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Review On Recent Advancement of Perovskite Solar Cell

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Abstract: *The photovoltaic industry is witnessing a growing demand for highly efficient and cost-effective devices capable of converting solar irradiation into electricity. As the global need for clean and sustainable energy sources continues to rise, solar energy conversion has become a central focus of research and technological advancement. The field has progressed from conventional silicon-based solar cells to emerging alternatives such as perovskite, organic, quantum dot, and tandem solar cells, each offering distinct advantages and facing unique challenges. Among these, organometal-trihalide perovskite semiconductors have emerged as particularly significant, serving as active layers in next-generation solar cells that aim to balance high efficiency with economic feasibility.*

This discussion highlights the potential of organometal-trihalide perovskite solar cell technologies, and perovskite/ hetero junction silicon tandem configurations, which represent a promising pathway for future breakthroughs in renewable energy.

Keywords :*, Organometal-trihalide perovskite solar cell, perovskite/Si tandem solar cell*

I. Introduction:

A key characteristic of perovskite materials is their ultrafast response to light, occurring within quadrillionths of a second. When deposited on solar cells without structural imperfections, perovskites enable the free flow of photogenerated electrons, a property that can facilitate the development of thicker absorber layers capable of capturing more light and thereby producing higher electrical output. In recent years, hybrid metal halide perovskites have transformed the photovoltaic field, with their power conversion efficiency (PCE) rising rapidly from 3.8% in 2009 to 22.6% in 2017 (certified 22.1%), while maintaining low production costs. Owing to their high optical absorption coefficient and long carrier diffusion lengths—exceeding 1 μm for both electrons and holes—organic–inorganic perovskites are regarded as excellent absorber materials for solar cells. This article reviews the advancement of perovskite solar cells, focusing on efficiency improvements in device architecture, material engineering, and interface modification.

II. Materials and Methods:

Perovskite solar cell:

Recently perovskite absorber layer which are used in solar cell contains organic –inorganic cations and anions maintaining the structure ABX_3.Where A is organic cation (i.e $CH_3NH_3^+$, $NH_2CH{=}NH_2^+$, $CH_3CH_2NH_3^+$), B is metal cation (Pb^{+2}, Sn^{+2}, Ge^{+2}) and X is halogen anion (F^-, Cl^-, Br^-, I^-) are the most relevant structure of perovskite layer. The typical structure of perovskite solar cell with perovskite used as an absorber layer is given in the figure. Configuration of PSC is transparent conducting oxide (TCO)/blocking layer (Electron transport layer ETL)/perovskite absorber layer/Hole transport layer (HTL)/Gold (Au). The perovskite absorber layer captures sunlight and generates electron–hole pairs. These charge carriers then diffuse and are separated by electron- and hole-selective contact layers. Once the electrons reach the cathode and the holes reach the anode, they flow through an external circuit when connected to a load, thereby delivering electrical power.Tio_2, ZnO, SnO_2 are used as ETL materials. Spiro-OMeTAD is used as HTL materials. In 2009, Miyasaka et al. [1] first introduced perovskite-based solar cells using $CH_3NH_3PbBr_3/TiO_2$ and $CH_3NH_3PbI_3/TiO_2$ configurations, achieving power conversion efficiencies (PCE) of 3.13% and 3.81%, respectively. Miyasaka proposed perovskite as a potential alternative to traditional dye sensitizers. However, a major challenge arose as the liquid electrolyte used in the device rapidly dissolved the perovskite layer within minutes. This issue was addressed in 2012 by M. Grätzel, N. G. Park, and colleagues [2], who developed more stable perovskite solar cell architecture by employing perovskite as the light-absorbing layer and replacing the liquid electrolyte with a solid-state hole-transporting layer (HTL). They utilized Spiro-OMeTAD as the HTL, achieving a significantly improved efficiency of 9%. In 2013, M. Z. Liu, M. B. Johnston, and H. J. Snaith [3] made a significant breakthrough by fabricating planar heterojunction perovskite solar cells using vapor deposition methods,

achieving power conversion efficiency (PCE) of 15.4%. This advancement marked a turning point, sparking rapid growth in research and development of organic–inorganic halide perovskite solar cells.

