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REVOLUTIONARY INNOVATION IN SOLAR CELLS IS BREAKING IMPORTANT ENERGY THRESHOLDS

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ABSTRACT1

Tandem solar cells represent a revolutionary advancement in photovoltaic technology, aiming to overcome the efficiency limitations inherent in traditional single-junction cells. This paper presents a comprehensive exploration of tandem solar cell technology, beginning with an introduction to its underlying principles rooted in the Shockley-Queasier limit.

Key factors influencing the selection between organic and inorganic tandem cells, such as efficiency, cost, flexibility, and longevity, are thoroughly examined. The intricate working principle of tandem cells is elucidated, delineating how they leverage stacked sub-cells with differing bandgaps to capture a broader spectrum of solar radiation and enhance overall energy conversion efficiency. Furthermore, the paper delves into the crucial role of the interconnection layer in 2T tandem cells, proposing strategies to facilitate efficient electron and hole transport between sub-cells. Various techniques, including the utilization of conductive layers and tunnel junctions, are explored to address the challenges associated with interconnecting sub-cells while maintaining optimal performance. Through a synthesis of theoretical insights and practical considerations, this research provides valuable guidance for researchers, engineers, and policymakers navigating the evolving landscape of tandem solar cells. By offering a nuanced understanding of materials, configurations, and interconnection methods, this paper contributes to the ongoing efforts to harness solar energy more efficiently and sustainably.

Keywords: Tandem solar cells, Photovoltaic technology, Efficiency enhancement, Organic materials, Inorganic materials, Interconnection layer, Energy conversion efficiency.

1. INTRODUCTION

Tandem solar cells represent a significant advancement in photovoltaic technology, aiming to surpass the efficiency limitations of traditional single-junction solar cells. These innovative devices work by stacking multiple layers of cells, each designed to capture different segments of the solar spectrum. The concept of tandem cells is rooted in the Shockley-Queisser limit, which posits that a single-layer cell cannot absorb all available solar energy due to its inherent material properties. By combining two or more sub-cells with varying bandgaps, tandem cells can harness a broader range of light frequencies, thereby converting more sunlight into electricity and boosting overall cell efficiency. The development of tandem cells involves intricate material science and engineering to ensure that each layer functions optimally and in harmony with the others. For instance, the top cell in a tandem configuration is typically semi-transparent, allowing it to efficiently convert high-energy photons into electricity while letting lower-energy photons pass through to the subsequent cell. This layered approach not only increases the electrical output but also presents opportunities for innovation in cell materials and configurations. Researchers are exploring various combinations of materials for tandem cells, including silicon, gallium arsenide (GaAs), copper indium gallium selenide (CIGS), and perovskites. Each material brings unique advantages and challenges, and the choice often depends on factors such as cost, availability, and compatibility with existing manufacturing processes. The pursuit of the ideal tandem cell continues, with scientists and engineers striving to find the perfect balance between performance, durability, and economic viability.

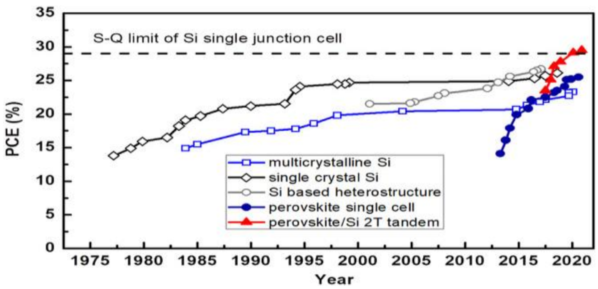

Figure 01 : Evolution of various PV technologies.

