What is the most effective method of incorporating reduced graphene oxide (rGO) into perovskite solar cells to optimize it for commercialization in underdeveloped, tropical climates?

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Abstract

Perovskite solar cells (PSCs) have strong photovoltaic potential but degrade under humid, high-temperature conditions. This study investigates the most effective way of incorporating reduced graphene oxide (rGO) into PSCs to fulfill >3,000 hours of operational stability under tropical climates (30°C, 80% relative humidity (RH)) whilst minimizing incorporation cost of ≤ \$5-10/m² and maintaining ≥80% efficiency retention. Three approaches will be evaluated: HTL doping, interfacial layering and ETL doping.

Introduction

As of 2023, an estimated 750 million people lack access to electricity. 80% of them reside in Sub-Saharan Africa (SSA) (IEA, 2024). Despite receiving some of the highest solar irradiance, solar power remains economically unviable in underdeveloped regions in SSA. Instead, households rely on inefficient alternatives such as biomass, kerosene and diesel generators, which are detrimental to their health and consume a relatively large proportion of income (WHO, 2024). These consequences highlight the urgency for the integration of low-cost, durable and scalable renewable energy sources in SSA such as PSCs. PSCs offer a promising pathway for localised manufacturing due to their low-temperature, solution-based processing compared to silicon photovoltaics (Roose et al.). However, their instability in humid conditions prevent its large-scale deployment in essential regions such as SSA. To address this issue, integration of rGO in PSCs permits moisture barrier formation and grain boundary passivation enabling high power conversion energy (PCE) retention in humid conditions (Hasan, M. M., et al. 2026). This research will systematically optimize rGO grain boundary engineering to make it suitable for tropical solar deployment.

Literature Review

In the past decade, perovskite solar cells reached PCE of up to 23%, excellent performance for commercial use solar cells (EcoFlow, Kafle, BhimP.). However, PSCs can withstand 55% humidity for only 480 hours, far from IEC's standards of 1000 hours of consistent performance in non-laboratory conditions including 85% humidity at 85°C ("Perovskite Solar Cells: Causes of Degradation"). To mitigate these limitations, Min et al. (2021) reports chlorine-mediated modification of perovskite interfaces reduces defect density and improves charge transport. Unencapsulated devices maintain ~90% of their initial efficiency after 500 hours of continuous light exposure. However, although halide-mediated interfacial engineering improves charge transport, it introduces process complexity thus reducing compatibility with resource-constrained manufacturing as compared to carbon-based additives including rGO which would offer similar performance for a more cost-sensitive and robust product for scaled deployment. Marchezi et al. (2021) supports this as devices with rGO-20h exhibited a higher stability due to the formation of larger crystalline grains which reduced grain boundary density and therefore slowed degradation. Similarly, Kim et al. (2020) demonstrated that rGO in the spiro-MeOTAD layer passivates interfaces and prevents thermal crystallisation at high temperatures. PSCs with rGO content (9.67%) lead to greater stability at 85°C and 45% RH. Mahmoudi et al. (2018) and Hasan (2026) further fortifies roles of graphene in device protection via its 2D structure and hydrophobic traits, refining PCE and stability under humid conditions. Nevertheless, these studies impose constraints on scalable deployment as translation from laboratory-scale synthesis to locally manufacturable systems is not feasibly explored. These successful studies demonstrate that rGO integration across various interfacial and grain boundary engineering strategies in PSCs support its viability in enhancing durability and stability in harsh conditions. Accordingly, this reinforces the hypothesis that rGO-enabled PSCs could facilitate scalable deployment in underdeveloped regions given it is further tested and validated under real-world tropical conditions.

Methodology

Identical n-i-p structures PSCs (FTO/TiO_2/$MAPbI_3$/Spiro-OMeTAD/Au) will be fabricated in parallel to ensure experimental control. A control group without rGO will establish performance reference for comparison with fabrication parameters such as deposition conditions, annealing profile, device architecture and precursor composition staying constant

The independent variable is the method of incorporation of rGO: i) HTL doping at various concentrations, ii) Deposition as an interfacial layer between the perovskite and HTL and iii) Incorporation within electron transport layer (ETL). This study prioritises testing under realistic tropical environments (30°C, 80% RH, continuous illumination) to better reflect deployment conditions in regions such as SSA. PSC performance will be monitored over a set time by measuring PCE at fixed intervals over a short-term testing period. Degradation trends will then be used to project longer-term stability. Stability will be quantified using the standardised metric T_{80} (time taken for the PCE to drop to 80% of its initial value), and degradation rates will be calculated from efficiency-time profiles to facilitate direct comparisons between rGO incorporation methods. When applicable, results will be contextualised against existing ISOS-D-3 (85°C, 85% RH) findings to ensure consistency and comparability with prior work. This approach reinforces experimental feasibility whilst maintaining relevance to tropical climates and possible deployment to SSA.

Results will be analysed by constructing PCE-time curves for each device, from which degradation rates (percentage efficiency loss per hour) will be calculated and operational stability can then be drawn from this by calculating T_{80}.

To evaluate cost-performance trade-offs, material usage of rGO will be quantified for each configuration and converted to cost per unit area ($\$/m^2$). These metrics enable quantitative comparisons. The different strategies will be evaluated by comparing initial PCE, degradation rate, T_{80} and additional cost per unit area to aforementioned values in the Abstract along with quantification using this formula: Figure of Merit (FoM) = (cost×degradation rate)/(PCE×T_{80}). The FoMs are then compared to identify the largest FoM and therefore optimal strategy.

Conclusion

By identifying the optimal method of rGO integration across efficiency, stability and cost, this study confronts a critical barrier to commercialization of PSCs in regions like SSA. Ultimately, findings could pioneer implementation of durable, low-cost perovskite solar panels for widespread energy access across sub-Saharan Africa.

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