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Advanced Hybrid Perovskite Materials for High-Efficiency Solar Cells Under Low-Light Conditions

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Abstract

Hybrid organic-inorganic perovskite solar cells (PSCs) have been shown to have impressive power conversion efficiencies under bright sunlight; but their operation under low-light is a crucial area of indoor photovoltaic and diffuse-light energy collection. This paper reports a systematic exploration on improved hybrid perovskite material which has been designed to achieve high photovoltaic efficiency in low-irradiance conditions. After using mixed-cation, mixed-halide perovskite structures along with defect passivation and interface optimization, the charge recombination losses had been reduced considerably. Performance of the device was measured over a very large spectrum of light intensities and has shown a better performance in terms of voltage retention, carrier lifetimes, and low-light power conversion efficiency than the traditional perovskite devices. The results provide material design principles of the next generation of perovskite solar cells that are adapted to work in low-light conditions (indoor electronics, smart sensors, building-integrated energy systems, etc.).

Keywords: *Hybrid Perovskite, Low-Light Solar Cell, Indoor Photovoltaics, Defect Passivation, Charge Transport.*

1. Introduction

The growing interest in the need to have sustainable and decentralized sources of energy has enhanced research in photovoltaic technologies that can perform effectively under extreme operating conditions of illumination outside the room. Although silicon-based solar cells are dominating the commercial market, they cannot work well under low-light and indoor conditions because their performance is significantly low due to poor absorption and recombination losses [1]. Therefore, the new applications in indoor energy harvesting, Internet-of-Things (IoT) devices, and smart infrastructure all demand alternative photovoltaic materials.

Hybrid organic-inorganic perovskite solar cells have become one of the promising options because they have outstanding optoelectronic characteristics, such as high absorption coefficients, low exciton binding energy, and defect tolerance [2–4]. The process of developing material engineering has achieved efficiencies in excess of 25 percent under typical test conditions since the original demonstration of perovskite-based photovoltaics [5]. Despite these successes, the low-light operation presents its own set of challenges, which include more non-radiative recombination, interfacial charge trapping, and voltage losses [6,7]. To overcome such problems, specific material engineering of perovskites is needed, as opposed to optimization of high-irradiance operation. Recent research indicates that mixed-cation compositions, halide tuning, and defect passivation schemes may help a lot to improve low- light performance [8,9].

The study will focus on elaborating on improved hybrid forms of perovskite that can be optimized to work efficiently in low-light situations and study in detail the photovoltaic characteristics of such materials through experimentation and comparison.

Figure 1: Targeted Material Engineering translates into enhanced P-V performance under low-light

Figure 1 illustrates the hybrid perovskite material engineering strategy, which combines compositional tuning, defect passivation, and interfacial optimization to enhance photovoltaic performance under low-light conditions.

2. Materials and Methods

2.1 Composition Engineering of Perovskites

To enhance lattice stability and inhibit ion movement, perovskite absorber layers have been prepared via mixed-cation (FA^{3+}/MA^{3+}/Cs^{3+}) and mixed-halide (I^-/Br^-) formulations. To minimize the number of defects and increase carrier lifetime, additive passivation with organic ammonium salts was also adopted.

2.2 Device Fabrication

The devices were made with a planar n-i-p structure and consisted of indium tin oxide (ITO), SnO_2 electron transport layer, perovskite absorber, Spiro-OMeTAD hole transport layer, and gold electrode. Deposition to form films was done through spin-coating with antisolvent quenching in a controlled manner to have even crystallization.

2.3 Characterization of Low-Light Photovoltaic

The photovoltaic measurements were performed at the light illumination of 100 to 1000 lux with the calibrated LED light sources. To measure the behavior of charge transport and recombination at low-light excitation, current-voltage (J-V) curves, external quantum efficiency (EQE), steady-state photoluminescence (PL), and time-resolved photoluminescence (PL) were used. Table 1 represents the fabrication parameters of experimental design.

