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Low-Temperature Solution-Processed $LaNiO_3$ Hole-Transport Layer for UV-stable Inverted Perovskite Solar Cells

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Experimental section

Synthesis of LNO NPs

The LNO NPs were prepared with a modified low-temperature solution-processed. In a typical procedure, $Ni(NO_3)_2 \cdot 6H_2O$ (50 mmol) , $La(NO_3)_3 \cdot 6H_2O$ (50 mmol) and citric acid were first dissolved in H_2O_2 water (30% H_2O_2) with ice bath, then a certain amount of ammonia was added as precipitating agent. The precipitates were then centrifuged and rinsed with DI water three times and vacuum-dried overnight at 100 °C. Finally, the dried powder was ground and sintered at 600, 650 and 700 °C for 2 hours to form LNO-1, LNO-2, LNO-3 NPs, respectively. The as-prepared LNO NPs are then dispersed in 2-methoxyethanol at 2 mg/mL and filtered (0.45 μm nylon filter). The LNO film is prepared by spin-coating the colloidal solution on the ITO at 4000 rpm for 30 s and annealed at 150 °C for 30 min. After that, a thin 2PACz film (3 mg/mL in ethanol) was spin-coated on LNO film at 8000 rpm for 30 s and annealed at 150 °C for 30 min.

Solar cell fabrication

First, perovskite precursor (1.5 M) consisting of PbI_2, FAI and MAI in a mixture of DMF and DMSO (4:1 v/v) with a perovskite formula as $FA_{0.4}MA_{0.6}PbI_3$ was filtered with 0.2 μm nylon filter and coated onto the ITO/LNO substrate by using one-step deposition method with EA anti-solvent with a speed of 5000 rpm for 30 s, followed by annealing at 120 °C for 15 min. After that, a thin PCBM (2 wt% in CB) was spin-coated at 3000 rpm for 30 s on top of the perovskite film and annealed at 100 °C for 10 min.

Finally, The BCP solution (0.5 mg/mL in IPA) was spin-coated at 4000 rpm for 30 s

on top of the PCBM layer, followed by the deposition of a 100 nm Ag electrode by thermal evaporation.

Characterizations

The X-ray diffraction (XRD) and the transmission electron microscope (TEM) characterizations of the LNO NPs were carried out with Bruker Advanced D8 X-ray diffractometer using Cu Kα (λ=0.154 nm) radiation and TEM, JEM-2100 (HR), JEOL Co.Ltd, respectively. The scanning electron microscope (SEM) characterization was obtained with FE-SEM, Hitachi SU8010. The UV-Vis spectra of the LNO film were measured with UV-2600 spectrophotometer (Shimadzu, Japan). The x-ray photoelectron spectroscopy (XPS) and ultraviolet photoelectron spectroscopy (UPS) characterizations of the LNO films were obtained with the Thermo Fisher ESCALAB 250XL (USA). The photoluminescence (PL) characterization and time-resolved photoluminescence (TRPL) of the perovskite films were carried out with DW-PLE03 (Fluo Time 300) at a 635 nm excitation wavelength. Photocurrent density–voltage *(J–V)* curves of PSCs were measured with a Keithley 2400 source meter under 1 sun-simulated illumination (AM 1.5 G, 100 mW $cm^{-2)}$ at a scan rate of 0.05 V s^{-1}. The external quantum efficiency (EQE) of the PSC was collected with a specialized EQE setup (Newport TLS130B-300X).

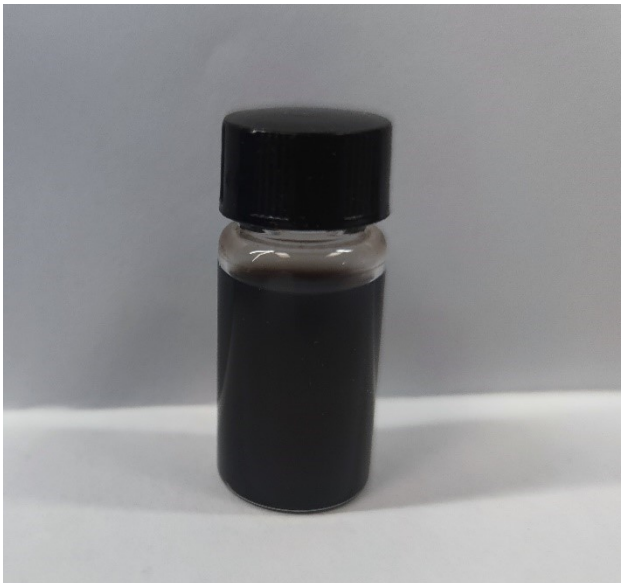

Figure S1. The LNO-2 NPs dispersed in

2ME at a concentration of 2 mg/mL.

