**Perovskite-Silicon Tandem Cells**

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Perovskite and silicon used together in tandem solar cells complement each other and should be used to augment each other, perovskite with its light absorption qualities, and silicon for its proven stability. Silicon PV has greater stability than perovskite, reliably functioning for over two decades, whereas perovskite PVs degrade after just a few months to a few years of operation. Manufacturing is different for silicon and perovskite, as high-purity silicon requires more intense manufacturing conditions, such as temperatures over 1,000 degrees Celsius, which carries higher economic and environmental costs. Perovskites can be produced at lower temperatures, around 200 degrees Celsius, and tandem cells have low manufacturing costs because perovskite is cheap (Kim et al., 2024). Manufacturing complexity is a concern with tandem cells, as creating efficient tandem cells requires precise control over the interface between the perovskite and silicon layers. Rather than replace silicon in solar cells, which is currently the primary material in 95% of solar panels, you can layer perovskite on silicon to create tandem cells. The extra electricity provided by tandem cells could offset their additional manufacturing costs, particularly in crowded urban areas or industrial sites where space is at a premium. Silicon solar panels may have up to ten times more lead in their soldered contacts than a perovskite panel (Peplow, 2023). Tandem perovskite-silicon solar cells possess a higher power conversion efficiency as compared to single-junction cells, because the combination of minerals allows the cell to absorb a wider range of the solar spectrum, potentially delivering at least 20% more power than a silicon cell alone (Peplow, 2023). Tandem cells utilize a larger portion of the solar spectrum, with the perovskite layer absorbing high-energy visible light, and the silicon layer absorbing lower-energy infrared light. This broader spectral absorption in tandem cells is due to engineering the bandgaps of the flexible perovskite and silicon layers to produce higher energy yields. Tandem cells can be lighter and thinner than traditional silicon panels, because perovskite layers are very thin. Integrating perovskite with a stable silicon substrate can help mitigate the stability concerns associated with perovskite materials alone. The silicon bottom cell can be heterojunction, TOPCon, or PERC (Bush et al., 2017; Sahli et al., 2018). JinkoSolar’s N-type high-efficiency monocrystalline TOPCon solar cell as the bottom cell uses n-type wafers, and contributes innovations such as full-area passivated contact technology, perovskite interfacial defect passivation technology, and bulk defect passivation technology.

The efficiency threshold for perovskite-silicon tandem cells ranges from 39.5% (Bellini, 2025G), to 43% (Mishra, 2025C), and exceeding this threshold will require a change in cell architecture, such as replacing buckminsterfullerene (C60) with a more transparent electron transport layer, and finding more transparent alternatives to indium tin oxide (ITO) layers. The Shockley-Queisser (SQ) limit for single-junction solar cells (33.7%).

Perovskite-silicon tandem solar cells are created by stacking a perovskite absorber layer (including HTL and ETL), on top of an n-type c-Si layer, featuring a recombination layer between them, made out of hydrogenated a-Si (a-Si:H) or nanocrystalline silicon (nc-Si). These solar cells work by taking advantage of c-Si harnessing long-wavelengths and perovskite harnessing short-wavelengths to generate electricity. Perovskite-silicon tandem solar cells partially stabilize perovskite material by featuring a wide bandgap and maintaining the efficient charge carrier transport of the original perovskites. Just like with single-junction perovskite solar cells, perovskite silicon tandem solar cells face several setbacks like a reduced lifetime for the cell due to the effect of halide segregation and other factors (Jowett, 2024B). A steep absorption edge, exceptionally low sub-gap absorption, tunable bandgap (by changing halide composition), and desirable Voc of 1.15 V corroborate the hybrid perovskite as a suitable candidate for top wide-bandgap cells in the tandem configuration. The low-temperature fabrication of perovskite helps to monolithically integrate it as a top cell without damaging the bottom cell (Soonmin et al., 2023).

***Tandem perovskite-silicon solar cells have several key advantages:***

1. The proliferation of tandem cells would far surpass efficiencies from existing silicon or perovskite cells which are nearly 30%.
2. With only a thinning perovskite film in a tandem perovskite cell, less lead and other materials are needed compared to in thicker standalone perovskite cells.
3. Tandem cell technology can be used as part of an N-type PV cell manufacturing process that is compatible with the prevailing industry trends.
4. Lower sensitivity to temperature variations can appear – the perovskite top cell also builds efficiency stability in high temperatures.
5. Durability or longevity
6. Efficiency retention when scaled to larger sizes or larger module areas— issues that have hindered their leap from laboratory to commercial viability.

