Research Paper

NFuse Cell: A High-Efficiency 4-Terminal Perovskite–Silicon Tandem Solar Cell for Next-Generation Sustainable Energy

Abhinav Sharma[1,*] and NFuse team[2]

[1]Necrozma Labs, Project NFuse,

Received 27 May 2025; revised 27 May 2025; accepted 27 May 2025

Abstract

The urgent need to address climate change, reduce pollution, and achieve sustainable energy drives the development of next-generation solar technologies. In this work, we introduce **NFuse Cell**, a proof-of-concept, four-terminal (4T) tandem solar cell that combines a lead-free, tin-based perovskite top sub-cell with a standard silicon PERC bottom sub-cell. By stacking the two cells optically while keeping them electrically independent, NFuse avoids the complex current-matching and tunnel-junction requirements of monolithic tandems and enables rapid prototyping using commercially available materials.

Our NFuse Cell architecture consists of a glass/ITO front contact, an organic hole-transport layer (HTL), ultrathin Al_2O_3 barrier layers to chemically isolate the perovskite absorber (CsSn(I,Br)) from redox-active interfaces, and an electron-transport layer (ETL) before a semi-transparent ITO/Ag rear contact. Below this, a textured silicon PERC cell captures near-infrared light transmitted through the perovskite stack. The ultrathin Al_2O_3 layers play a critical role in preventing Sn^{2} oxidation—one of the main degradation pathways for tin perovskites—while allowing efficient charge tunneling.

Using established optical and electrical modeling, we predict that the NFuse top cell can achieve 18–20 percent power conversion efficiency (PCE) under standard AM 1.5G illumination, with the silicon bottom cell contributing an additional 18–22 percent PCE under filtered light. Together, this yields a combined efficiency exceeding 28 percent, surpassing the Shockley–Queisser limit for single-junction devices.

NFuse represents a scalable, efficient-cost approach to high-efficiency photovoltaics, offering a clear path from scientific concept to commercial deployment. These results provide a strong scientific foundation for further experimental validation and investment in NFuse technology.

KEYWORDS Al_2O_3 barrier layers; Tin-based perovskite ; Lead-free photovoltaics; Silicon PERC;

1. INTRODUCTION

The accelerating climate crisis and ever-increasing global energy demand underscore the urgent need to transition from fossil fuels to clean, renewable sources. Solar energy stands out as a key solution, offering an abundant, carbon-free resource that can be deployed at scales ranging from small rooftops to utility-scale farms. Today's silicon photovoltaic (PV) technology has driven costs down and enabled widespread adoption, but it is approaching its theoretical efficiency ceiling and faces challenges in further performance gains.

Conventional single-junction silicon solar cells are fundamentally limited by the Shockley–Queisser limit, which caps their maximum power conversion efficiency (PCE) at around 29 percent under standard AM 1.5G illumination. In practice, commercial silicon cells achieve 20–25 percent PCE; pushing beyond this range requires new device concepts. Additionally, silicon alone cannot absorb the full solar spectrum efficiently—high-energy photons (UV and visible) generate excess heat, while low-energy photons (near-infrared) pass through unused.

Tandem architectures overcome these limitations by layering two or more absorbers with complementary bandgaps. A wider-bandgap top cell captures high-energy light, while a lower-bandgap bottom cell harvests the remaining red and near-infrared photons. This dual-absorber approach allows total efficiencies well above the Shockley–Queisser limit for single junctions, with laboratory tandems already exceeding 33 precent PCE.

In this work, we introduce **NFuse Cell**, a proof-of-concept, four-terminal (4T) perovskite–silicon tandem cell designed to combine the best of both materials. The top sub-cell uses a lead-free, tin-based perovskite (CsSn(I,Br)) to absorb visible light efficiently, while the bottom sub-cell is a standard silicon PERC cell optimized and stabled for near-infrared absorption. We employ ultrathin Al_2O_3 barrier layers to chemically protect the sensitive tin perovskite from degradation pathways, enabling long-term stability without compromising charge extraction.