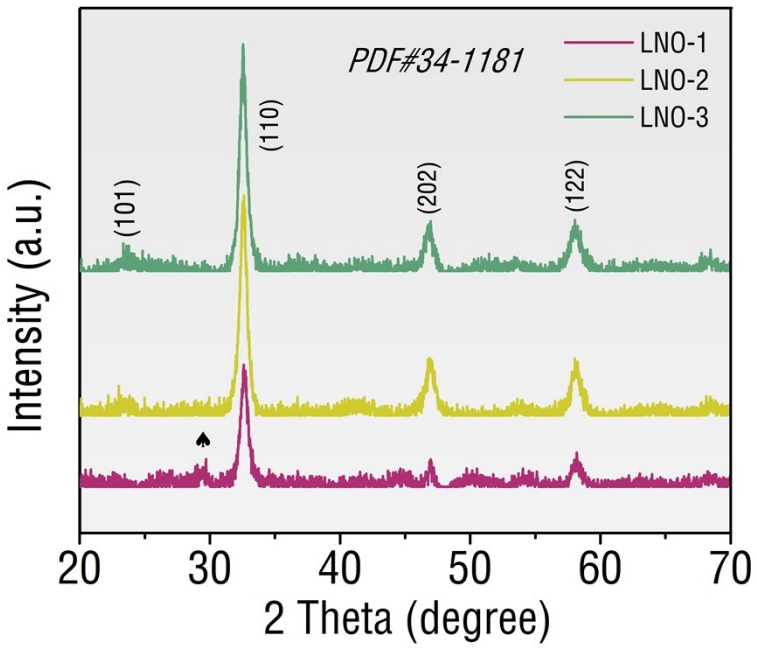

Figure S2. c) XRD spectra of the as prepared LNO-1, LNO-2 and LNO-3 NPs.

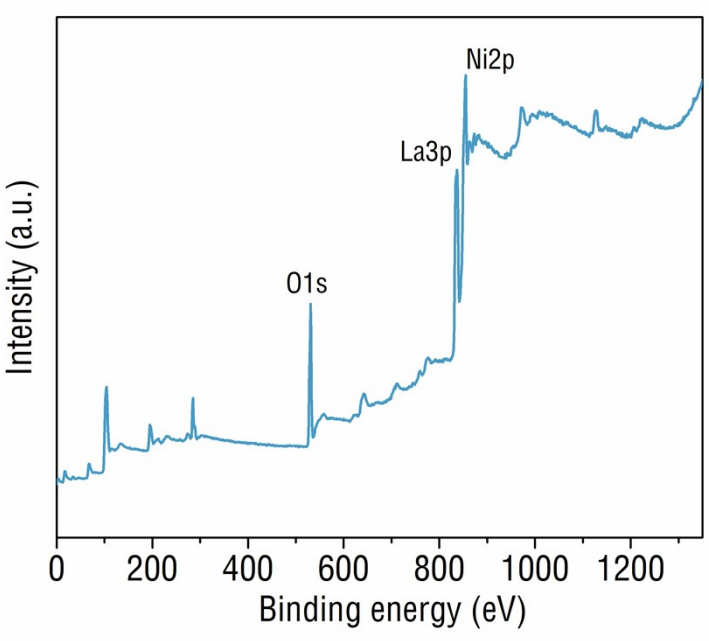

Figure S3.The survey XPS spectra of the LNO-2 NPs.