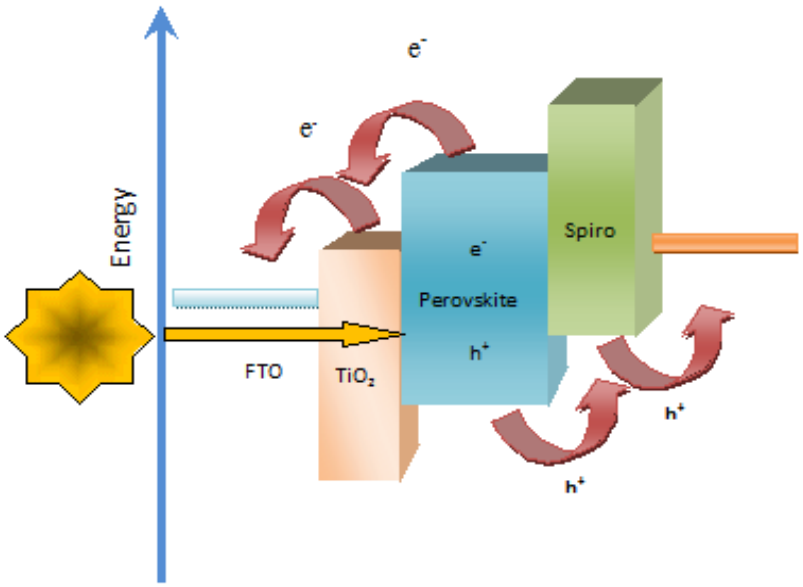

Fig. 1 Schematic diagram of Perovskite solar cell

Jeffrey A. Christians et al. [4] investigated organo-lead halide perovskite solar cells, identifying challenges such as high material costs and low hole mobility. Despite these limitations, perovskite solar cells have continued to demonstrate remarkable and steady improvements in efficiency, thereby attracting increasing attention in the photovoltaic community. A key driver of this efficiency enhancement has been the development of diverse solution-processing and film deposition techniques, which enable precise control over the morphology and composition of hybrid perovskite layers. In 2014, Yixin Zhao, Kai Zhu, and colleagues [5] explored a one-step solution method for synthesizing $CH_3NH_3PbI_3$ perovskite films. By incorporating methylammonium chloride (MACl) into the standard precursor solution, they achieved high-purity $CH_3NH_3PbI_3$ films, leading to improved device performance and increased efficiency.

In 2015, Mohammad Khaja Nazeeruddin and Henry Snaith [6] reported a notable advancement in methylammonium lead triiodide ($MAPbI_3$)-based perovskite solar cells, achieving a power conversion efficiency (PCE) of up to 20%. These devices demonstrated superior photovoltaic performance compared to traditional thin-film and crystalline silicon solar cells. Building on this progress, S. I. Seok et al. [7] in 2017 introduced additional iodide ions into the organic cation precursor solution through an intramolecular ion exchange method. This approach effectively reduced deep-level defects in the perovskite layer, resulting in an enhanced PCE of 22.1%.

More recently, single-crystal $MAPbI_2$ perovskite solar cells have achieved efficiencies exceeding 21% [8], owing to their low defect densities and enhanced charge transport properties. In 2019, Seo et al. [9] reported certified power conversion efficiency (PCE) of 25.2%, representing a major milestone in the advancement of perovskite solar cells. These impressive efficiencies are largely due to key material advantages such as long charge carrier lifetimes, minimal defect levels, and high carrier mobility.

Table no 1: Shows the year-wise efficiencies of perovskite solar cell.

