017A; Leijtens et al., 2018A; Zhao et al., 2018B). Jen and coworkers reported the first four terminal perovskite–perovskite tandem cells with an efficiency of 19.1% (Yang et al., 2016A), and the efficiency has now gone up to 23.1% (Zhao et al., 2018C) to 25% (Tong et al., 2019).

To date, the reported narrowest bandgap of NBG perovskites is ~1.22 eV that gives matched JSC with a wide bandgap (WBG) layer of around 1.80 eV bandgap in a monolithic tandem solar cell (Rajagopal et al., 2017A). Considering the main limitation for the PCE of NBG PSCs is from JSC, an optical simulation was performed to find out what is the optimal thickness of NBG perovskite layer in the tandem solar cells. Here, FA0.5MA0.45Cs0.05Pb0.5Sn0.5I3 with a bandgap of 1.22 eV and FA0.6Cs0.4Pb(I0.65Br0.35)3 with a bandgap of 1.80 eV are used for optical simulation in the perovskite–perovskite monolithic tandem solar cells. In the simulation, the JSC of tandem cell is determined by the smaller one of the two sub-cells, where the EQEs in the whole absorption spectrum are set to be 90%. As shown in Fig. 1a, the maximum JSC achievable for the tandem cell with these two chosen subcell bandgaps is 16.0 mA cm−2. In order to reach this maximum JSC, the NBG perovskite layer needs to be 1000 nm thick so that its photocurrent can match that from the 400 nm thick WBG perovskite layer. Figure 1b shows the absorption coefficient of Cs0.05MA0.45FA0.5Pb0.5Sn0.5I3, which also tells that a minimal thickness of 1000 nm is required for the NBG perovskite to absorb 90% of incident light in the near-infrared region (Yang et al., 2019).

Finally, this Cd-containing NBG perovskite was used in perovskite–perovskite monolithic tandem solar cells with a structure of ITO/PTAA/FA0.6Cs0.4Pb(I0.65Br0.35)3 (1.80 eV)/C60/SnO2/ITO/PEDOT:PSS/PTAA/Cd-FA0.5MA0.45Cs0.05Pb0.5Sn0.5I3/C60/BCP

/Cu (Yang et al., 2019)

efficient mixed tin–lead iodide low-bandgap (∼1.25 eV) perovskite solar cells with open-circuit voltages up to 0.85 V and over 70% external quantum efficiencies in the infrared wavelength range of 700–900 nm, delivering a short-circuit current density of over 29 mA cm−2 and demonstrating suitability for bottom-cell applications in all-perovskite tandem solar cells (Zhao et al., 2017)

Lead (Pb) and tin (Sn) halide perovskites exhibit excellent bandgap tunability. Pb mixed iodide (I) and bromine (Br) perovskites cover the bandgap range of 1.58 (pure I) to 2.20 eV (pure Br)1, while mixed Sn and Pb iodide perovskites exhibit bandgaps from 1.17 (50% Sn and 50% Pb) to 1.58 eV (pure Pb) (Hao et al., 2014; Im et al., 2015; Stoumpos et al., 2013; Liao et al., 2016A), making them suitable for the top- and bottom-cell application in tandem solar cells, respectively. Additionally, the low-temperature processing used for both wide- and low-bandgap metal-halide perovskites avoids undesirable damage, making the fabrication of all-perovskite tandem cells feasible.

Fabricating efficient all-metal-halide perovskite tandem solar cells requires the development of both wide- and low-bandgap PVSCs with efficient performance and high open-circuit voltages (Voc) with respect to their absorber layer bandgaps. However, the progress in developing high-Voc and efficient wide-bandgap PVSCs is far ahead of developing efficient low-bandgap PVSCs.

We found that (FASnI3)0.6(MAPbI3)0.4 perovskite films exhibit a bandgap of approximately 1.25 eV and the inverted planar PVSCs with a structure of indium-doped tin oxide (ITO)/poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS)/(FASnI3)0.6(MAPbI3)0.4/fullerene (C60)/2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP)/Ag can achieve PCEs up to ∼15% (Liao et al., 2016A).

We mechanically stacked a (FASnI3)0.6(MAPbI3)0.4 bottom cell with a semi-transparent wide-bandgap (∼1.58 eV) FA0.3MA0.7PbI3 top cell to form an all-perovskite 4-terminal tandem cell. The top cell has a regular cell configuration of glass/FTO/SnO2/fullerene-self-assembly monolayer (C60-SAM)/FA0.3MA0.7PbI3/Spiro-MeTAD/MoOx(10 nm)/Au(8.5 nm)/MoOx(10 nm). A MoOx wetting layer changes the growth mechanism and allows the deposition of ultrathin Au without the formation of islands, which is desirable for enhancing transparency and reducing sheet resistance (Zhao et al., 2015). The second MoOx layer is employed to form a dielectric–metal–dielectric stack to tune the light dispersion characteristics of the semi-transparent electrode (Supplementary Fig. 9), further enhancing the transparency so that more light can pass through the top cell (Zhao et al., 2015).

