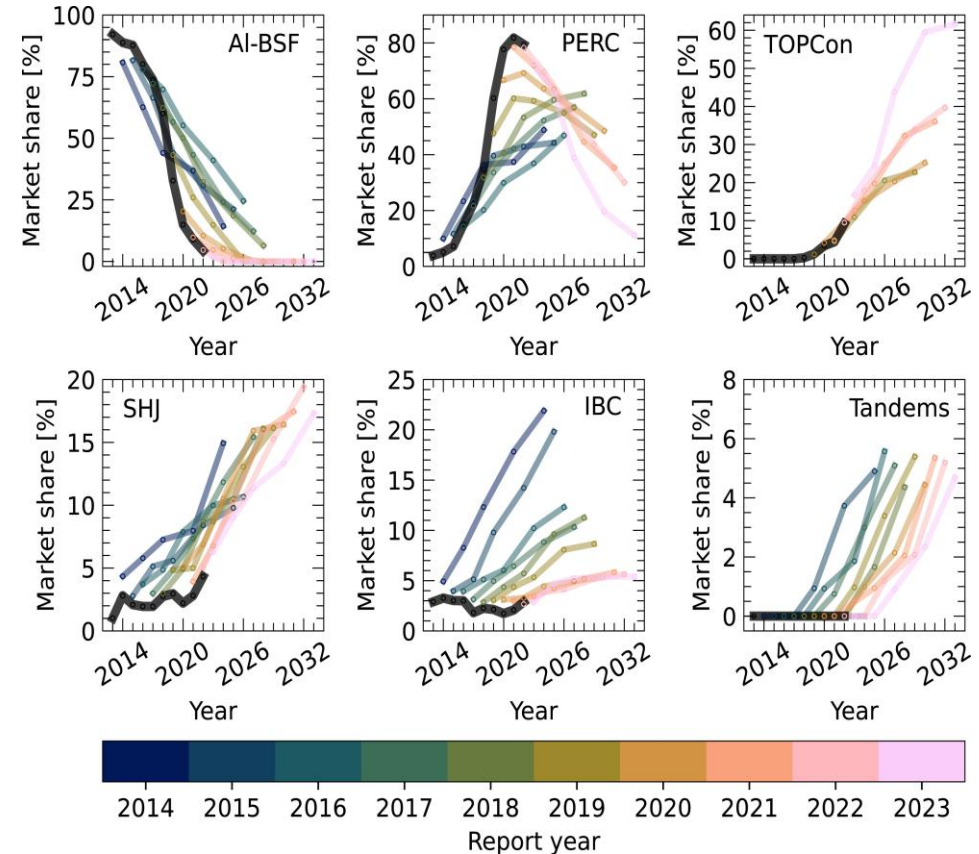


AI-BSF	PERC	TOPCon	SHJ
Texturing	Texturing	Texturing	Texturing
Cleaning	Cleaning	Cleaning	Cleaning
P diffusion	P diffusion	B diffusion	Front a-Si(i):H + a-Si(n):H
Rear etch	Rear etch	Rear etch	Rear a-Si(i):H + a-Si(p):H
	Rear $\text{Al}_2\text{O}_3 + \text{SiN}_x\text{:H}$	$\text{SiO}_x + \text{Poly-Si(i)}$	Front + rear TCO sputtering
		P diffusion	Front + rear Screen-printing
		Front etch	Curing
Front passivation	Front passivation	Front passivation	Hydrogenation
	Rear opening	Rear passivation	
Front + rear Screen-printing	Front + rear Screen-printing	Front + rear Screen-printing	
Firing	Firing	Firing	
Hydrogenation	Hydrogenation	Hydrogenation	

Processes introduced with: PERC TOPCon SHJ



Incentives - HJT – Minimal number of process steps & increasing market share while market share of TOPCon is slowing

Preamble – 10+ Reasons to Think HJT Solar Cells

1. Enjoys a relatively clearer, less-litigated IP landscape
2. Efficiency ~24 to 26%; high efficiency potential (~29.2%)
3. Excellent temperature coefficient $-0.26\% / ^\circ\text{C}$ (Best for heat)
4. Features the fewest manufacturing steps (4 Core Steps)
5. Outstanding low-light performance
6. Very low annual degradation (High resistance to LID, PID)
7. Low temperature processing ($< 200^\circ\text{C}$)
8. Longer Lifespan (≥ 30 Years)
9. Excellent bifaciality factor due to symmetrical design (90-95%)
10. Premium price with high-end energy yield

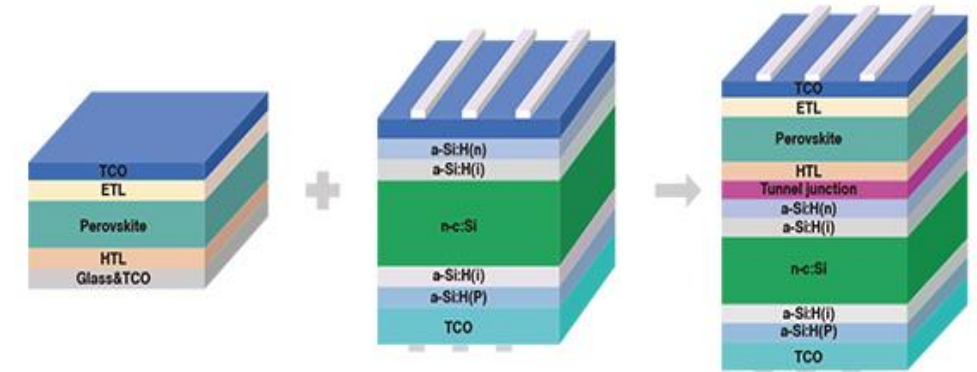


Technology Drivers:

- HJT as the bottom cell for the next generation perovskite-silicon tandem solar cells
- Due to their high power density in space constrained areas ($230-235 \text{ W/m}^2 = 10.14-10.36\text{W}$ for a G12 wafer), HJT is prime candidates for Building-Integrated Photovoltaics (BIPV)
- Ultrathin silicon wafers ($65\mu\text{m} \approx 151.5\text{g/m}^2$) facilitate the fabrication of light weight HJT solar cells for space applications (areal mass density= 300g/m^2) and specific power $\geq 750\text{W/Kg}$.

Perovskite

HJT



HJT – The Value Proposition

Solar cells for Space ~180 W/kg for standard III-V multijunction cells, and $>1,000 \text{ W/kg}$ for ultra-thin flexible cells (such as MicroLink devices under $40 \mu\text{m}$ thick)

<https://www.lessosolar.com/news/the-competition-between-hjt-and-topcon-why-perovskite-tandem-cells-are-the-new-darling-of-photovoltaic-technology/>

The Next Generation of Cell Technologies: Which Architectures Will Define the 2030s?

10.14.2026

San Francisco, CA

- Introduction
- HJT Solar Cells Today – Current Status
- HJT Solar Cells - The Road Ahead
- HJT Solar Cells – An R&D Perspective
- HJT Solar Cells 2.0 – The Next Phase
- Example of Indium Reduction
- HJT Solar Cells - Next Generation
- Perovskites
- Perovskite Solar Cells
- Multi-Junction Solar Cells
- Summary
- Postamble

Evolution in Solar Cell Architecture

- Back Surface Field – 1970s – $\eta \approx 20\%$ Efficiency
- Passivated Emitter and Rear Cell (PERC) – 1989 Patent – University of New South Wales – $\eta = 23$ to 24.5%
- Tunnel Oxide Passivated Contact (TOPCon) - 2013 Fraunhofer ISE - $\eta = 25-26\%+$
- *Heterojunction Technology (HJT) – 1980s - as HIT (Heterojunction with Intrinsic Thin-Layers), Sanyo/Panasonic - Among the highest commercial η ($26\%+$) with exceptional temperature stability*
- Interdigitated Back Contact (IBC) - Developed in the 1970s, popularized commercially by SunPower in the 2000s, $\eta = 22.8\%-26\%+$.