Year-wise efficiencies					
Year	2009	2012	2013	2017	2021
Efficiency	3.8%	9.7%	15.4%	22.1%	25.2%

Key Challenges in Perovskite Solar Cells: Perovskite solar cells have shown remarkable efficiency gains, but several challenges limit their commercial viability. The most critical issue is poor long-term stability, as perovskite materials degrade quickly under moisture, heat, oxygen, and UV exposure. Ion migration within the material causes hysteresis and inconsistent performance. Most high-efficiency perovskites also contain toxic lead, raising environmental concerns. Additionally, the materials are thermally and mechanically unstable, and fabrication techniques like spin-coating are hard to scale for large-area production. Interfacial defects and poor encapsulation further reduce efficiency and durability, while the lack of standardization makes reproducibility difficult across research and industry.
The world record device efficiency of single-junction solar cells based on organic–inorganic hybrid perovskites has reached 25.5%. Further improvement in device power conversion efficiency (PCE) can be achieved by either optimizing perovskite films or designing novel device structures such as perovskite/Si tandem solar cells.

Tandem Solar Cells:

By stacking photovoltaic materials with different bandgaps, tandem solar cells are capable of capturing a wider range of the solar spectrum, thus enhancing overall energy conversion efficiency. Among these, perovskite-hetero-junction silicon tandem configurations have gained considerable attention. It is a type of multijunction photovoltaic device that stacks to different absorber materials- perovskite at the top cell and heterojunction silicon as the bottom cell designed to capture a broader portion of solar spectrum and achieve higher power conversion efficiency than either material alone.

Structure and Working Principle: The top cell is made of perovskite layer has a tunable bandgap 1.6 to 1.8 eV. It absorbs high-energy, short-wavelength photons (e.g., blue and UV light), while lower-energy, long-wavelength photons (such as red and infrared) continue through to the hetero junction silicon cell, which captures them. Two subcells are connected either in series (two-terminal configuration or independently (four-terminal configuration). Each sub-cell is tailored to operate efficiently within its designated spectral range, allowing the tandem configuration to convert sunlight into electricity more effectively than traditional single-junction solar cells. Again low cost solution processable perovskite layers allow low temperature fabrication techniques compatible with temperature limit of fabrication of heterojunction silicon and flexible substrate making it suitable for integration with silicon.

Perovskite–silicon tandem solar cells Architecture: A highly efficient two-terminal (2T) monolithic perovskite–silicon tandem solar cell represents one of the most promising architectures. Perovskite top cell integrates Si bottom cell into a single, series-connected device fabricated layer by layer on the same substrate. Light enters through the transparent front electrode and passes through the wide-bandgap perovskite absorber, which captures high-energy photons, while lower-energy photons continue to the bottom cell. The subcells are electrically linked by a tunnel recombination junction—typically an ultrathin transparent conductive oxide or doped microcrystalline-Si layers—that enables charge recombination without impeding light transmission. This compact architecture minimizes optical losses, reduces material use, and can be more cost-effective than four-terminal designs, but precise current matching between subcells and low-temperature fabrication for the perovskite layer is the prime requirements. A two-terminal (2T) perovskite–silicon tandem solar cell is a

