**Beyond Lead: Advances in Eco-Friendly Perovskite Solar Cell Technologies**

Dr. Priti Goyal

Associate Professor, Department of Physics

Acharya Narendra Dev College, University of Delhi, Delhi, India

E-mail : pritigoyal@andc.du.ac.in

**Abstract**

Perovskite solar cells have emerged as one of the most promising technologies for next-generation photovoltaics due to their remarkable power conversion efficiencies, which have surged from 3.8% in 2009 to over 25% in just over a decade. Despite this progress, the integration of lead in the perovskite structure remains a pressing concern due to its toxicity and potential environmental hazards. This chapter delves into the development and application of lead-free perovskite materials specifically for photovoltaic purposes. It explores various material systems that replace lead with environmentally benign elements such as tin (Sn), germanium (Ge), bismuth (Bi), and antimony (Sb), and assesses their suitability based on structural, optical, and electronic properties. Particular emphasis is placed on how these lead-free compositions influence photovoltaic device performance, including parameters like band gap alignment, charge carrier mobility, stability, and efficiency. The paper also discusses key innovations in device architectures, encapsulation techniques, and interface engineering that aim to enhance the longevity and power conversion of lead-free perovskite solar cells. The culmination of this exploration provides insights into the future landscape of sustainable solar energy, highlighting the potential of lead-free perovskites as scalable and eco-friendly alternatives for commercial photovoltaic applications.

**Keywords**

Lead free Perovskites, Photovoltaic efficiency, Double Perovskites, Band gap Engineering, Tandem Solar Cells, Environment Sustainability

 **Introduction**

The emergence of perovskite solar cells (PSCs) has significantly altered the landscape of solar energy research due to their remarkable light-harvesting capabilities, ease of fabrication, and potential for high efficiency at low cost. The archetypal perovskite absorber, methylammonium lead iodide (CH3NH3PbI3), has demonstrated outstanding optoelectronic properties, such as a suitable direct band gap, high absorption coefficient, long carrier diffusion length, and high defect tolerance. Nevertheless, the incorporation of lead presents a serious drawback, particularly when considering environmental sustainability and large-scale deployment. This has inspired scientists to look at substitute lead-free perovskite compounds that minimize toxicity while preserving the beneficial qualities of their lead-based equivalents.

**Crystal Structure and Material Design**

Lead-free perovskite materials maintain the classic ABX₃ architecture: A is a monovalent cation (Cs⁺, MA⁺, FA⁺), B is a metal cation, and X is a halide.To maintain the integrity of the perovskite framework, Pb2+ substitution at the B-site necessitates equivalent ionic radius, oxidation state, and structural stability.

**Tin-based perovskites** There have been reports of using a number of tin-based perovskites, including CsSnI3, MASnI3, and FASnI3, to create lead-free PSCs1. Recent research indicates that because of its exceptional optoelectronic qualities and bandgap (~1.3 eV), formamidinium tin iodide (FASnI3) is a promising contender2, but are marred by rapid oxidation of Sn²⁺ to Sn⁴⁺, triggering p-type self-doping and defect formation that severely degrade device performance3,4.The chemically labile nature of Sn²⁺ under ambient conditions necessitates strategies like SnF₂ additives, mixed A-site cations (e.g., Cs⁺/FA⁺), and reducing environments to inhibit oxidation and control film morphologyThe maximum solar cell efficiency reported and certified is 16.65% for a triple-cation, double-anion (Cs,FA,PEA)Sn(I,Br)3 5, 14.6% for a modified formamidinium tin triiodide-based (CH(NH2)2SnI3 or FASnI3) composition with additional NH4SCN and PEABr content6,5.73% for CH3NH3SnIBr27,  3% for CsSnI3 (5.03% in quantum dots), and over 10% for different formamidinium tin tri-iodide based compositions8. When applied as a thin layer, FASnI3 in particular appears to have the potential to exceed the Shockley–Queisser limit by allowing hot-electron capture, which might greatly boost efficiency9. By adding mixed halides (such as I-/Br- blends) or alloying with Ge or Pb, TPSCs' band gap can be adjusted, affecting their absorption characteristics and energy conversion efficiency.. According to recent research, bandgap engineering can improve multi-junction solar cell architectural efficiency by minimizing recombination losses and optimizing carrier transport characteristics.. Additionally, studies demonstrate that reducing energy-level mismatch in formamidinium tin iodide perovskites significantly improves carrier transport and efficiency10. The stability of Sn-based PSCs is greatly dependent on the fabrication process and perovskite composition11. The stability and power conversion efficiency of lead-based perovskite solar cells may be surpassed by tin-based perovskites12. There are lots of ways to enhance the stability. Several experimental and simulation studies have predicted that the addition of the cesium Cs + can enhance the thermodynamic structural stability of FASnI3, prevent Sn2+ oxidation, and increase geometric symmetry13, by alloying Ge (II) in CsSnI3 to develop a CsSn0.5Ge0.5I3 composition perovskite, thin films of CsSnI3-based PSCs can become very stable and air tolerant14, Additionally, Qiu et al. proposed a two-step sequential deposition method for producing superior B-γ CsSnI3 thin films15. The solvent SnI2 is also one of the additives commonly used in Sn-based alloys to reduce the impurity of the Sn source16. Various other methods include : *Antioxidant additives*: Incorporation of SnF2 and pyrazine to maintain Sn2+ stability and limit oxidation17, *Encapsulation techniques* : Longer gadget lifespan due to protective barrier layers that stop moisture and oxygen from penetrating Combining FA, MA, and Cs improves structural robustness and reduces phase instability in mixed-cation formulations. *Gradient doping techniques*: Recent studies have shown that adding Ge or other dopants increases stability and improves charge separation18.