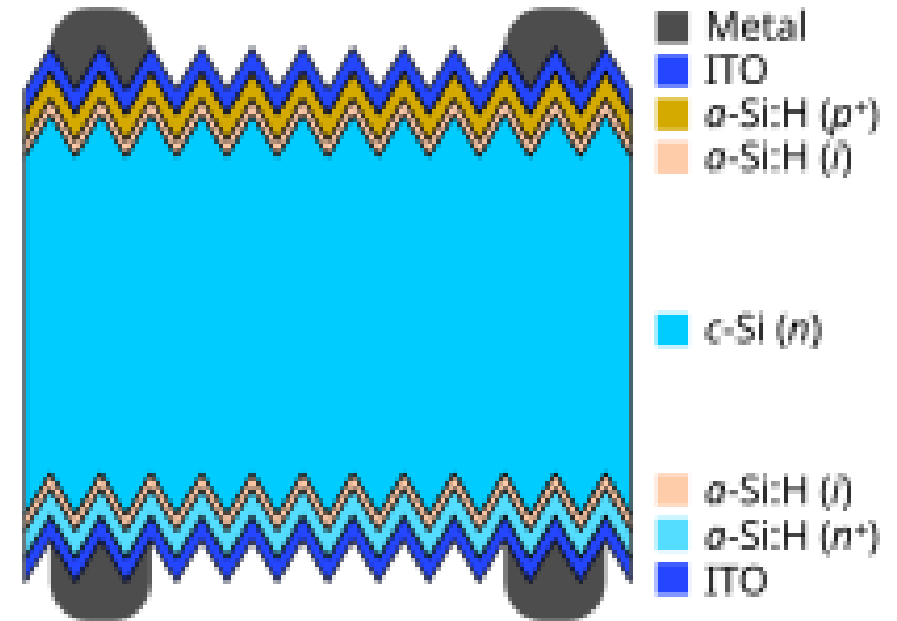


Illustration of an HJT Cell

https://en.wikipedia.org/wiki/Heterojunction_solar_cell#/media/File:Bifacial_Silicon_heterojunction_solar_cell_cross-section_schematic.svg

HJT – Industry Driven Mature Technology

HJT - Low Temperature Device Processing; High Temperature Device Stability

Introduction

DYCM Power is an American domestic solar module manufacturer building a fully traceable, Foreign Entity of Concern (FEOC)-compliant supply chain in the United States.

DYCM Power will go into production of Solar Modules in Early 2027.

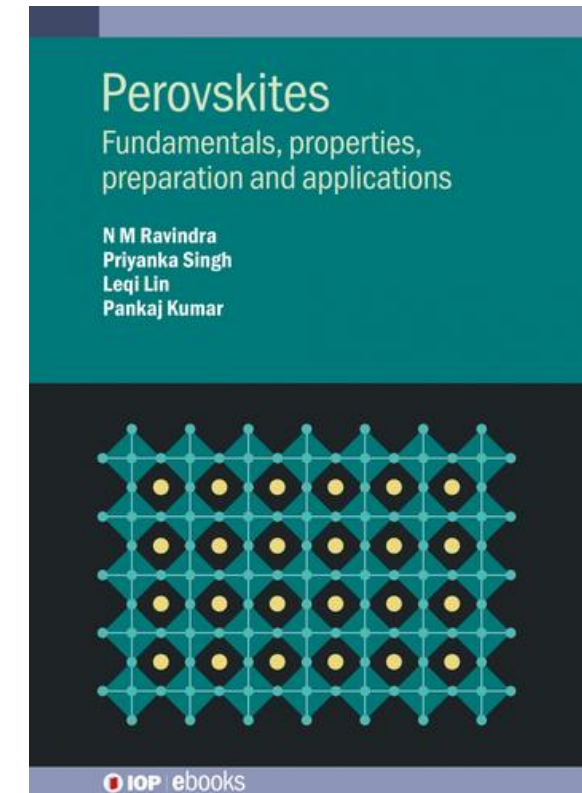
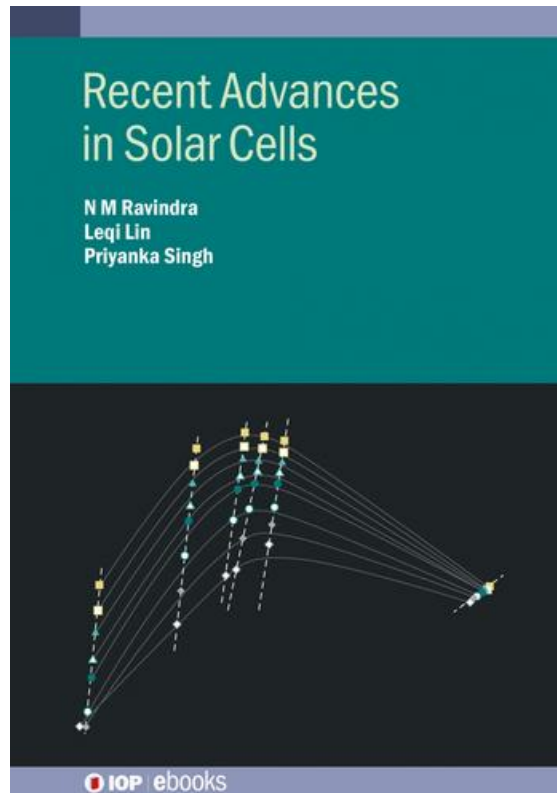
Dedicated Team of Visionaries



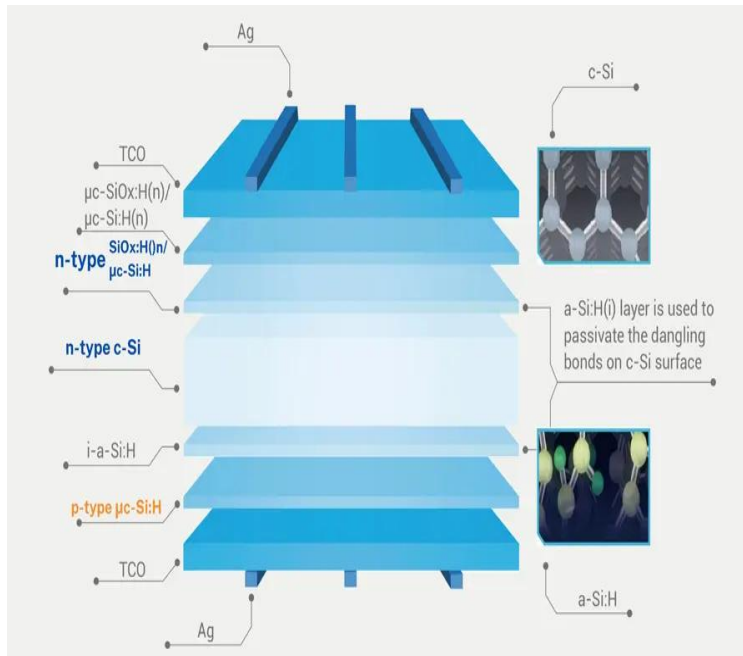
Livermore, CA – The Future is Here!!