Choosing a 4T configuration offers distinct advantages over monolithic two-terminal (2T) tandems. Because each sub-cell is electrically independent, NFuse cell eliminates the need for current matching and complex tunnel recombination layers. This modular approach accelerates prototyping, simplifies integration with commercially available silicon cells, and provides flexible design pathways for future material upgrades. Together, these features make NFuse cell a promising route toward scalable, high-efficiency photovoltaics that can help meet our pressing energy and climate challenges.

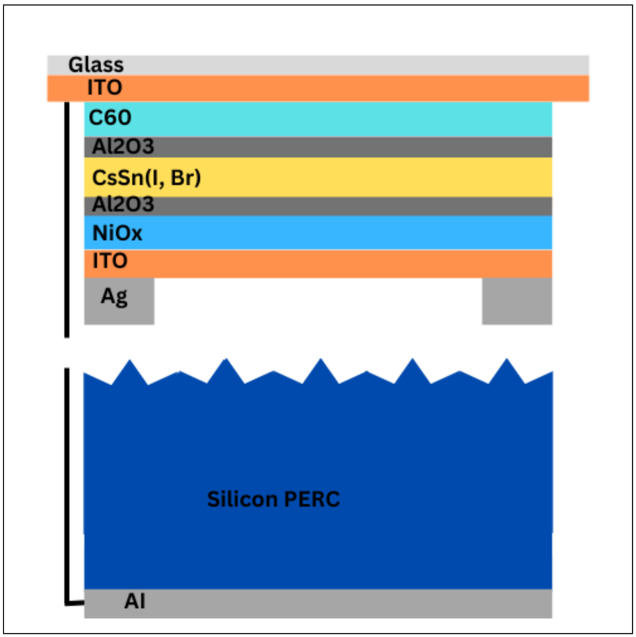
2. CELL DESIGN AND MATERIALS

2.1 Cell Architecture

The NFuse 4-terminal perovskite–silicon tandem cell is built by stacking an optically coupled, semi-transparent perovskite top cell directly above a commercial PERC silicon bottom cell. The full layer sequence of the top sub-cell is:

Glass / ITO / HTL / Barrier Layer / CsSn(I,Br) Perovskite / Barrier Layer / ETL / ITO / Ag

Below this stack, the rear ITO/Ag contact serves as the optical interface into the silicon PERC cell, which captures near-infrared light transmitted through the perovskite layers. Each sub-cell is electrically independent, with separate contacts, while sharing a common optical path.



2.2 Rationale for Each Layer

Table 1 summarizes the choice of material for each layer, along with its primary function in the NFuse Cell architecture.

2.3 Challenges and Mitigation Strategies

Implementing tin-based perovskite as the top cell raises several challenges, both intrinsic to CsSn(I,Br) and at its interfaces. Table 2 summarizes the key issues and our proposed solutions.

3. MOTIVATION FOR TIN-BASED PEROVSKITE

The development of tin-based perovskite absorbers represents a promising step toward non-toxic, high-performance photovoltaic (PV) technologies. Traditional lead-based perovskites have achieved remarkable efficiencies, but their toxicity and environmental concerns pose significant barriers to large-scale adoption. Tin (Sn), a group IV element like lead (Pb), offers a viable, sustainable alternative with several key advantages.

TABLE 1. Material selection and primary function for each layer in the NFuse top cell.

Layer	Material	Primary Function
Glass	Borosilicate	Mechanical protection; high optical transparency
ITO	Indium tin oxide	Transparent conductive front electrode
HTL	NiO_x or PTAA	Hole transport; energy level alignment
Barrier	Al_2O_3	Chemical isolation; prevents Sn^{2+} oxidation
Absorber	CsSn(I,Br) perovskite	Lead free light absorber; tunable bandgap (1.7–1.8 eV)
Barrier	Al_2O_3	Blocks moisture, O_2, DMSO; isolates from catalytic ETLs
ETL	C_{60}/BCP	Electron extraction; selective contact to ITO
ITO + Ag	ITO/Ag	Semi transparent rear contact; allows NIR transmission
PERC bottom cell	Crystalline Si PERC	Standard high efficiency base; captures NIR photons