**Germanium-based perovskites** (e.g., CsSn₀.₅Ge₀.₅I₃) offer promising band gaps and enhanced photostability; yet Ge²⁺ also faces stability challenges, with photo-oxidation and lattice distortion limiting durability and scalable device implementation. Germanium is structurally suitable for integration into the perovskite lattice without significantly altering the material's symmetry or electronic properties as it belongs to the same group as lead and tin on the periodic table and has a similar valence electron configuration and ionic radius.

In terms of optoelectronic characteristics, germanium-based halide perovskites such as CsGeI₃ and MAGeI₃ possess direct band gaps typically ranging between 1.6 and 2.1 eV, which are tunable by altering the halide composition. These band gaps are adequate for single-junction photovoltaic applications and even more suitable for the top cell in tandem solar configurations. Moreover, these materials demonstrate strong light absorption in the visible spectrum, although not as efficient as their lead-based counterparts. The charge carrier mobilities and diffusion lengths in Ge-based perovskites are moderate, but they are often compromised by intrinsic defects and grain boundary effects19. Nevertheless, the absence of toxic heavy metals gives them a significant edge in terms of safety and environmental sustainability.

Germanium-based perovskites have significant stability issues despite their potential, especially given Ge2+'s vulnerability to oxidation20. Under ambient conditions, Ge²⁺ tends to oxidize to Ge⁴⁺, leading to structural degradation, formation of non-perovskite secondary phases, and the introduction of deep-level trap states. This oxidation significantly limits the operational lifetime and performance of Ge-based perovskite solar cells21. In addition to chemical instability, these materials are prone to decomposition under thermal stress and moisture exposure, which further hinders their practical application. Another challenge is the relatively high density of defects in the crystal lattice, which arises from incomplete or unstable crystallization processes.

To address these challenges, researchers are employing various strategies aimed at improving the stability and performance of Ge-based perovskites. Compositional engineering, such as mixing different A-site cations (e.g., Cs⁺, MA⁺, FA⁺), can enhance lattice symmetry and stability22. Surface passivation techniques using organic molecules, halide salts, or polymeric layers are being explored to suppress non-radiative recombination and shield the active layer from environmental degradation. Moreover, robust encapsulation techniques have been developed to protect the material from oxygen and moisture ingress, thereby extending device longevity23. Efforts are also underway to alloy Ge with other metals like tin or bismuth, which may help balance the trade-offs between stability and photovoltaic performance24.

In terms of performance, germanium-based perovskite solar cells are still at an early stage of development. The best-performing devices have achieved power conversion efficiencies around 3–5%, which is significantly lower than the >25% efficiencies reported for lead-based counterparts. Nonetheless, there have been promising reports where optimized interface engineering, surface treatments, and low-dimensional architectures have led to improved efficiencies and air stability. Additionally, the use of Ge-based perovskites in tandem or multi-junction architectures is being investigated, leveraging their relatively wide bandgap to absorb high-energy photons in a complementary fashion.

Compared to other lead-free alternatives like tin-based perovskites, germanium perovskites offer better resistance to rapid oxidation but still lag in terms of electronic quality and device efficiency. With continuous research into novel heterostructures involving germanium, theoretical modeling for defect tolerance, and new synthesis protocols, the field is still very dynamic. As understanding deepens and fabrication techniques mature, germanium-based perovskites hold the potential to contribute meaningfully to the development of safe, sustainable, and high-performance photovoltaic technologies.

**Double perovskites** Double perovskite solar cells represent a significant advancement in the quest for stable, non-toxic alternatives to traditional lead-based perovskite solar cells, are characterized by the general formula A₂BB'X₆. In this structure, the single divalent B-site cation is replaced by two different metal cations with different valence states, typically one monovalent (B⁺) and one trivalent (B'³⁺) cation, creating a charge-balanced lattice. This substitution results in a more complex, yet highly tunable, crystal structure. The motivation behind this design is twofold: to eliminate toxic elements such as lead and to improve the chemical and structural stability of the perovskite lattice under operational conditions.

The development of double perovskites has focused largely on compositions where the B⁺ and B'³⁺ cations are chosen to mimic the electronic configuration and lattice behavior of Pb²⁺. A well-studied example is Cs₂AgBiBr₆, where cesium (Cs⁺) occupies the A-site, silver (Ag⁺) the monovalent B-site, and bismuth (Bi³⁺) the trivalent B'-site. This compound exhibits good air stability and a stable cubic structure at room temperature25, making it more durable than many traditional lead-based perovskites. However, its indirect bandgap, typically around 1.9 to 2.1 eV, limits light absorption and reduces photovoltaic efficiency. Nonetheless, research is ongoing to reduce the bandgap through anion substitution (e.g., replacing Br⁻ with I⁻), cation mixing, or quantum confinement in nanostructured films.