All-perovskite–based polycrystalline thin-film tandem solar cells have the potential to deliver efficiencies of >30%. However, the performance of all-perovskite–based tandem devices has been limited by the lack of high-efficiency, low–band gap tin-lead (Sn-Pb) mixed-perovskite solar cells (PSCs). We found that the addition of guanidinium thiocyanate (GuaSCN) resulted in marked improvements in the structural and optoelectronic properties of Sn-Pb mixed, low–band gap (~1.25 electron volt) perovskite films. The films have defect densities that are lower by a factor of 10, leading to carrier lifetimes of greater than 1 microsecond and diffusion lengths of 2.5 micrometers. These improved properties enable our demonstration of >20% efficient low–band gap PSCs. When combined with wider–band gap PSCs, we achieve 25% efficient four-terminal and 23.1% efficient two-terminal all-perovskite–based polycrystalline thin-film tandem solar cells. Reaching a >30% efficient all-perovskite thin-film tandem solar cell requires the low–band gap absorber to be at least 21 to 22% efficient. Thus, high-quality Sn-Pb low–band gap perovskite thin films with greater than micrometer thickness are needed to permit sufficient light harvesting, as well as several micrometer-long carrier diffusion lengths to ensure effective charge-carrier transport and extraction (Leijtens et al., 2018B; Hörantner et al., 2017; Tong et al., 2019).

The lower performance of Sn-Pb mixed low–band gap PSCs arises from both materials and device issues. The high defect density associated with Sn2+ oxidation limits carrier lifetime and charge collection, and additives such as SnF2 (Ma et al., 2016; , Liao et al., 2016B), SnF2-pyrazine complex (Lee et al., 2016), or fluoroalkyl-substituted fullerene (Rajagopal et al., 2017B) have been used to suppress the defect density. It has also proven difficult to synthesize uniform, pinhole-free, Sn-based thin films because Sn-based perovskite films crystallize rapidly (Yokoyama et al., 2016). Despite the several strategies (e.g., lattice strain, interface energetics, halide alloying) explored to improve the performance of low–band gap Sn-Pb–based PSCs (Yang et al., 2017; Kapil et al., 2018; Prasanna et al., 2017), their performance in tandem PSCs has lagged behind that of their Pb counterparts (Tong et al., 2019).

We report using guanidinium thiocyanate (GuaSCN) to improve the structural and optoelectronic properties of low–band gap (1.25 eV) perovskite thin films [(FASnI3)0.6(MAPbI3)0.4, where FA and MA denote formamidinium and methylammonium, respectively] in several ways. This method (i) reduced energetic disorder, with defect densities decreased by a factor of >10; (ii) increased carrier lifetimes to >1 µs; (iii) increased carrier diffusion length from ~500 nm to 2.5 µm; (iv) reduced surface recombination velocity by about a factor of 10, to 1.0 × 102 cm/s; and (v) improved film morphology, resulting in fewer structural defects. We attribute these improvements to the formation of two-dimensional (2D) structures at grain boundaries that appeared to passivate grain boundaries, suppress the formation of excessive Sn vacancies, and enhance the stability of low–band gap perovskite films. With these improved properties, we have demonstrated >20% efficient, 1.25-eV, low–band gap, single-junction PSCs. When combined with wider–band gap PSCs, we achieve 25% efficient 4-T and 23.1% efficient 2-T all-perovskite–based polycrystalline thin-film tandem cells (Tong et al., 2019).

We used (FASnI3)0.6(MAPbI3)0.4 as the baseline composition for the low–band gap perovskite (Zhao et al., 2017). The films were prepared by spin-coating a stoichiometric mixture of components (FAI, SnI2, MAI, and PbI2) and SnF2 in a mixed solvent of dimethyl formamide and dimethyl sulfoxide (DMF/DMSO). These perovskite films were modified by adding GuaSCN at various molar ratios with respect to MAI. The device stack used was glass/indium tin oxide (ITO)/poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS)/perovskite/fullerene (C60)/bathocuproine (BCP)/silver (Ag). Figure 1A compares the typical photocurrent density–voltage (J-V) curves of PSCs based on the low–band gap (FASnI3)0.6(MAPbI3)0.4 perovskite thin films prepared with and without addition of 7% GuaSCN; the detailed photovoltaic (PV) parameters are given in table S1. The cross-sectional scanning electron microscope (SEM) image of a typical PSC is shown in fig. S1. Devices with or without GuaSCN exhibited negligible hysteresis (<0.5%) between forward- and reverse-scan J-V curves. For 7% GuaSCN, the device PCE improved from 15.3% to 18.4% because of increases in short-circuit photocurrent density (Jsc) by ~1 mA/cm2, open-circuit voltage (Voc) by ~60 mV, and fill factor (FF) by ~6%. The statistical comparison of device parameters is shown in Fig. 1B (for 20 devices each). The external quantum efficiency (EQE) spectra of the two devices are shown in Fig. 1C; the integrated photocurrent density over the AM 1.5G solar spectrum is within 3% of the values obtained from J-V characterization.

**Perovskite-Chalcopyrite**

Chalcopyrite (CuGaSe2) has an energy bandgap of 1.7 eV and has been used in solar cells with limited fill factor and open-circuit voltage. Japanese researchers are developing flexible chalcopyrite modules with a tandem perovskite-chalcopyrite solar cell technology, with a focus on durability improvement, for use in a range of vehicle-integrated PV (VIPV) applications, such as solar-powered portable refrigerated containers, a solar-integrated passenger car, and an electric tricycle, with future plans to power data centers with clean energy, supply power to portable base stations to be deployed in disaster-affected areas during emergencies, and on ultra-lightweight high altitude platform station (HAPS), the solar-powered aircraft meant to operate at an altitude of 20 km above the earth’s surface carrying telecommunications base stations as the payload (Thompson, 2024D).

