HJT is the Bottom Cell of Choice for Tandem Solar Cells

A technical perspective on HJT vs. TOPCon silicon bottom cells for perovskite–silicon tandem PV architectures.

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Summary

Silicon heterojunction technology (HJT) is the best bottom cell for perovskite–silicon tandem modules. Because HJT offers the highest open-circuit voltage among commercial silicon technologies, superior optical compatibility with tandem architectures, lowest degradation rate, and the lowest temperature coefficient, it is the technology of choice as the bottom cell in two-terminal (2T) perovskite-silicon tandems. Importantly, the historical efficiency tradeoffs in the HJT cell architecture balancing light absorption and passivation quality are mitigated in the tandem structure. The HJT manufacturing process flow is the simplest of all c-Si technologies, and is directly translatable to tandem production. In short, when optimizing a bottom cell for integration into 2T tandems, the benefits of HJT single junction technology are further enhanced, while tradeoffs relative to TOPCon become less significant. Finally, by minimizing the impact of radiation damage, HJT offers advantages for space solar power.

Summary of Technological Advantages of HJT cells for Tandem Applications compared to TOPCon

HJT technical differentiation	Benefit relative to TOPCon based tandems	Why	Net Tandem Benefit relative to TOPCon
HJT c-Si passivation	1.5% PCE gain	Voc and FF benefit without and current penalty	2.5-3% PCE gain
HJT optimal front side texture	1-1.5% PCE gain	Improved light trapping	
HJT shunt protection	Production yield gain	Resistivity of a-Si provides shunt protection for the perovskite top cell	Improved manufacturing economics
Reduced Tempco (0.25 vs 0.29)	Energy yield gain	Improved passivation	Improved project economics
Reduced degradation rate	More energy produced over module lifetime	Reduced light+heat activated degradation of HJT bottom cell	
Manufacturing flow	Simple integration	No modification of existing equipment	Easiest tandem process flow integration

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Manufacturing cost of bottom cells	Similar or lower cost	Bottom cell costs are lower than full cell costs for HJT but not TOPCon	Cell production cost
Space applications	Lower radiation damage	Ability to use P-type HJT technology minimizes radiation damage to bottom cells	Ideal space PV technology

Introduction

The photovoltaic industry has advanced through successive generations of silicon cell technology—Al-BSF, PERC, TOPCon, HJT, and back-contact architectures—each delivering increments in efficiency and performance. As silicon approaches its practical efficiency limits, perovskite-silicon tandem technology represents the next major step forward, with demonstrated cell efficiencies approaching 35% and a clear path beyond that.

In a tandem architecture, the silicon cell serves as the bottom absorber, capturing infrared photons that pass through the perovskite top cell. The choice of silicon technology therefore plays a critical role in determining the ultimate efficiency, manufacturability, and cost of tandem modules.

Two silicon technologies dominate the roadmap for high-efficiency solar cells today: TOPCon and heterojunction (HJT). While TOPCon currently leads in manufacturing volume, heterojunction technology offers several structural advantages that make it uniquely well suited as the bottom cell in tandem architectures.

Single-Junction Benchmarks

Before discussing tandem integration, it is helpful to benchmark the performance of leading silicon technologies in conventional single-junction cells and modules.

Technology	Record Efficiency	Production Cell Efficiencies	Field Degradation Rate	Temperature Coefficient
HJT	26.8%	~25-26.5%	~0.2-0.3%/year	-0.25 %/K
TOPCon	26.6%	~25-26%	~0.3-0.4%/year	-0.29 %/K
PERC	24.1%	~22.5-23.5%	~0.4-0.5%/year	-0.35 %/K

HJT consistently demonstrates the highest cell efficiencies among non-back contact architectures, along with the lowest field degradation rate and lowest temperature coefficients among commercial silicon technologies. The degradation rate and temperature coefficient enhance energy production in most climates. Note that this comparison excludes back contact schemes or novel device architectures, just focusing on designs currently in production.

Why HJT Makes the Best Bottom Cell for Tandems

1. Best surface passivation

Surface passivation of crystalline silicon wafers has been the primary driver for the remarkably improved efficiencies in c-Si technology over the last decades. The amorphous silicon passivation layers employed in HJT designs offer the most effective passivation of all existing options, resulting in open-circuit voltages (Voc) approximately 20mV higher and fill factors (FF) 3% higher in HJT production cells than in TOPCon production cells.

Technology	Voc	FF	PCE
Production HJT	~0.75 V	0.86-0.87	26.2%
Production TOPCon	~0.73 V	0.83-0.84	25.8%
Tandem Efficiency benefit from HJT vs TOPCon (relative %)	~1%	3.5%	4.5% relative 1.5% absolute

Despite the large FF and Voc advantage of HJT, the production efficiency of the two technologies is fairly similar because the a-Si passivation layers used in HJT cells parasitically absorb some visible light, reducing current relative to TOPCon. In tandem devices, however, visible light is all absorbed by the perovskite top cell anyway; the a-Si passivation layer then provides passivation benefits with no parasitic absorption loss. As a result, the improved Voc and FF translate directly to tandems, raising the attainable tandem efficiency for HJT bottom cells by ~4.5% relative to TOPCon bottom cells.