The optoelectronic properties of double perovskites vary widely depending on their exact composition. Many of them exhibit wider bandgaps and lower carrier mobilities compared to traditional perovskites, which results in lower power conversion efficiencies (PCEs). For instance, early devices based on Cs₂AgBiBr₆ reported efficiencies below 1%, primarily due to poor light absorption and limited charge carrier diffusion lengths26. However, progress has been made through interface engineering, doping, and the introduction of low-dimensional layered structures, which improve charge separation and reduce recombination losses. Surface passivation with organic molecules and incorporation of transport layers tailored to match the energy levels of the absorber have also contributed to improved device performance, with some reports now achieving efficiencies in the range of 2–4%, and even higher in tandem or hybrid architectures27.

One of the significant advantages of double perovskites is their inherent stability. Unlike lead halide perovskites, which readily degrade in the presence of moisture, oxygen, or light, double perovskites like Cs₂AgBiBr₆ exhibit excellent environmental tolerance and thermal robustness28. This stability arises from the strong bonding interactions between Bi³⁺ and halide ions, and the lower tendency of the double perovskite lattice to undergo ion migration, which is a key contributor to degradation in conventional perovskite devices. As a result, double perovskite solar cells have demonstrated operational stability for hundreds to thousands of hours under continuous illumination and elevated temperatures, even without encapsulation.

Another promising line of research involves the use of lead-free double perovskites for tandem solar cells, where they are used as wide-bandgap top cells in combination with silicon or low-bandgap absorbers29. Their relatively high band gaps make them suitable for harvesting high-energy photons in a tandem configuration, thereby increasing the overall device efficiency beyond the Shockley–Queisser limit for single-junction cells. Moreover, the modular nature of the double perovskite structure allows for extensive compositional tuning. Researchers are investigating substitutions involving other monovalent and trivalent cations, such as Na⁺, K⁺, In³⁺, Sb³⁺, and Tl⁺ (although toxicity concerns limit some of these options), as well as mixed-halide systems to better match the solar spectrum and enhance photophysical properties.

However, several challenges remain before double perovskite solar cells can achieve commercial viability. Lowering the bandgap to the ideal range (~1.3–1.5 eV) for single-junction solar cells while preserving high stability and low toxicity is the most important of these.. Additionally, the indirect bandgap nature of many double perovskites reduces their absorption coefficient and hinders charge separation, requiring thicker films that complicate fabrication. Strategies such as strain engineering, low-dimensional confinement, defect passivation, and cation/anion alloying are being actively pursued to overcome these limitations. Furthermore, improving the quality of thin films through better deposition techniques such as solution processing, vapor deposition, or sequential cation exchange is crucial for enhancing device performance.

In conclusion, double perovskite solar cells represent a promising pathway toward stable, non-toxic, and environmentally friendly photovoltaic technologies. While their current efficiencies lag behind those of lead-based perovskites, their superior long-term stability and compositional flexibility make them ideal candidates for future development. Continued progress in material design, interface optimization, and device architecture will be essential to unlocking the full potential of double perovskites and advancing them from lab-scale prototypes to commercially viable solar cell technologies.

Introduce trivalent cations such as Bi³⁺ and Sb³⁺ in compositions like Cs₂AgBiBr₆, which feature alternating ordered AgBr₆ and BiBr₆ octahedra. This structure reduces toxicity and significantly improves thermal and chemical stability. However, these materials inherently possess wide, often indirect, band gaps (~2.0–2.2 eV), hampering full-spectrum solar absorption and charge transport efficacy due to large exciton binding energies . Recent improvements have been made by passivating bromide vacancies with HBr, boosting photovoltaic efficiency by over 68%30. Band gap engineering through B-site alloying (e.g., partial replacement with Ga³⁺ or Fe³⁺) has successfully reduced the gap to ~1.6–1.8 eV while maintaining lattice stability, yielding PCEs up to ~6.4% .

Ongoing research focuses on dimensional engineering (e.g., 2D/2D hybrid layers), A-site alkali doping (such as Na⁺), surface/interfacial passivation ligands, and post-deposition treatments to tune optoelectronic properties, mitigate defects, and enhance film quality .

 **Optical and Electronic Properties for Photovoltaics**

A photovoltaic absorber material must have a direct band gap in the range of 1.1 to 1.6 eV, high absorption coefficients to capture sunlight efficiently, and excellent charge transport properties. Tin- and germanium-based perovskites offer favorable band gaps and spectral absorption but are hampered by poor environmental stability and defect formation32. In contrast, double perovskites often display wide band gaps (~2.0 eV) and high exciton binding energies, which necessitate the use of energy-alignment strategies or tandem device architectures to ensure efficient charge separation. Furthermore, while charge carrier mobilities in tin-based materials can be on par with those in lead perovskites, they are often coupled with shorter carrier lifetimes due to the presence of intrinsic defects and oxidation-related traps. Through careful compositional tuning and the incorporation of passivating additives, researchers are making strides in optimizing the electronic structure of these materials for photovoltaic relevance.

