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Enhancing Stability and Efficiency in Tandem Perovskite- Silicon Based Solar Cells

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Abstract: Tandem Solar Cells that combine perovskite and silicon absorbers are gaining attention for their ability to overcome the efficiency ceilings faced by single- junction technologies. This work systematically investigates methods for simultaneously improving the durability and energy conversion efficiency of perovskite silicon tandem cells through material engineering, interface optimization, and advanced encapsulation techniques. A detailed investigation of perovskite composition modifications, interface passivation layers, and barrier coatings is conducted to suppress degradation mechanisms caused by moisture, UV exposure, and thermal stress. The study also examines the impact of scalable fabrication processes, such as vapor deposition and low-temperature solution methods, on device reliability and uniformity. Experimental results demonstrate improved stability under accelerated aging conditions and a significant gain in overall efficiency due to optimized charge transport and reduced recombination losses. The findings contribute to advancing the commercial viability of tandem perovskite–silicon solar technologies for next-generation renewable energy systems.

Keywords: Tandem solar cells, Perovskite–silicon photovoltaics, Stability enhancement, Efficiency optimization, Interface engineering, Encapsulation techniques, Renewable energy

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INTRODUCTION

Photovoltaic technology now plays a central role in the transition towards sustainable energy, yet single-junction silicon solar cells are increasingly constrained by their fundamental efficiency limit, the Shockley–Queisser boundary. Tandem architectures, which synergistically couple a wide-bandgap perovskite layer atop a conventional silicon cell, offer a promising solution by extending the range of sunlight that can be harvested and effectively converted to electricity. This dual-junction approach has enabled practical power conversion efficiencies exceeding 32%, with laboratory prototypes showing even higher values.

However, the long-term deployment of perovskite–silicon tandem devices is hampered by notable stability challenges—perovskite materials tend to degrade under environmental stressors such as heat, moisture, and UV radiation, whereas silicon exhibits high reliability over decades. Bridging this stability gap while simultaneously advancing device efficiency forms the crux of current research in this field.

EFFICIENCY ENHANCEMENT MECHANISMS

Bandgap Engineering and Lattice Matching

Efficiency gains in tandem cells are fundamentally tied to the alignment of sub-cell bandgaps. Perovskites are engineered for a bandgap of approximately 1.7–1.8 eV, while silicon provides a 1.12 eV absorber. Perfecting this combination enables greater photon conversion across the solar spectrum, with tandem designs breaking the single-junction ceiling and approaching the theoretical maximum efficiency of nearly

43%.

Interface Optimization

Interfaces between the perovskite and silicon are critical in determining charge transport and recombination rates. Highly selective, low-defect interlayers, such as tailored metal oxides or organic molecules, serve to passivate surface traps and balance charge extraction. Studies demonstrate that effective passivation can significantly boost open-circuit voltage and fill factor, directly impacting overall PCE.

Advanced Deposition Techniques

The development of scalable and controllable deposition processes, including vapor-assisted and hybrid solution-based methods, has enabled consistent fabrication of high-quality, pinhole-free perovskite films atop textured silicon wafers. This ensures uniform light absorption, efficient carrier collection, and reproducible device performance at the module scale.

OVERCOMING STABILITY BARRIERS

Perovskite Material Stability

Intrinsic instability in perovskite materials, particularly toward moisture and thermal stress, remains a paramount concern. Researchers have adopted mixed-cation, mixed-halide perovskite formulations, incorporating ions such as cesium and formamidinium, to bolster environmental tolerance without compromising optoelectronic properties. Inorganic additives and engineered crystal orientations are giving rise to perovskites with markedly improved phase stability and longevity.

Interfacial Passivation and Encapsulation

Interfacial layers not only support efficiency but are pivotal for stability. The introduction of ultrathin passivation films—such as atomic-layer-deposited metal oxides—significantly reduces both ion migration and chemical interaction between the perovskite and silicon sub-cells. On the macroscale, modern encapsulation techniques employing ultraviolet-resistant barrier coatings and multi-layer polymer/glass laminates safeguard the entire stack from ambient degradation over extended outdoor lifetimes.

