Open air slot-die technology: a platform for engineering high quality thin films for the development of perovskite PV modules with high efficiencies (POSTER)

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In photovoltaic industry, one of the major research focuses on transferring high performance cycle efficiency (PCE) reported for modules based on perovskite thin films – both single junction[1] and tandems[2] devices – from lab scale to industrial scale with minimal efficiency loss. One significant advantage of metal halides materials is their solution processing capability, which allows perovskite solar panels to be manufactured by vacuum free and low-cost technologies. Among these latter, slot-die has emerged as one of the most suitable approaches for the coating of a thin film over large area. In practice, to facilitate perovskite crystallization, Nitrogen gas flows (N2-knife) is widely used to control the drying of the wet film inducing therefore crystal nucleation and later thermal annealing is applied to favor crystal growth. However, the deposition of a homogeneous layer when combining slot-die and N2-knife remains challenging due to the complexity of perovskite crystallization: substrate pretreatment[3], the use of many additives, hot air[4] are some examples of strategies often used to overcome this issue.

Here we propose the vacuum flash method as alternative to N2-knife. We start our investigation using an ink based on a mixture of 2 solvents: dimethylformamide (DMF) which ensures precursors dissolution and *N*-methyl-2-pyrrolidone (NMP) for extending the coating window of the wet film. When using N2-knife, uniform film are obtained but it is associated with high N2 flow rate (>200 L/min) and low velocity (< 5 mm/s), which is detrimental for industrial production. On the contrary to N2-knife where many optimization tests were conducted, a ‘‘unform’’ film is quickly obtained when combining slot-die and the vacuum flash method. DMF and NMP possessing high boiling point, the DMF/NMP solvent ratio is tuned to favor solvent removal within the vacuum chamber: the intermediate phase formation shouldn't be too fast (regarding process reproducibility) and too long (regarding film properties). Ink engineering and deposition parameters experiment plans have been conducted to optimize the perovskite deposition based on various parameters (e.g. ink concentration, delay between coating and drying, vacuum quenching time, dispense rate, etc.). Double cation CsFA-based perovskite thin layer of 500 nm is obtained in ambient atmosphere: our optimized open-air slot-die conditions offer the possibility to obtain this thickness both on small (25 cm^2) and large surface (225 cm^2) with little variation (SEM, AFM, profilometer). Finally, semitransparent inverted p-i-n minimodules (FTO/NiO_x/CsFA perovskite/C_{60}/SnO_2/ITO) are fabricated using only industrializable processes, exhibiting a repeatable 15% efficiency on 64 cm^2 (active area).

1. Li, J., Zhu, S., Yin, C., Chen, C., Yuan, J., Zhao, H., ... & Bai, S. (2025). Homogenizing the Halogen Distribution via a Multifunctional Fluorine-Containing Additive Toward High-Performance Inverted Wide-Bandgap Perovskite Solar Cells. *Advanced Functional Materials*, *35*(22), 2422175.
2. Yang, D., Zhang, X., Hou, Y., Wang, K., Ye, T., Yoon, J., ... & Priya, S. (2021). 28.3%-efficiency perovskite/silicon tandem solar cell by optimal transparent electrode for high efficient semitransparent top cell. *Nano Energy*, *84*, 105934.
3. Cheng, Y., Xu, X., Xie, Y., Li, H. W., Qing, J., Ma, C., ... & Tsang, S. W. (2017). 18% high-efficiency air-processed perovskite solar cells made in a humid atmosphere of 70% RH. *Solar RRL*, *1*(9), 1700097.
4. Liu, Y., Shin, I., Hwang, I. W., Lee, J., Kim, S., Lee, D. Y., ... & Kim, K. H. (2017). Effective hot-air annealing for improving the performance of perovskite solar cells. *Solar Energy*, *146*, 359-367.