**Perovskite-Organic Tandem Cells**

(Liu et al., 2016)

German and Chinese researchers have developed a perovskite-organic tandem cell based on a wide-bandgap perovskite bottom cell and a narrow-bandgap organic top device, using a compound known as cyclohexane 1,4-diammonium diiodide for surface passivation. Using an organic cell as a bottom device offers the advantage in terms of low carbon footprint compared to cell technologies based on crystalline silicon or copper, indium, gallium and selenium (CIGS) thin-film, which require high processing temperatures, whereas perovskite and organic solar cells are both processed at low temperatures. To address the fact that tandem solar cells are limited by the perovskite layer, which shows strong efficiency losses if adjusted to absorb only blue/green parts of the sun spectrum, Jiang et al. (2024) used a passivation layer applied to the perovskite that reduces material defects and improves the performance of the whole cell, a red/infrared absorbing organic solar cell that reportedly extends its absorption even further into the infrared (Jiang et al., 2024A; Bellini, 2024M).

A biomass-derived polymer, PBDF-DFC, has been used to increase the efficiency of hybrid organic-inorganic perovskite solar cell, and is also claimed to enable potentially simpler fabrication processes. Conjugated polymers based on petroleum-based thiophene require precursor solvents and are more complicated to fabricate. In this experiment, furan is extracted from agricultural waste that contains chalcogen aromatic compounds. The PBDF-DFC polymers based on it are highly soluble in perovskite precursor solvents, enabling a simplified direct precursor integration fabrication method. Furan-based polymers typically have yields of 15%, so new furan synthesis approaches are needed to come close to the 70% yield of traditional thiophene-based synthesis. Further, the furan-based polymers must be integrated directly into the device stack.

Tandem devices which integrate perovskite and organic solar cells enable the capture of different parts of the light spectrum, as they harvest energy from the infrared and ultraviolet parts of the sun's rays, but not from visible light. The cost-effectiveness of the mineral perovskite and carbon-based materials in organic solar cells makes this type of tandem cell affordable (Jowett, 2025A).

An all-organic cell was developed with organic electrodes with high conductivity that required no acid doping or high-temperature heating, which avoids damage to the plastic substrates. First, a transparent electrode was developed based on conductive polymer PEDOT:PSS that was fabricated at 80 degrees without using acids or bases. It demonstrated sufficient conductivity, with a sheet resistance of less than 70 Ω/sq, for film-type solar cells. Previous preparation of high-conductivity organic materials had required high-temperature annealing, of over 150 degrees, which can damage organic substrate films and organic semiconducting layers, leading to a reduction in the performance of the organic solar cell. A lamination method was developed of carbon nanotube electrodes, which addressed the difficulty of stacking multiple layers in the film-type solar cell device without damaging the underlying layers. The lamination technique involved forming electrodes separately on the barrier films of solar cells and then attaching them to the device, avoiding damage to the bottom organic films during electrode fabrication (Hashida et al., 2025; Jowett, 2025B).

**Perovskite-Colloidal Quantum Dot (CQD) Tandem Cells**

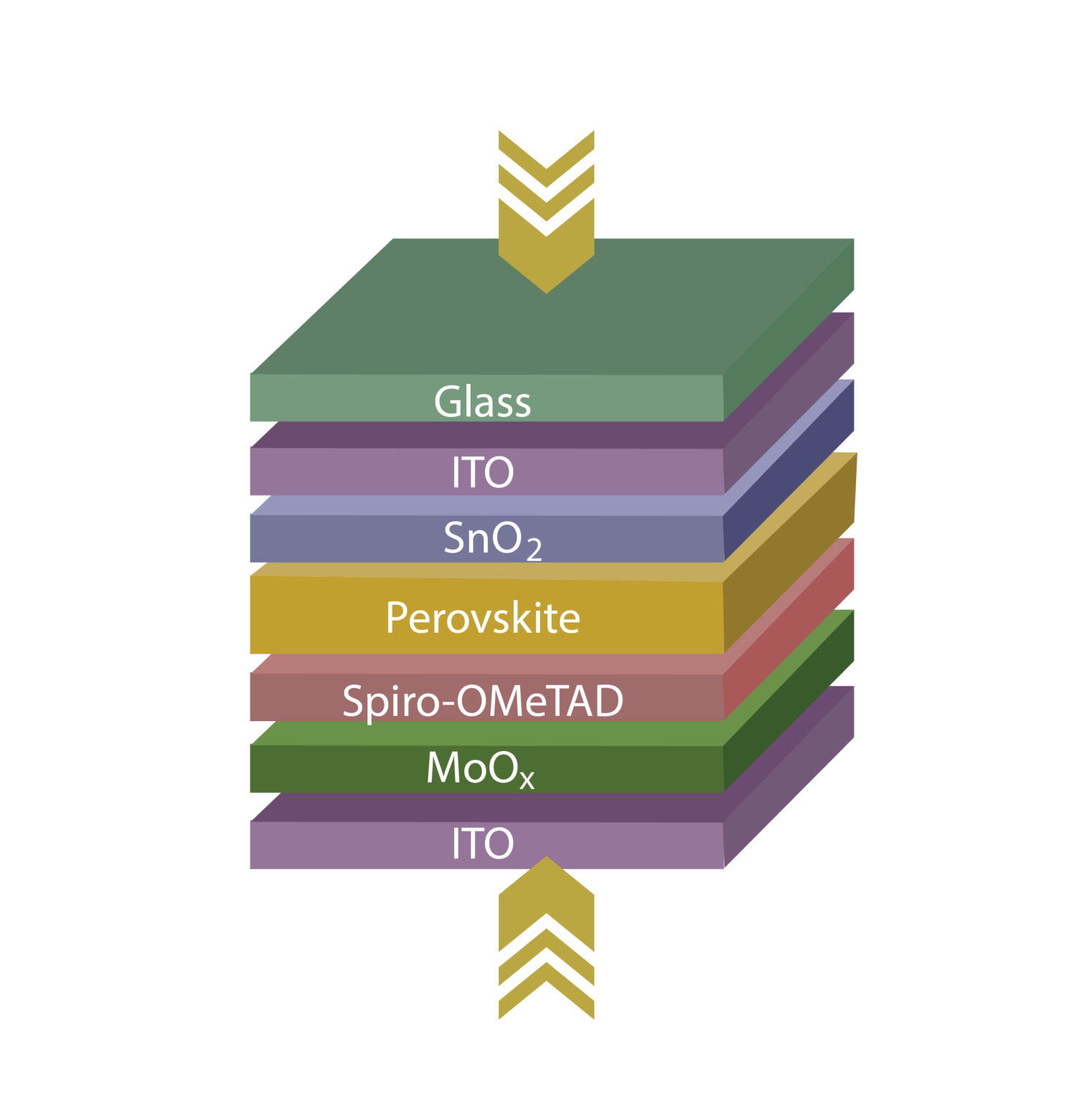
(Karani et al., 2018; Zhang et al., 2018C; Manekkathodi et al., 2019)