Device Architecture Designs

The two-terminal (2T) monolithic and four-terminal (4T) mechanically stacked architectures each bring unique stability and efficiency trade-offs. Two-terminal tandems offer lower optical and electrical losses but necessitate precise current matching, while the four-terminal design allows more flexibility in device selection at the cost of additional optical interface complexity.

SCALABLE FABRICATION AND COMMERCIALIZATION

Large Area Uniformity and Reliability

Recent progress in uniform perovskite deposition, such as blade coating, slot-die coating, and inkjet printing, demonstrates significant promise for upscaling tandem technology to the module and panel level.

Ensuring reproducibility of high PCEs and long-term operational reliability across large areas remains a focus, requiring continuous innovation in in-line diagnostics and process control.

Integration with Existing Silicon Infrastructure

Detailed compatibility assessments have shown that tandem processes can be adapted to established silicon PV manufacturing lines, minimizing production disruption and cost. Hybrid modules leveraging silicon's proven durability and perovskite's high upfront efficiency may reach market parity more quickly as reliability data and accelerated life testing accumulate.

CASE STUDIES AND BREAKTHROUGH DEMONSTRATIONS

Recent laboratory demonstrations underscore the rapid pace of progress in this area. Flexible perovskite–silicon tandem modules have achieved efficiencies surpassing 33%; record cell values above 34% have been certified in independent laboratories. Prototype modules, when subject to standardized protocols for stress and environmental cycling, have exhibited less than 10% degradation after 1,000+ hours of operation, illustrating the tangible viability of contemporary encapsulation and interface strategies.

PERSPECTIVES AND OUTLOOK

The push towards reliable, ultra-high-efficiency photovoltaic modules will inevitably be shaped by ongoing convergence of material science, scalable engineering, and field reliability testing. Immediate research priorities include:

- Further optimization of perovskite formulations for extended outdoor lifetime.
- Innovation in defect-tolerant interface materials designed for both 2T and 4T architectures.
- Tailored encapsulation solutions compatible with cost-effective, high-throughput processing.
- Continued improvement in simulation and diagnostic tools to accelerate development cycles.

The synergy between perovskite and silicon can enable revolutionary reductions in the levelized cost of energy, driving a swift uptake of solar technology worldwide and supporting decarbonization efforts across the globe.

CONCLUSION

The advancement of tandem perovskite–silicon solar cells epitomizes a significant breakthrough in photovoltaic technology, offering the promise of surpassing the efficiency ceilings faced by conventional single-junction silicon devices. This paper has explored numerous strategies aimed at simultaneously enhancing cell efficiency and operational stability—two critical factors for real-world application and commercial viability. Through innovative perovskite material formulations, interface passivation techniques, and protective encapsulation methodologies, researchers have been able to substantially mitigate common degradation pathways such as moisture ingress, ion migration, and photochemical breakdown.

In addition, improvements in scalable deposition processes and interface engineering have contributed to more consistent and reproducible device fabrication, enabling large-area uniformity and integration compatibility with established silicon manufacturing. These combined efforts have led to tandem devices achieving remarkable power conversion efficiencies exceeding 34%, while also demonstrating enhanced longevity under accelerated aging and environmental stress tests.

Despite these encouraging developments, challenges remain before widespread commercial deployment becomes fully feasible. Further research is needed to extend operational lifetimes under harsh outdoor conditions, optimize cost-effective material usage, and streamline scalable encapsulation solutions without sacrificing performance. Moreover, as the photovoltaic landscape evolves, tandem technology must continuously adapt amidst competing next-generation solar architectures.

Looking forward, the synergistic union of perovskite and silicon technologies is expected to be a cornerstone in the global renewable energy transition, helping deliver affordable, clean, and reliable electricity. Continuous innovation in material science, device engineering, and manufacturing scalability will be essential to transform laboratory successes into durable, commercially available solar products. The ongoing progress in this field not only advances solar cell efficiency and stability but also reinforces the foundational role of photovoltaic technology in addressing future energy challenges.

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