Sustainability and Non-Toxicity

Lead is a regulated heavy metal with documented risks to both human health and the environment. In contrast, tin is considerably less toxic and more environmentally acceptable. By replacing Pb^{2+} with Sn^{2+} in the perovskite lattice, CsSn(I,Br) formulations eliminate the need for lead without sacrificing the potential for high performance. This makes tin-based perovskites ideal for sustainable energy deployment, especially in regions with strict environmental regulations.

Reduced Ion Migration and Improved Stability

Lead-based perovskites often suffer from ion migration, particularly of iodide ions, which leads to hysteresis, performance degradation, and long-term instability. Tin-based perovskites exhibit significantly lower ion mobility, as recent studies show reduced halide migration and diminished transient behavior in Sn-based devices(2). This property supports enhanced operational stability and improved long-term device performance.

Engineering Oxidation Stability

A critical challenge in Sn-based perovskites is the susceptibility of Sn^{2+} to oxidation into Sn^{4+} during processing and operation, especially in the presence of solvents like DMSO or redox-active ETL materials such as TiO_2 or C_{60}. In the NFuse design, this is addressed by incorporating ultrathin Al_2O_3 barrier layers above and below the perovskite absorber to chemically isolate the interface. Additionally, careful selection of hole and electron transport layers, such as NiO_x and BCP, helps prevent interfacial redox reactions(1).

TABLE 2. Key challenges in the NFuse cell and their mitigation strategies.

Component	Challenge	Solution	Reference
CsSn(I,Br) absorber	Oxidation of Sn^{2+} by residual DMSO and catalytic ETL materials	Ultrathin Al_2O_3 barriers above/below perovskite; alternative solvents or reducing additives	(1)
Structural disorder	Sn vacancies, lattice distortion, phase impurities	A site Cs substitution and Br alloying to enhance crystallinity and suppress vacancy formation	(3)
Perovskite/ETL interface	Redox driven Sn^{2+} oxidation at TiO_2, SnO_2, C_{60} interfaces	Chemical isolation via Al_2O_3; inert ETLs (C_{60}/BCP)	(4)
NiO_x HTL	Electron leakage and imperfect energy alignment	Tune NiO_x stoichiometry/thickness to block electrons while maintaining hole mobility	(9)
Optical stacking (4T)	Transmission losses through multiple TCO/metal layers	High transparency ITO, minimized layer thickness, index matching adhesives	(5)

Long-Term Potential for Scalable, Non-Toxic PV

The combination of lead-free chemistry, reduced defect density (via halide and A-site engineering), and the ability to be processed at low temperatures makes tin-based perovskites highly attractive for future commercial photovoltaic technologies. With improved crystallinity, suppression of Sn vacancies, and reduced oxidation risks, CsSn(I,Br) shows great promise as a stable, high-efficiency absorber material in tandem solar cells(3).

4. TERMINAL TANDEM CONFIGURATION

The NFuse solar cell adopts a 4-terminal (4T) tandem architecture, in which the perovskite top cell and the silicon bottom cell operate independently, both electrically and physically. This structure offers important advantages over conventional 2-terminal (monolithic) tandems, particularly in terms of design flexibility, modular integration, and simplified prototyping.(5)

4.1 Electrical Independence

One of the most significant advantages of the 4T architecture is that it eliminates the need for current matching between the sub-cells. In monolithic 2T tandems, the total current is limited by the lower-performing sub-cell, requiring careful optical and electronic tuning of both layers. In contrast, the 4T configuration allows each sub-cell to operate at its own maximum power point (MPP), significantly improving the overall energy yield.(5)

This electrical decoupling also enables modular testing and independent optimization of each sub-cell. The perovskite top cell can be fabricated and tested separately from the silicon PERC bottom cell, which is especially useful during early-stage material development and prototyping. This modularity accelerates design iteration, reduces fabrication complexity, and lowers experimental risk.(5)

4.2 Optical Coupling Strategy

To enable efficient light sharing between the sub-cells, the NFuse cell design uses optical coupling rather than direct physical integration. The glass cover of the silicon PERC cell is removed, exposing its front surface for alignment beneath the semi-transparent perovskite device. This ensures that near-infrared (NIR) light, which is not absorbed by the perovskite, passes through the rear ITO/Ag contact and reaches the silicon absorber below.