**Perovskite-CIGS Tandem Cells (copper-indium-gallium-selenide)**

These cells combine a perovskite subcell with a Cu(In,Ga)Se2 (CIGS) subcell, which is a well-established thin-film technology. CIGS offers good performance and cost-effectiveness, but it may face challenges in matching the electrical characteristics of the perovskite subcell (Han et al., 2018; Shen et al., 2018).

A perovskite-copper indium gallium selenide (CIGS) tandem solar cell was constructed using the high-performance cluster system Koala, which enables the deposition of perovskites and contact layers in vacuum at Germany’s Helmholtz-Zentrum Berlin (HZB). The scientists built the cell with a contact layer, an intermediate layer of aluminum-doped zinc oxide, an ultra-thin perovskite layer, an indium-doped zinc oxide layer, and an anti-reflective coating (Bellini, 2025J).

A four-terminal (4T) perovskite-CIGS tandem solar cell was built based on a top semi-transparent perovskite device and a bottom cell relying on copper-indium-gallium-selenide (CIGS), using a stepwise dimethyl sulfoxide (DMSO) solvent-annealing strategy to produce a perovskite film with full coverage, larger grains, higher crystallinity and free of detectable lead iodide impurity (purer phase), according to electrochemical impedance spectroscopy (EIS) analysis. Films were fabricated with a wide bandgap of 1.68 eV via two consecutive heating steps: annealing at 100 C and then 80 C, with the first step intended to induce fast nucleation and efficient growth of film grains with high crystallinity, and the second step aimed at releasing DMSO molecules preventing the sublimation of volatile organic halide species, thus avoiding lead(ii)iodide (PbI2) impurity phase growth. 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).



*Chen, D., Yang, F., Yang, M., et al. (2025) A stepwise solvent-annealing strategy for high-efficiency four-terminal Perovskite/Cu(InGa)Se2 tandem solar cells, Materials Today Energy, Volume 49, 101816,* [*https://doi.org/10.1016/j.mtener.2025.101816*](https://doi.org/10.1016/j.mtener.2025.101816)

A four-terminal (4T) perovskite-CIGS tandem solar cell has been built with a perovskite-based top cell joined with a copper-indium-gallium-selenide (CIGS) bottom cell. This multi-layered approach allows the tandem cell to effectively harness different wavelengths of sunlight. While the perovskite top cell absorbs high-energy photons, the bottom cell uses low-energy photons, which optimizes energy conversion. Using stepwise, the researchers applied a solvent-annealing method of dimethyl sulfoxide (DMSO) onto the perovskite layer to enhance its quality. It also heated the material twice, first at 100°C, then at 80°C, to help the crystal grow (Sanusha, 2025).

**Perovskite-CSI Tandem Solar Cell copper/indium/selenium**

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. “We then vary the optical pathways within the semi-transparent front cell to realize the control of the interference spectrum,” the team explained. “By matching the optical interference with the AM 1.5 G irradiance spectrum, the perovskite front cell achieves high average NIR transmittance (ANT) of 81.5% and an efficiency of 21.8%.” The academics also explained that the MDADI-treated film can reach a much higher quasi-Fermi level splitting (QFLS) compared with the one without the treatment. “The pseudo current-voltage (J-V) plot shows that the MDADI-treated film reaches an implied open-circuit voltage of 1.29 V, whereas the untreated film reaches only 1.24 V, and this marks a difference of around 50 mV.” his top cell was then combined in a tandem device with a bottom cell made with a glass substrate coated with molybdenum (Mo), a CIS absorber, a cadmium sulfide (CdS) buffer layer, and a window layer of zinc oxide (i-ZnO). This device has an efficiency of 17.3%, an open-circuit voltage of 0.60 V, a short-circuit current density of 39.7 mA/cm2, and a fill factor of 72.9% (Liang et al., 2023; Bellini, 2023E).