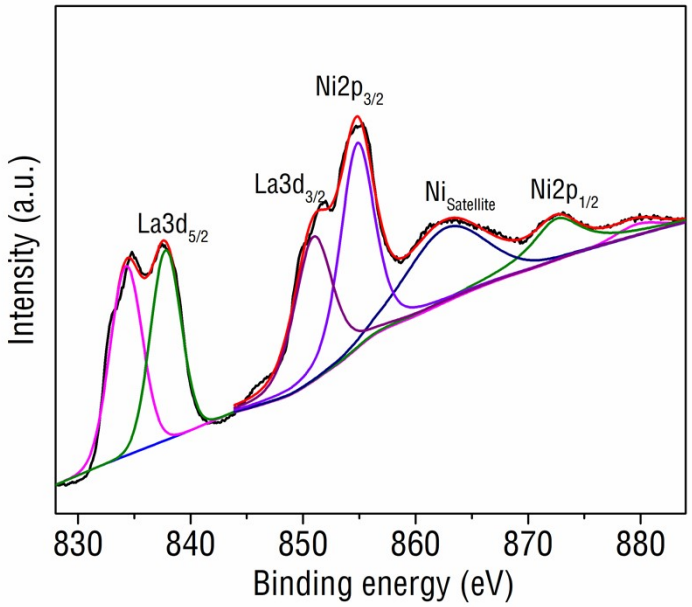

Figure S4.The overlapping La 3d, and Ni 2p XPS spectra of the LNO-2 NPs.

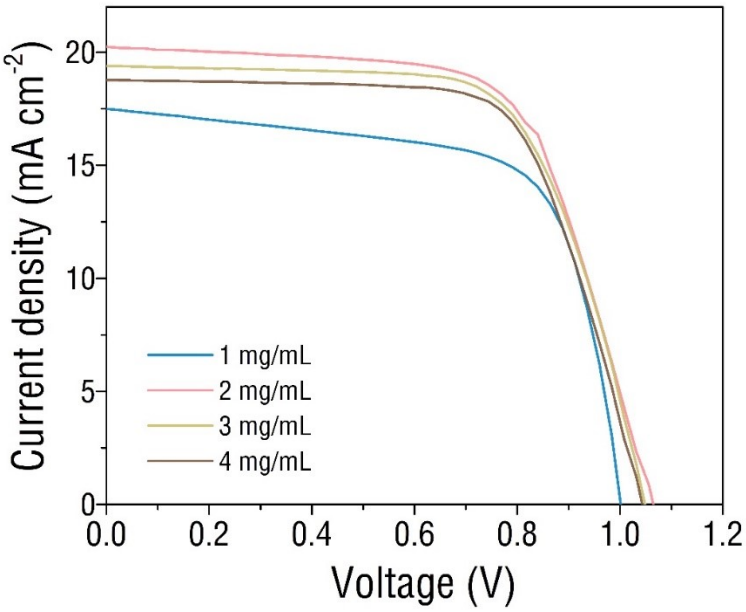

Figure S5. The *J–V* curves of devices with LNO HTL with different concentrations of colloidal solution at sintering temperature of 650℃.

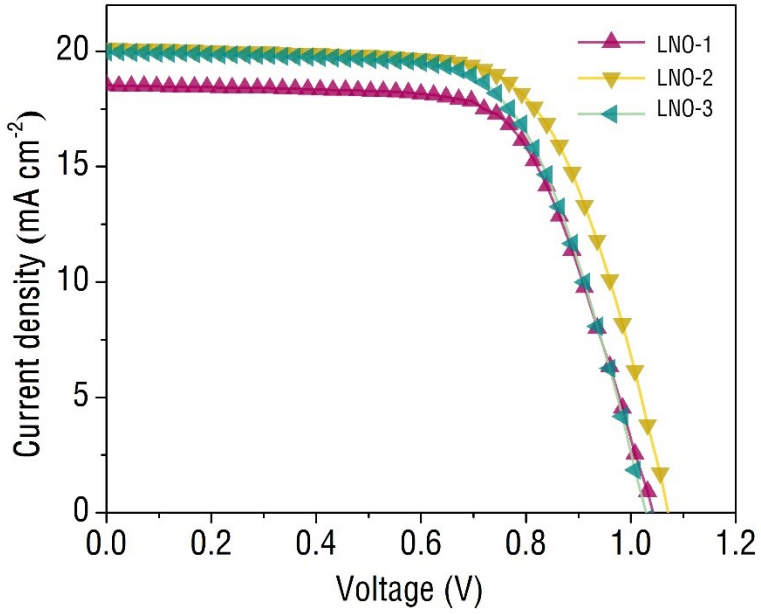

Figure S6. The representative *J–V c*urves of devices with three LNO HTLs at concentration of 2 mg/mL