PROTECTING SOLAR PANELS FROM DAMAGE DUE TO OVERHEATING

Patent No.: **US 11,876,484 B2**
Date of Patent: **Jan. 16, 2024**



HJT Solar Cells Today – Current Status



>26.8%

Certified HJT cell efficiency (2026)

>750 mV

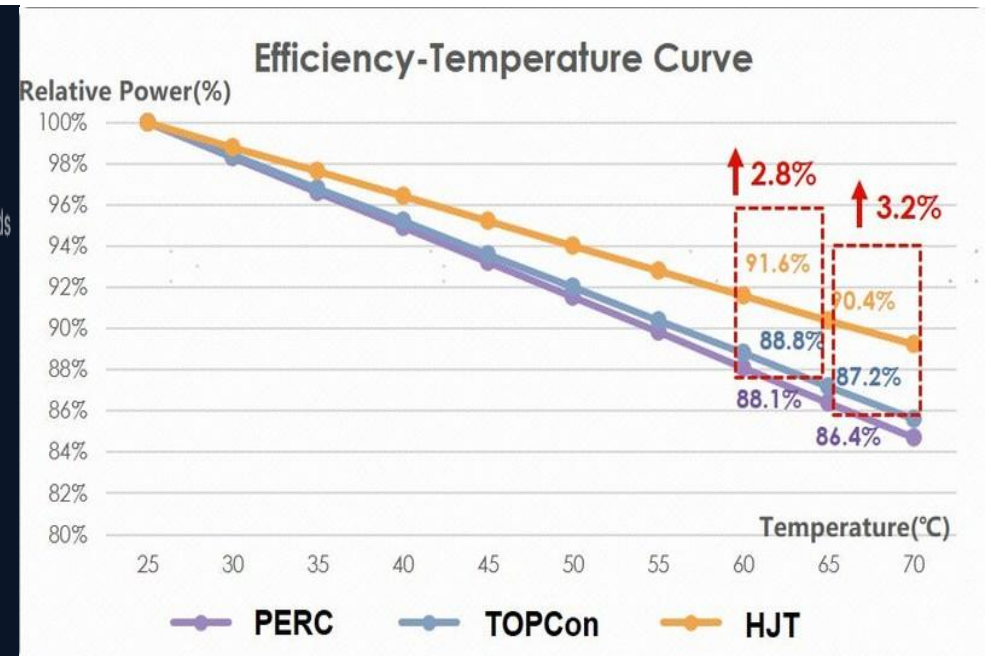
Open-circuit voltage enabled by a-Si:H passivation

60+

Patent & literature records analysed (2009-2026)

>29%

Perovskite/Si tandem efficiency demonstrated



Superior Performance: High Efficiency (26.81%); Exceptionally Low Temperature Coefficient (-0.243%/°C); High Bifaciality Rate (95%); Streamlined Manufacturing Process: 4 Core Steps [Step 1 - Wet Chemistry (Cleaning & Texturing); Step 2 – PECVD of intrinsic and doped a-Si on both sides; (Cleaning & Texturing Low Temperature Processing; Step 3 – PVD of ITO on both sides; Step 4 – Metallization (Screen Printing) of special conductive paste (generally silver); the entire cell is dried and cured at temperatures < 200°C]; Thinner Wafer Compatibility; Superior Low-Light Performance; Very Low Power Degradation; Reduced Carbon Footprint; Immunity to Degradation; Perfect Perovskite Tandem Platform; Enhanced Durability and Microcrack Resistance; Symmetrical Sandwich Structure built around n-Si, less exposure to patent infringement lawsuits.

<https://canalsolar.com.br>

HJT Solar Cells Today – Current Status

Silicon HJT Cells in Space - Silicon Heterojunction (HJT) solar cells are emerging as a disruptive technology for space applications

US Government Initiatives – Techwerx - <https://www.techwerx.org>

Breakthroughs in p-type HJT (p-HJT) architectures, **ultra-thin manufacturing**, and **perovskite tandem integration**

Extreme Cost Efficiency - One-hundredth (1/100th) of cost of traditional Group III–V space solar cells, enabling a 90% reduction in overall satellite solar power system costs

Doubled Specific Power - HJT technology is uniquely compatible with ultra-thin silicon wafers (**50µm**) and flexible device architectures. Case studies show that ultra-thin HJT cells can deliver roughly twice specific power (W/kg) of triple-junction cells

Radiation Tolerance & Self-Healing - **p-type HJT cells exhibit remarkably strong radiation tolerance** compared to other silicon types such as TOPCon

Superior Temperature Coefficient - HJT - best temperature coefficients in industry

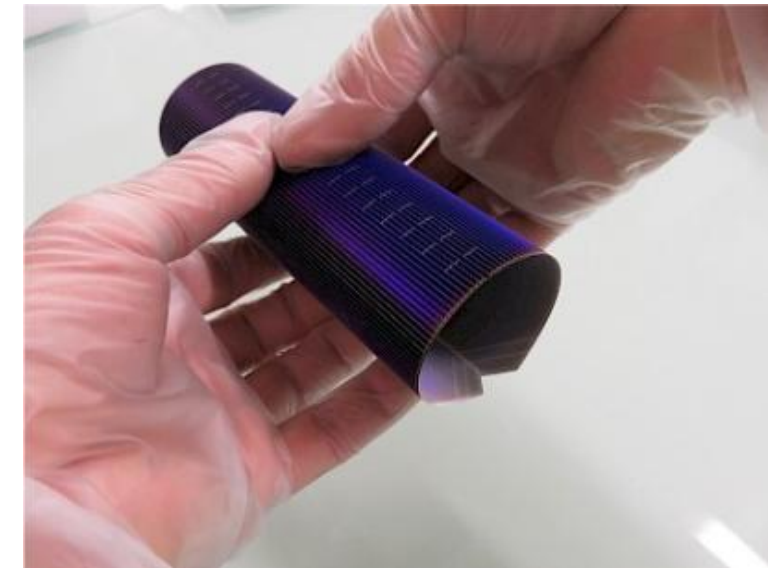
Recent News - JA Solar successfully launched prototype P-HJT modules into Earth orbit, First Orbital Validation

Next-Gen Perovskite-HJT Tandems – Companies use HJT as foundation for perovskite tandem cells, achieving efficiency of **~30.99%**

AI-Enabled Space Production - First AI-enabled pilot line dedicated exclusively to manufacturing ultra-thin, flexible HJT cells for space and near-space applications

Commercial Interest - Maturity and extreme temperature tolerance of HJT have caught attention of SpaceX and xAI space-based Data Centers.

