RADemics

# Advances in Perovskite and Tandem Solar Cells for High-Performance Photovoltaics

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## Abstract

Perovskite solar cells (PSCs) have emerged as a transformative photovoltaic technology, offering high power conversion efficiency, low-cost fabrication, and tunable optoelectronic properties. However, their long-term operational stability remains a critical barrier to commercial deployment. This book chapter provides a comprehensive analysis of the fundamental degradation mechanisms affecting perovskite solar cells, with a focus on interface and contact degradation, thermal instability, and environmental stress factors. The role of grain boundaries in accelerating perovskite decomposition, the impact of mechanical stress on flexible devices, and the influence of ion migration on interfacial recombination are discussed in detail. Advanced material engineering approaches, including doping strategies, passivation techniques, and the integration of thermally conductive layers, are explored to mitigate stability challenges. Novel encapsulation methodologies compatible with large-area module fabrication are examined to enhance environmental resilience. Device design modifications for improving thermal dissipation and suppressing phase segregation are also evaluated. A systematic review of recent advancements and emerging strategies highlights the potential pathways to achieving stable, high-efficiency perovskite photovoltaics. The insights presented in this chapter will contribute to the development of next-generation PSCs with improved durability and commercial viability.

**Keywords:** Perovskite solar cells, interface degradation, thermal stability, encapsulation strategies, ion migration, photovoltaic reliability

## Introduction

Perovskite solar cells (PSCs) have emerged as a disruptive technology in the field of photovoltaics, exhibiting remarkable power conversion efficiencies (PCEs) that rival traditional silicon-based solar cells [1]. The rapid progress in PSC research has been driven by their unique optoelectronic properties, including high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps [2]. These attributes, combined with low-temperature solution processing, have enabled the fabrication of cost-effective and high-performance photovoltaic devices [3]. The stability of PSCs remains a significant challenge, preventing their large-scale commercialization [4]. Unlike silicon photovoltaics, which have demonstrated operational lifetimes exceeding 25 years, PSCs suffer from various degradation mechanisms that lead to efficiency losses and structural deterioration over time [5]. Understanding the factors contributing to instability and developing robust mitigation strategies are essential to advancing PSC technology toward practical deployment [6].

The degradation of PSCs is attributed to both intrinsic and extrinsic factors. Intrinsic instability arises from ion migration, phase segregation, and chemical decomposition of the perovskite material [7]. Ion migration, facilitated by the soft ionic nature of hybrid perovskites, results in the redistribution of mobile species, leading to charge accumulation and hysteresis effects [8]. Phase segregation in mixed-halide perovskites under illumination introduces inhomogeneities that degrade photovoltaic performance [9]. Chemical decomposition of the perovskite structure, particularly in the presence of defects and grain boundaries, further exacerbates stability concerns. These intrinsic degradation mechanisms necessitate careful material engineering and device optimization to enhance operational longevity [10].

Extrinsic degradation mechanisms are primarily driven by environmental stress factors, including moisture, oxygen, heat, and ultraviolet (UV) radiation. Perovskite materials are highly sensitive to humidity, which promotes the formation of hydrated phases that compromise device performance [11]. Oxygen exposure leads to oxidative degradation, particularly at the interfaces between the perovskite and charge transport layers [12]. Thermal fluctuations induce mechanical stress and accelerate the decomposition of the perovskite absorber layer, while prolonged UV exposure results in photo-induced degradation [13]. The combined effects of these environmental stressors necessitate the implementation of protective strategies such as advanced encapsulation techniques, thermally stable charge transport layers, and UV-filtering coatings to improve the resilience of PSCs under real-world operating conditions [14].

Interface engineering plays a crucial role in addressing stability challenges by minimizing charge recombination and mitigating interfacial degradation [15]. Defect passivation techniques, including the incorporation of two-dimensional (2D) perovskites, organic ligands, and self-assembled monolayers (SAMs), have been shown to improve interfacial stability and reduce defect-assisted recombination losses [16]. Doping strategies tailored for charge transport layers have enhanced carrier extraction while suppressing interfacial charge accumulation [17]. The introduction of thermally conductive transport layers further aids in heat dissipation, reducing the risk of thermally induced degradation [18]. By optimizing interfacial properties and employing passivation strategies, researchers have achieved significant improvements in PSC efficiency and durability [19].