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2. TYPES OF TANDEM CELLS

Tandem solar cells are a fascinating and innovative approach to enhancing the efficiency of photovoltaic cells by stacking different types of solar cells on top of each other. These cells work together to capture a broader range of the solar spectrum compared to single-junction cells. The types of tandem cells can be broadly categorized based on the materials used, such as organic, inorganic, and hybrid tandem cells. Organic tandem cells focus on cost-effectiveness and are generally less efficient but cheaper to produce. In contrast, inorganic tandem cells, which are the only commercial tandem cells currently available, are made from III-V group materials known for their high efficiency. Hybrid tandem cells combine elements of both organic and inorganic materials to leverage the benefits of each. Another classification criterion is the connection type of the sub-cells, which can be stacked, monolithic, or involve optical splitting. Stacked tandem cells are simply layered on top of each other, while monolithic tandem cells are interconnected as layers on the same substrate, and optical splitting involves the use of optics to direct light to different types of cells. This technology is still evolving, with research teams around the world working to overcome the theoretical limits of single cell efficiency and to make tandem cells a more common product in the market.

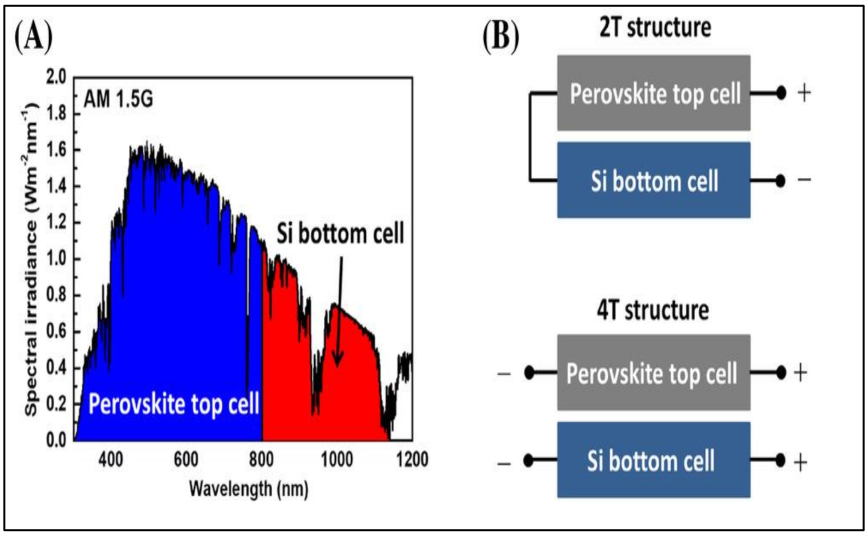

Figure 01: Figure: 2A) Spectra response of perovskite top cell and Si bottom cell in a tandem configuration. 2B) Device structure of 2T and 4T perovskite/Si Tandem Cell

Factors Considered while Selecting Type of Tandem Material: Choosing between organic and inorganic tandem solar cells for your application involves considering several factors such as efficiency, cost, flexibility, and longevity. Organic tandem cells, while generally less efficient in converting sunlight to electricity, offer advantages in terms of manufacturability, flexibility, and light weight. They are also typically cheaper to produce and can be made using roll-to-roll processes, making them suitable for large-scale production and applications where flexibility and weight are critical factors. Inorganic tandem cells, on the other hand, are known for their high efficiency and stability. They are made from materials like silicon or III-V group materials, which have a proven track record in the photovoltaic industry. However, they are usually more expensive to manufacture and are not as flexible as organic cells. The high cost is partly due to the need for high-quality crystal growth and strict lattice matching. When deciding which type to use, consider the specific requirements of your application. If high efficiency and longevity are paramount, and the budget allows for it, inorganic tandem cells may be the better choice. If the application requires flexibility, lightweight, and lower costs, and if slightly lower efficiency is acceptable, organic tandem cells could be more appropriate. Additionally, hybrid tandem cells that combine elements of both organic and inorganic materials might offer a balance of efficiency and cost benefits. It's also important to consider the future scalability of the technology and the environmental conditions it will be exposed to. Organic cells might degrade faster under harsh environmental conditions, whereas inorganic cells typically offer better durability. Ultimately, the choice between organic and inorganic tandem solar cells will depend on a careful assessment of these factors in relation to the goals and constraints of your specific application. Consulting with experts in the field or referring to recent research and case studies can also provide valuable insights into the best choice for your needs.