**Convergence:
Federal, Private, Terrestrial, Space
Interests in HJT**



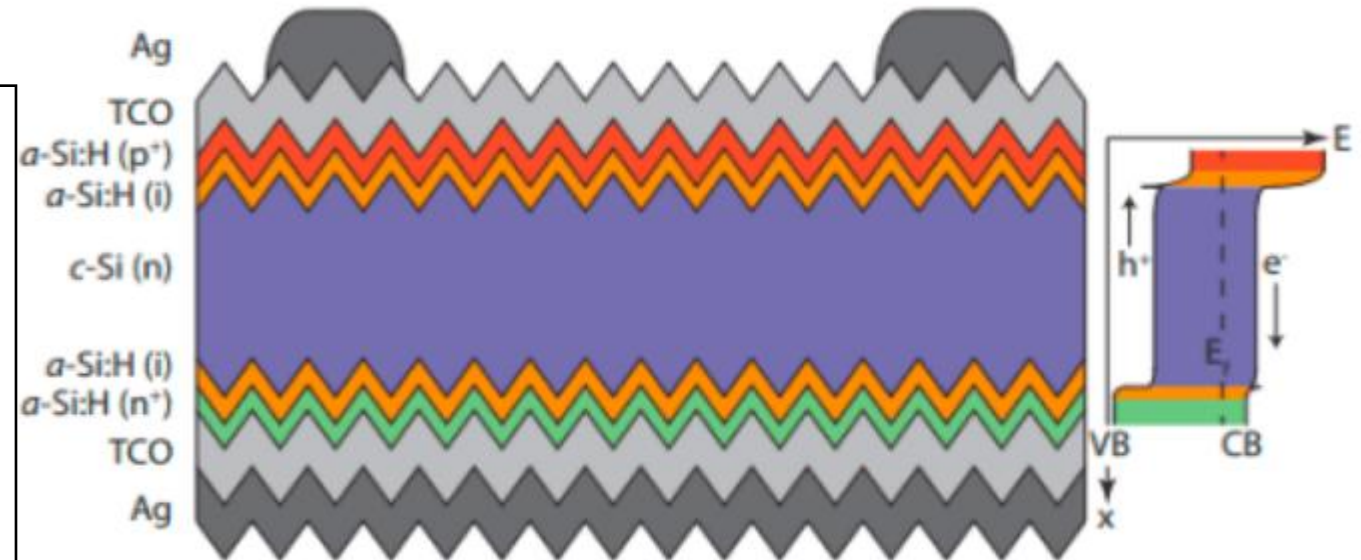
60µm Si p-type Heterojunction Solar Cells

HAL Id: cea-04513443
<https://cea.hal.science/cea-04513443v1>

HJT Solar Cells – The Road Ahead

MANTRA: MATERIAL = STRUCTURE = DEVICE

ITO- $\approx 80\text{-}100\text{nm}$ thick ----->
 $\text{a-Si:H(p}^+)$ – $\approx \text{B doped} - 10\text{nm}$ ----->
 a-Si:H(i) – $\approx 5 \text{ to } 10\text{nm}$ ----->
 C-Si(n) – $\approx 120\text{-}160\mu\text{m}$ ----->
 a-Si:H(i) – $\approx 5 \text{ to } 10\text{nm}$ ----->
 $\text{a-Si:H(n}^+)$ – $\approx \text{P doped} - 10\text{nm}$ ----->
ITO- $\approx 80\text{-}100\text{nm}$ thick ----->



TCO/ITO – Conductor; $\text{a-Si:H(p}^+)$ – Emitter Layer; a-Si:H(i) – Passivation Layer to reduce surface defects; C-Si(n) – Light absorbing base; a-Si:H(i) – Rear surface passivation; $\text{a-Si:H(n}^+)$ – Back surface field; TCO/ITO – Conductor.

Printed silver paste fingers (grid lines) typically have a width of $30\text{-}32\mu\text{m}$, with advanced fine-line printing and steel stencils have finger widths of $\sim 10\mu\text{m}$, while the wet emulsion (EOM) screen printing thickness is $\sim 12 \text{ to } 20\mu\text{m}$.

HJT manufacturing processes consume $\sim 13.5\text{-}20 \text{ mg/W}$ of indium of target material.

Silver metallization cost = $6\text{-}12 \text{ mg/W}$; 30% of total cell production costs

An R&D Perspective

Silicon Heterojunction (HJT) solar cell technology is an excellent candidate for

Process-Properties-Performance (PPP) Correlation Framework

Process Variables	Material Properties	Device Performance
PECVD Gas Ratios (H_2/SiH_4 , B_2H_6 , PH_3)	Microstructure & Passivation: Microcrystalline Fraction ($X_c \approx 40-70\%$), Si-H bond Density (Hydrogen Content $C_H \approx 10-25\%$), interface Defect Density ($D_{it} \approx 5 \times 10^{10} - 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$)	$V_{oc} > 750 \text{ mV}$
PVD Deposition: Sputtering Power, Working Pressure, Oxygen Flow Rate	Optoelectronic: TCO Work Function (4.4 to 4.7 eV for untreated films; 5.0 to 5.3 eV for plasma-treated or Zr or Mo Co-Doping); Carrier Mobility ($\mu_e \approx 30-100 \text{ cm}^2/\text{V.s}$), Sheet Resistance ($R_{sh} \approx 40 \text{ } \Omega/\square$ to $120 \text{ } \Omega/\square$), Band Offsets ($\Delta E_c \approx 0.14 \text{ eV}$, $\Delta E_v \approx 0.45 \text{ eV}$); $E_G _{\text{TCO=ITO}} > 3.5 \text{ eV}$	$\text{FF} > 85.5\%$
Thermal Budget: Metallization Curing Profile, Light Annealing Parameters	Electrical & Geometric: Contact Resistivity (ρ_c 1 to $300 \text{ m}\Omega \cdot \text{cm}^2$ function of (interface, layer thicknesses, and doping), Layer Thickness (5–10 nm), Wafer Texturing Morphology ($\sim 1 \mu\text{m}$).	$\eta > 26.5\%$, low UV ($E > 3.3 \text{ eV}$, $\lambda < 370 \text{ nm}$)/LeTID degradation = $\sim 3.8\%-5.46\%$ yearly degradation in heavy-exposure tests).

HJT – The Opportunity

Light and elevated Temperature-Induced Degradation

The Next Generation of Cell Technologies: Which Architectures Will Define the 2030s?

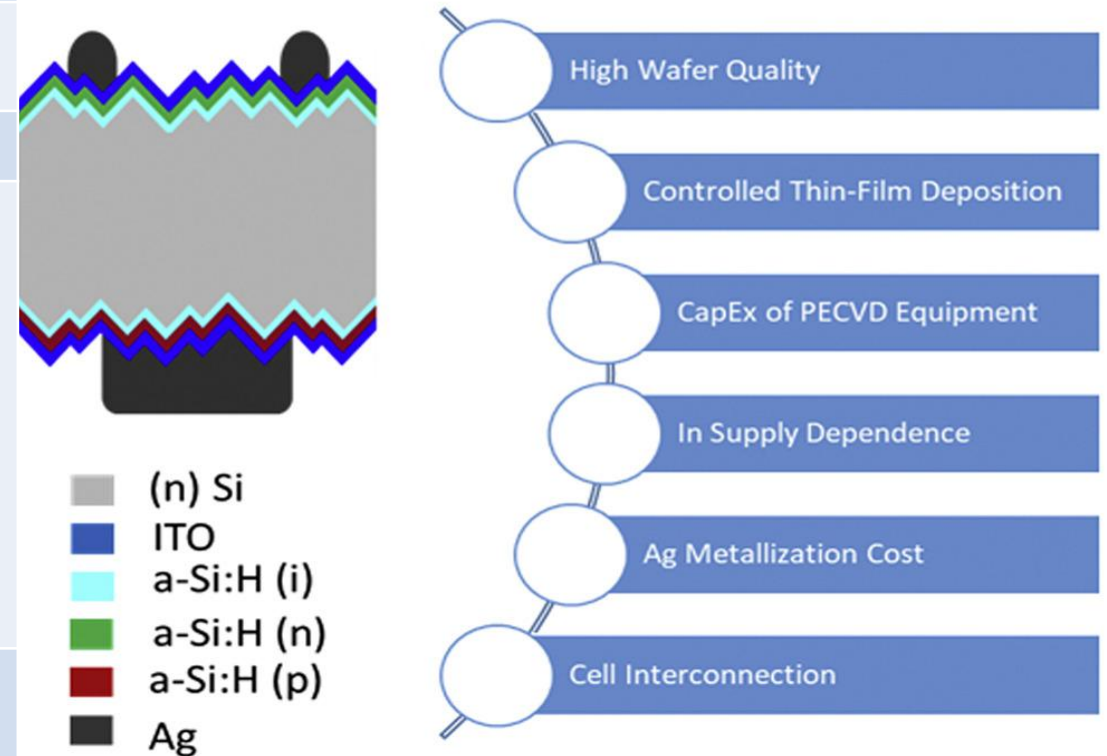
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HJT 2.0 – The Next Phase

