

## Experimental details (Methods)

The perovskite solar cell devices were fabricated on FTO-coated glass substrates supplied from OPV-Tech, Taiwan. The substrates were cleaned by consecutive sonication in detergent added water, deionized water, acetone and isopropyl alcohol for 15 minutes each. Prior to deposition of electron transport layer (ETL), the substrates were blow dried by nitrogen gas flow and UV-ozone treated for 30 minutes. The ETL comprised SnO<sub>2</sub> quantum dot (QD) layer and SnO<sub>2</sub> nanoparticle (NP) layer. SnO<sub>2</sub> QD precursor solution were prepared as described previously by Z. Ren *et al.* [1]. For SnO<sub>2</sub> NP solution commercial 15% tin (II) oxide dispersion in H<sub>2</sub>O from Alfa Aesar, USA, was diluted with DI water in [1:5] v/v ratio. Both SnO<sub>2</sub> QD and NP solutions were spin coated at 3000 rpm for 30 s, and QD film was annealed at 200 °C for 1 hour and NP film was annealed at 150 °C for 30 minutes.

The perovskite layer was spin coated on top of formed ETL inside the glove box under the controlled inert atmosphere. The mixed cation and mixed halide perovskite precursor solution comprised 1.0 M FAI (Greatcell Solar Materials), 1.1 M PbI<sub>2</sub> (99%, Sigma Aldrich), 0.2 M MABr (Greatcell Solar Materials) and 0.2 M PbBr<sub>2</sub> (≥98%, Sigma Aldrich) dissolved in 1 mL of the mixture of dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) in the [4:1] v/v ratio. Then, CsI (1.5 M stock solution in DMSO) was added into the precursor solution in a volume ratio of 8:92 to form 1 mL final perovskite precursor solution. The perovskite was grown via cryogenic-treatment process including four steps [2]: i.) spin-coating of the precursor solution at 2000 rpm for 30 s; ii) cryogenic treatment; (iii) blow-drying under nitrogen gas flow for 60 s; and (iv) thermal annealing at 105 °C for 30 min on a hotplate.

For hole-transport layer (HTL) 80 mg of ,2',7,7'-Tetrakis(N,N-di-p-methoxyphenylamino)-9,9'-spirobifluorene (Spiro-MeOTAD) was dissolved in 954 µl of CB. The solution was doped by 29 µl of 4-tert butylpyridine (TBP) and by 17.5 µl of lithium salt solution prepared by dissolving 520 mg of Bis(trifluoromethane)sulfonimide lithium salt (Li-TFSI) in 1 mL of acetonitrile. The HTL solution was filtered using 0.45 micron syringe filters prior to deposition. The HTL was formed via spin coating at 3500 rpm for 30 s inside the glove box filled with nitrogen gas. The back electrodes were formed by thermal evaporation of 70 nm thick gold film on top of HTL. The evaporation was performed under the vacuum of 10<sup>-7</sup> Torr.

## References:

1. Z. Ren, K. Liu, H. Hu, X. Guo Y. Gao, P. W. K. Fong, Q. Liang, H. Tang, J. Huang, H. Zhang, M. Qin, L. Cui, H. T. Chandran, D. Shen, M.-F. Lo, A. Ng, C. Surya, M. Shao, C.-S. Lee, X. Lu, F. Laquai, Y. Zhu and G. Li, Room-temperature multiple ligands-tailored SnO<sub>2</sub> quantum dots endow in situ dual-interface binding for upscaling efficient

perovskite photovoltaics with high  $V_{oc}$ , *Light Sci. Appl.* 10, 239 (2021), <https://doi.org/10.1038/s41377-021-00676-6>

2. A. Ng, Z. Ren, H. Hu, P.W.K. Fong, Q. Shen, S.H. Cheung, P. Qin, J.-W. Lee, A. B. Djurišić, S.K. So, G. Li, Y. Yang, C. Surya, A Cryogenic process for antisolvent-free high-performance perovskite solar cells, *Adv. Mater.* 30 (2018) 1804402, <https://doi.org/10.1002/adma.201804402>