

# Doping Electron Transporting Layer: An Effective Method to Enhance $J_{SC}$ of All-Inorganic Perovskite Solar Cells

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**All-inorganic metal-halide CsPbBr<sub>3</sub> perovskite has emerged as an attractive photovoltaic material for its outstanding environmental stability. However, due to the wide bandgap, the performance of CsPbBr<sub>3</sub> perovskite solar cells (PSCs) is limited, especially for the short-circuit current density ( $J_{SC}$ ). In this issue of Energy & Environmental Materials, Guo et al. employed Nb-doped SnO<sub>2</sub> as electron transporting layers (ETLs), which could greatly improve the  $J_{SC}$  of the PSCs based on all-inorganic CsPbBr<sub>3</sub>.**

Metal-halide perovskites were firstly introduced to a dye-sensitized solar cell (DSSC) as visible-light absorbers by Miyasaka and his coworkers in 2009. At that time, the device demonstrated a light-to-electricity power conversion efficiency (PCE) of 3.8%.<sup>[1]</sup> Subsequently, based on these perovskites, Park et al. developed a solid-state DSSC by substituting the liquid electrolytes with spiro-MeOTAD as the hole conductors.<sup>[2]</sup> The PCE of the photovoltaic device is boosted to 9.7% and the device stability is also greatly enhanced. In 2013, the researches further revealed that these solution-processed metal-halide perovskites possess long-range balanced electron- and hole-transport lengths,<sup>[3,4]</sup> which suggests that the DSSC architecture designed for decoupling light absorption and charge carrier transport is not necessarily needed. In the same year, Snaith and his coworkers constructed high efficiency (over 15%) perovskite solar cell (PSC) with a planar heterojunction (PHJ) architecture,<sup>[5]</sup> which confirms the previous finding. Up to now, highly efficient perovskite-based solar cells with a broad range of configurations have been demonstrated.<sup>[6]</sup> The highest certified PCE value is over 25%.<sup>[7]</sup> Since the perovskites have been revealed as super semiconductors, most of the reported PSCs were constructed with a traditional p-i-n device structure. The photo-induced charge carrier dynamics within the device could be described by the classic physics in a traditional thin-film solar cell.

Recently, due to the excellent environmental stability of all-inorganic PSCs, related research is getting more and more attention. Unfortunately, the performance of the device is limited, especially for the  $J_{SC}$ , because of the narrow visible-light absorption spectral window.<sup>[8]</sup> In this issue of Energy & Environmental Materials, Guo et al. increased the  $J_{SC}$  of PSCs around 19% (from 7.51 to 8.92 mA cm<sup>-2</sup>) by employing high target utilization sputtering Nb-doped SnO<sub>2</sub> ETLs.<sup>[9]</sup> The carrier concentration of ETLs can be increased from 10<sup>18</sup> to 10<sup>19</sup> cm<sup>-3</sup> by 3%

Nb doping, which will greatly affect the distribution of the depletion layer. The width of the depletion region can be described by the following equation:

$$\omega_{scr} = \omega_p + \omega_n = \sqrt{\frac{2\epsilon_s}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) V_{bi}}$$

where  $\omega_{scr}$  is total depletion region width,  $\omega_p$  is p-type depletion region width,  $\omega_n$  is n-type depletion region width,  $\epsilon_s$  is the semiconductor layer permittivity,  $q$  is the electron charge,  $N_a$  is the acceptor concentration,  $N_d$  is the donor concentration, and  $V_{bi}$  is the built-in voltage. Here, the doping concentration of the perovskite layer (acceptor) remains constant, while the doping concentration of ETL (donor) is increased by 3% Nb doping, leading to narrow n-type depletion region width. The narrow depletion region width in the ETL can result in a radical change in the band structure, acting as a “cliff,” which effectively blocks the minority carriers, facilitating the separation of photogenerated electron-hole pairs and reducing charge carrier recombination.<sup>[10]</sup> In addition, when the p-n junction is close to the ETL, more free electrons in the p-type depletion region will diffuse and reach the ETL-perovskite interface, thus improves the  $J_{SC}$  and open-circuit photovoltage ( $V_{OC}$ ) of PSCs simultaneously. However, according to ultraviolet photoelectron spectroscopy (UPS) results, the change significantly causes a drop in the conduction band minimum ( $E_c$ ) after 3% Nb doping ( $\Delta E_c = 0.18$  eV). Therefore, the device mainly exhibits an increase in  $J_{SC}$ . Nevertheless, the  $V_{OC}$  increase is not significant, which may be due to the almost constant Fermi level ( $E_F$ ) after 3% Nb doping ( $\Delta E_F = 0.07$  eV). In addition, Nazeeruddin et al. even think  $V_{OC}$  cannot be governed by any internal electric field established by the different work functions of ETL.<sup>[11]</sup>

However, when they further increase doping concentration to 6% (over 10<sup>20</sup> cm<sup>-3</sup>), the performance of PSCs is significantly reduced, corresponding to another publication.<sup>[12]</sup> The decrease in performance is attributed to the formation of interface defects and aggravation of auger recombination. In future work, studies should focus on reducing interface defects, such as interface passivation,<sup>[13]</sup> to avoid the  $E_F$  pinning, thereby enhancing the  $J_{SC}$  and PCE of PSCs.<sup>[14]</sup> This report will extend the understanding of perovskite photovoltaics, including all-inorganic PSCs, and organic-inorganic hybrid PSCs.

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## Conflict of Interest

The authors declare no conflict of interest.

## Keywords

all-inorganic perovskite, depletion region width, doping, planar heterojunction

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