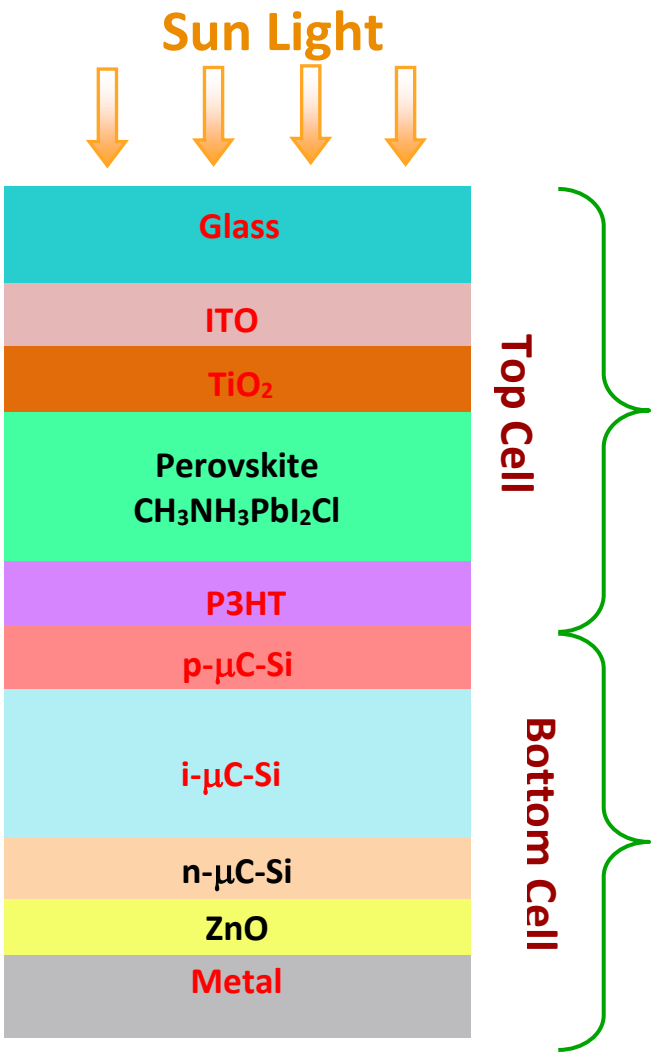

Fig 2. Diagram (schematic) of Perovskite-µc-Si Tandem Solar Cell.

Monolithically integrated device in which both subcells are electrically connected in series, sharing the same current path. In a typical superstrate configuration, light enters through a glass substrate coated with a transparent conductive oxide (TCO) such as fluorine-doped SnO_2 or indium tin oxide.

The front perovskite top cell comprises an electron transport layer (e.g., SnO_2 or TiO_2), a wide-bandgap perovskite absorber layer (~1.65–1.75 eV) optimized to capture high-energy photons, and a hole transport layer (e.g., Spiro-OMeTAD, PTAA, or NiO_x). The bottom Si subcell typically follows a p–i–n structure with a thin p-doped layer (~10–30 nm), an intrinsic absorber (~100–300 nm) for lower-energy photons, and a thin n-doped layer (~10–30 nm), with a reflective metal contact such as silver or aluminum. To get high efficiency in this architecture optical and electrical design of the cell structure must be very sensitive to ensure current matching between subcells, as the lower current device dominates overall output. While 2T designs are compact and cost-efficient compared to four-terminal tandems, they face challenges in stability, tunnel junction optimization, and low-temperature fabrication compatibility to prevent perovskite degradation. Two-terminal (2T) perovskite–silicon tandem solar cells combine wide-bandgap perovskite and narrow-bandgap Si for broader spectrum absorption and higher efficiency potential. Their compact monolithic design reduces optical losses, material use, and costs, while low-temperature processing enables lightweight, flexible, and scalable production for portable and building-integrated photovoltaics. A four-terminal (4T) mechanically stacked perovskite–silicon tandem solar cell consists of two independent photovoltaic subcells—typically a semi-transparent perovskite top cell and a conventional hetero junction Si bottom cell—physically stacked one above the other. Each subcell has its own electrodes and operates at its own maximum power point, eliminating the need for current matching and

allowing greater flexibility in material and thickness optimization. The top perovskite cell, fabricated on glass or flexible substrates with a transparent back electrode, transmits the longer-wavelength light to the underlying Si cell, which is usually a standard thin-film device on glass. This configuration avoids the complexities of tunnel recombination junctions, reduces interlayer processing constraints, and improves tolerance to spectral variations, but it adds optical interfaces that can introduce reflection losses and slightly increase manufacturing complexity compared to monolithic 2T designs.

First monolithic perovskite silicon tandem device in (2015) [10] with an efficiency of 13.6% tandem performance was substantially increased to up to a certified efficiency of 28% [11] reported by Oxford PV in the end of (2018). The highest efficiency with published solar cell structure is 26.0% [12].