**Device Architecture Optimization: Heterojunction and 2D/3D Cells**

1. Heterojunction Engineering of Perovskite Solar Cells
2. Exploring 2D/3D Layered Perovskites for Enhanced Stability

**Heterojunction Engineering of Perovskite Solar Cells**

Khatoon, S., Chakraborty, V., Yadav, S.K., et al. (2023B) Simulation study of CsPbIxBr 1–x and MAPbI3 heterojunction solar cell using SCAPS-1D, Sol. Energy, 254, pp. 137-157

To improve PSCs, semiconductors can be doped to form heterojunctions. Barnham and Duggan (1990) define a quantum well (QW) solar cell as a multiple band-gap device with intermediate properties between heterojunction cells and multi-junction cells. In a heterojunction solar cell, the total current is the sum of the currents generated in the different materials but voltage is controlled by the lowest of the bandgaps, while in a multi-junction cell, the total voltage is the sum of the voltages but the current is determined by the worst of the sub-cells (Solanki and Beaucarne, 2007).

HJT stands for hetero-junction solar cells, and due to HJT’s fewer number of cell processing steps, and a much lower cell processing temperatures, this architecture has the potential to simplify the current solar cell manufacturing lines that are currently heavily based on PERC technology. HJT cells are also known as Silicon heterojunctions (SHJ) or Heterojunction with Intrinsic Thin Layer (HIT). HJT is very different from the conventional PERC structure, and as a result, HJT requires significant capital investment in new equipment to start mass production. HJT demonstrates high solar cell efficiency thanks to the high quality hydrogenated intrinsic amorphous Si (a-Si:H) that can provide impressive defect passivation to both the front and rear surface of Si wafers (both n-type and p-type polarity). The use of ITO as transparent contacts also improves current flows, while also acting the anti-reflection layer to provide optimal light capturing. Moreover, ITO can also be deposited via sputtering at low temperature, thus avoiding the re-crystallisation of the amorphous layer that will impact the passivation quality of the materials on the bulk Si surface. HJT combines thin film with traditional silicon technology, and HJT cells are made of three layers of photovoltaic material. The top layer is amorphous silicon, which catches sunlight before it hits the crystalline layer. The middle layer is monocrystalline silicon, which turns most of the sunlight into electricity. The bottom layer is another amorphous silicon layer, which captures any remaining photons. Thin-film technology is used in HJT cells. HJT cells have thin amorphous silicon (a-Si) layers on the front and back of the cell. They are made up of layers of amorphous silicon on top of crystalline silicon wafers, which improve passivation and lower recombination losses. HJT cells possess a superior temperature coefficient, as HJT cells are less affected by changes in temperature, and they have a high bifacial rate, as they can absorb sunlight from both the front and back sides.

**Exploring 2D/3D Layered Perovskites for Enhanced Stability**

Hsinhan Tsai, The challenges and promises of layered 2D perovskites, Chem, Volume 8, Issue 4, 2022, Pages 890-891, <https://doi.org/10.1016/j.chempr.2022.03.021>

2D perovskites act like a barrier layer to protect the 3D perovskite layer, however, 2D perovskites can be even more fragile (Tan et al., 2025; Thompson, 2025I).

Two-dimensional perovskites are more stable than three-dimensional perovskites (Schlipf et al., 2019; Alidaei et al., 2022; Ali Ahmed et al., 2021; Krishna et al., 2019; Zhou et al., 2019). 2D perovskite solar cells are made from perovskite materials with a layered crystal structure, while 2D/3D perovskite solar cells are a combination of 2D and 3D perovskites. 2D perovskites have a layered structure of metal-halide sheets separated by organic cations, have improved stability compared to 3D perovskites, have a large bandgap and limited charge transport, and have greater synthetic versatility. 2D perovskites have a layered structure that changes its optical and electronic properties and exhibits better stability and moisture resistance compared to their 3D counterparts, though are less efficient in converting sunlight into electricity than 3D perovskites. 2D perovskites have high exciton binding energies and poor charge transport in the out-of-plane direction. 3D perovskites, with the general formula ABX3, are known for their high efficiency in converting sunlight into electricity, though they can suffer from instability from environmental stressors such as humidity.

The 2D perovskite structure is composed of alternating layers of inorganic metal halide octahedra (like PbI6) located between layers of large organic cations, acting as spacers, which effectively create a two-dimensional sheet-like structure within the crystal lattice; the general chemical formula for a 2D perovskite is (RNH3)2(A)n-1MX3n+1, where R is the organic spacer cation, A is a smaller cation, M is the metal cation (like Pb), X is the halide ion, and n represents the number of inorganic perovskite layers between spacer layers. Large organic spacer cations like butylammonium (BA) or phenylethylamine (PEA) are crucial for creating the 2D structure by separating the inorganic octahedral layers. The inorganic layer consists of metal halide octahedra where the metal is typically lead (Pb) and the halide is iodine (I). Due to the confinement of charge carriers within the inorganic layers, 2D perovskites exhibit quantum well effects, leading to unique optoelectronic properties. By adjusting the number of inorganic layers (n value), the thickness of the 2D perovskite can be tuned.