Figure XXX.



Bellini, Emiliano (2024K) PV Magazine, Perovskite-HJT tandem solar cell based on phosphonic acid, self-assembled monolayer achieves 30.22% efficiency,

<https://www.pv-magazine.com/2024/12/24/perovskite-hjt-tandem-solar-cell-based-on-phosphonic-acid-self-assembled-monolayer-achieves-30-22-efficiency/?utm_source=Global+%7C+Newsletter&utm_campaign=dc4657fc55-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-dc4657fc55-160603208>

Figure XXX.



Bellini, Emiliano (2025D) PV Magazine, Taiwanese researchers unveil 31.5%-efficient perovskite-silicon tandem solar cell,

<https://www.pv-magazine.com/2025/01/22/taiwanese-researchers-unveil-31-5-efficient-perovskite-silicon-tandem-solar-cell/?utm_source=Global+%7C+Newsletter&utm_campaign=c2df1123d6-dailynl_gl&utm_medium=email&utm_term=0_6916ce32b6-c2df1123d6-160603208>

Figure XXX.



Afroz, M.A., Sharma, B., Sharma, R.K., et al. (2025) Solution processable perovskite-hybrid heterojunction silicon 4T tandem solar cells, Materials Today Advances, Volume 25, 100558, <https://doi.org/10.1016/j.mtadv.2025.100558>

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).

However, suppressing interfacial recombination at the wide-bandgap perovskite/electron transport layer interface, without compromising its superior charge transport performance, remains a substantial challenge for perovskite/silicon tandem cells (Al-Ashouri et al., 2020; Chen et al., 2024). By exploiting the nanoscale discretely distributed lithium fluoride ultrathin layer followed by an additional deposition of diammonium diiodide molecule, we have devised a bilayer-intertwined passivation strategy that combines efficient electron extraction with further suppression of non-radiative recombination. We constructed perovskite/silicon tandem devices on a double-textured Czochralski-based silicon heterojunction cell, which featured a mildly textured front surface and a heavily textured rear surface, leading to simultaneously enhanced photocurrent and uncompromised rear passivation (Liu et al., 2024B).

A tandem solar cell was developed by Risen Solar relying on a top perovskite cell and a bottom silicon heterojunction (HJT) device was achieved with a 10 mm x 10 mm cell size (Shaw, 2025). A bendable tandem solar cell based on a top semi-transparent inverted perovskite cell and a flexible bottom thin-film silicon heterojunction (HJT) PV device was produced. Stable and flexible silicon heterojunctions can be fabricated by thinning silicon, and for the thinning of the 21.1%-efficient bottom cell, a technique known as potassium hydroxide (KOH) etching was used, which is a wet chemical etching process used to create cavities in silicon. It was used to texture the cell wafer on the back side, while the front side was micro-textured and rounded. The scientists also deposited a protective layer made of silicon nitride (SiNx) film on both sides of the wafer by chemical vapor deposition (CVD). The wafer was then cut into 5 cm square pieces, and the SiNx film along the outer edges was removed using a laser (Shishido et al., 2025; Bellini, 2025CC).

Copper metallization methods to avoid using silver for tandem silicon-perovskite cells compatible with either TOPCon or heterojunction bottom cells include screen printing, FlexTrail printing and rotary printing (flexographic printing and indirect gravure printing) (Thompson, 2024B). A perovskite-silicon tandem solar cell of more than 100 sq cm was produced with screen-printed metallization, using a combination of vapor deposition and wet-chemical deposition to ensure an even depositing of the perovskite layer on the textured silicon surface. Characterization data and an opto-electrical simulation model can be used to analyze the efficiency and stability of solar cells. A transmission electron microscope (TEM) is used to evaluate cells in high resolution to evaluate low-energy focused ion beam techniques for the preparation of industrial tandem solar cells, using absorber and contact layers to deposit using direct deposition on TEM substrates. The thickness, degree of coverage, and chemical bonding of self-organized molecular monolayers are analyzed. Calculation models can be used to describe the structural and photovoltaic properties of relevant absorber materials and their interfaces with optically transparent and electrically conductive contact materials (Jowett, 2024B).