 **Photovoltaic Device Performance**

Substantial progress has been made in the development of lead-free perovskite solar cells. Devices based on tin halide perovskites have reached efficiencies close to 15% through improvements in material synthesis, interface engineering, and the use of suitable hole and electron transport layers. Bismuth- and antimony-based double perovskite devices, although generally less efficient, offer superior stability under operational conditions and provide a safer route for commercialization. Innovations such as mixed-dimensional perovskite architectures, where 2D and 3D structures are combined, have shown promise in balancing charge transport and environmental resilience31. Additionally, incorporation of interfacial layers and surface passivation strategies have led to enhanced device stability and efficiency33.

 **Stability and Encapsulation Strategies**

The instability of lead-free perovskites, especially under environmental stressors like moisture, oxygen, and heat, remains a key challenge. Sn2+ readily oxidizes to Sn4+, making tin-based perovskites more vulnerable.. Strategies to combat this include the use of encapsulation techniques such as polymer coatings and UV-blocking layers, which protect the active layer from external degradation34. Moreover, chemical approaches such as additive engineering, which introduces stabilizing agents or passivating molecules, have shown significant improvements in maintaining the perovskite phase and electronic integrity. Surface and grain boundary passivation further contribute to suppressing defect-related recombination pathways, thereby extending the operational lifetime of solar devices35.

**Emerging Trends and Future Prospects**

The pursuit of high-performance, stable, and environmentally benign perovskite solar cells (PSCs) has led to several emerging trends that are reshaping the research landscape. As lead-free perovskites advance, new directions are being explored to overcome long-standing limitations related to stability, toxicity, and sub-optimal power conversion efficiencies (PCEs). These efforts are increasingly interdisciplinary, integrating advances in materials science, chemistry, data science, and device engineering.

**1. High-Throughput Computational Screening and Machine Learning**

One of the most transformative trends is the application of high-throughput computational screening combined with machine learning (ML) algorithms to accelerate the discovery of novel lead-free perovskite compositions36,37. By training ML models on large datasets of known materials, researchers can predict new ABX₃ or A₂BB'X₆ formulations with favorable optoelectronic properties, band gap energies within the optimal photovoltaic window (1.1–1.6 eV), enhanced defect tolerance, and improved thermodynamic stability. For example, ML-assisted descriptors can rapidly filter potential B-site and X-site cations for toxicity-free perovskites with desirable energy alignment and light absorption features38.

**2. Tandem and Multi-Junction Architectures**

Given the relatively wide band gaps of many lead-free perovskites (especially double perovskites), integrating them as top cells in tandem solar architectures is a rapidly growing trend. Tandem configurations, where lead-free perovskites are coupled with silicon, CIGS, or narrow-bandgap organic cells, allow broader solar spectrum utilization and significantly higher theoretical efficiencies—exceeding the Shockley–Queisser limit39. The incorporation of wide-bandgap perovskites like Cs₂AgBiBr₆ in tandem structures has shown promise, especially when combined with interface engineering to minimize recombination and enhance current matching.

**3. Dimensional Engineering and Low-Dimensional Perovskites**

The stability and charge transport limitations of lead-free perovskites are increasingly being addressed through dimensional engineering, particularly using 2D/3D hybrid perovskite structures. Low-dimensional perovskites, with their natural moisture resistance and reduced ion migration pathways, offer superior phase stability. Layered perovskites with alternating organic and inorganic sheets provide improved environmental robustness while enabling tunable optoelectronic properties. Combining these with 3D counterparts helps maintain strong charge transport and suppress non-radiative recombination, resulting in better efficiency-stability trade-offs40.

**4. Advanced Encapsulation and Interface Engineering**

Environmental degradation—especially from moisture, oxygen, and UV radiation—remains a major bottleneck for tin- and germanium-based PSCs. Recent advancements in encapsulation strategies using UV-blocking polymers, atomic layer deposition (ALD) of thin oxide barriers, and hybrid coatings have dramatically extended device lifetimes41,42 . Moreover, interface engineering—using passivation layers (e.g., fullerene derivatives, self-assembled monolayers) and energy-aligned transport layers—has helped reduce trap states, minimize hysteresis, and boost PCEs. Surface modification techniques now play a central role in enabling device longevity.

**5. Alloying and Doping Strategies**

Compositional tuning through alloying and doping has emerged as a powerful tool to fine-tune the optoelectronic properties of lead-free perovskites. Strategies such as alloying Sn with Ge, or partially substituting Bi with Sb or In in double perovskites, have been shown to reduce the band gap, enhance phase purity, and suppress defect formation43. Doping with alkali cations (Na⁺, Rb⁺) or rare-earth elements can further improve crystallinity and carrier mobility, opening new avenues for customized photovoltaic materials tailored for specific applications44.

**6. Printable and Flexible Solar Technologies**

The low-temperature processing of lead-free perovskites makes them particularly suitable for flexible, lightweight, and printable photovoltaic devices, which are gaining attention for portable electronics, building-integrated photovoltaics (BIPV), and wearable applications45. The development of roll-to-roll coating methods, inkjet printing, and slot-die deposition tailored for lead-free compositions is expected to facilitate the commercialization of scalable and cost-effective devices46.

**7. Sustainability and Life-Cycle Analysis**

With increasing focus on green energy transitions, researchers are also exploring the life-cycle environmental impacts of perovskite solar cells. Lead-free alternatives offer intrinsic advantages in terms of reduced e-waste and lower toxicity. Future work will likely include in-depth assessments of manufacturing carbon footprints, material recyclability, and long-term environmental impact, making sustainability a core consideration in perovskite research and commercialization.