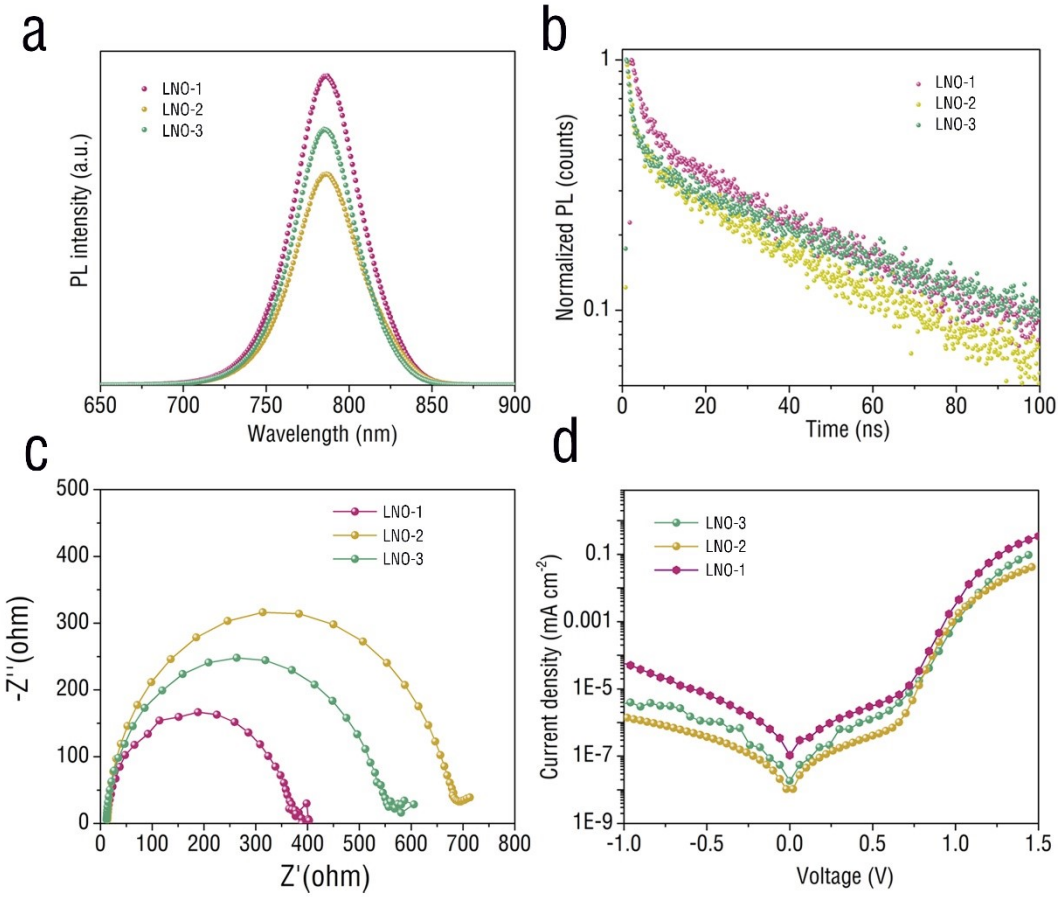

Figure S7. a) Normalized steady PL, b) TRPL, c) Nyquist plots, and d) dark *J–V* curves of the corresponding perovskite films on three different LNO HTL.

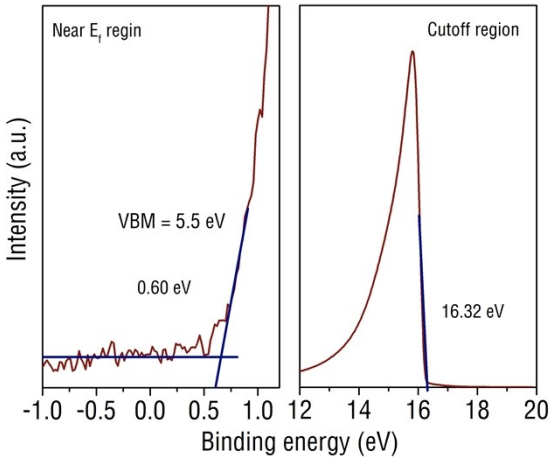

Figure S8. The UPS spectra of 2PACz on LNO HTL.

