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Efficiency enhancement in planar perovskite solar cells under low-light illumination and ambient lighting

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Abstract. Hybrid organic-inorganic perovskite solar cells (PSCs) have attracted significant interest owing to their high power conversion efficiency (PCE) and low cost. Moreover, PSCs demonstrate high performance under low light illumination without significant reduction in PCE. However, photovoltaic properties of PSCs under low light conditions are rarely reported. Here, the potential of planar PSCs for efficient performance under low illuminance conditions was investigated. Planar perovskite solar cells with FTO/c-TiO₂/c-SnO₂/CH₃NH₃PbI₃/Spiro-MeOTAD/Au architecture were studied under variable illumination intensities in the range of $10 - 1000 \text{ W/m}^2$. Significant enhancement in PCE up to 18.4% was observed for planar PSCs under low light conditions (<100 W/m²), as compared to the 16% PCE value obtained under AM1.5 illumination. This was attributed to the decreased charge accumulation at the ETL/perovskite interface and increased charge collection efficiency under low light illumination. PSCs performance was additionally studied under artificial LED lighting (5500K, 1000 lux) and the PCE values exceeding 24% were obtained. The results of this work verify excellent low-light performance of planar PSCs and provide the possibility for their application as power sources for various low-power wireless devices (sensors, detectors, Internet of Things devices, etc.).

1. Introduction

Perovskite solar cells (PSCs) based on hybrid organo-inorganic perovskite materials with the general formula ABX₃, where A – CH₃NH₃⁺, HC(NH₂)₂⁺, Cs⁺; B – Pb²⁺, Sn²⁺; X – I⁻, Br⁻, Cl⁻, have attracted much attention during the last decade due to their excellent optoelectronic properties and ease of fabrication [1]. The power conversion efficiency (PCE) of PSCs have been boosted to 25%, which is competitive to the PCE values for crystalline silicon solar cells [2]. PSCs consist of multilayer structures where the light-absorbing perovskite layer is sandwiched between the electron transport layer (ETL) and hole transport material (HTL). High PCE values obtained for PSCs are associated with the efficient light absorption and large diffusion length of photo-generated charge carriers inside the perovskite layer, which ensures good charge separation in the volume of the light-absorbing material and efficient charge transport to the selective contacts (ETL and HTL) [3,4]. In the n-i-p configuration (n-type electron transport layer, intrinsic perovskite layer and p-type hole transport layer) metal oxides such as TiO_2 or SnO_2 are usually used as an electron transport layer [3,5]. TiO_2 represents the most common choice for ETL and is generally deposited as a 200-300 nm mesoscopic layer consisted of small TiO₂ nanoparticles (meso-PSCs). Additionally, planar architecture (without mesoscopic layer) could be used, employing thin (30-50 nm) compact TiO₂ or SnO₂ layer as ETL.

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A significant advantage of PSCs over conventional crystalline silicon solar cells is their ability to work under low light illumination without significant reduction in PCE [6,7]. Similar behavior was previously well established for dye-sensitized solar cells (DSSCs), for which even the increase in PCE was observed on decrease in illumination intensity [8,9]. Recently, the performance of mesoscopic TiO₂-based PSCs under low light illumination was studied, showing ~20% decrease in PCE values at intensities lower than 100 W/m² as compared for the corresponding values under AM1.5 illumination (1000 W/m²) [7]. Moreover, it was shown that the low-light performance of mesoscopic and planar PSCs could be somewhat different [6]. Namely, planar-type PSCs showed better photovoltaic characteristics than that of mesostructured PSCs under low illuminance conditions. This was attributed to the fact that the mesoporous TiO₂ layer acts as an internal resistance and decreases V_{oC} to a larger extent under low illuminance intensities. Additionally, it was shown that perovskite solar cells could achieve PCE values of more than 25% under artificial ambient lighting [10-13], providing the possibility for efficient indoor light harvesting for various low-power wireless devices (sensors, detectors, Internet of Things devices, etc.).

It should be noted, however, that the data describing the photovoltaic performance of perovskite solar cells under low illuminance conditions is still limited, especially for planar-type PSCs. In this work, we studied the photoelectric parameters of planar PSCs based on $CH_3NH_3PbI_3$ (MAPbI₃) perovskite under variable illumination intensities in the range of $10 - 1000 \text{ W/m}^2$ and under artificial LED lighting. A detailed investigation focused on the photovoltaic characteristics of PSCs under low-light conditions could improve our understanding on the low-light performance of PSCs and establish an optimized PSC device architecture for various low-light and indoor applications.

2. Materials and methods

Fluorine-doped tin oxide (FTO) coated glass substrates (sheet resistance 8 $\Omega \cdot cm^{-2}$) were purchased from Sigma-Aldrich (USA). The SnO₂ colloid precursor solution was purchased from Alfa Aesar (tin (IV) oxide, 15% in H₂O colloidal dispersion). Methylammonium iodide (CH₃NH₃I) and lead iodide (PbI₂) were purchased from TCI Chemicals (Japan). All other chemicals, unless otherwise stated, were purchased from Sigma-Aldrich (USA) and were ACS-grade reagents.