Working Principle of Tandem Cell: As per figure 2A, in a tandem design, high-energy photons (such as those in the ultraviolet and visible spectrum) are absorbed by the top solar cell's relatively wide bandgap, while low-energy photons (such as those in the near infrared region of the solar spectrum) are harvested by the bottom solar cell's relatively narrow bandgap. More photons can be taken in and transformed into electricity in this manner. The architecture of a tandem solar cell can generally be described as either a mechanical stack, where the two sub cells are only coupled optically but electrically separated (4T tandem cell), or as a monolithically integrated device, where the wide bandgap top cell is directly fabricated on top of the narrow bandgap bottom cell to form a series connection between the two sub cells (2T tandem cell). This is illustrated in Figure 2B. The analogous circuit for perovskite/Si tandem solar cells is depicted in Figure 2C. Current matching between the top and bottom cells is always necessary in a 2T tandem device because the sub cells are connected in series, which prevents the sub cell with lower current from limiting the device's total current. However, because the top and bottom cells of the 4T tandem solar cells are electrically isolated, they are not susceptible to current matching. Therefore, a 4T tandem's overall device performance can be increased by either optimizing the top cell or increasing the bottom cell's efficiency.

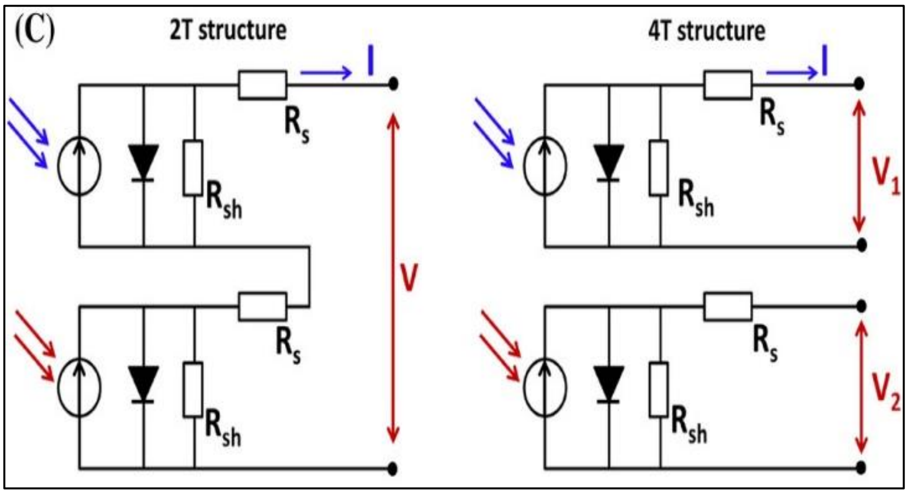

Figure: 2C) Structure of 2T and 4T Tandem Cell

Because composition engineering allows for the tuning of perovskite's bandgap to over 2 eV, organic–inorganic hybrid perovskite materials are regarded as promising semiconductors for tandem devices. According to earlier calculations, crystalline Si (1.1 eV) bottom cell and top cell with bandgap between 1.6 and 1.8 eV are ideal for building a tandem device. Moreover, the ultralow sub bandgap absorption of the perovskite materials shows that the top cell of the perovskite is very transparent at photon energies below its bandgap and lowers the optical loss for the bottom cell. Lastly, it is simple to create a perovskite top cell on the surface of a Si bottom cell directly because the perovskite layer can be created using a solution-process or vacuum-based thermal evaporation.