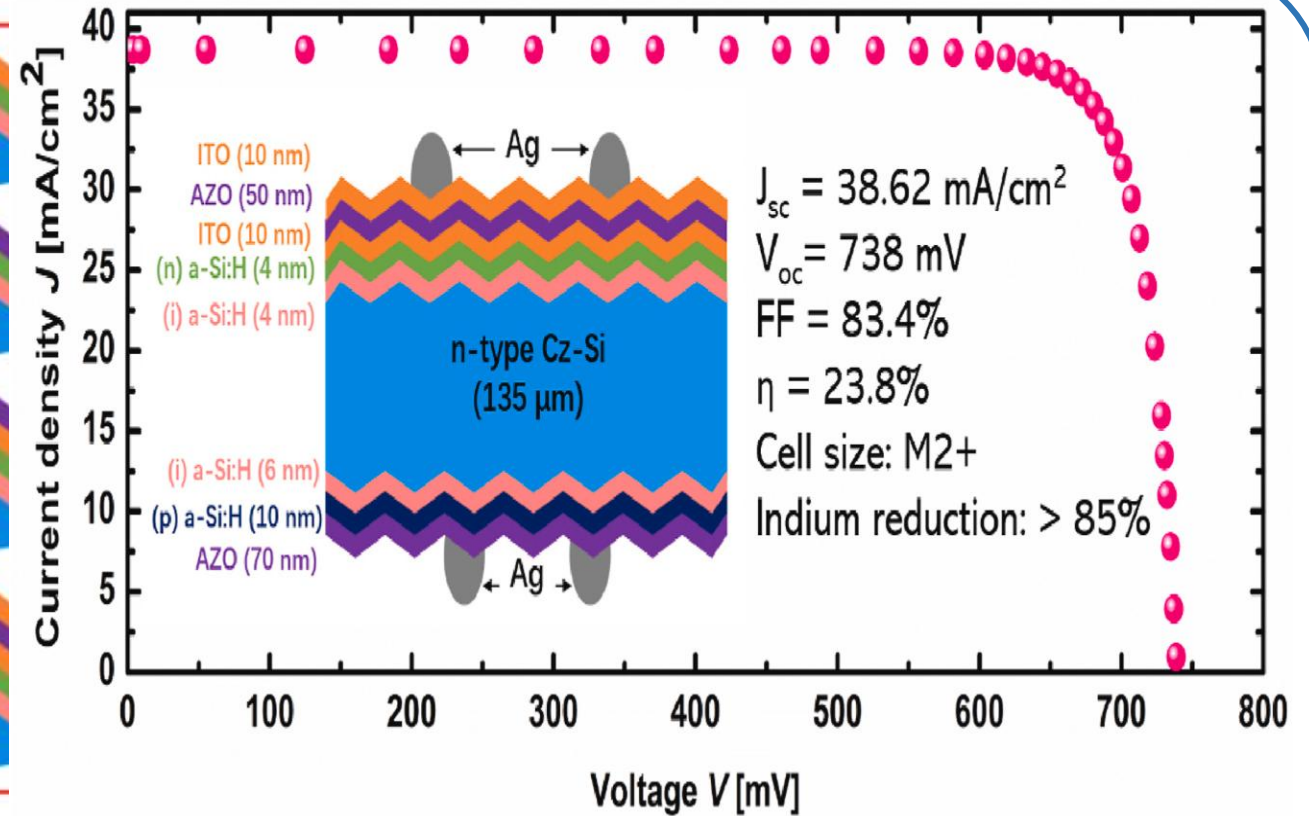
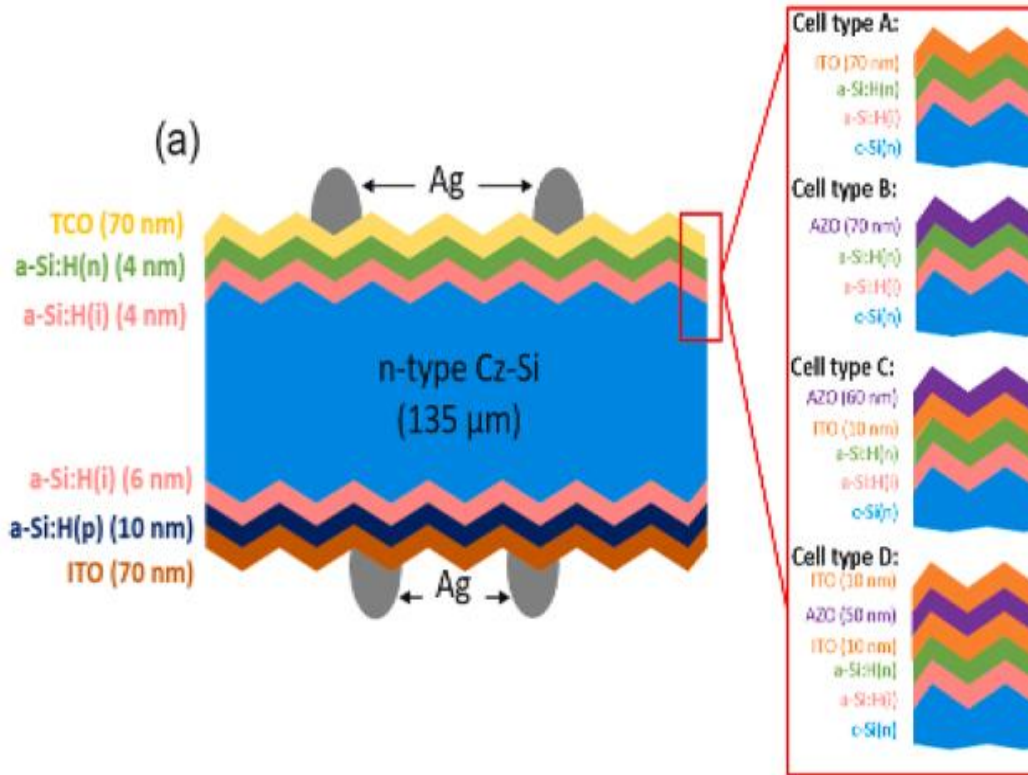
Challenge	Solution
Equipment Costs	Increase Automation, Adopt domestic equipment manufacturing
Silicon Wafers	Reduce wafer thickness (~ 50% of total cell cost)
a-Si:H	Replace by $\mu\text{c-Si:H}$ or nc-Si:H
Low Temperature Ag Paste	Use Ni or Cu coated Ag pastes, adopt Ag free methods such as Cu electroplating, replace printed fingers with low-cost Cu wires.
Multi-Busbar (MBB) & Zero-Busbar (OBB) Designs	Adopt busbar-less technologies or thinner rounded copper wires.
Optimize printing	Decrease screen-printing thickness or change patterns to minimize the use of paste.
Indium	Rear side - Thinning ITO or hydrogenated In_2O_3 ; Use Front side - Ultra-thin ITO (~15nm) + alternate AR coatings such as SiO_x , SiN_x or AlO_x .