The general formula for a 3D perovskite is ABX3, where A is an organic or inorganic monovalent cation (like MA+ or FA+), B is a divalent cation (Pb2+ or Sn2+), and X is a halide (I-, Br-, or Cl-). Common precursors for 3D perovskites include methylammonium iodide (MAI) (CH3NH3I), formamidinium iodide (FAI) (NH2CH=NH2I), and lead iodide (PbI2). These precursors are dissolved in a polar solvent like dimethylformamide (DMF) or dimethyl sulfoxide (DMSO) to form a solution that can be deposited onto a substrate. 2D perovskites have a layered structure, often described as (A')2(A)n-1BnX3n+1, where A' is a monovalent cation (Ruddlesden-Popper, RP) or a divalent cation (Dion-Jacobson, DJ). 2D perovskites can be formed by incorporating long-chain organic molecules into the 3D perovskite structure, or by adding 2D perovskite precursors to the 3D perovskite precursor solution. Examples of 2D perovskite precursors include butylammonium iodide (BAI), phenylethylammonium iodide (PEAI), and other long-chain organic cations. 2D perovskites are often used as a capping layer or passivation layer on top of 3D perovskites. For example, a solution containing both MAI/PbI2 (for 3D) and BAI/PbI2 (for 2D) can be used.

2D/3D perovskites combine the advantages of 2D and 3D perovskites, the high efficiency of 3D perovskites and the enhanced stability of 2D perovskites, and can maintain long-term stability and high performance, can have improved film quality and charge extraction, and can have decreased defect density. 2D perovskites can act as a passivation layer on top of 3D perovskites, reducing interfacial recombination and improving charge extraction. 2D perovskites can impede ion migration, which is a major cause of degradation in 3D perovskite solar cells. 3D/2D perovskite heterostructures have demonstrated improved stability under various conditions, including humidity and light exposure. The 2D/3D perovskite has higher charge mobility and power conversion efficiency, less non-radiative charge recombination, and a smaller bandgap than 2D perovskites. The 2D layers in 2D/3D perovskite materials improve stability, prevent ion migration, and increase the effectiveness of charge collection.

Uniform 2D layers can be deposited on the 3D perovskite layer by adjusting the donor number and dielectric constant of solvents for the 2D layer deposition, in order to control the thickness of the interlayer. Azmi et al. (2022) adjusted the number of inorganic layers (n) at the interlayer, considering the temperature effect of the interlayer formed by post-treatment with oleylammonium iodide. Their experiment showed that high-temperature (100 °C) post-treatment mainly leads to the formation of a 2D perovskite passivation layer with n = 1, while a quasi 2D perovskite passivation layer with n = 2 was dominant after overnight storage at room temperature. The energy level of the quasi 2D with n = 2 was more compatible with that of C60, which is beneficial for charge transfer and reduces charge accumulation. The thermal stability of three-dimensional perovskite solar cells can be improved by adding ammonium ligands that create a two-dimensional perovskite capping layers, but such ligands are prone to intercalation into the bulk. Sidhik et al. (2022) reports that two-dimensional (2D) halide perovskite passivation layers grown on three-dimensional (3D) perovskite can boost the power conversion efficiency (PCE) of solar cells, but spin-coating of these layers usually forms heterogeneous 2D phases or only ultrathin layers. Solvents with the appropriate dielectric constant and donor strength, Gutmann donor number, could grow phase-pure 2D halide perovskite phases of controlled thickness, composition, and bandgap on 3D substrates without dissolving them (Sidhik et al., 2022). Different organic ammonium salts have been tested to develop 3D/2D solar cells, with halogenated analogs of phenethylammonium iodide (PEAI) salts being the preferred choice due to their potential to enhance hole extraction. 3D/2D perovskite heterostructures are typically formed by dissolving suitable ligands in polar solvents, which affects charge transport and cell stability, though in this experiment the researchers used MAP ligands and solvent post-dripping, as after solvent post-dripping, the 2D-MAP sample showed a more ordered 2D phase parallel to the 3D perovskite layer with a more infiltrated structure (Chang et al., 2025; Bellini, 2025K).

Perovskite solar cells can be manufactured combining a Dion-Jacobson (DJ) 2D layer with a 3D lead-free halide perovskite, as two-dimensional (2D) Dion-Jacobson (DJ) phase perovskites are known for their stability against harsh environmental conditions and their competitive performance in optoelectronic applications. Verma et al. (2025) constructed a perovskite solar cell using a DJ 2D material known as PeDAMA4Pb5I16, and a 3D lead-free perovskite material known as CsGeI3-xBrx, using the SCAPS-1D solar cell capacitance software (Verma et al., 2025; Thompson, 2025H). Using a two-dimensional perovskite as an intermediate phase on the film surface to control the crystal orientation without compromising charge transport can help to suppress non-radiative recombination. Augmenting the quantity of two-dimensional phases through surface composition engineering reduces the need for excessive two-dimensional ligands that otherwise impede carrier transport. Liu et al. (2025B) incorporated phenylethylamine iodide (PEAI) and methylammonium iodide (MAI) into the anti-solvent during fabrication, forming a 2D perovskite layer on the surface of the wide-bandgap perovskite subcell, which served as heterogeneous nucleation sites, facilitating the vertical growth of (100)-oriented 3D perovskite crystals due to the reduced interfacial energy associated with the 2D/3D heterostructures. One approach for the WBG films was to add the PEAI into the precursor solution as a direct additive (DA), and another approach introduced PEAI into the anti-solvent as a solution-process additive (SPA). Another SPA had a mixture of MAI and PEAI with a weight ratio of 1:2 as the mixed solution-process additive (M-SPA) to create a local MA-rich environment (Liu et al., 2025B; Thompson, 2025C).

