Sputtered NiO_x with SAM interlayer for Low-Temperature Processing of *p-i-n* Perovskite Solar Cells: Effect of Annealing Atmosphere and Temperature

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Ion-beam sputtering (IBS) is demonstrated as a robust, low-temperature route ($< 150\,^\circ$C) for depositing ultra-thin nickel oxide (NiO_x, < 10 nm) hole transport layers (HTLs) in inverted (*p-i-n*) perovskite solar cells (PSCs). Using a 3N ceramic NiO target, 8 nm NiO_x films were grown on ITO substrates and annealed at $150\,^\circ$C in ambient air or an inert glovebox atmosphere-compatible with flexible substrates or Si-heterostructures for tandems. Oxygen plasma treatment and an TPATC (5-[4-(diphenylamino)phenyl]thiophene-2-carboxylic acid) self-assembled monolayer (SAM) passivated non-stoichiometric surface traps. Champion PCE of 17.26 % ($V_{oc} = 1.067$ V, FF = 76.95 %) for glovebox-annealed IBS-NiO_x at $150\,^\circ$C closely matches the 17.36 % solution-processed reference requiring $300\,^\circ$C, establishing IBS as a scalable, temperature-compatible HTL deposition strategy.

Keywords: ion beam sputtering, NiO_x, hole transport layer, perovskite solar cells, low-temperature, self-assembled monolayer, oxygen plasma.

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