TW-Scale Silicon Heterojunction Manufacturing Challenges



[https://www.cell.com/joule/fulltext/S2542-4351\(22\)00090-3](https://www.cell.com/joule/fulltext/S2542-4351(22)00090-3)

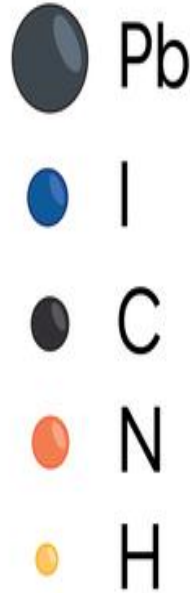
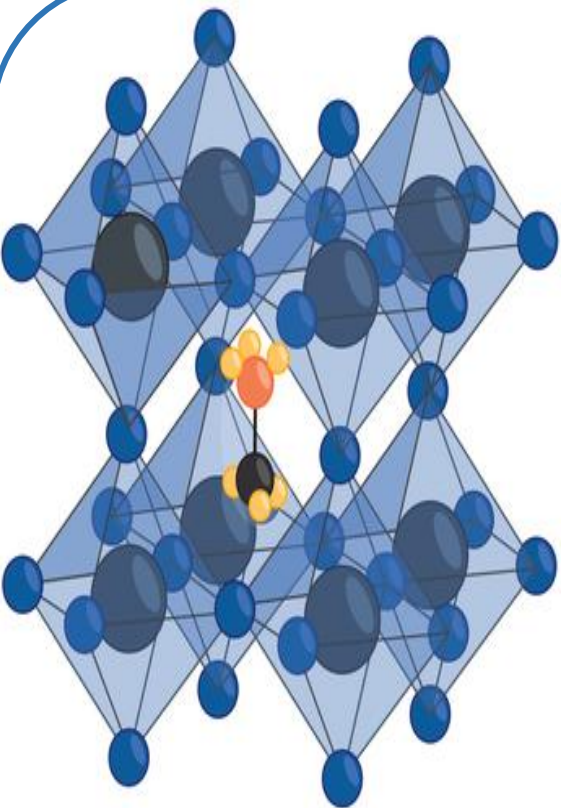
Reduction of use of Indium



The side-view schematic of small SHJ solar cells (19 × 19 mm²) with 70 nm rear ITO and different front TCO configurations: 70 nm ITO; 70 nm AZO; 10 nm ITO/60 nm AZO; 10 nm ITO/50 nm AZO/10 nm ITO.

Solar Energy Materials & Solar Cells 251 (2023) 112120

Perovskites



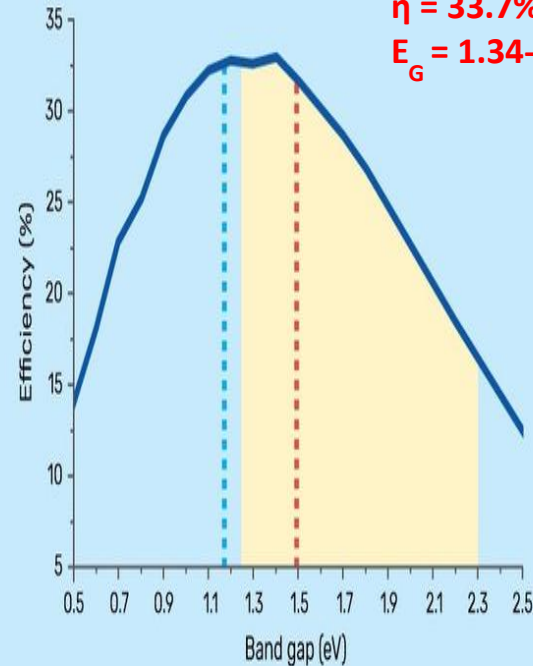
Methyl ammonium lead triiodide, or MAPbI_3 , is one of the more common perovskites; however, researchers are exploring the use of different elements and structures to improve stability.

Most Interesting Of Perovskites For The Solar Industry Are Crystals Built Out Of Organic And Inorganic Molecules Connected To Atoms Of Lead Or Tin.

<https://www.energy.gov/cmei/systems/perovskite-solar-cells>

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

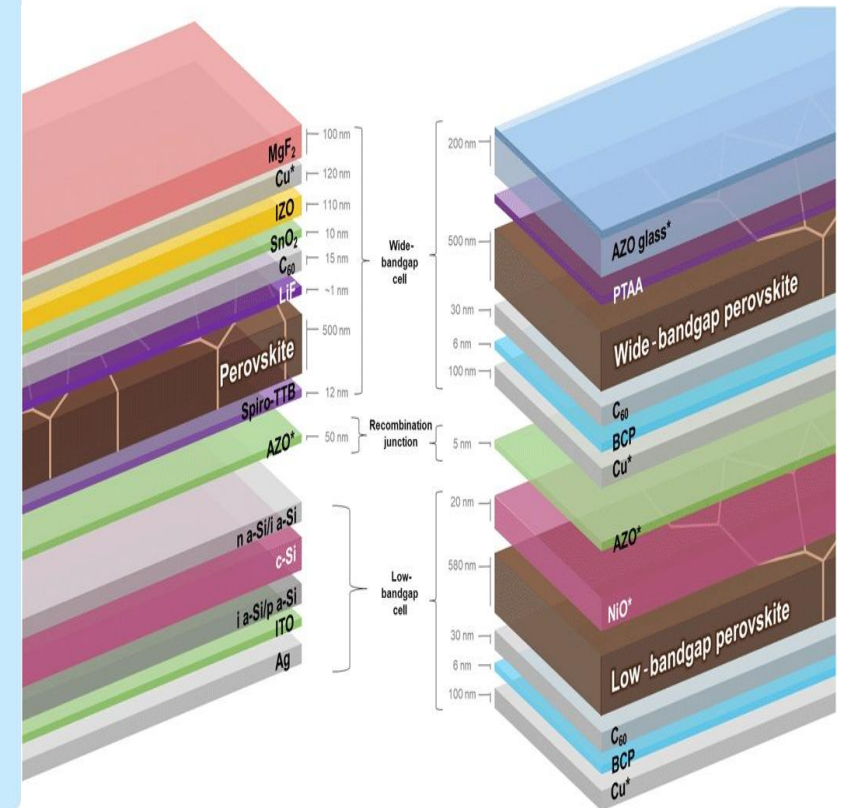
Shockley-Queisser limit



Single Junction
AM = 1.5
 $\eta = 33.7\%$
 $E_G = 1.34-1.4 \text{ eV}$

 Silicon
 CdTe thin film
 Perovskite

Perovskites can be tuned to various bandgaps within a wide range.