V. Development in Tandem Cells over the Years:

Year	Tandem structure	Perovskite composition	Perovskite bandgap (eV)	Interconnection layer	Top electrode	Tandem PCE (%)
2015	2T	$MAPbI_3$	1.58	n^{++} Si/p^{++} Si	Ag nanowire	13.7
2015	2T	$FAMAPbI_{3-x}Br_x$	1.62	Sputter ITO	Sputter ITO	18.0
2016	2T	$MAPbI_3$	1.58	Sputter IZO	Sputter IO:H/ITO	21.2
2017	2T	$FAMACsPbI_{3-x}Br_x$	1.69	n^{++} Si/p^{++} Si	Sputter ITO	20.57
2018	2T	$FAMACsPbI_{3-x}Br_x$	1.69	Sputter ITO	Sputter ITO	22.22
2018	2T	$CsRbFAMAPbI_{3-x}Br_x$	1.62	Interlayer-free	IZO	24.5
2019	2T	$CsFAMAPbI_{3-x}Br_x$	1.63	Sputter ITO	Sputter ITO	25.2
2019	2T	$CsFAMAPbI_{3-x}Br_x$	1.64	Sputter ITO	Sputter IZO	25.4

Year	Tandem structure	Perovskite composition	Perovskite bandgap (eV)	Interconnection layer	Top electrode	Tandem PCE (%)
2020	2T	$FACsPbI_{3-x}Br_x$	1.63	Sputter ITO	Sputter ITO	25
2020	2T	$CsFAMAPbI_{3-x}Br_x$	1.68	Sputter ITO	Sputter ITO	26.7
2020	2T	$CsFAMAPbI_{3-x}Br_x$	1.68	Sputter ITO	Sputter IZO	25.7
2020	2T	$CsFAMAPbI_{3-x}Br_x$	1.68	Sputter ITO	Sputter IZO	29.15
2014	4T	$MAPbI_3$	1.58	NA	Sputter ITO	13.4
2014	4T	$MAPbI_3$	1.58	NA	Ag nanowire	17.0
2016	4T	$FACsPbI_{3-x}Br_x$	1.74	NA	Sputter ITO	25.2
2016	4T	$MAPbI_3$	1.58	NA	Cu (1 nm)/Au (7 nm)	23.0
2017	4T	$RbFAMAPbI_{3-x}Br_x$	1.73	NA	Sputter ITO	26.6
2018	4T	$CsFAPbI_{3-x}Br_x$	1.77	NA	Sputter ITO	27.1
2019	4T	$MAPbI_3$	1.58	NA	Sputter ITO	25.5
2020	4T	$CsFAPbI_{3-x}Br_x$	1.65	NA	Sputter ITO	25.7
2020	4T	$CsFAMAPbI_{3-x}Br_x$	1.68	NA	Sputter IZO	28.2
2020	4T	FACsPbI3	1.46	NA	Cr (1 nm)/Au (7 nm)	28.3

Evolving Efficient Perovskite/Si Tandem Solar Cells

1.Interconnection layer for 2T Tandem Cell:

Since it acts as an optical and electrical link between the top and bottom sub cells, the interconnection layer is an essential part of a 2T tandem device. In a solar cell, the n-type layer is typically utilized for the extraction and transportation of electrons, whereas the p-type layer is typically employed to transport and extract positive holes. A 2T tandem setup necessitates a series connection between the two subcells, as seen in Figure 4A. A n-p junction will form between the two sub cells if the n-type layers of the two subcells are directly connected to each other. This will prevent current from flowing between the two cells.

The interconnection layer between the two sub cells should be either a recombination layer or a tunnel junction layer in order to resolve this connection problem. The first method to connect the two sub cells in series is to use a conductive layer that can move both electrons and holes, as seen in Figure 4B. Consequently, a conductive layer of this kind will give holes from one sub cell and electrons from another sub cell recombination sites. Using an ultrathin metal film as a conductive layer, this technique has been widely employed to build tandem solar cells based on organic materials. As seen in Figure 4C, creating a highly doped n^{++} Si/p^{++} Si tunnel junction as an interconnection layer is another efficient method of connecting the subcells in series. This method has generally been used extensively in tandem solar cells based on silicon. The Si surface is heavily doped to create the tunnel junction, which needs to be a thin layer to allow the charge carrier to move through and recombine.

