# Highly Efficient and Stable Perovskite Solar Cells Enabled by All-Crosslinked Charge-Transporting Layers

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# Crossing Up Charge Extraction Layers

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**Photovoltaics based on low-temperature processed thin films are a promising technology for inexpensive renewable energy. The efficiency of thin-film solar cells is greatly influenced by the design of the materials that extract charge from the light-absorbing layer. These charge extraction layers are additionally a critical determinant of device stability. In this issue of *Joule*, Zhu and colleagues have developed crosslinked molecular charge extraction layers that enhance the environmental, thermal, and photo-stability of thin-film perovskite photovoltaics.**

Thin-film solar cells are an attractive alternative to widely used silicon photovoltaics (PV) due to their inexpensive and scalable fabrication methods. Solar cells based on thin films of copper indium gallium diselenide, cadmium telluride, or amorphous silicon are commercialized technologies with a total combined market share of 6% global PV production in 2016.[1] One of the more promising emerging materials to use as the absorbing layer for thin-film solar cells is the family of metal halide perovskites.[2] This class of materials has demonstrated high photovoltaic efficiency in both small lab-scale cells[3] and larger modules.[4] However, the stability of perovskites remains a persistent and considerable challenge for the research field.[5]

The stability of a solar cell in the presence of moisture, elevated temperature, and illumination is a critical consideration for commercial applications. Stability is typically achieved in three ways: (1) improving the intrinsic stability of the active material, (2) engineering more stable architectures and interfaces, and (3) device encapsulation. Progress on each of these fronts over the last few years has continued to push the boundaries of stability in perovskite photovoltaics, but there are still many challenges to overcome, and new strategies are needed.

In this issue of *Joule*, Zhu and colleagues have developed crosslinked molecular charge extraction layers for perovskite solar cells that exhibit enhanced stability under moisture, heat, and illumination.[6] Charge extraction layers are a component in thin-film solar cell architectures that facilitate the transfer and transport of photocarriers to the electrodes and external circuit. They are a critical component for achieving high efficiency and, additionally, if unstable under operating conditions they can limit the overall stability of the cell. Conversely, if these materials are resistant to environmental conditions, they can act as effective self-encapsulants that protect the active material and can further passivate unstable interfaces.

The authors have recently synthesized a series of hexaazatrinaphthylene (HATNA) organic small molecule materials as an alternative to common fullerene-based electron extraction layers.[7] These materials exhibit excellent band structure tunability and can be controllably doped to optimize their properties for photovoltaics. Motivated by the need to improve the stability of perovskite solar cells, here they develop a low-temperature method to polymerize crosslinked HATNA (c-HATNA) into a robustly stable electron extraction layer. By incorporating pentaerythritol tetrakis(3-mercaptopropionate) (PETMP) into the polymerization reaction, the crosslinking temperature is greatly reduced to 110°C. To improve the electronic transport properties of c-HATNA, they show that it can successfully be doped n-type using triethylamine, increasing the electron mobility by over an order of magnitude.

The authors then deposited an optimized 150 nm layer of c-HATNA as the top electron extracting electrode in a planar p-i-n architecture: ITO/NiO/perovskite/c-HATNA/bis-$C_{60}$/Ag. The perovskite composition used in this study is the pure-phase of $MAPbI_3$. Water droplets placed on top of the device do not result in any visible degradation, unlike a control top electrode based solely on bis-$C_{60}$. The best-performing solar cell exhibited a stabilized power conversion efficiency (PCE) of 18%. In an inert environment and with repeated heating at 70°C, there is no significant performance degradation observed over 1,000 hr. For a more rigorous test, the devices are then tested in air at 50% relative humidity under constant solar irradiation and with repeated heating to 70°C. These cells maintain 90% of their initial PCE after 100 hr of testing, where the control devices based on bis-$C_{60}$ had almost completely degraded after 10 hr. Devices based on c-HATNA hole extraction layers further show excellent repeatability—through a study of 50 devices, 80% had demonstrated a power conversion efficiency greater than 16%.

This combination of both high efficiency and robust stability without encapsulation is excellent, particularly for the pure $MAPbI_3$ perovskite, which almost entirely degrades within minutes of