Structure of perovskite-silicon tandem solar cell (on the left) and perovskite-perovskite tandem solar cell (on the right).

<https://www.perovskite-info.com/advantages-perovskite-solar-technology>

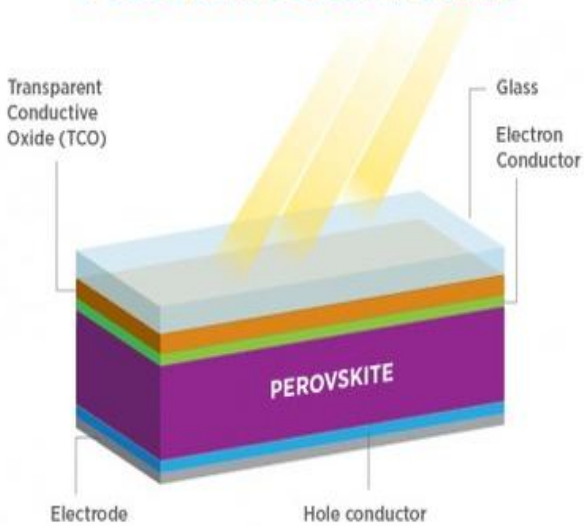
The Next Generation of Cell Technologies: Which Architectures Will Define the 2030s?

10.14.2026

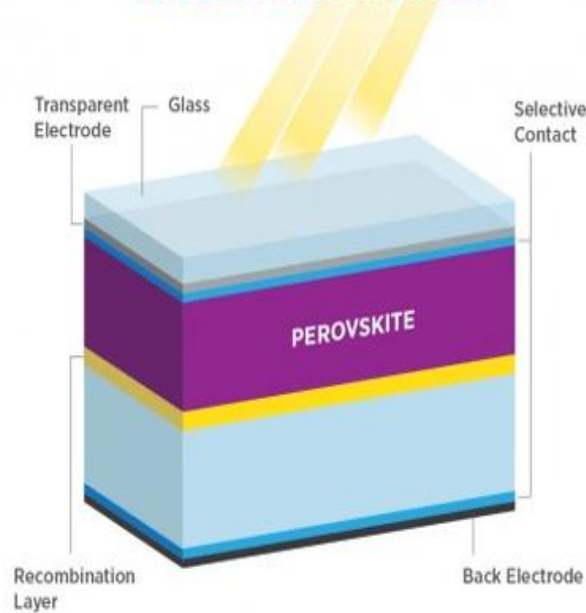
San Francisco, CA

Perovskite Solar Cells

**THIN FILM
PEROVSKITE SOLAR CELL**



**PEROVSKITE ON SILICON
TANDEM SOLAR CELL**



Pre-2005

Perovskite development for non-solar applications



2009

First perovskite solar cell



2013

First perovskite cell achieves >10% efficiency



2014

First perovskite-Si tandem cell



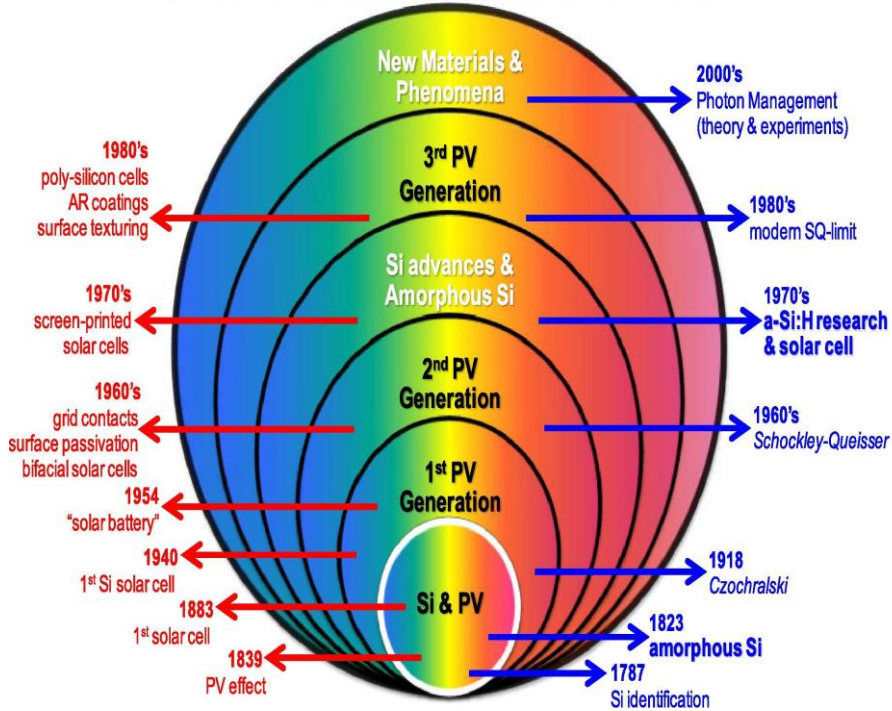
2024

Record cell efficiency >26%, research toward commercialization continues

<https://www.energy.gov/cmei/systems/perovskite-solar-cells>

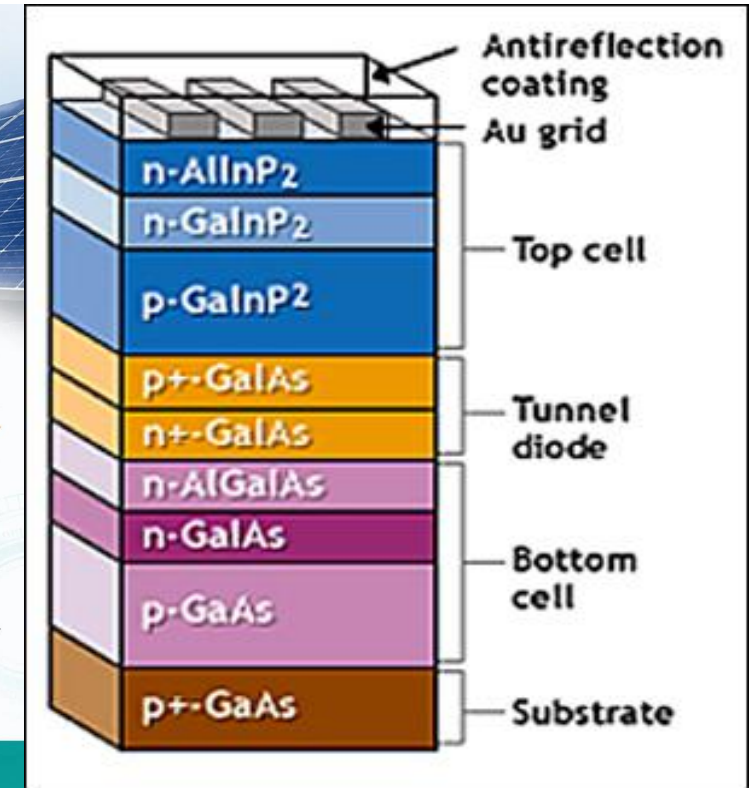
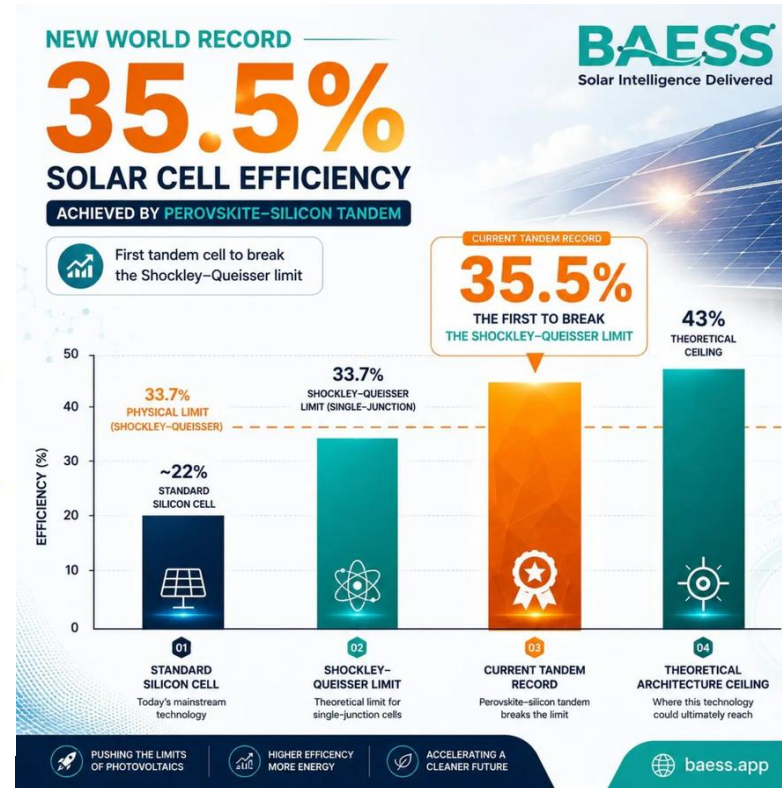
Multi-junction Solar Cells - "Tandem Cells"