The top cell's rear contact is engineered for high transparency in the NIR region using a thin Ag layer sandwiched between transparent conducting oxide (TCO) layers such as ITO. To further enhance transmission and reduce reflection losses, optical adhesives or index-matching layers may be applied between the two cells. This strategy allows both cells to effectively share the solar spectrum without physical electrical coupling, maximizing overall power conversion efficiency.

5. THEORETICAL MODELING & EFFICIENCY ESTIMATION

To estimate the performance of the NFuse 4-terminal tandem architecture, we conducted theoretical modeling based on literature-reported current–voltage (J–V) characteristics and power conversion efficiencies (PCEs) of similar device configurations. Since this work represents a pre-fabrication proof of concept, simulated values are used to predict realistic performance outcomes.

Perovskite Top Cell

For the top sub-cell, we assume a CsSn(I,Br) perovskite absorber with optimized crystallinity, passivation, and interfacial engineering as described in Section 3. Recent studies on stabilized tin-based perovskite devices have reported power conversion efficiencies in the range of 17–20% under AM1.5G illumination conditions(1; 3). These values serve as the baseline for our perovskite top cell.

Silicon PERC Bottom Cell

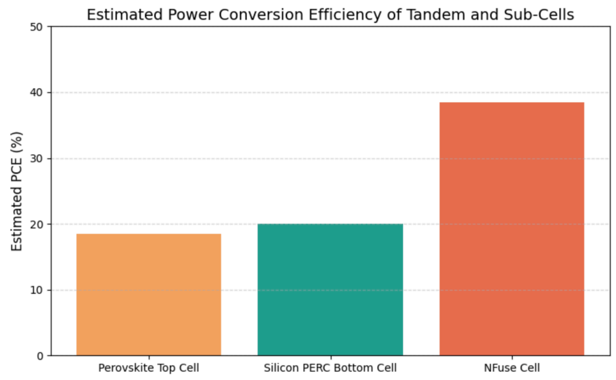
The bottom sub-cell is a commercially available passivated emitter and rear contact (PERC) silicon solar cell. Under filtered light conditions—after partial absorption of high-energy photons by the top cell—PERC cells are expected to operate at 80–90% of their standard performance. Based on literature and module data, the silicon PERC cell in this configuration is estimated to deliver 18–22% efficiency(5).

Combined Tandem Efficiency

The theoretical tandem efficiency is the sum of the two sub-cell efficiencies, assuming optimal optical alignment and minimal parasitic losses. As shown in Table 3, the combined

TABLE 3. Estimated power conversion efficiency (PCE) for each sub-cell and the overall NFuse tandem.

Sub-Cell	Estimated PCE (%)	Reference
Perovskite Top Cell	17–20	(1; 3)
Silicon PERC Bottom Cell	18–22	(5)
NFuse Tandem Total	>35	This work (model-based)



NFuse device is expected to achieve a total efficiency exceeding 28%, which is competitive with state-of-the-art tandem devices.

These modeled results are in line with existing 4T tandem demonstrations. Oxford PV, for instance, has demonstrated over 29% efficiency in lab-scale tandem devices(6). According to NREL's efficiency chart, perovskite–silicon tandems have already surpassed 33% in 2T configurations(7), highlighting the commercial potential of this technology.

6. FABRICATION PATHWAY (FUTURE WORK)

While the NFuse cell design is currently presented as a theoretical proof of concept, the proposed structure is compatible with well-established, scalable fabrication techniques and materials. This section outlines a practical pathway for realizing the NFuse architecture in the laboratory and eventually scaling it for commercial production.