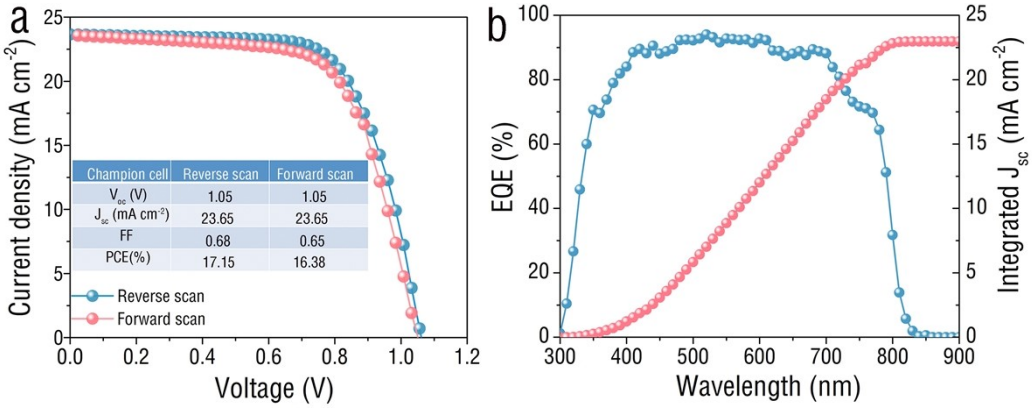

Figure S9. *J-V* curves and EQE spectra of the best-performed PSC with LNO-2 HTL with surface passivating of 2PACz.

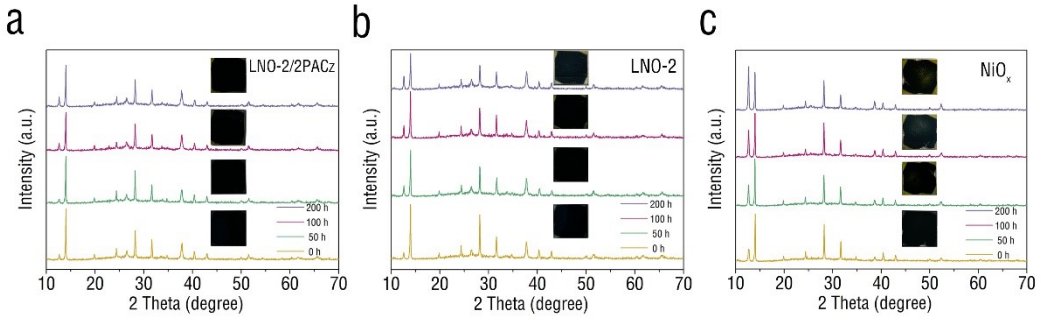

Figure S10. a-c) The evolution of XRD patterns and corresponding photographs of perovskite films deposited on different substrates under continuous UV light irradiance (365 nm, 8 W m^{-2}) in ambient atmosphere with 43% relative humidity.

Table S1 The device performances of LNO-2 at different concentrations

Concentrations (mg/mL)	J_{SC} [mA cm^{-2}]	V_{OC} [V]	FF	PCE [%]

1	17.49	1.01	0.67	11.86
2	20.24	1.06	0.65	13.98
3	19.39	1.05	0.69	13.64
4	18.77	1.03	0.69	13.39

Table S2 The device performances of LNO NPs at different sintering temperatures.

Substrates	J_{SC} [mA cm^{-2}]	V_{OC} [V]	FF	PCE [%]
LNO-1	18.55	1.04	0.67	12.91
LNO-2	20.13	1.07	0.67	14.39
LNO-3	19.97	1.03	0.66	13.52

Table S3 PL decay curves of corresponding perovskite films on LNO HTL at different sintering temperatures fitted by a bi-exponential function $I(t)= A1\exp(-t/\tau_1) + A2\exp(-t/\tau_2)$, and $\tau avg= \tau_1 \times (A1/A1+A2) + \tau_2 \times (A2/A1+A2)$

Substrates	A1/A1+A2 (%)	τ_1（ns）	A2/A1+A2 (%)	τ_2（ns）	τavg（ns）
LNO-1	65.75	34.25	5.00	64.60	56.90
LNO-2	29.72	70.27	3.49	45.95	44.63
LNO-3	66.17	33.83	3.68	60.56	54.54