Silicon and Silicon-based Solar Cells



<https://doi.org/10.1016/j.rio.2022.100320>

<https://www.google.com/url?sa=t&source=web&rct=j&url=https%3A%2F%2Fwww.instagram.com%2Fp%2FDbbZE3EGcyJ%2F&ved=0CBYQjRxqGAoTCJDNyvCbi5cDFQAAAAAdAAAAABCOAg&opi=89978449>



5-Cell Tandem Approach – Australian National University
Efficiency of 43%

The Next Generation of Cell Technologies: Which Architectures Will Define the 2030s?

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HJT Roadmap

Year	η (%)	Module Output Power * (W)	Wafers (HC)	Material Options
2026	25+	720+ ; 630+	G12 ; G12R	Incorporation of nc-Si and μ c-Si into a-Si:H is already in progress.
2026-2028**	26+ to 28+	780-800; 700+	G12 ; G12R	Decrease in Ag consumption via OBB, Ag coated Cu pastes, low In-TCO films
2030 & Beyond	~30-32.5	~1000		Perovskite + HJT Integration; Space Applications

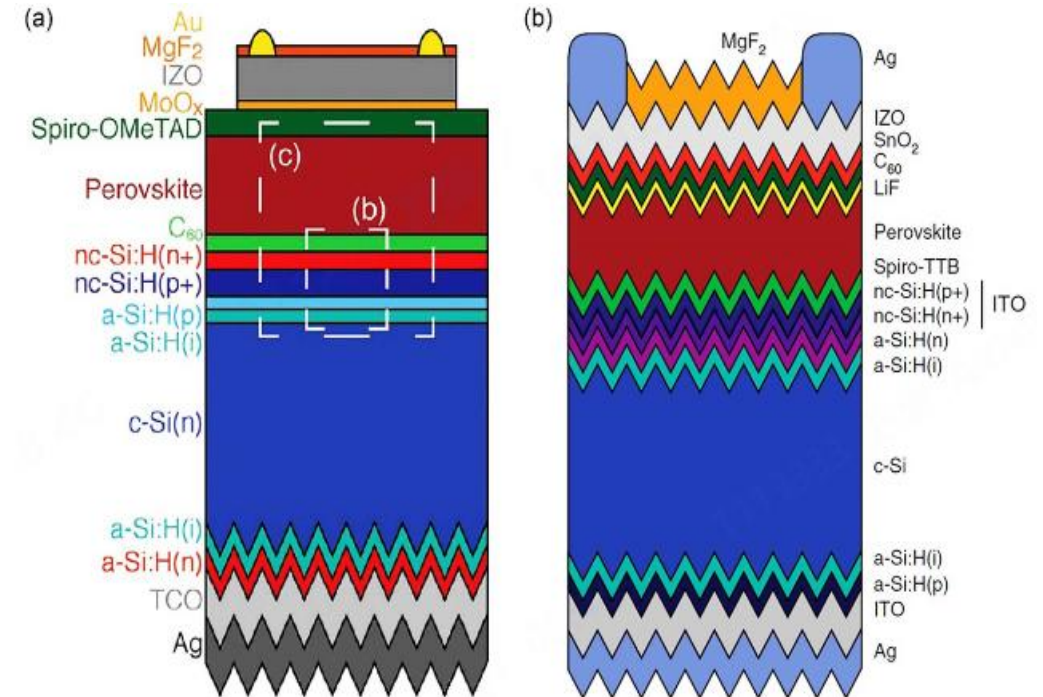
***144 HC Panel**

****90 μ m Thick**

Low Temperature Device Processing of HJT combined with High Temperature Device. Stability is a natural gateway to Perovskite-HJT Tandem Cells, HJT Cells for Space and Thin Wafers

- Heterojunction Technology (HJT) Solar Cells represent a major advancement in photovoltaic (PV) innovation. By integrating crystalline silicon with amorphous silicon thin-film layers, these devices deliver significantly higher efficiency than traditional solar cell designs.
- HJT Solar Cell is widely recognized as the ideal "bottom cell" for the next-generation perovskite-silicon tandem solar cells.
- HJT has become the enabler of thin silicon wafers ($\approx 50\mu\text{m}$)
- HJT solar cells now provide a versatile, all-in-one solution for both terrestrial and space applications.
- *Recommendation: Round Robin Experiments focusing on exchange of laboratory results from across the world would be extremely beneficial for the growth of HJT.*

HJT presents a unique opportunity for manufacturing in the US; The market and the technology are aligned



Different tandem cell configurations: (a) n-i-p perovskite paired with a silicon heterojunction (SHJ) cell featuring rear texturing, shown as a front-emission tandem cell [80] John Wiley & Sons. [© 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim], and (b) p-i-n perovskite combined with a double-side texturing SHJ, depicted as a rear-emission tandem cell. AZO refers to aluminum-doped zinc oxide. Adapted from [81], with permission from Springer Nature. Haocheng Wang et al 2025 Semicond. Sci. Technol. 40 023001.

The Evolution of Solar Cell Technology

From a scientific discovery in 1839 to high-efficiency technologies today, solar cells have come a long way. Driven by innovation, better materials and advanced manufacturing, they continue to power a cleaner, greener future.

*Same Sun.
Smarter Technology.
Higher Efficiency.*




Representative Research-Cell Efficiency Milestones

These are the highest reported (research/record) cell efficiencies for each technology, not commercial module efficiencies.



Record values vary with cell area, test conditions and certification; commercial module efficiency is lower.

CLEANER ENERGY • BRIGHTER TOMORROW

CREATIVITY AT WORK

Thank You!!