 **Conclusion**

The global pursuit of sustainable and non-toxic energy solutions has catalyzed the exploration of lead-free perovskite materials as next-generation photovoltaic absorbers. This chapter has comprehensively examined the progress in tin-, germanium-, and bismuth/antimony-based perovskites, along with double perovskite architectures, highlighting their potential to balance efficiency, stability, and environmental safety. Tin-based perovskites, particularly FASnI₃ and its derivatives, exhibit promising optoelectronic properties and tunable band gaps conducive for high-efficiency single-junction solar cells. However, their performance is still hindered by rapid Sn²⁺ oxidation and structural instability. Germanium-based analogues offer improved resistance to oxidation but suffer from intrinsic defects and limited charge transport, keeping their PCEs relatively low despite high theoretical appeal.

A unique pathway with intrinsic heat and moisture stability, low toxicity, and structural robustness is offered by double perovskites such as Cs₂AgBiBr₆. While current efficiencies remain modest due to wide indirect band gaps and low carrier mobilities, compositional engineering and dimensional tailoring have shown encouraging trends toward better light absorption and charge separation. Notably, recent innovations in interfacial passivation, additive engineering, and encapsulation techniques have collectively advanced the operational lifetime of these devices, narrowing the performance gap with their lead-based counterparts.

Looking ahead, the integration of high-throughput computational screening and machine learning for materials discovery, alongside the development of scalable fabrication techniques and tandem cell architectures, is expected to revolutionize the field. The future of perovskite photovoltaics lies in synergizing toxicity-free chemistry with high-efficiency design. With sustained interdisciplinary efforts, lead-free perovskite solar cells hold the promise to evolve from experimental concepts into viable commercial products, powering a cleaner and safer solar energy future.

**REFERENCES**

[1] Weijun K., Stoumpos Constantinos S. C., Kanatzidis, M. G. [Unleaded Perovskites: Status Quo and Future Prospects of Tin-Based Perovskite Solar Cells](https://advanced.onlinelibrary.wiley.com/doi/10.1002/adma.201803230). *Advanced Materials*. 2019, 31 (47), 1803230 <https://doi.org/10.1002/adma.201803230>

[2] Shuzhang Y., Jincheng W., Yanqiu W., Huihui Z., Ao L., Yuanyuan H. [Unlocking the Potential of Tin-Based Perovskites: Properties, Progress, and Applications in New-Era Electronics](https://onlinelibrary.wiley.com/doi/10.1002/smll.202304626). *Small*. 2024 Jan, 20 (1), e2304626**.**,<https://doi.org/10.1002/smll.202304626>

[3] Makhsud I. Saidaminov M., Spanopoulos I., Abed J. Ke W. Wicks J. Kanatzidis M.G., Sargen E.H., Conventional solvent oxidizes Sn(II) in perovskite inks. *ACS Energy Lett.*2020; 5, 1153–1155 . <https://doi.org/10.1021/acsenergylett.0c00402>

[4]  [Pascual](https://pubs.rsc.org/en/results?searchtext=Author%3AJorge%20Pascual) J.,[Nasti](https://pubs.rsc.org/en/results?searchtext=Author%3AGiuseppe%20Nasti) G. [Aldamasy](https://pubs.rsc.org/en/results?searchtext=Author%3AMahmoud%20H.%20Aldamasy) M.H, [Smith](https://pubs.rsc.org/en/results?searchtext=Author%3AJoel%20A.%20Smith) J.A. [Flatken](https://pubs.rsc.org/en/results?searchtext=Author%3AMarion%20Flatken),M*.*[Phung](https://pubs.rsc.org/en/results?searchtext=Author%3ANga%20Phung) N. Origin of Sn(ii) oxidation in tin halide perovskites. Mater. Adv. 2020, 1, 1066–1070. <https://doi.org/10.1039/D0MA00245C>

[5] Dongxu H. , Chen P., Steele Julian A., Wang Z. , Xu H. , Zhang M. et al.; [Homogeneous 2D/3D heterostructured tin halide perovskite photovoltaics](https://www.nature.com/articles/s41565-025-01905-4). Nature Nanotechnology. 2025 Apr , 20, 779–786. <https://doi.org/10.1038/s41565-025-01905-4>

[6] Xianyuan J., Hansheng L., Qilin Z., Wei Q., Jiang M., Luozhen J.. One-Step Synthesis of SnI2·(DMSO)*x* Adducts for High-Performance Tin Perovskite Solar Cells, Journal of the American Chemical Society, 2021 July, **143** (29), 10970–10976. <https://doi.org/10.1021/jacs.1c03032>

[7] Feng H., Stoumpos C. C.; Cao D. H., Chang Robert P. H., Kanatzidis Mercouri G. . Lead-free solid-state organic–inorganic halide perovskite solar cells. Nature Photonics 2014 June, **8** (6): 489–494. <https://doi.org/10.1038/nphoton.2014.82>

[8] Shao S., Liu J., Portale G., Fang H.H., Blake G.R., Gert H. [Highly Reproducible Sn-Based Hybrid Perovskite Solar Cells with 9% Efficiency](https://doi.org/10.1002/aenm.201702019). Advanced Energy Materials. 2018, **8** (4): 1702019. <https://doi.org/10.1002/aenm.201702019>