This is a great example where only the efficiency advantage of the HJT passivation approach applies to tandems, not the disadvantage.

2. Optimal Surface Texture for Tandem Optics

Modern solar cells can harvest most of the incident light because the front and back surfaces of the silicon wafer are etched to produce micron-sized pyramids, which reduce reflection losses and maximize current. It is most important for the top light-facing side of the cell to feature such pyramids to maximize light absorption. In HJT cells, texture is applied in one step to both front and back of the cell, enabling excellent light trapping and low reflection losses across the tandem stack. In typical n-type TOPCon structures, however, the light-facing side of the tandem is the opposite of the light-facing side in the single junction cell - the result is that 2T tandem cells based on TOPCon bottom cells do not benefit from optimal light trapping the same way that HJT-based tandems can. It is likely possible to modify the TOPCon bottom cell process to enable the pyramidal texture on both sides of the cell, but this requires redesigning production equipment and modifying poly-Si passivation processes - non-trivial.

In practice, this can translate to roughly a 1–1.5% absolute efficiency advantage for tandem cells with optimized texturing. This benefit is even stronger for future triple junction solar cells with over 40% efficiency - the pyramidal texture helps mitigate the significant reflection losses caused by the many thin layers used in a triple junction design.

3. More Forgiving Tandem Integration

The a-Si passivation layers used in HJT cells provide additional electrical isolation and shunt tolerance between top and bottom cells in a tandem compared with other silicon architectures. This can make the integration of the perovskite top cell more forgiving during manufacturing. With such a thin perovskite solar cell stack (~1um), the probability of pinholes and shunt pathways forming is higher than with other existing PV technologies, especially in early stages of process scale-up. The additional shunt protection offered by HJT architectures is thus likely to improve yield in early tandem production lines.

4. Energy Yield Advantages

The superior passivation in HJT cells results in lower temperature coefficients than TOPCon (~-0.25 vs -0.29 %/K for TOPCon). Because perovskites typically offer low temperature coefficients of -0.2%/K or lower, the net temperature coefficient of the tandem is typically dominated by that of the bottom cell - for this discussion we can assume the tandem temperature coefficient is the same as that of the bottom cell. Since PV modules typically operate 10-20K hotter than the ambient temperature, the lower temperature coefficient implies significant improvement in operating efficiency - a 30% tandem solar cell based on HJT would perform at 28.2% vs. 27.8% with TOPCon at a typical operating temperature of 45ºC. When modeled across a range of climates, these improvements translate into meaningful gains in system energy production over the lifetime of a PV installation.

Similarly, the lower degradation rate of HJT bottom cells will result in improved energy production over the course of the module’s life. While the lifetimes of early generations of tandem modules are expected to be limited by the perovskite component, the bottom cell can still contribute ~5-10% relative degradation over its lifetime, with HJT bottom cells closer to 5% vs. 10% for TOPCon , based on degradation rates quoted on existing product spec sheets.

Manufacturing Synergies

HJT manufacturing platforms align naturally with tandem manufacturing. Both technologies rely heavily on physical vapor deposition (PVD) processes and employ similar automation strategies to transfer wafers from cassette to tray and back again.

In addition, the recombination layer used to connect the perovskite and silicon subcells requires little modification when applied to an HJT structure. This simplifies tandem integration compared with alternative silicon technologies.

HJT bottom cells also require fewer total process steps—roughly 6 compared with up to 12 for TOPCon—reducing manufacturing complexity and potential sources of yield loss. Representative manufacturing process flows for tandem-ready bottom cell production are provided below.

It is worth noting that the HJT single junction cell already includes TCO deposition steps, while a new TCO deposition step must be added for the TOPCon process flow. This also introduces another etching step for the TOPCon cell stack, as the n-type poly-Si passivation layers form native oxides during the metallization and firing steps, which must be etched back to enable good contact between the poly-Si layer and TCO recombination layer, as outlined in the process flows above.

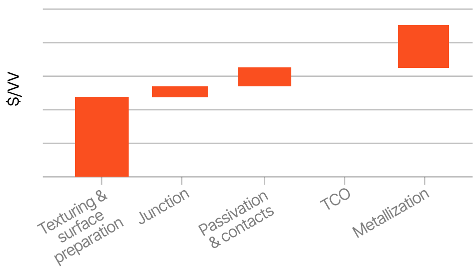
It is clear that the HJT structure wins from a simplicity point of view. Still, TOPCon is the dominant technology in production - this is likely because of the relative simplicity of upgrading PERC equipment and production infrastructure to TOPCon rather than technological superiority. The result was a lower required upfront capital investment to upgrade cell production to TOPCon over the last decade. Now, as the industry looks towards the next node in technology via tandem architectures, the HJT path offers significant advantages.