FTO-glass substrates were etched with zinc powder and 2 M HCl. The substrates were cleaned with Triton X-100, ethanol and acetone in ultrasonic bath for 15 min. To prepare the electron transport layer (ETL), 0.15 M titanium diisopropoxide bis(acetylacetonate) (75 wt % in isopropanol) solution in 1-butanol was spin-coated on FTO glass substrate at 3000 rpm for 30 s with subsequent drying at 500 °C for 30 min. Then the SnO₂ nanoparticle film was spin-coated onto the FTO-glass/compact TiO₂ substrate using diluted tin oxide colloid precursor (2.67%, diluted by deionized water) at 3000 rpm for 30 s, and annealed in ambient atmosphere at 150 °C for 30 min. Perovskite layer deposition was carried out under ambient conditions (~30% humidity). The perovskite precursor solution was prepared by mixing 461 mg PbI₂, 159 mg CH₃NH₃I and 71 µl DMSO in 635 µl of DMF. This solution was spin-coated on the FTO/TiO₂/SnO₂ substrate at 4000 rpm for 25 s and 0.5 mL of diethyl ether was dripped on the rotating substrate as an antisolvent [14]. Obtained perovskite layer was annealed at 100 °C for 10 min. A hole-transporting layer (HTL) was spin-coated on top of the perovskite layer at 3000 rpm for 30 s using solution consisting of 72.3 mg Spiro-OMeTAD, 28.8 µl 4-tert-butylpiridine and 17.5 µl bis(trifluoromethane) sulfonimide lithium salt (Li-TFSI) solution (520 mg Li-TSFI in 1 ml of acetonitrile) in 1 ml of chlorobenzene. Finally, 80-nm Au layer was deposited as the top contact using thermal evaporation.

The current density-voltage (J–V) characteristics of PSCs were measured using the SCS-4200 parameter analyzer (Keithley, USA) under standard AM1.5G illumination at an intensity of 1000 W/m² (Abet Technologies 10500 solar simulator) and device active area of 0.08 cm². Average values of PV parameters (J_{SC} , V_{OC} , FF) were obtained for a series of 10 PSC samples. The best-performing PSC device was studied under varied (10-1000 W/m²) illumination conditions using solar simulator as a light source and ND optical filters (Marumi, Japan) providing uniform decrease of the light flux in the spectral range of 300-1100 nm. The light intensity was calibrated by means of a Si photodiode.

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3. Results and discussion

Statistical data on the PCE obtained for a series of 10 PSC samples is shown in figure 1. All PSCs showed PCE values higher than 15%, with the average value of 15.5%, which indicates good reproducibility of the fabrication process. The best performing PSC device showed the following PV parameters: $J_{SC} = 20.25 \text{ mA/cm}^2$, $V_{OC} = 1.045 \text{ V}$, FF = 0.759, giving a PCE value of 16.1%.



Figure 1. a) Statistical data on the PCE for a series of the developed PSCs and b) the J–V curve for the best performing device.

Photovoltaic parameters for the champion planar PSC device were studied under variable illumination intensities in the range of $10 - 1000 \text{ W/m}^2$ using solar simulator as a light source and ND optical filters for light intensity adjustment.



Figure 2. Evolution of the main photovoltaic parameters for planar PSC under variable illumination intensities (10 – 1000 W/m²): a) PCE, b) short circuit current density normalized by corresponding light intensity values, c) open circuit voltage, d) FF.

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Figure 2 shows the main photovoltaic parameters obtained for planar PSC under variable illumination intensities $(10 - 1000 \text{ W/m}^2)$. Significant enhancement in power conversion efficiency up to 18% was observed for planar PSCs under low light conditions (<100 W/m²), as compared to the 16.1% PCE value obtained under AM1.5 illumination. Additionally, values for the FF and the short circuit current density normalized by corresponding light intensity also showed the tendency to increase on decrease in illumination intensity.

Previously, such behavior was observed for single junction organic solar cells [15] and this was attributed to the increase in the collection efficiency with decrease in intensity. Decrease in illumination intensity leads to the decrease of the space-charge density inside the active layer and corresponding less effective screening of the built-in electric field. Therefore, the collection efficiency is increased leading to the increase in PCE on decrease in illumination intensity. Light-induced space-charge accumulation was also observed for various planar PSC configurations [16], suggesting that the same mechanism shown for organic solar cells could account for the observed increase in PCE for planar PSCs.

PSCs performance was additionally studied under artificial LED lighting (5500K, 1000 lux, incident power $P_{in} = 3 \text{ W/m}^2$) and the corresponding J-V curve is shown in figure 3. The following PV parameters were obtained: $J_{SC} = 0.114 \text{ mA/cm}^2$, $V_{OC} = 0.835 \text{ V}$, FF = 0.77, leading to PCE value of 24.4%. Observed high performance of planar PSCs under low-intensity LED lighting provides the possibility for their indoor applications as power sources for various low-power wireless devices.



Figure 3. J–V curve for the champion PSC device under indoor LED lighting (1000 lux).

4. Conclusion

In this study photoelectric parameters of planar PSCs based on MAPbI₃ perovskite were studied under variable illumination intensities and under artificial LED lighting. Significant enhancement in PCE up to 18.4% was observed for planar PSCs under low light illumination (<100 W/m²), as compared to the 16% PCE value obtained under standard AM1.5 conditions. Excellent low-light performance of planar PSCs provides the possibility for their efficient application both under outdoor low intensity illumination (cloudy weather) and indoor artificial lighting.

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