The simulations framework considered different heterojunction (HJT) and TOPCon solar cell architectures based on several CSC designs, including poly-silicon (poly-Si) and dopant-free structures. It also took into account metallization pitch, c-Si thickness, and wafer resistivity, with some of the analyzed cell designs being based on transparent conductive oxide (TCO) or being dopants-free (Procel-Moya et al., 2025; Bellini, 2025Q)

Four-terminal (4T) semi-transparent perovskite-silicon tandem solar cells can be manufactured with an indium oxide ($In\_{2}O\_{3}$) 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. Using the e-beam evaporation technique can be used to fabricate the $In\_{2}O\_{3}$ SBL, the researchers found that the optical and electrical properties of the $In\_{2}O\_{3}$ film exhibited a strong dependence on the deposition rate, as a higher deposition rate resulted in In-rich $In\_{2}O\_{3}$ films with poor transmittance and increased parasitic absorption (Du et al., 2025; Bellini, 2024G). To manufacture a tandem cell, Kan et al. (2024) deposited the perovskite precursor ink with CuSCN directly on the recombination layer made of indium tin oxide (ITO) of a 24.42%-efficient silicon heterojunction (SHJ) bottom cell, which formed local hole-collecting contacts by embedded CuSCN in device, resulting in a different device structure from that of a common and classic p-i-n configuration based on a thin self-assembly monolayer (SAM) on recombination layers like ITO (Kan et al., 2024; Bellini, 2024H). Swiss researchers have fabricated a tandem solar cell based on a perovskite top cell and a heterojunction (HJT) bottom device, utilizing a z-silicon (Cz-Si) bottom cell, with a thickness of 100–150 μm and double-sided micro-textured surfaces, which is a double-sided textured bottom cell, and circumvents the film formation issue associated with the use of phosphonic acid (Harter et al., 2024, Bellini, 2024K).

Harter et al. (2024) developed a HJT cell by wet-etching random pyramids, with their height being adjusted by alkaline texturing, and the perovskite absorber thickness thicker than the pyramid texture height. As high-quality wide band gap perovskite absorbers are typically 600–800 nm thick and do not usually conformally cover the surface when processed from solution, the pyramid height must be adjusted accordingly (Harter et al., 2024, Bellini, 2024K).

A two-terminal (2T) perovskite-silicon tandem solar cell has been developed that utilizes hybrid interconnecting layers (ICLs) to reduce recombination losses in the top perovskite device by preventing direct contact between the perovskite absorber and transparent conductive oxide (TCO). To address the issues of poor uniformity and compactness when self–assembled monolayers (SAMs) are placed directly on a transparent-conductive-oxide (TCO) recombination layer, thus resulting in significant current leakage losses and poor reproducibility of tandem solar cells, a sputtered nickel oxide (NiOx) can be used as the seed layer of SAMs to build the hybrid interconnecting layers, as the sputtered treatment technique allows for an easy coating on a complex substrate with high reproducibility. NiOx materials can further increase the coupling of SAM molecules with the substrate. Thus, the hybrid ICLs could improve the uniformity of the interface between the TCO and the SAM based on MeO-2PACz, which is also known as [2-(3,6-Dimethoxy-9H-carbazol-9-yl)ethyl]phosphonic acid, by decreasing the interface defects and bulk defects, and reduce the leakage current. A good energy level alignment between perovskite and hybrid ICLs was built, which is beneficial to carrier extraction and transportation (Zheng et al., 2024; Bellini, 2024J). Solar cells in both two-terminal (2T) and four-terminal (4T) configurations. The 4T tandem arrangement offers a broader bandgap selection window for the constituent cells (Leijtens et al., 2018B; Yu et al., 2016).

Metal halide four-terminal (4T) perovskite-silicon tandem solar cells can be made with a stability-enhancing interfacial treatment, enhancing the stability and reliability of perovskite films in tests, and in fabrication conditions (Thompson, 2024C).

Advancements in material engineering have made perovskite one of the most promising materials used in solar cells. The perovskite-silicon tandem cells can achieve 40% efficiency, and standalone perovskite cells are still breaking new ground. The impressive performance of the 4T perovskite-CIGS tandem solar cell proves that perovskite is no longer an ideal material but a leading material for the future of renewable energy (Sanusha, 2025).

A research group in India has embedded a hybrid heterojunction solar cell (HHSC) as a bottom device in a four-terminal (4T) perovskite-silicon solar cell using a solution processing technique. HHSCs have a simple structure and low-temperature fabrication processes, and aim to eliminate up to 35 % of energy consumption during solar cell production and exploit the advantages of both functional layer and Si materials in a cost-effective approach. HHSCs are based on carrier-selective functional layers relying on either molybdenum oxide (MoOx), graphene, carbon nanotube (CNT), PEDOT:PSS, or poly(3-hexylthiophene) (P3HT) (Afroz et al., 2025; Bellini, 2025S).