Fluorinated aniliniums offer interfacial passivation and simultaneously minimize reactivity with perovskites. Park et al. (2023) showed that the smallest aromatic ligand, anilinium, had the lowest ligand reactivity with three-dimensional perovskites because of steric hindrance near the ammonium group, and a fluorinated derivative of this ligand created a robust interface structure. As 2D lower dimension perovskite solar cells show better stability compared to their 3D counterparts, the combination of Ruddlesden–Popper (RP) 2D-layered perovskites with conventional 3D perovskites has improved the stability of the device as the 2D perovskite passivates/encapsulates the device (Jeong et al., 2021). 2D halide perovskite layers must be constructed by synthesizing layers that exhibit only a single phase throughout, as materials are phase-dependent. However, when synthesis methods for higher n value 2D perovskites generate uneven crystal growth, crystals with mixed phases form due to the lack of control over crystallization kinetics, which is the dynamic interplay between temperature and time (Hou et al., 2024; Clark, 2023). In 2D perovskites, crystals with layer thicknesses, or quantum well thickness, also known as (n) value, greater than two must be produced, as an (n) value higher than four means materials have a narrower band gap and higher electrical conductivity, which is a crucial factor for application in electronic devices. By controlling the temperature and slowing down the crystallization process, each kinetics parameter can be tuned gradually to produce the ideal spot for phase-pure synthesis (Hou et al., 2024; Clark, 2023).

A 2D/3D THP cell recently developed uses a 2D perovskite layer at the interface between the perovskite and the hole transport layer, which can improve charge-carrier transport/extraction while suppressing ion migration. Cells with this architecture usually exhibit large exciton binding energies and are generally more stable than conventional 3D devices due to the protection provided by the organic ligands (He et al., 2025; Bellini, 2025EE).

**Organic-Inorganic Perovskites**

Sebastian, V. and Kurian, J. (2021) Simulation and optimization studies on CsPbI3 based inorganic perovskite solar cells, Sol. Energy, 221 (2021), pp. 99-108

The most widely investigated perovskite material for solar cell application is the hybrid organic–inorganic methylammonium lead halides CH3NH3Pb(I; Cl; Br)3.

Organic–inorganic perovskites contain 3-dimensional arrays of inorganic PbX6 anions surrounded by organic ammonium counter ions. This perspective paper focuses on the dimensionality of organic–inorganic halide perovskites and their relevant advantages over 3D perovskites. The charges in two-dimensional (2D) materials are restricted in their movement to the two-dimensional plane; however, their confined structure allows one to tune the optical and electronic properties by varying their thickness. Here we focus on the main advantages of 2D halide perovskites including their enhanced stability; several recent reports discussing this point are summarized. It was observed that 2D perovskites exhibit enhanced moisture resistivity, starting from films to complete solar cells. Organic–inorganic perovskite crystals have the configuration R2(CH3NH3)n−1MnX3n+1, where R is an organic group, M is a divalent metal in the oxidized state (such as Cu2+, Mn2+, Sn2+, Fe2+, and Pb2+), and X is a halide (Cl−, Br−, or I−).41 The inorganic layers consist of sheets of corner-sharing metal halide octahedra. The M cation is generally a divalent metal that satisfies charge balancing and adopts octahedral anion coordination.42 The inorganic layers are usually termed perovskite sheets, because they are derived from a three-dimensional AMX3 perovskite structure (A-cation), by making a one-layer-thick cut along the 〈100〉 direction of the three-dimensional crystal lattice. The structure can be modified by changing the compositions of the organic and inorganic salts in the starting solution to tailor the electronic, optical, and magnetic properties. The organic component consists of a bilayer or a monolayer of organic cations. With a monolayer (monoammonium, for example), the ammonium head of the cation bonds to the halogens in one inorganic layer, and the organic group extends into the space between the inorganic layers. The organic ammonium groups form a layer with a low dielectric constant of ∼2.4, whereas the metal halide layers have a high dielectric constant of more than 6,43 and function as a periodic array of barriers and quantum wells, respectively (Etgar, 2018).

Stranks et al. (2013) uncovered a 10-fold greater diffusion length in a chloride-doped material, which correlates with the material's particularly efficient overall performance. Organic-inorganic perovskites have shown promise as high-performance absorbers in solar cells, first as a coating on a mesoporous metal oxide scaffold and more recently as a solid layer in planar heterojunction architectures. mixed halide and triiodide perovskite absorbers. We found that the diffusion lengths are greater than 1 micrometer in the mixed halide perovskite, which is an order of magnitude greater than the absorption depth. In contrast, the triiodide absorber has electron-hole diffusion lengths of ~100 nanometers (Stranks et al., 2013).

**Inorganic Perovskites**

In general, perovskites display low thermal decomposition temperatures due to their less stable organic monovalent cation. For instance, MAPbI3 has been shown to degrade at 85°C in an inert atmosphere79 and rapidly at 150°C in air.6 As their name implies, inorganic perovskites remove this organic cation altogether, providing another promising pathway to improve the overall stability of perovskites. To satisfy the Goldschmidt tolerance factor, a suitably sized inorganic monovalent cation could be used to replace the organic cations. The Cs+ cation turns out to be a very suitable candidate and has already shown excellent stability improvements when mixed with MA+ and/or FA+ organic cations.42,80–83 As discussed below, it can also be used as the sole cation on the A site. Figures 2A and 2B list the VOC and efficiencies of such Cs-based inorganic perovskites. A full list of the inorganic PSCs and their architecture from literature is provided in Table S3. The CsPbBr3 structure is a good starting point for inorganic perovskites, despite its undesirable high bandgap of 2.3 eV (even for multijunctions).