The integration of perovskite solar cells in 2-terminal monolithically connected tandem solar cells with silicon Heterojunction bottom cells was fabricated by Bett et al (2018) [13]. This configuration is the most promising architecture for a future commercialization. The realized tandem solar cells consist of a mesoscopic n-i-p perovskite solar cell on top of a rear-side textured heterojunction silicon solar cell. The bottom solar cell features boron and phosphorous doped amorphous silicon (a-Si) as selective contacts and intrinsic a-Si as passivation layers. Due to this passivation the bottom cells show high open-circuit voltages of up to 0.725 V in SunsVOC measurement.
Mamun et al. [14] in 2020 demonstrated a perovskite/micro crystalline Si tandems with ~ 13-15% PCE exceeding single-junction a-Si:H devices. They designed and simulated Perovskite-Microcrystalline thin-Film Tandem Solar Cell. The perovskite solar cell is used as the top cell, where the silicon cell is acted as the bottom cell for better and higher spectrum of light absorption. They get a well-matched short-circuit current with the top intrinsic layer at 100 nm and the bottom intrinsic layer at 2700 nm. At this configuration, the top cell delivers 10.91 mA/cm², while the bottom cell provides 10.56 mA/cm². The quantum efficiency of the tandem solar cell was simulated, and the resulting conversion efficiency was calculated to be 23.30%.

Key Challenges in Tandem Solar Cells: Though perovskite/si tandem solar cell gives high PCE, but Perovskite–amorphous silicon tandem solar cells still is in the early stage of development. They face several challenges that hinder their widespread adoption. One of the primary issues is stability, as both absorbers face challenges, perovskites are prone to degradation under moisture, oxygen, UV exposure, and thermal stress, while a-Si:H suffers from the Staebler–Wronski effect, leading to light-induced degradation. Recent advances have focused on compositional engineering of perovskites (e.g., mixed cations/anions), robust encapsulation, and optimized layer stacks to mitigate these degradation pathways. Another concern **is** interface recombination, where charge carriers are lost at the junctions between different layers, lowering the cell's power output. The use of lead (Pb) in most high-performance perovskites poses environmental and toxicity risks, especially in large-scale applications or during the disposal after the end of lifetime. To address the challenges facing perovskite–amorphous silicon tandem solar cells, researchers are employing several strategic approaches. Bandgap engineering involves tuning the perovskite composition—often by incorporating a mix of formamidinium (FA), cesium (Cs), and methylammonium (MA**)**—to optimize light absorption and current matching with the amorphous silicon bottom cell. Interface engineering is another challenge, where passivation or buffer layers are introduced to minimize charge recombination at critical junctions. Enhancing stability is also a priority, with stabilization techniques such as the use of chemical additives, incorporation of two-dimensional (2D) perovskite layers, and UV filtering materials showing promising results. The development of improved transparent conductive oxides (TCOs)**,** such as optimized inter layers, is helping to enhance both optical transparency and electrical conductivity. Additionally, effective encapsulation strategies are being designed to shield the device from moisture and ultraviolet radiation, significantly extending the operational lifespan of tandem solar cells.

Optical management has also been a critical research direction, since the relatively wide bandgap of a-Si:H (\~1.7–1.8 eV) limits infrared absorption. To address this, optical textures, dielectric spacers, and nanophotonic structures have been integrated to enhance light trapping and boost bottom-cell photocurrent. Such strategies are essential to balance current matching in 2T devices, which is often a bottleneck in tandem operation.Four-terminal (4T) mechanically stacked tandems have also been investigated. These configurations relax current-matching constraints and simplify integration with existing a-Si:H production lines, but they often introduce additional optical complexity and require high-quality transparent electrodes.

Overall, perovskite/a-Si:H tandem solar cells remain in an early stage compared to perovskite/crystalline silicon tandems, but they offer unique opportunities for lightweight, flexible, and building-integrated photovoltaic (BIPV) applications. Continued improvements in interface passivation, recombination layers, and long-term stability are expected to play a decisive role in their future commercialization.

III. Conclusion:

Tandem solar cells mark a significant advancement in photovoltaic technology, offering the potential for greater efficiency and wider applicability across diverse industries. By utilizing multiple semiconductor layers to harness a broader range of the solar spectrum, they overcome the efficiency limits of conventional single-junction solar cells. As research and innovation continue to progress, tandem solar cells are expected to become a key driver in the transition toward more efficient and sustainable renewable energy systems.

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