## Efficient Perovskite Solar Cells utilizing Tungsten-doped Zinc Oxide as the Electron Transport Material

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**[Introduction]** Perovskite solar cells (PSCs) have been extensively researched, and the power conversion efficiency (PCE) has reached 25.5%.[1] To date, several metal oxides, such as ZnO, TiO<sub>2</sub>, and SnO<sub>2</sub> are used as the electron transport layer (ETL) for the fabrication of efficient PSCs. Particularly, ZnO showed favorable energy level, smooth surface coverage and most importantly low-cost deposition capabilities are highly desired for efficient device performances. The application of ZnO ETL to PSCs remains limited by drawbacks such as low conductivity and large amounts defects, which inevitably lead to carrier recombination. Notable efforts have been made using doping, nanocomposites or interface engineering strategies to resolve these drawbacks to enhance the device performance. Tungsten (W) is one of the candidates for doping ZnO due to the similar ionic radius of Zn<sup>2+</sup> (0.074 nm) and W<sup>6+</sup> (0.064 nm). In this study, we introduce W-doped ZnO as the ETL and investigate their influences of PSCs performance.

**[Materials and Method]** Pristine ZnO and W-doped ZnO precursor solutions were prepared from pristine ZnO and W-doped ZnO powders, respectively, and spin-coated on ITO-patterned glass substrates.  $Cs_{0.1}FA_{0.9}PbI_3$  perovskite solution was prepared according to the procedure described by D. Zheng et al. [2]. The perovskite solution was spin-coated on pristine ZnO and W-doped ZnO layers, respectively. 2,2', 7,7' -Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9' - spirobifluorene (Spiro-OMeTAD) solution was spin-coated on the perovskite layer. Finally, 100-nm-thick Au electrode was deposited.

**[Results and Discussion] Figure 1a** shows the top-view of SEM image of  $Cs_{0.1}FA_{0.9}PbI_3$  perovskite film fabricated on W-doped ZnO and exhibited smooth and flat surface morphology. Inset showed a dense and smooth surface morphology of W-doped ZnO deposited on the ITO-patterned glass substrate. The

XRD of ITO/pristine ZnO/Cs0.1FA0.9PbI3 and ITO/W-doped ZnO/Cs<sub>0.1</sub>FA<sub>0.9</sub>PbI<sub>3</sub> films is shown in Figure 1b. Higher crystallinity was observed for the perovskite layer formed on W-doped ZnO because the as-prepared W-doped ZnO material started with better crystallinity. Ultimately, PSCs with W-doped ZnO ETL exhibited PCEs as high as 16.2%, which is superior to those of PSCs with pristine ZnO as the ETL (12.9%) (Figure **1c**). The enhancement of  $J_{sc}$  and FF can be attributed to the lowering of the injection barrier at the interface between the W-doped ZnO and perovskite, which facilitated efficient electron flow. The integrated  $J_{sc}$  values of the IPCE spectra are 20.4 and 22.5 mAcm<sup>-2</sup> for the pristine ZnO and W-doped ZnO based PSCs, respectively (Figure 1d). These values are coherent with the  $J_{\rm sc}$  values extracted from the J-V curves. The PSCs with W-doped ZnO exhibited a maximum



Fig. 1. a) Top-view SEM image of W-doped  $ZnO/Cs_{0.1}FA_{0.9}PbI_3$  and ITO/W-doped ZnO; (b) XRD patterns of  $Cs_{0.1}FA_{0.9}PbI_3$  formed on pristine ZnO and W-doped ZnO films, c) *J-V* curve and (d) IPCE of PSCs with ZnO and W-doped ZnO ETLs.

IPCE of 90% while pristine ZnO yields 80%, which is consistent with its high photocurrent. Hence, the present study provides a significant advance to the design of photovoltaic devices with respect to charge transport and electron-hole recombination.

**(Acknowledgements)** This study was supported by a Grant-in-Aid for Scientific Research (no. 20H02838). **(References)** [1]M. Shahiduzzaman, T. Taima et al., *Chem. Eng. J.* (2021) 128461. [2] A. Facchetti et al., *Adv. Funct. Mater.* 29 (2019) 1900265.