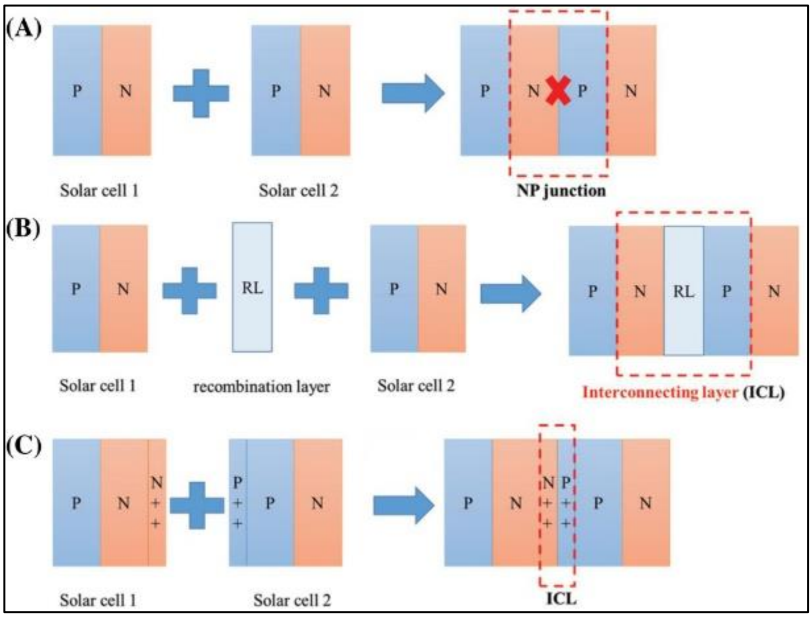

Figure 03 : Interconnection layer of 2T Cell

In order to transmit charge carriers in a 2T perovskite/Si tandem solar cell, the interconnection layer needs to have both acceptable electrical qualities and a reasonable level of transparency to allow the Si bottom cell to absorb infrared light. As a result, the connecting layer's thickness affects how well the device performs. Sputtered zinc-doped tin oxide (ZTO) was used by Werner et al. as the connecting layer between a homojunction silicon bottom cell and a mesoscopic perovskite top cell. They discovered that the ZTO thickness had a significant impact on the 2T tandem device's EQE spectrum and current density–voltage (J–V) curve. Because the interconnection layer is used for carrier recombination between subcells, significant vertical conductivity of the thin layer is not strictly necessary. The interference effect generated by the charge-transporting layer's and ZTO layer's distinct refractive indices had the greatest impact on ZTO thickness. As a result, in another study using well-matched refractive indices, the thickness of the connective layer had no discernible effect on tandem performance.

2. Indium Tin Oxide

Researchers have been exploring the use of indium tin oxide (ITO) as a transparent electrode in Si-based PV technology as shown in figure 5A. Albrecht et al. used a sputtered ITO layer as the interconnection layer between subcells in a Si bottom cell. The n-type SnO_2 layer was deposited using atomic layer deposited (ALD) technique, followed by a perovskite layer coating, p-type spiro-OMeTAD layer deposition, MoO_3 evaporation, and top transparent ITO electrode deposition. The cross-section scanning electron microscope (SEM) image showed that a flat and fully covered perovskite film can be achieved on a polished Si bottom cell via spin coating method. ITO has been used as the recombination layer in 2T device configurations, and other transparent conductive metal oxides, such as aluminium-doped zinc oxide (AZO) or zinc doped indium oxide (IZO), are also suitable.