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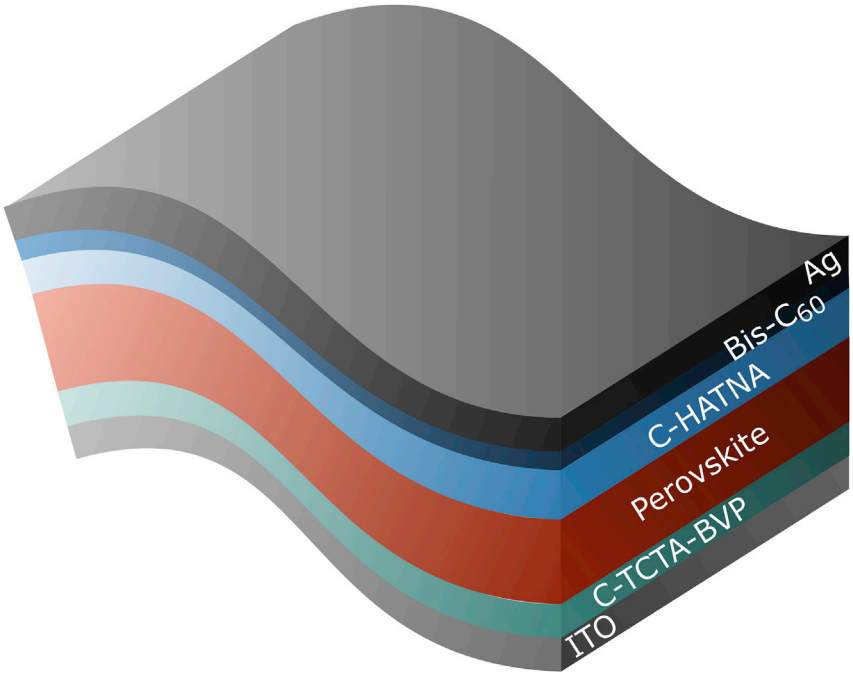


**Figure 1. A Schematic of a Flexible Planar p-i-n Perovskite Solar Cell Using Low-Temperature Processed All-Crosslinked Charge Extraction Layers**

heating at elevated temperatures.[8] To further demonstrate the potential and broad applications of crosslinked extraction layers, the authors replace the NiO hole transporting layer with c-TCTA-BVP, a p-type crosslinked material. This forms a perovskite solar cell with all-crosslinked charge extraction layers. This device, again, shows excellent stability in reference to the control cell based on NiO and bis-$C_{60}$. Additionally, since the crosslinking temperature of these layers is well below the thermal budget for most non-rigid substrates, they are able to fabricate a flexible device (see Figure 1) with a PCE of 13% and greatly enhanced stability.

This work by Zhu and colleagues has demonstrated the potential of crosslinked organic molecules in stable and efficient perovskite solar cells. Investigations of perovskite solar cell stability most commonly focus on moisture resistance, with less emphasis placed on thermal or photo-induced degradation. This work motivates more studies to look at all three simultaneously and develop new approaches that show benefit across all forms of stability. Many leading-performing perovskite photovoltaics still rely on relatively unstable top transport layers, such as Spiro-OMeTAD. There is a wide space of crosslinkable materials with tunable properties and promising stability still to be explored.

1. Fraunhofer Institute for Solar Energy Systems. (2017). Photovoltaics Report. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

2. Grätzel, M. (2017). The rise of highly efficient and stable perovskite solar cells. Acc. Chem. Res. *50*, 487–491.

3. Yang, W.S., Park, B.W., Jung, E.H., Jeon, N.J., Kim, Y.C., Lee, D.U., Shin, S.S., Seo, J., Kim, E.K., Noh, J.H., and Seok, S.I. (2017). Iodide management in formamidinium-lead-halide-based perovskite layers for efficient solar cells. Science *356*, 1376–1379.

4. Liao, H.-C., Guo, P., Hsu, C.-P., Lin, M., Wang, B., Zeng, L., Huang, W., Soe, C.M.M., Su, W.-F., Bedzyk, M.J., et al. (2017). Enhanced efficiency of hot-cast large-area planar perovskite solar cells/modules having controlled chloride incorporation. Adv. Energy Mater. *7*, 1601660.

5. Leijtens, T., Bush, K., Cheacharoen, R., Beal, R., Bowringa, A., and McGehee, M.D. (2017). Towards enabling stable lead halide perovskite solar cells; interplay between structural, environmental, and thermal stability. J. Mater. Chem. A. *5*, 11483–11500.

6. Zhu, Z., Zhao, D., Chueh, C.-C., Shi, X., Li, Z., and Jen, A.K.-Y. (2017). Highly efficient and stable perovskite solar cells enabled by all-crosslinked charge-transporting layers. Joule *2*, this issue, 168–183.

7. Zhao, D., Zhu, Z., Kuo, M.-Y., Chueh, C.-C., and Jen, A.K.-Y. (2016). Hexaazatrinaphthylene derivatives: efficient electron-transporting materials with tunable energy levels for inverted perovskite solar cells. Angew. Chem. Int. Ed. *55*, 8999–9003.

8. Fan, Z., Xiao, H., Wang, Y., Zhao, Z., Lin, Z., Cheng, H.-C., Lee, S.-J., Wang, G., Feng, Z., Goddard, W.A., III, et al. (2017). Layer-by-layer degradation of methylammonium lead tri-iodide perovskite microplates. Joule *1*, 548–562.