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Table 4. 2D perovskite absorber layer-based PSCs (Khatoon et al., 2023A)

| **spacer cation** | **perovskite** | **Efficiency(%)** | **stability** |
| --- | --- | --- | --- |
|  | FTO/TiO2/(CH3(CH2)3NH3)2PbI4/  spiro-OMeTAD/Au  (Cao et al., 2015) | 4.02 |  |
| Butyl ammonium | FTO/PEDOT:PSS/(BA)2(MA)3Pb4I13/  PCBM/Al  (Tsai et al., 2016) | 12.52 | 60% efficiency remains at 65% RH 2250 h without encapsulation |
| PEA | FTO/TiO2/[(C6H5C2H4NH3)2(CH3NH3)n-1  PbnI3n + 1/spiro-OMeTAD/Au  (Quan et al., 2016) | 15.3 | no performance loss after 60d at 90% RH |
| PEI | FTO/PEDOT:PSS/(PEI)2(MA)6Pb7I22/  PCBM/Au  (Yao et al., 2016) | 8.77 | 95% efficiency remains after 500 h light soaking without encapsulation |
| ALA | ITO/TiO2/ALA2(MA0.14FA0.81Cs0.05)9Pb10  (I0.85Br0.15)29/Spiro-OMeTAD/Au  (Proppe et al., 2018) | 16.50% | 90% efficiency remains after 650 h in ambient air |
| PEA2PBI4 | FTO/c-TiO2/m-TiO2/(FAPbI3)0.85(MAPbBr3)0.15/  spiro-OMeTAD/Au  (Lee et al., 2018B) | 17.2 | 100% of initial PCE after 1200 h of RH 70% under dark |
| benzyl ammonium | FTO/bl-TiO2/m-TiO2/(C6H5CH2NH3)2(FA)8Pb9I28  Spiro-OMeTAD/Au  (Zheng et al., 2018) | 17.4 | 80% initial efficiency remains after 500 h under80% RH |
| bromo benzyl ammonium | ITO/PTAA/PVK/PBBM/Cr/Au  (Yang et al., 2018E) | 18.2 | 82% initial efficiency remains after 2400 h with 40% RH without encapsulation |
|  | ITO/PTAA/PEA2MAn-1PbnI3n + 1/  PC61BM/PEI/Ag  (Zhang et al., 2019A) | 18.04 | 96% efficiencyremains after 8 months of storage |
| MTEAC | ITO/PEDOT:PSS/(MTEA)2(MA)4Pb5I16/  PC61BM/Cr/Au  (Ren et al., 2020) | 18.06 | 85% efficiency remains after 1000 h at MPP |
| (4F-PEA)2(FAxMA1−x)4Pb5I16 | (ITO)/ (PTAA)/ 2D RP perovskites/(PCBM)/(BCP)/Ag.  (Shao et al., 2022) | 21.07 | 97% of their initial efficiency at 85 °C persistent heating after 1500 h |
| (2-CF3-PEA)2PbI4 | ITO/SnO2/perovskite/(2-CF3-PEA)2PbI4/Spiro-OMeTAD/MoO2/Ag  (Zhou et al., 2022A) | 23.17 | 850 h |

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Table 5. Multidimensional absorber layer-based PSCs (Khatoon et al., 2023A)

| **Additive** | **Perovskite** | **device structure** | **Efficiency (%)** | **stability** |
| --- | --- | --- | --- | --- |
| EDAPBI4 | CsPbI3 | FTO/c-TiO2/PVK/spiro-OMeTAD/Ag  (Zhang et al., 2017) | 11.8 | 100% of initial PCE after 720 h in a dark dry box |
| BA2PBI4 | FAPBI3 | FTO/c-TiO2/PVK/spiro-OMeTAD/Au  (Niu et al., 2018) | 20.62 | 80% of initial PCE after 2280 h under dark with RH 40% |
| PEAI + Pb(SCN)2 | (FA0.65MA0.20Cs0.15)  Pb(I0.8Br0.2)3 | ITO/PTAA/perovskite/C60/BCP/Ag  (Kim et al., 2019B) | 19.8 | 96% of initial PCE after 4000 h under dark |
| FEAbI3 | MAPBI3 | FTO/c-TiO2/m-TiO2/PVK/ spiro-OMeTAD/Au  (Bi et al., 2016) | 18 | 92% of initial PCE after 2880 h under dark |
| IMPbI3 | MAPBI3 | FTO/c-TiO2/m-TiO2/PVK/ spiro-OMeTAD/Au  (Zhang et al., 2019B) | 20.14 | Over 70% of initial PCE after 1000 h under continuous operation at MPPT |
| AVAI |  | FTO/c-TiO2/m-TiO2/PVK/Spiro-OMeTAD/Au  (Grancini et al., 2017) | 14.6 | 10000 h stability without any loss in performance |
| [(FEA)2PbI4] | FAMACs | FTO/TiO2/PVK/Spiro-OMeTAD/Au  (Liu et al., 2019C) | 22.2 | 90% efficiency remains after 1000 h at 40% RH |
| GA+ | CsPbBr3 | ITO/SnO2/PVK/SIM/Spiro-OMeTAD/Au  (Zheng et al., 2020B) | 18.06 | 81% efficiency remains after1000h in ambient air |
| BA | FA0.83Cs0.17Pb  (I0.6Br0.4)3 | FTO/SnO2/PCBM/PVK/Spiro-OMeTAD/Au  (Wang et al., 2017) | 17.5 | 80% efficiency remains after 4000 h with encapsulation |
| (NpMA)2PbI4 |  | (Zhou et al., 2022B) | 24.37% | 98% of its initial efficiency after 1500 h by (MPP) tracking under continuous light irradiation. |

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