**Perovskite-PERC Tandem Solar Cell**

Tatineni, Sekhar (2025) PV Magazine, Beyond the hype: Why PERC still powers a stronger solar future,

<https://www.pv-magazine.com/2025/05/13/beyond-the-hype-why-perc-still-powers-a-stronger-solar-future/>

PERC (Passivated Emitter and Rear Cell): An advancement of conventional solar cells that uses an additional layer on the back of the solar cell that also reflects sunlight into the cell.

PERC-based modules have consistently demonstrated linear and predictable degradation rates—typically around 0.4% per year, whileTOPCon remains relatively unproven over a 25- to 30-year lifespan in the field. Compared to TOPCon, PERC manufacturing is simpler, requires less specialized training and offers higher initial yields, which lowers the barrier to entry and accelerates the path to profitability. The supply chain for PERC is also more mature and often easier to localize, reducing dependency on global components and mitigating risks associated with tariffs or trade restrictions. Another important consideration is intellectual property. TOPCon technology is currently the subject of several high-profile patent disputes, creating uncertainty for manufacturers and developers alike. A project or facility relying on contested technology could face costly legal consequences down the road (Tatineni, 2025).

PERC stands for passivated rear emitter contact solar cell, and in this cell both the front and rear surfaces of the device are passivated by dielectrics. Small pockets of the rear dielectric layer are opened (etched away) with a laser so that metal can be contacted to the rear surface of the device. Compared to a conventional Si solar cell, PERC is able to improve the efficiency of Si solar cells mainly due to the additional passivating dielectric layer on the rear side. Rear side passivation prevents minority carriers (current generated from light absorption) from recombining (eliminated) at the rear surface. Also, the extra rear dielectric layer reflects long wavelength photons from the rear surface back to the device for more light absorption and current generation.

PERC technology can be used as the bottom cell concept for a perovskite–silicon tandem devices. For PERC-like bottom cells, an adapted front-side design is needed, because such an updated PERC bottom cell only needs to absorb long wavelength photons, and transport about half the current flows. A monolithic tandem perovskite-PERC cell, can feature one-dimensional current transport, and thus no lateral transport is needed, and also the use of firing-through local silver contacts is not needed. The phosphorus-diffused front emitter and the interconnection layers towards the top perovskite cell need to be investigated further for perovskite-PERC cells. Standard PERC emitters have been optimized regarding short wavelengths response, surface passivation, lateral transport towards the local metal contacts, low recombination and contact resistance at the screen-printed silver contacts, and gettering of impurities (Messmer et al., 2022).

Monolithic perovskite-PERC tandem solar cells can utilize a tunnel recombination junction (TRJ) based on indium tin oxide (ITO), nickel(II) oxide (NiO), and carbazole (2PACz). TRJs are usually based on ITO and 2PACz alone, as 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 (Bellini, 2023H; Phung et al., 2023). The group deposited the NiO layer through atomic layer deposition (ALD), which they claim largely improves the uniformity of coverage of the self-assembled monolayer (SAM) of the TRJ. The researchers built the top perovskite cell with the proposed TRJ, a perovskite absorber, an electron transport layer based on buckminsterfullerene (C60) and tin(IV) oxide (SnO2) layer, an ITO electrode, a silver (Ag) metal contact, and an antireflective coating based on magnesium fluoride (MgF2) (Bellini, 2023H; Phung et al., 2023).

**Perovskite-TOPCon**

TOPCon (Tunnel Oxide Passivated Contact): A type of solar cell technology that uses a tunnel oxide layer to passivate the surface of the cell, which can improve efficiency.

TOPCON stands for “Tunnel Oxide Passivated Contact”. TOPCON (also known as passivated contact) solar cell, is the next generation of solar cell technology after PERC, and TOPCON can be upgraded from the current PERC or PERT line. To upgrade an n-PERT solar cell to a n-TOPCON solar cell, only an additional ultra thin $SiO\_{2}$ layer and a doped poly-Si layer are required. The ultrathin $SiO\_{2}$ acts as a surface passivation layer between the rear Si surface and the rear contact, the poly-Si layer. In addition, the $SiO\_{2}$ layer also needs to be thin enough so that current can tunnel through it quantum mechanically. The poly-Si layer is highly doped to produce a high conductivity layer. This high conductivity layer will then acts as a contact for current collection. Additionally, in a n-type TOPCON, the poly-Si layer is typically doped with phosphorus to provide field passivation (back surface field). This is similar to the phosphorus doped rear surface of n-PERT. A tunnel oxide layer that offers passivation on the cell’s backside distinguishes TOPCon solar cells from other solar cells. This structure efficiently lowers recombination losses, enhancing cell functionality as a whole. TOPCon cells typically use conventional silicon wafers as its primary building block.