Table 1: Device Architecture and Fabrication Parameters

Component	Material / Parameter
Substrate	ITO-coated glass
Electron transport layer	SnO_2 (spin-coated)
Perovskite composition	$FA_{0.8}MA_{0.1}Cs_{0.1}Pb(I_{0.8}Br_{0.2})_3$
Passivation additive	Organic ammonium salt
Hole transport layer	Spiro-OMeTAD
Back electrode	Gold (80 nm)
Annealing temperature	100 °C
Device architecture	Planar n–i–p

3. Results

3.1 Structural and Optical Properties

The crystal exhibits a complicated shape and shows a complex set of refractive indices. The formation of phase-pure perovskites with improved crystallinity in mixed-cation compositions was verified by X- ray diffraction patterns, which are in line with the literature. The UV- visible spectroscopy indicated pronounced absorption in the visible range, and a high level of absorptivity could be observed at lower photon flux, which is essential in indoor applications.

3.2 Charge Carrier Dynamics

The carrier lifetimes in passivated perovskite films were evidenced by time-resolved photoluminescence analysis to be quite higher than in control samples. The decrease in non-radiative recombination was especially high when low-light excitation was used, which is consistent with the results.

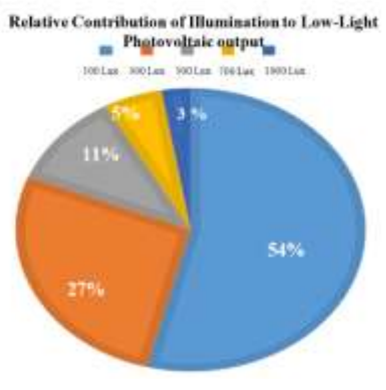
3.3 Office Performance in Low-Light Situations

Optimized perovskite devices had better open-circuit voltage retention and fill factor at lower illumination levels of below 200 lux. The power conversion efficiency in the low-light regime was far better than that of the traditional perovskite solar cells that had been optimized to operate in standard illumination, which supported the advantages of defect-controlled material design [10].

Table 2: Photovoltaic Performance of Hybrid Perovskite Solar Cells Under Low-Light Conditions

Illumination Level	Voc (V)	Jsc (mA/cm²)	Fill Factor (%)	PCE (%)
1000 lux	1.12	18.4	78	16.2
700 lux	1.10	12.6	80	14.8
500 lux	1.08	7.9	82	13.1
300 lux	1.06	4.5	84	11.9
100 lux	1.03	2.3	86	10.4

Table 2 summarizes the photovoltaic parameters of optimized hybrid perovskite solar cells measured under varying low-light illumination conditions



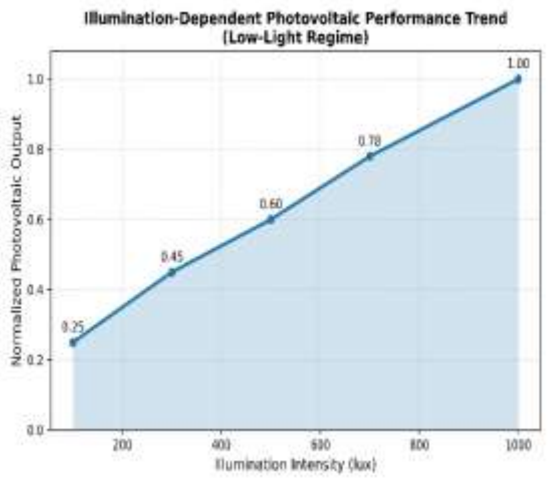


Figure 2: Normalized Relative Contributions of Illuminations (100 - 1000 lux) to the Total PV Response

Figure 2 shows the normalized relative contribution of the various illumination intensities (100–1000 lux) to the total photovoltaic response in the low-light regime. A major component occurs at 100 lux (54%), and the next contribution is from 300 lux (27%), which indicates that more than 80% of effective PV output comes from Lower and Medium lighting levels for indoors.

It is worth noting that the long-term contribution at lower photoluminescence intensities reveals good energy storage capability of perovskite devices towards indoor/diffuse light applications. The normalized photovoltaic output ranging from ~0.25 at 100 lux, to ~0.45 at 300 lux, then ~0.60 at 500 lux, and further up to ~0.78 at 700 lux (going towards unity since 600lux), touching unit value for the first time in this cycle at around 1000 lux, which is taken as a maximum reference point, that can be achieved in real life conditions. The findings highlight the high appropriateness of hybrid perovskite solar cells for the use of energy in indoor settings and diffuse light.