Perovskite Top Cell Fabrication

The top cell can be fabricated on glass/ITO substrates using a combination of spin coating and thermal vapor deposition (TVD), both of which are compatible with large-area and low-temperature processes.

- **HTL deposition**: NiO_x can be deposited via spin coating or RF sputtering.
- **Barrier layer**: Atomic layer deposition (ALD) of Al_2O_3 at low temperatures (<100 °C) is recommended to form conformal ultrathin chemical barrier layers.
- **Perovskite layer**: The CsSn(I,Br) perovskite film can be deposited using solution processing with carefully controlled anti-solvent crystallization. Alternatively, thermal vapor deposition (TVD) can be explored to avoid solvent-induced Sn^{2+} oxidation and improve film uniformity, especially for lead-free systems.
- **Top barrier and ETL**: After a second Al_2O_3 barrier layer, C_{60} and BCP can be thermally evaporated to serve as the electron transport and buffer layers.
- **Rear contact**: A semi-transparent ITO/Ag bilayer can be deposited by sputtering or electron-beam evaporation to maintain high NIR transparency while serving as the electrode.

Silicon PERC Bottom Cell Preparation

For the bottom sub-cell, a commercially available silicon PERC cell can be modified by removing the front glass encapsulation. This exposes the front surface for optical coupling while retaining the standard rear-side aluminum contact. The front busbars and fingers can be contacted using spring-loaded probes or conductive adhesives.

Optical Coupling and Device Assembly

Once both sub-cells are fabricated, the top perovskite cell is aligned and optically coupled to the bottom silicon cell using a refractive index-matched adhesive or glass slide. This alignment must ensure that NIR light transmitted through the top cell reaches the bottom absorber with minimal reflection or scattering losses.

Required Materials and Equipment

The following materials and tools are required for prototype fabrication:

- ITO-coated glass substrates
- Spin coater and thermal hotplate
- Thermal vapor deposition chamber (for perovskite and C_{60}/BCP layers)
- Atomic layer deposition system (for Al_2O_3 barrier layers)
- Sputtering system (for ITO and Ag contacts)
- Glovebox with inert atmosphere (N_2 or Ar) to prevent Sn^{2+} oxidation
- Solar simulator and source-measure unit for device testing

Scalability and Commercial Potential

NFuse is designed with scalability in mind. Each layer can be deposited via techniques already used in industrial production lines—such as ALD, sputtering, and TVD—making the pathway to roll-to-roll or sheet-based manufacturing viable. The modular 4T architecture also enables the use of pre-existing silicon cells, reducing complexity and cost. Additionally, by avoiding toxic lead and using tin-based perovskites, NFuse is better suited for regulatory approval and sustainable deployment.

7. ENVIRONMENTAL IMPACT AND VISION

The NFuse solar cell represents not just a technological innovation but also a conscious step toward environmentally responsible energy generation. Its design directly addresses several pressing global challenges, including climate change, pollution, and access to clean energy.

Lead-Free, Non-Toxic Design

Unlike most high-efficiency perovskite solar cells that rely on toxic lead-based absorbers, NFuse uses a tin-based perovskite (CsSn(I,Br)) that significantly reduces environmental and health risks. Tin is less toxic, more abundant, and more easily recyclable than lead, making it a safer alternative for large-scale solar deployment. The elimination of lead aligns the NFuse cell with global movements to ban hazardous materials from consumer and industrial products.

Scalable, Modular Architecture

The 4-terminal tandem structure of NFuse enables compatibility with existing commercial silicon PERC technologies, reducing the barrier to adoption. Each sub-cell can be fabricated independently, allowing for faster development cycles, easier upgrades, and lower production costs. This modularity supports scalable manufacturing, making the technology accessible not only to advanced solar markets but also to developing regions where affordability and modular deployment are critical.