[9] Fang H. H., Adjokatse S. , Shao S. , Even, J., Loi, Antonietta M. [Long-lived hot-carrier light emission and large blue shift in formamidinium tin triiodide perovskites](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5770436). [Nature Communications](https://en.wikipedia.org/wiki/Nature_Communications). 2018, Jan, **9** (243): 243. <https://doi.org/10.1038/s41467-017-02684-w>

[10] Xiao L., Yanbo W., Fengxian X.; Xudong Y., Liyuan H.. [Improving the Performance of Inverted Formamidinium Tin Iodide Perovskite Solar Cells by Reducing the Energy-Level Mismatch](https://pubs.acs.org/doi/10.1021/acsenergylett.8b00383). ACS Energy Letters. 2018 May, **3** (5): 1116–1121. <https://doi.org/10.1021/acsenergylett.8b00383>

[11] Qidong T., Jiupeng C., Tianyue W., Feng Y. [Recent advances toward efficient and stable tin-based perovskite solar cells](https://doi.org/10.1002/eom2.12004). EcoMat. 2019, **1** (1), e12004. <https://doi.org/10.1002/eom2.12004>

[12] Antonio A. [Stable Tin-Based Perovskite Solar Cells](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10111406). ACS Energy Letters 2023 April, **8** (4): 1896–1899. <https://doi.org/10.1021/acsenergylett.3c00282>

[13] Liu X., Wang Y., Xie F., Yang X., Han L., Improving the performance of inverted formamidinium tin iodide perovskite solar cells by reducing the energy-level mismatch, ACS Energy Lett. 2018, 3 (5) 1116–1121, <https://doi.org/10.1021/acsenergylett.8b00383>

[14] Chen M., Ju M.G., Garces H.F., Carl A.D., Ono, L.K., Hawash, Z., et al Highly Stable and Efficient All-Inorganic Lead-Free Perovskite Solar Cells with Native-Oxide Passivation. Nat. Commun. 2019, 10, 16. <https://doi.org/10.1038/s41467-018-07951-y>

[15] Qiu X., Cao B., Yuan S., Chen X., Qiu Z., Jiang Y., et al. From Unstable CsSnI3 to Air-Stable Cs2SnI6: A Lead-Free Perovskite Solar Cell Light Absorber with Bandgap of 1.48 eV and High Absorption Coefficient. Sol. Energy Mater. Sol. Cells 2017, 159, 227–234. <https://doi.org/10.1016/j.solmat.2016.09.022>

[16] Lye Y. E., Chan, K.Y, Neng N.Z.. [A Review on the Progress, Challenges, and Performances of Tin-Based Perovskite Solar Cells](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9920041), Nanomaterials. 2023 Feb, **13** (3), 585. <https://doi.org/10.3390/nano13030585>

[17] Yao H., Zhou F. Li Z., Ci Z., Ding L., Jin Z., [Strategies for Improving the Stability of Tin-Based Perovskite (ASnX3) Solar Cells](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7237862). *Advanced Science*. 2020, **7** (10): 1903540. <https://doi.org/10.1002/advs.201903540>

 [18] Sen, P., Bhattacharya, P., Mukherjee, G., Ganguly, J., Marik, B., Thapliyal, D. et al. Advancements in Doping Strategies for Enhanced Photocatalysts and Adsorbents in Environmental Remediation. Technologies 2023,11,144. <https://doi.org/10.3390/technologies11050144>

[19] Ritu, Priyanka, Kumar V. , Kumar R., Fakir Chand, Performance analysis of ecofriendly Ge based perovskite solar cell using computational approach, [Materials Letters](https://www.sciencedirect.com/journal/materials-letters), April 2024, [361](https://www.sciencedirect.com/journal/materials-letters/vol/361/suppl/C)(15) 136145 <https://doi.org/10.1016/j.matlet.2024.136145>

[20] Chiara R., Morana M., and Malavasi L., Germanium-Based Halide Perovskites: Materials, Properties, and Applications, ChemPlusChem 2021, 86, 879–888 <https://doi.org/10.1002/cplu.202100191>

[21]Kumar A., Tripathi S.K., Shkir M. , Alqahtani A., AlFaify S. Prospective and challenges for lead-free pure inorganic perovskite semiconductor materials in photovoltaic application: A comprehensive review, [Applied Surface Science Advances](https://www.sciencedirect.com/journal/applied-surface-science-advances), 2023 Dec, 18, 100495, <https://doi.org/10.1016/j.apsadv.2023.100495>

[22] [Byranvand](https://advanced.onlinelibrary.wiley.com/authored-by/Byranvand/Mahdi%2BMalekshahi) M.M., [Martínez](https://advanced.onlinelibrary.wiley.com/authored-by/Otero%E2%80%90Mart%C3%ADnez/Clara) C.O., [Zuo](https://advanced.onlinelibrary.wiley.com/authored-by/Zuo/Weiwei) W., [Manna](https://advanced.onlinelibrary.wiley.com/authored-by/Manna/Liberato) L., [Saliba](https://advanced.onlinelibrary.wiley.com/authored-by/Saliba/Michael) M., [Hoye](https://advanced.onlinelibrary.wiley.com/authored-by/Hoye/Robert%2BL.%2BZ.) R.L.Z., et al. Recent Progress in Mixed A-Site Cation Halide Perovskite Thin-Films and Nanocrystals for Solar Cells and Light-Emitting Diodes, Adv. Optical Mater. 2022, 10, 22004232022, <https://doi.org/10.1002/adom.202200423>