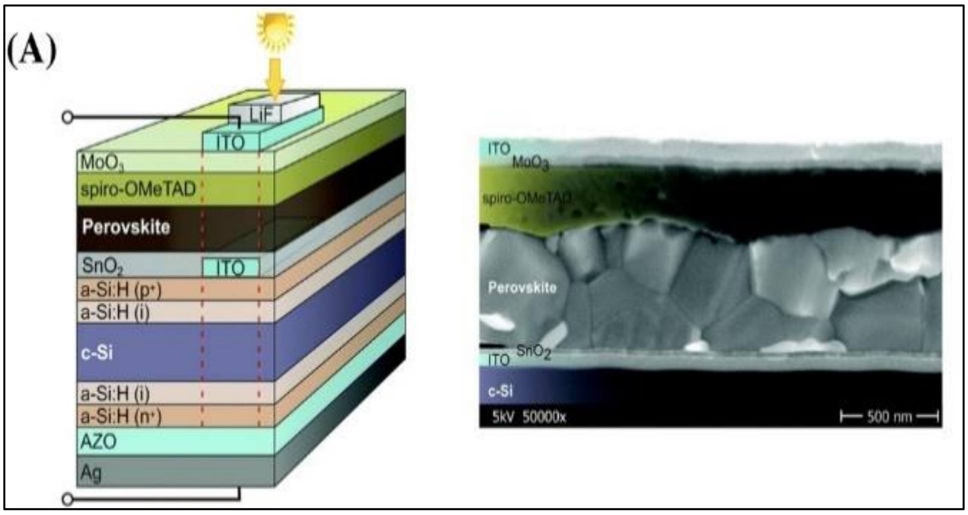

Figure 04 : ITO Layer

3. Tunnel Junction

In figure 5B, the tunnel junction is a common choice for interconnection layers in 2T tandem devices. Mailoa et al. fabricated a 2T tandem device using an n-type Si base, a p^{++} Si layer, and a heavily doped n^{++} Si using plasma-enhanced chemical vapor deposition. The dopant concentration on the interface was measured, indicating high conductivity for carrier transportation and recombination. Figure 5C illustrates the perovskite top cell was fabricated directly on the top of the n^{++} Si layer, with Ag nanowire as the top transparent electrode and LiF as the antireflection layer for light trapping. During device operation, photogenerated holes from the n-type Si base travel through the p-type emitter, while electrons from the perovskite layer pass through the TiO_2 electron transport layer. Shen et al. created a 2T perovskite/Si tandem solar cell without an interlayer by directly depositing TiO2 on top of the p+ Si emitter without creating an interface. This interlayer-free concept was also realized using ALD SnO_2 deposited on the surface of the p^+ Si emitter for 2T tandem devices.

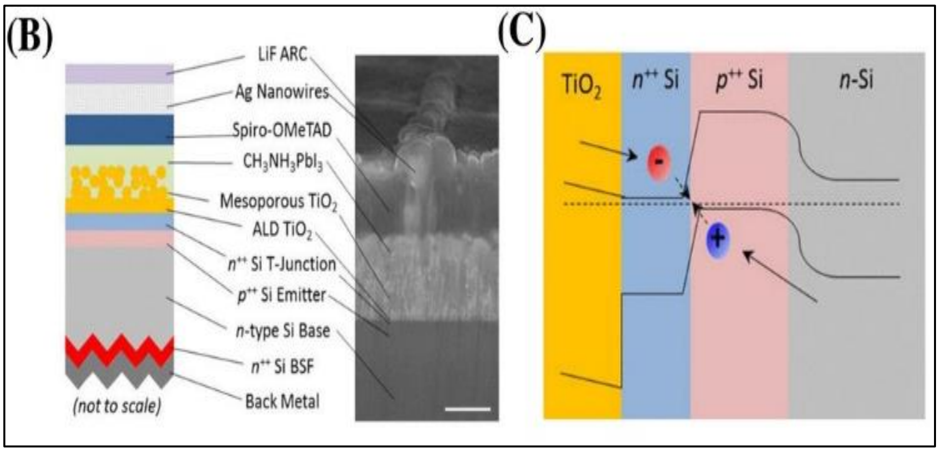

Figure 05 : Tunnel Junction

Device Architecture of Perovskite Top Cells:

The traditional n-i-p structure and the inverted p-i-n structure are the two main device configurations for perovskite single junction solar cells and the inverted p-i-n structure. A standard n-i-p structure PVSC begins with an n-type electron transporting layer on a conductive glass substrate, followed by a perovskite layer and a p-type hole transporting layer. The inverted p-i-n structure PVSC, on the other hand, is created by depositing a p-type hole transporting layer on a conductive glass substrate, followed by a perovskite layer and a top n-type electron transporting layer. In a 2T tandem device, the perovskite top cell is directly manufactured on top of a Si bottom cell. Figure 6A shows a perovskite top cell with a regular n-i-p structure of $SnO_2/CH_3NH_3PbI_3$/Spiro-OMeTAD/ITO was employed to generate 2T.

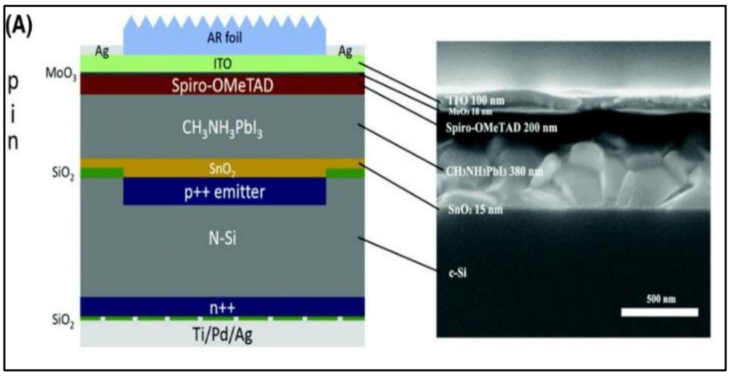

Figure 06: Device Structure 2T Tandem Cell

Unlike the 2T arrangement, a 4T tandem device simply requires optical connectivity between subcells. As a result, the perovskite cell and Si cell are manufactured independently and then combined to make a 4T tandem device. Chen et al. created a semi-transparent perovskite top cell with a regular n-i-p structure of Zr-doped $In2O_3$ (IZrO) glass/SnO_2/perovskite/spiro-OMeTAD/MoO_3/IZO. It was discovered that the sputtered IZrO coated glass substrate is more transparent than the commercial ITO glass substrate, increasing the transparency of the perovskite top cell and thereby improving the device performance of the bottom Si cell under the perovskite cell filter. Finally, the authors developed a semi-transparent perovskite top cell with a PCE of 19%.

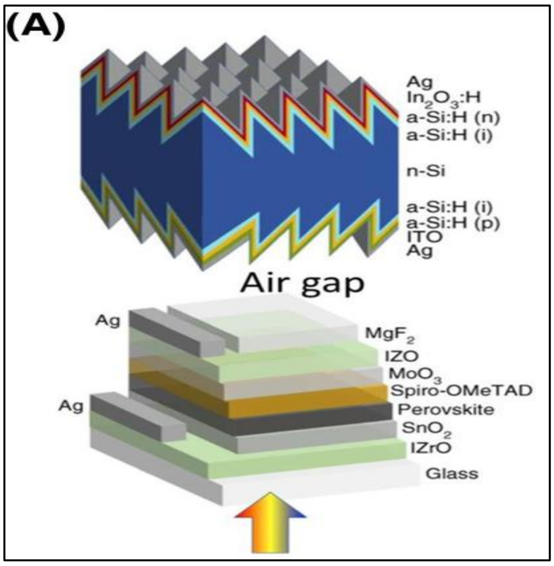

Figure 07: Device Structure 4T Tandem Cell

1.Optimization of Perovskite Films :