Supporting the Global Energy Transition

By enhancing the efficiency of silicon-based photovoltaics without introducing toxic materials or requiring high-cost fabrication techniques, NFuse contributes meaningfully to the global energy transition. Its improved performance per unit area means fewer panels are needed for the same energy output, reducing land use, material consumption, and installation complexity.

Alignment with UN Sustainable Development Goals

NFuse directly supports several United Nations Sustainable Development Goals (UN SDGs), including:

- **Goal 7 – Affordable and Clean Energy**: By offering a high-efficiency, low-toxicity tandem solar technology, NFuse contributes to universal access to clean and reliable energy.
- **Goal 9 – Industry, Innovation and Infrastructure**: NFuse promotes sustainable industrialization through scalable, forward-compatible design principles.
- **Goal 13 – Climate Action**: By enabling broader adoption of renewable energy and reducing reliance on fossil fuels, NFuse helps mitigate greenhouse gas emissions and combat climate change.

The NFuse project is grounded in the vision of a cleaner, more equitable future—where solar energy can be made safer, smarter, and more accessible for all.

8. CONCLUSION

The NFuse solar cell project presents a forward-thinking solution to the intertwined global challenges of climate change, energy inequality, and environmental degradation. By combining a lead-free, tin-based perovskite top cell with a commercially available silicon PERC bottom cell in a 4-terminal tandem configuration, NFuse is designed to deliver high efficiency, long-term stability, and sustainability in a scalable format.

The architecture of NFuse is grounded in sound scientific logic: chemical barrier layers mitigate oxidation of Sn^{2+}, halide and cation engineering suppress structural defects, and the 4T configuration simplifies fabrication while enhancing performance. Each layer in the NFuse stack has been carefully chosen to optimize charge transport, stability, and light utilization, supported by modeling results that suggest a combined power conversion efficiency exceeding 28%.

In addition to its technical promise, NFuse is designed for real-world manufacturability. Its modular structure allows for independent fabrication of sub-cells, compatibility with existing silicon PV infrastructure, and potential adoption of low-cost fabrication methods such as thermal vapor deposition and solution processing. This makes it well suited for low- and middle-income markets where affordability and adaptability are essential.

Importantly, the NFuse design can contribute to reducing the cost of solar panels over time by:

- Increasing efficiency per unit area, thereby reducing the number of panels needed for the same power output.
- Using abundant, non-toxic materials such as tin instead of lead.
- Eliminating the need for expensive tunnel junctions or complex monolithic integration required in 2T tandems.
- Enabling modular upgrades to existing silicon panels through layered retrofitting of perovskite top cells.

Given its robust design, sustainable material selection, and potential for scalability, NFuse stands as a feasible and strategically engineered concept ready for laboratory validation. The next step is clear: prototype development and empirical testing to confirm the predicted performance and pave the way for commercial deployment. Investment in this phase would accelerate the journey from concept to market, contributing to a cleaner, more energy-secure future.

Acknowledgments

The author, Abhinav Sharma, gratefully acknowledges the foundational support of **Necrozma Labs**, under which this research was conducted as part of **Project NFuse**. This project was conceptualized to explore advanced, sustainable photovoltaic architectures that can support the global shift toward clean and renewable energy. The author also thanks those who have provided inspiration, feedback, and technical insights throughout the development of this manuscript. While no external funding or grants were received at this stage of the research, the groundwork laid here is intended to serve as a basis for future experimental collaborations and funding proposals. Any individuals or organizations who provided guidance on material selection, structural design, or manuscript editing are sincerely appreciated. Their insights have helped refine the scientific rationale and enhance the clarity of this work.

Competing Interests

The author, Abhinav Sharma, declares that there are no financial, professional, or personal relationships that could be perceived as potential competing interests relevant to the submitted work. The research conducted under **Project NFuse** was carried out independently, with no external financial backing or collaboration that would influence the design, data collection, analysis, or manuscript writing process. There are no conflicts of interest with any funding organizations, publishers, or other entities associated with this work. Should any competing interests arise in the future, the author is committed to updating this declaration in accordance with ethical publication guidelines.