Wu et al. (2022) employed an industrially fabricated, tunnelling oxide passivating contact (TOPCon) c-Si bottom device utilizing an n-type silicon substrate, as cells based on n-type substrates generally display higher lifetimes and reduced degradation compared to cells based on p-type substrates. This device features a damage-etched (but not textured) top surface. The perovskite top cell was fabricated conformally on the damage-etched (not textured) front surface to mitigate the negative impacts of rough c-Si substrates, thus preventing shunt paths across carrier transport layers, absorber layers, and their interfaces in relevance. Photon harvest should be evaluated in the entire tandem layout with a focus on the optimization of the front transparent conductive oxide (TCO) to balance the reflectance and series resistance losses (Wu et al., 2022). Jiang et al. (2024) textured the silicon solar cell with micro/nano-structures, evaluating an industrial-level sub-micron random pyramid (sMRP) structure on the front side of a p-i-n typed perovskite/TOPCon solar cell using a simple alkaline texturing process. Reduced passivation quality of the bottom silicon sub-cells and difficulties in perovskite formation on textured substrates remain challenges to superior electrical performance. Texturing the front side of silicon solar cells with suitable micro-/nano-structures is critical to make full use of incident light. Research into textured structures for perovskite-silicon TOPCon cells include commercial micron-scale random pyramids (MRP) (Sahli et al., 2018), black silicon (Ying et al., 2022), and periodic nanostructured textures, etc. (Jošt et al., 2018).

In highly passivated perovskite-silicon p-type TOPCon cells, numerous defects from the fragile silicon oxide/c-Si interface and the low field-effect passivation due to the inadequate boron in-diffusion in p-type polycrystalline silicon (poly-Si) passivated contact reduce their open-circuit voltages $(V\_{OC}s)$, though this can be corrected by optimizing the oxidation conditions, boron in-diffusion, and aluminium oxide hydrogenation, thus pronouncedly improving the implied $V\_{OC}$ $(iV\_{OC})$. Texturing the front side of the silicon cell in a perovskite-silicon tandem is necessary to reduce the reflection of incident photons and extend the propagation length of photons in the absorbers (Sahli et al., 2018; Tockhorn et al., 2022; Mao et al., 2022). Possibly due to the weak passivation of the textured p-type side, TOPCon bottom cells have been reported to contribute lower voltage in TSCs as compared to silicon heterojunction (SHJ) bottom cells (Ding et al., 2024).

A perovskite-silicon tandem solar cell that has a two terminal configuration (2T) and a 2D perovskite layer at the bottom interface achieved efficient charge extraction and interface passivation, using blade-coated perovskites and contact passivation with 2D perovskites. Blade coating was used to deposit the 3D perovskite onto a 2D perovskite layer in the perovskite top device, which had a p-i-n inverted device configuration. To minimize the energy level mismatch at the bottom interface, achieve efficient hole extraction, and reduce performance losses in our blade-coated p-i-n devices, the team tuned the targeted dimensionality (n) of the 2D perovskite film, which is made prior to the 3D perovskite (Subbiah et al., 2024; Bellini, 2024I). The researchers used blade-coated perovskites and contact passivation using 2D perovskites (Subbiah et al., 2024; Bellini, 2024I).

Researchers have fabricated a TOPCon solar cell with a nickel (Ni) contact and significantly lower silver (Ag) content of only 0.5 mg/W, compared to the 13–20 mg/W used in standard silver contacts, with the device achieving almost the same efficiency as TOPCon devices produced via full silver metallization. For the metallization process, the research team used different four types of Ag-doped Ni metal pastes and a reference product based on aluminum (Al) and Ag provided by German specialist Heraeus. The cells were based on M10 182 mm x 182 mm n-type wafers and featured a tunnel oxide layer of silicon monoxide (SiOX) less than 2 nm thick and an n-doped polysilicon layer, serving as a passivating carrier-selective contact. The devices also relied on amorphous hydrogenated silicon nitride (a-SiNx) layers, which the scientists said are key to providing hydrogenation to passivate dangling bonds at the Si/SiOX interface. Oxides were used to enable the glass frit to effectively etch the antireflective coating (ARC) and to form a passivating interlayer that improves the overall contact resistance. A nickel oxide (NiO) layer was applied to increase the adhesion and stability of the residual glass layer (Unsur et al., 2025; Bellini, 2025DD).

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