In a tandem design, the wide-bandgap top cell and narrow-bandgap bottom cell work together to maximize the sunlight spectrum. Perovskite materials are thought to be promising for tandem devices due to their good optoelectronic capabilities and adjustable bandgap. It has been shown that halide and metal substitutions can significantly alter the bandgap of perovskite materials. Previous computational studies indicate that a perovskite top cell with a bandgap in the region of 1.6-2 eV is ideal for creating tandem solar cells with a Si bottom cell. Figure displays a image of FA and FACs-based perovskite films with varying levels of Br component. The photographs indicate that the perovskite films exhibit "yellowing" when the Br concentration is increased with an x value greater than 0.3 for $FAPb[I_{(1-x)}Br_x]_3$ and 0.7 for $FA_{0.83}Cs_{0.17}$ $Pb[I(1-x)Br_x]_3$ films. The ultraviolet-visible absorption spectra show that both types of perovskite films grow increasingly transparent as the Br content increases. After optimization, it was discovered that a perovskite single junction solar cell with 1.74 eV bandgap can reach a Voc of 1.2 V and a PCE of more than 17%. Combined with a silicon bottom cell with an efficiency of 19%, the total PCE of the 4T device reaches over 25%.

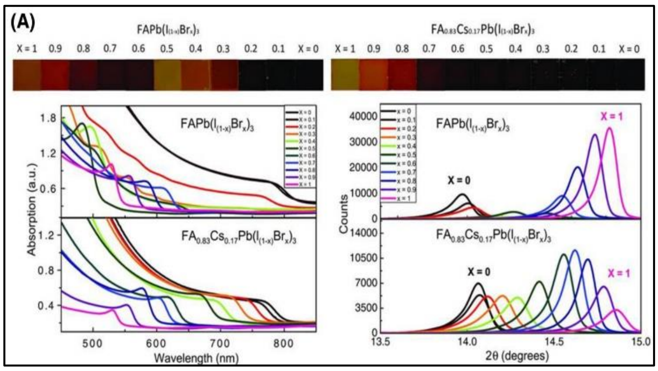

Figure 08 : Photographs, ultraviolet-visible absorbance spectra, and X-ray diffraction pattern of $FAPb[I_{(1-x)}Br_x]_3$ and $FA_{0.83}Cs_{0.17}$ $Pb[I_{(1-x)}Br_x]_3$ perovskite films with different Br composition from x = 0–1

3. CONCLUSION

The exploration of tandem solar cell technology presented in this paper underscores its pivotal role in advancing photovoltaic efficiency beyond the confines of single-junction cells. By delving into the fundamental principles, material considerations, and engineering intricacies of tandem cells, this research provides valuable insights for stakeholders across academia, industry, and policymaking realms.

The significance of tandem solar cells lies in their ability to transcend the efficiency limitations dictated by the Shockley-Queisser limit through the strategic integration of multiple sub-cells with varying bandgaps. This approach enables a more comprehensive utilization of the solar spectrum, thereby maximizing energy conversion efficiency. Moreover, the flexible configuration of tandem cells opens avenues for innovation in materials, designs, and interconnection methods, further enhancing their performance and applicability.

The selection between organic and inorganic materials for tandem cells is a critical decision point, influenced by factors such as efficiency, cost, flexibility, and longevity. While each material presents its own set of advantages and challenges, ongoing research and development efforts seek to optimize tandem cell performance while addressing scalability and cost-effectiveness concerns.

Central to the success of tandem solar cells is the optimization of the interconnection layer, which facilitates efficient electron and hole transport between sub-cells. Through the exploration of various techniques, including the use of conductive layers and tunnel junctions, this paper highlights strategies to overcome interconnection challenges and maintain peak performance across the tandem structure.

As the quest for the ideal tandem cell continues, collaboration among researchers, engineers, and policymakers remains paramount. By fostering interdisciplinary dialogue and leveraging advancements in materials science, device fabrication, and system integration, the solar energy community can accelerate the transition towards more efficient and sustainable photovoltaic technologies.

In essence, this research contributes to the ongoing evolution of tandem solar cells, offering a nuanced understanding of their principles, materials, and interconnection strategies. By bridging theoretical insights with practical considerations, this paper lays the groundwork for future innovations that promise to unlock new frontiers in solar energy conversion, paving the way for a cleaner, greener energy future.

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