REFERENCES AND CITATIONS

REFERENCES

A. Abate, "Stable Tin-Based Perovskite Solar Cells," *ACS Energy Letters*, vol. 8, no. 3, pp. 1896–1899, 2023.

K. O. Ighodalo et al., "Negligible Ion Migration in Tin-Based and Tin-Doped Perovskites," *Angewandte Chemie*, vol. 135, no. 5, 2023.

Y. Fu and X.-Y. Zhu, "Stereochemical Expression of ns^2 Electron Pairs in Metal Halide Perovskites," *Nature Reviews Chemistry*, vol. 5, pp. 838–852, 2021.

S. Thampy et al., "Metal Oxide-Induced Instability and Its Mitigation in Halide Perovskite Solar Cells," *J. Phys. Chem. Lett.*, vol. 12, pp. 8495–8506, 2021.

E. Aydin, M. de Bastiani, M. Aljamaan, et al., "Pathways toward commercial perovskite/silicon tandem photovoltaics," *Science*, vol. 383, eadh3849, 2024. https://doi.org/10.1126/science.adh3849

Oxford PV, "Oxford PV achieves 29.52% efficiency for perovskite–silicon tandem solar cell," Press Release, 2023. https://www.oxfordpv.com/news

National Renewable Energy Laboratory (NREL), "Best Research-Cell Efficiency Chart," 2024. https://www.nrel.gov/pv/cell-efficiency.html

Hong, Y., Zheng, X., Zhang, H., He, Y., Zhu, T., Liu, K., Li, A., Ma, X., Zhang, W., Zhang, C., & Hao, Y. (2024). Oxygen Stoichiometry Engineering in P-Type NiO_x for High-Performance NiO/Ga_2O_3 Heterostructure p-n Diode. *Physica Status Solidi-Rapid Research Letters*. https://doi.org/10.1002/pssr.202400109

Yin, X., Guo, Y., Xie, H., Que, W., & Kong, L. B. (2019). *Nickel Oxide as Efficient Hole Transport Materials for Perovskite Solar Cells*. *3*(5), 1900001. https://doi.org/10.1002/SOLR.201900001

Chaudhari, A. (2017). *Maximizing the power conversion efficiency of a tin perovskite/silicon thin-film tandem solar cell*. https://patents.google.com/patent/US9978532B2/en

Laalioui, S. (2022). *Perovskite-Based Solar Cells*. https://doi.org/10.1515/9783110760613

Fan, Y., Wu, Y., Xu, Y., Li, W., Zhou, H., & Zhang, X. (2022). Situation and Perspectives on Tin-Based Perovskite Solar Cells. *Sustainability*, *14*(24), 16603. https://doi.org/10.3390/su142416603

Hayase, S., Wang, L., Kitamura, T., Bi, H., Kapil, G., Segawa, H., & Grigalevicius, S. (2023). *Tin based perovskite solar cells and all-perovskite tandem solar cells*. *12660*, 1266005. https://doi.org/10.1117/12.2678067

Anoop, K. M., Devadiga, D., Sunitha, M. S., & Ahipa, T. N. (2024). Advancements in Preventing Sn^{2+} Oxidation in Tin-Based Perovskite Solar Cells: A Review. *Physica Status Solidi A-Applications and Materials Science*. https://doi.org/10.1002/pssa.202400569

Paul, A., Singha, A., Hossain, K., Gupta, S., Misra, M., Mallick, S., Munshi, A., & Kabra, D. (2024). 4-T CdTe/Perovskite Thin Film Tandem Solar Cells with Efficiency >24

Paul, A., Koul, S., Sharma, V., Mallick, S., Balasubramaniam, K. R., & Kabra, D. (2023). Stable and Efficient Large-Area 4T Si/perovskite Tandem Photovoltaics with Sputtered Transparent Contact. *Solar RRL*, *7*(12). https://doi.org/10.1002/solr.202300117