Supplementary Information

Totally Room-temperature Solution-Processing Method for Fabricating Flexible Perovskite Solar Cells Using Nb₂O₅-TiO₂ Electron Transport Layer

Jun Jiang, Shubo Wang, Xuguang Jia, Xiang Fang, Shuai Zhang, Jing Zhang, Wei Liu, Jianning Ding*, Ningyi Yuan*

School of Materials Science and Engineering, Jiangsu Collaborative Innovation Center of Photovoltaic Science and Engineering, Jiangsu Province Cultivation Base for State Key Laboratory of Photovoltaic Science and Technology, Changzhou University, Changzhou 213164, Jiangsu China.

* Corresponding authors: dingjn@cczu.edu.cn; nyyuan@cczu.edu.cn
Fig. S1 Photo of TiO$_2$ particle distribution results from adding different concentrations of niobium ethoxide.
Fig. S2 (a) Bright-field HRTEM image of TiO$_2$ nanocrystals deposited on a carbon film. (b) A selected area electron diffraction of TiO$_2$ NCs. (c) Bright-field HRTEM image of Nb$_2$O$_5$-TiO$_2$ nanocrystals deposited on a carbon film. (d) A selected area electron diffraction of Nb$_2$O$_5$-TiO$_2$ NCs.
Fig. S3 Energy-dispersive spectroscopy (EDS) of the Nb$_2$O$_5$-TiO$_2$ film.
Fig. S4 SEM image of TiO$_2$ NCs films with over concentrations of niobium ethoxide (a) concentration of 30% and (b) concentration of 40%.
**Electron mobility of TiO\(_2\) and Nb\(_2\)O\(_5\)-TiO\(_2\)**

Electron-only devices (Fig. S5b) were fabricated to calculate the electron mobility of the samples, including TiO\(_2\) and Nb\(_2\)O\(_5\)-TiO\(_2\) by the SCLC. The PCBM solution was prepared in chlorobenzene (20 mg/mL), and spin-coated on FTO/glass at 3000 rpm, then annealed at 100 \(^\circ\)C for 15 min. The TiO\(_2\) and Nb\(_2\)O\(_5\)-TiO\(_2\) were deposited on PCBM surface. Sequentially, the PCBM films were fabricated on previous samples surface. The 100 nm-thick Ag were deposited. The dark \(J-V\) characteristics of the electron-only devices were measured by a Keithley 2400 source. The mobility is extracted by fitting the \(J-V\) curves by the Mott-Gurney.\(^1,2\)

Fig. S5 (a) The electron mobility measurement of TiO\(_2\) and Nb\(_2\)O\(_5\)-TiO\(_2\) from the space charge limitation of current (SCLC) \(J-V\) characteristics obtained in the dark for electron-only devices. (b) The sample structure for this measurement.
Figure S6 Device structure of the PSC.
Fig. S7 Cross-sectional SEM image of the PSC completed device.
Fig. S8 Top-view SEM images of CH$_3$NH$_3$PbI$_3$ perovskite films coated on the Nb$_2$O$_5$-TiO$_2$ films.
|                  | $V_{oc}(V)$ | $J_{sc}$ (mA/cm$^2$) | FF (%) | PCE (%) | $R_s$ ($\Omega \cdot \text{cm}^2$) | $R_{sh}$ (K$\Omega \cdot \text{cm}^2$) |
|------------------|-------------|----------------------|--------|---------|-----------------------------------|-----------------------------------|
| TiO$_2$          | 0.99        | 19.55                | 0.698  | 13.47   | 8.12                              | 1.30                              |
| 10% Nb$_2$O$_5$-TiO$_2$ | 1.00      | 20.14                | 0.711  | 14.27   | 7.46                              | 2.61                              |
| 15% Nb$_2$O$_5$-TiO$_2$ | 1.04      | 20.49                | 0.716  | 15.25   | 7.11                              | 2.61                              |
| 20% Nb$_2$O$_5$-TiO$_2$ | 1.04      | 20.13                | 0.701  | 14.56   | 7.37                              | 1.32                              |
| 30% Nb$_2$O$_5$-TiO$_2$ | 1.01      | 20.26                | 0.648  | 13.28   | 8.51                              | 1.19                              |
| 40% Nb$_2$O$_5$-TiO$_2$ | 1.00      | 19.56                | 0.604  | 11.86   | 10.71                             | 0.62                              |

Table S1 Photovoltaic performance of TiO$_2$ and Nb$_2$O$_5$-TiO$_2$ ETLs
|                        | Amplitude of $\tau_1$ (%) | $\tau_1$ (ns) | Amplitude of $\tau_2$ (%) | $\tau_2$ (ns) | $\tau_{\text{ave}}$ (ns) |
|------------------------|---------------------------|---------------|---------------------------|---------------|--------------------------|
| glass/perovskite       | 1.89                      | 1.05          | 98.11%                    | 429.50        | 49.40                    |
| TiO$_2$/perovskite     | 2.93%                     | 1.36          | 97.07%                    | 255.33        | 39.48                    |
| Nb$_2$O$_5$-TiO$_2$/perovskite | 11.68%                  | 0.92          | 88.32%                    | 223.58        | 7.60                     |

Table S2 Time resolved photoluminescence (TRPL) parameters based on the glass/perovskite, TiO$_2$/perovskite and Nb$_2$O$_5$-TiO$_2$/perovskite, respectively.
| R       | $V_{oc}$ (V) | $J_{sc}$ (mA/cm²) | FF (%) | PCE (%) |
|---------|-------------|------------------|--------|---------|
| ∞       | 0.99        | 20.04            | 0.69   | 13.60   |
| 10mm    | 0.97        | 19.92            | 0.67   | 13.03   |
| 5mm     | 0.94        | 19.45            | 0.58   | 10.70   |
| 3mm     | 0.82        | 13.75            | 0.30   | 3.39    |

Table S3 Photovoltaic parameters of the flexible PSCs obtained after recovery from bending at different radius (R).
References

(1) Goodman, A. M.; Rose, A. Double Extraction of Uniformly Generated Electron-Hole Pairs from Insulators with Noninjecting Contacts, J. Appl. Phys. 1971, 42(7), 2823-2830.

(2) Goh, C.; Kline, R. J.; McGehee, M. D.; Kadnikova, E. N.; Frechet, J. M. J. Molecular-weight-dependent mobilities in regioregular poly(3-hexyl-thiophene) diodes, Appl Phys. Lett. 2005, 86 (12), 122110.