[23]Wang Y., Ahmad I., Leung T., Lin J., Chen W., Liu F., Ching Ng A.M., Zhang Y., Djurišić A.B., Encapsulation and Stability Testing of Perovskite Solar Cells for Real Life Applications, ACS Mater. 2022, 2, 3, 215–236, <https://doi.org/10.1021/acsmaterialsau.1c00045>

[24] Han S., Wu F., Qin W., Cao H., Yang L., Yin S. , Perovskite solar cell based on double-layer Ag/SnBi alloy as cathode, [Journal of Alloys and Compounds](https://www.sciencedirect.com/journal/journal-of-alloys-and-compounds), Dec 2021, [888](https://www.sciencedirect.com/journal/journal-of-alloys-and-compounds/vol/888/suppl/C), 161455, <https://doi.org/10.1016/j.jallcom.2021.161455>

[25] Liu Y, Cleveland I.J., Tran M.N., Aydil E.S.. Stability of the Halide Double Perovskite Cs2AgInBr6. J Phys Chem Lett. 2023, 14(12), 3000-3006.

<https://doi.org/10.1021/acs.jpclett.3c00303>

[26] Jöbsis H.J., Caselli V.M. Askes S. H. C., Garnett E. C., Savenije T. J., Rabouw F. T., Recombination and localization: Unfolding the pathways behind conductivity losses in Cs2AgBiBr6 thin filmsAppl. Phys. Lett. 2021, 119, 131908 <https://doi.org/10.1063/5.0061899>

[27] Zhang, Z., Sun, Q., Lu, Y. et al. Hydrogenated Cs2AgBiBr6 for significantly improved efficiency of lead-free inorganic double perovskite solar cell. Nat Commun, 2022 ,13, 3397. <https://doi.org/10.1038/s41467-022-31016-w>

[28] Reddy B.K.S., Kumar A.S., Akash R., Ramasamy E., Badhulika S.,Veerappan G., Pramod H. Borse, Ambient processed highly stable self-powered lead-free Cs2AgBiBr6 double perovskite photodetector in HTM-free architecture with Carbon as electrode , [Solar Energy](https://www.sciencedirect.com/journal/solar-energy), [Volume 283](https://www.sciencedirect.com/journal/solar-energy/vol/283/suppl/C), Nov. 2024, 112989, <https://doi.org/10.1016/j.solener.2024.112989>

[29] Chen Q., Zhou L., Zhang J., Chen D., Zhu W., Xi H., etal., Recent Progress of Wide Bandgap Perovskites towards Two-Terminal Perovskite/Silicon Tandem Solar Cells, *Nanomaterials* **2024**, *14*(2), 202; <https://doi.org/10.3390/nano14020202>

[30] [Chen](https://pubs.rsc.org/en/results?searchtext=Author%3AJunjie%20Chen) J., [Ma](https://pubs.rsc.org/en/results?searchtext=Author%3AXingyu%20Ma) X., [Gong](https://pubs.rsc.org/en/results?searchtext=Author%3ALi%20Gong) L., [Zhou](https://pubs.rsc.org/en/results?searchtext=Author%3AConghua%20Zhou) C., [Chen](https://pubs.rsc.org/en/results?searchtext=Author%3AJianlin%20Chen) J., [Lu](https://pubs.rsc.org/en/results?searchtext=Author%3AYangfan%20Lu) Y., et al. Improving the performance of lead-free Cs2AgBiBr6 double perovskite solar cells by passivating Br vacancies, *J. Mater. Chem. C*, 2024,12, 14074-14084, <https://doi.org/10.1039/D4TC02339K>

[31] Mohd Azizman S.A. , Azhari A.W., Ibrahim N., Halin D.S.C., Sepeai S., Ludin N.A., et al. April 2024,10(8) e29676, <https://doi.org/10.1016/j.heliyon.2024.e29676>

[32] Anum S., Fariha N., Ahmad F., Samiullah A., Wajeeha Q., Kainat Z., et al. Innovations in perovskite solar cells: a journey through 2D, 3D, and 2D/3D heterojunctions, *Reviews in Inorganic Chemistry*, 2024. <https://doi.org/10.1515/revic-2024-0029>

[33] Yajie Fu, Yang Li. , Xing G., [Cao](https://www.sciencedirect.com/author/7202124688/derong-cao) D., Surface passivation of perovskite with organic hole transport materials for highly efficient and stable perovskite solar cells, *Materials Today Advances,* December 2022,16, 100300, <https://doi.org/10.1016/j.mtadv.2022.100300>

[34] Akpo E, Colin C, Perrin A, Cambedouzou J, Cornu D. Encapsulation of Active Substances in Natural Polymer Coatings. Materials (Basel). 2024 June 6, 17(11), 2774. <https://doi.org/10.3390/ma17112774>