Cost: Tandem Architectures Change the Comparison

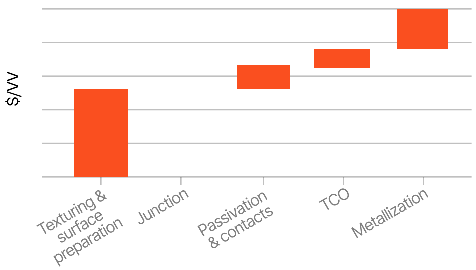
The simplified process flow of HJT bottom cell manufacturing also has implications for the cost structure. For single junction applications, HJT appears slightly more expensive mainly because of the TCO layers, low-temperature metallization, and the a-Si PECVD layers (contact stack). On the other hand, HJT saves some costs by not requiring emitter formation (junction) or edge isolation.

A representative waterfall chart is shown below using rough estimates for total (including materials, capex, opex) relative costs for each major portion of the process flow (excluding the wafer itself). These are rough estimates based on market reports of production in China and Southeast Asia rather than from a validated manufacturing cost model - hence absolute cost ($/W) values are not shown, just the relative contributions. The analysis estimates roughly a 0.01 $/W advantage for the TOPCon cell cost structure when used as a single junction. This is relative to a wafer price of ~0.03 $/W for Chinese wafers and more than 0.10 $/W for US made wafers. We also expect the emergence of silver-plated-copper pastes to shift the metallization costs back in favor of HJT technology because these typically require lower processing temperatures than those required during metallization of TOPCon cells.

TOPCon - SJ



HJT - SJ

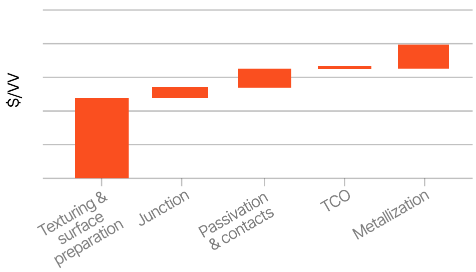


Tandem architectures fundamentally change this comparison because

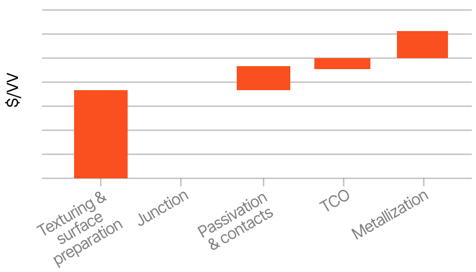
1. The contribution from TCO deposition shifts - the HJT bottom cell uses less TCO than it would have as a single junction HJT cell, while the TOPCon bottom cell adds a new TCO layer.
2. The low temperature metallization is only applied to the back of the bottom cell prior to tandem depositions, and the low temperature metallization is required for the front contact of a tandem regardless of bottom cell choice. In fact, the HJT technology could allow both front and back metallization to be applied at the end of the complete tandem process, simplifying the manufacturing flow. This option is not possible for TOPCon tandems because the backside metalization requires high sintering temperatures to form effective contact.

Relative cost structure of bottom cell processing is provided in the plots below. Note that the scale on the Y axis is the same for the SJ and Bottom cell plots.

TOPCon - Bottom Cell



HJT - Bottom Cell



The outcome is that the cost differential between HJT and TOPCon is halved in a tandem to very roughly 0.005 $/W. Manufacturing in the US, where labor and electricity prices are higher, will also favor HJT technology because fewer tools means fewer operators and HJT processes are less energy intensive and require less cooling water than those used in PERC and TOPCon manufacturing.

Compatibility with Space Applications

There is growing interest in deploying large PV systems in space, both for powering telecommunications satellites in Low Earth Orbit (LEO) (e.g., Starlink) and large-scale power generation for orbital data centers and power beaming. The high power density (per unit weight and area) of tandem technology can offer strong value for space applications - generating up to 40% more power for the same volume or mass of material launched into orbit can transform project economics and space system design.

Perovskites have been demonstrated to be surprisingly radiation tolerant, but c-Si solar technology is typically sensitive to radiation damage - radiated n-type cells in particular suffer a reduced minority carrier lifetime, dramatically reducing end of life (EOL) performance. The simplest cell-level change to improve radiation tolerance of c-Si cells is to employ p-type HJT cells. p-HJT demonstrates relatively strong radiation tolerance because p-type wafers are less prone to radiation-induced minority carrier lifetime decreases, and the strong double-sided passivation and electric field provided by the a-Si layers makes them less sensitive to such reductions in minority carrier lifetime.

HJT manufacturing lines can also be switched between producing n- and p-type cells without major equipment changes. A HJT cell manufacturer can make both n-type cells for terrestrial applications and p-type cells for space applications, unlocking terrestrial economies of scale for space solar. This makes HJT uniquely suited for PV systems deployed in space.

Conclusion

Silicon heterojunction technology combines the highest voltage, favorable optics, streamlined manufacturing, and strong field performance. When tandem architectures are considered holistically, HJT emerges as the superior bottom-cell platform for perovskite–silicon tandem modules.