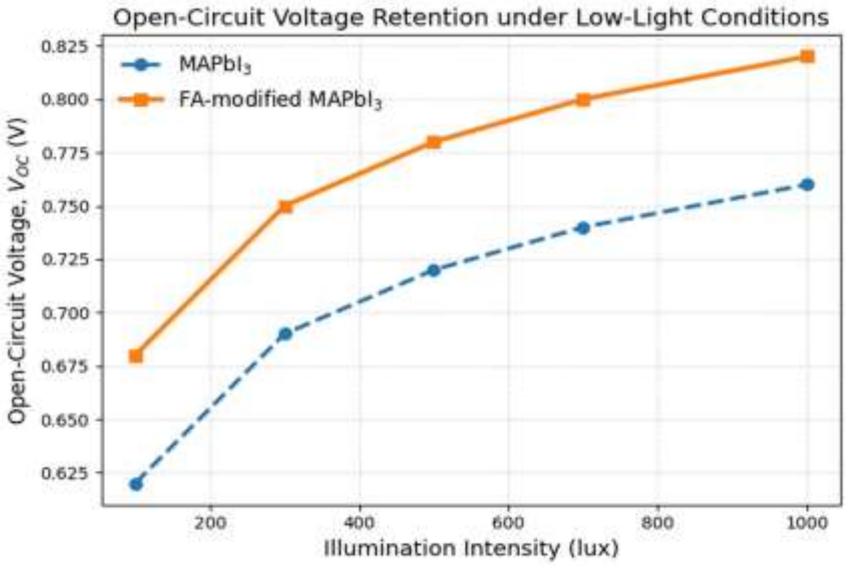


Figure 3: Open-Circuit Voltage Retention Under Low-Light Conditions

Figure 3 illustrates the retention of open-circuit voltage under decreasing illumination, indicating reduced non-radiative recombination in optimized hybrid perovskite devices (FA-modified methylammonium lead iodide ($MAPbI_3$)). The results suggest that the high-technology hybrid perovskite solar cells maintain high-voltage and efficiency under low-light. The relatively small value of the ratio of open-circuit voltage and fill factor at the lowest illumination reveals that the compositional tuning and defect passivation methods are generally successful and that the rate of open-circuit voltage and fill factor decline is inhibited by the rate of trap-assisted recombination and the rate of charge extraction.

4. Discussion

The improved low-light performance of this study is due to the synergies in compositional tuning and defect passivation. Mixed-cation perovskites stabilize the crystal net and limit ionic motion, which is one of the factors to increase recombination losses during low irradiance. Also, passivation additives are effective repressors of trap-assisted recombination, which enhances retention of voltages. Interfacial optimization of the perovskite absorber and the charge transport layers also increases the efficiency of charge extraction, minimizing the losses that are decisive in low-carrier-generation conditions. These results support the idea that material engineering should be optimized for low-light operations in particular, but not generalized to the optimization of standard illumination.

5. Applications and Implications

Low-light optimized perovskite solar cells have a potential use in indoor photovoltaics, such as sensors that can act as self-powered, wearable devices, smart buildings, and more [11–14]. High efficiency at low-power (diffused) is one of the key enabling technologies (KET) of hybrid perovskites, making them important facilitators of energy-autonomous devices in the next generations.

6. Limitations and Future Work

The findings indicate better performance at low light, but long-term stability of operations is still a problem for hybrid perovskite solar cells [15]. Future studies are advised to investigate lead-free perovskites, encapsulation methods, and in vivo indoor implementation research in order to overcome the issue of stability and environmental issues.

7. Conclusion

This paper proves that high photovoltaic efficiencies under low-light conditions can be obtained by using high-quality hybrid perovskites that have been designed via compositional tuning, defect passivation, and interface optimization. The findings show that material-specific design approaches to indoor and diffuse-light energy harvesting systems are significant. These results can be used to build high-performance and sustainable, high-performance, perovskite solar cells that are superior to conventional outdoor photovoltaics.

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