[35] Dong, W., Qiao, W., Xiong, S. Yang J.,Wang X.Ding L.*.* Surface Passivation and Energetic Modification Suppress Nonradiative Recombination in Perovskite Solar Cells. *Nano-Micro Lett.* 2022, 14, 108 . <https://doi.org/10.1007/s40820-022-00854-0>

[36] Yang, J., Kanakkithodi M., A. High-throughput computations and machine learning for halide perovskite discovery. *MRS Bulletin* 2022 47, 940–948 . <https://doi.org/10.1557/s43577-022-00414-2>

[37] Lotfi S., Zhang Z., Viswanathan G., Fortenberry K., Tehrani A.M., Brgoch J., Targeting Productive Composition Space through Machine-Learning-Directed Inorganic Synthesis

Matter, July 2020, 3, 261–272, <https://doi.org/10.1016/j.matt.2020.05.002>

[38] Wang J, Xu P, Ji X, Li M, Lu W. Feature Selection in Machine Learning for Perovskite Materials Design and Discovery. *Materials*. 2023, 16(8), 3134. <https://doi.org/10.3390/ma16083134>

[39] Khan F., Rezgui B.D., Khan M.T., Sulaiman F.A., Perovskite-based tandem solar cells: Device architecture, stability, and economic perspectives, [Renewable and Sustainable Energy Reviews](https://www.sciencedirect.com/journal/renewable-and-sustainable-energy-reviews), September 2022, [165](https://www.sciencedirect.com/journal/renewable-and-sustainable-energy-reviews/vol/165/suppl/C), 112553, <https://doi.org/10.1016/j.rser.2022.112553>

[40] Gao L., Hu P., Liu S.F. ,Low-dimensional perovskite modified 3D structures for higher-performance solar cells, [Journal of Energy Chemistry](https://www.sciencedirect.com/journal/journal-of-energy-chemistry), June 2023, [81](https://www.sciencedirect.com/journal/journal-of-energy-chemistry/vol/81/suppl/C),389-403, <https://doi.org/10.1016/j.jechem.2023.01.061>

[41] Petit R.R., Ozdemir R., Avermaet H.V., Giordano L., Kuhs J., Werbrouck A., Atomic Layer Deposition for Stable InP-Based On-Chip Quantum Dot microLEDs: Hybrid Quantum Dot Pockets, *ACS Appl. Mater. Interfaces* 2024, 16, 46, 63989–6400, <https://doi.org/10.1021/acsami.4c11391>

[42] Cao M, Ji W, Chao C, Li J, Dai F, Fan X. Recent Advances in UV-Cured Encapsulation for Stable and Durable Perovskite Solar Cell Devices. *Polymers*. 2023, 15(19) , 3911. <https://doi.org/10.3390/polym15193911>

[43] Luna P.S., Calbo J., Sebastiá N.A., Sessolo M., Palazón F., Ortí E., Impact of alkaline-earth doping on the mechanical, electronic, optical and photocatalytic properties of CsPb0.875AE0.125Br3 (AE = Be, Mg, Ca, Sr and Ba): Insights from DFT perspective Chemistry of Materials 2021 *33* (20), 8028-8035, [ttps://doi.org/10.1021/acs.chemmater.1c02236](https://doi.org/10.1021/acs.chemmater.1c02236)

[44] Chen C., Zhang Z., Zhang Y., Wang S., Cai Y., Gao S., et al. Impact of alkaline-earth doping on the mechanical, electronic, optical and photocatalytic properties of CsPb0.875AE0.125Br3 (AE = Be, Mg, Ca, Sr and Ba): Insights from DFT perspective, [Materials Science and Engineering: B](https://www.sciencedirect.com/journal/materials-science-and-engineering-b), Jan 2024, [299](https://www.sciencedirect.com/journal/materials-science-and-engineering-b/vol/299/suppl/C) 116923, <https://doi.org/10.1016/j.mseb.2023.116923>

[45] Priya P., Stonier A.A., Emerging innovations in solar photovoltaic (PV) technologies: The perovskite solar cells and more , [Energy Reports](https://www.sciencedirect.com/journal/energy-reports), Dec 2025, [14](https://www.sciencedirect.com/journal/energy-reports/vol/14/suppl/C), 216-242 <https://doi.org/10.1016/j.egyr.2025.06.003>

[46] [Hwang](https://advanced.onlinelibrary.wiley.com/authored-by/Hwang/Kyeongil) K., [Jung](https://advanced.onlinelibrary.wiley.com/authored-by/Jung/Yen%E2%80%90Sook) Y.S., [Heo](https://advanced.onlinelibrary.wiley.com/authored-by/Heo/Youn%E2%80%90Jung) Y.J., [Scholes](https://advanced.onlinelibrary.wiley.com/authored-by/Scholes/Fiona%2BH.) F.H., [Watkins](https://advanced.onlinelibrary.wiley.com/authored-by/Watkins/Scott%2BE.) S.E., [Subbiah](https://advanced.onlinelibrary.wiley.com/authored-by/Subbiah/Jegadesan) J.,et al , Toward Large Scale Roll-to-Roll Production of Fully Printed Perovskite Solar Cells, Advanced Materials, 2015, 27(7) , 1133-1299, , <https://doi.org/10.1002/adma.201404598>