

Previews

Navigating the path to stability in perovskite solar cells

So Min Park^{1,2,*} and Edward H. Sargent^{1,2,3,*}

Developing accurate and actionable physical models of degradation mechanisms in perovskite solar cells (PSCs) will be essential to developing bankable technologies. Princeton researchers have recently shown that the temperature-dependent degradation of all-inorganic PSCs follows the Arrhenius equation and mechanistically assigned the leading cause of degradation to iodide diffusion. With an ion-blocking two-dimensional capping layer, they achieve a projected 5 years of operating stability for PSCs based on an accelerated aging model.

Among solar cell technologies, perovskites are candidates of interest: they have seen rapid improvement in power conversion efficiency (PCE), solution-processed fabrication using earth-abundant elements, tuning of bandgap relevant to multi-junction solar cells, and promise in semi-transparent and flexible devices for building-integrated photovoltaics (BIPVs) and portable power devices.

Of remaining concern is stability under stress, such as temperature, light exposure, humidity, and electric fields.¹ The perovskite (ABX₃) photoactive layer itself is one factor (here A represents a monovalent cation such as methylammonium [MA⁺], formamidinium [FA⁺], cesium [Cs⁺], or a combination thereof; B corresponds to Pb²⁺ or Sn²⁺; and X stands for halides such as Cl⁻, Br⁻, or I⁻). Organic cations may contribute to thermal decomposition, while both A- and X-site ions have low activation energies for ion migration.² Phase transitions and halide segregation further contribute to perovskite degradation—activated by water molecules and photons.³ Materials interfaces also offer degradation pathways related to a low energy associated with defect formation,⁴ as well as a propensity to adsorb moisture and oxygen.⁵ The charge-transport layers (CTLs) and elec-

trodes can see chemical reactions, morphology changes, and ion diffusion.⁶

To address PSC degradation, researchers have focused on developing stable perovskite compositions, improving interface passivation,⁷ and developing more robust CTLs and electrodes. It will be important to give evidence that the lifespan of PSCs can match the 25–40 years operating time demanded of solar modules.⁸ This calls for the implementation of accelerated aging tests capable of projecting the stability of PSCs under realistic outdoor conditions.

Within the PV industry, there exist well-established standards tailored specifically for evaluating the long-term stability of commercial silicon and thin-film solar modules, e.g., the International Electrotechnical Commission (IEC) 61215 qualifications. Nevertheless, the criteria set by IEC 61215, such as thermal cycling and damp-heat tests, may not capture all the physics at play in PSCs, for perovskites' ionic nature may lead to new degradation pathways under illumination and electric fields. The International Summit on Organic Photovoltaic Stability (ISOS) tests have thus been proposed for a more complete assessment of emerging PV technologies.⁹ For PSCs, ISOS-L-3 is the most stringent protocol, one that com-

bines several key stressors, including continuous light exposure, temperature, and humidity, while testing devices under maximum power point (MPP) tracking. ISOS tests provide a platform for comparing stability results across different research labs, yet they need to be qualified as a predictive tool to estimate the field lifetime of PSCs at standard operating conditions. A key challenge relates to understanding the physical picture of the degradation processes themselves.

In a recent article published in *Science*, Zhao and colleagues conducted accelerated aging tests on PSCs using ISOS-L-3 protocols at elevated temperatures (Figure 1).¹⁰ They determined acceleration factors in PSCs and extrapolated the operating lifetime to one exceeding 5 years under continuous 1-sun illumination at 35°C. To make more stable devices, the authors focused on all-inorganic CsPbI₃ perovskites as the active layer, thus avoiding organic cation decomposition. They further identified a stable device materials stack, using TiO₂/Al₂O₃ and CuSCN as CTLs along with Cr/Au as the top electrode. To passivate interfaces, they applied a two-dimensional (2D) Cs₂PbI₂Cl₂ perovskite capping layer by treating the CsPbI₃ surface with a CsCl solution. Grazing-incidence wide-angle X-ray scattering (GIWAXS) measurements indicated a 2D-related crystalline structure in the capping layer. This ~20 nm thick layer on the top surface of the

¹Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, ON M5S 3G4, Canada

²Department of Chemistry, Northwestern University, Evanston, IL 60208, USA

³Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL 60208, USA

*Correspondence: ted.sargent@utoronto.ca (E.H.S.), somins.park@utoronto.ca (S.M.P.)

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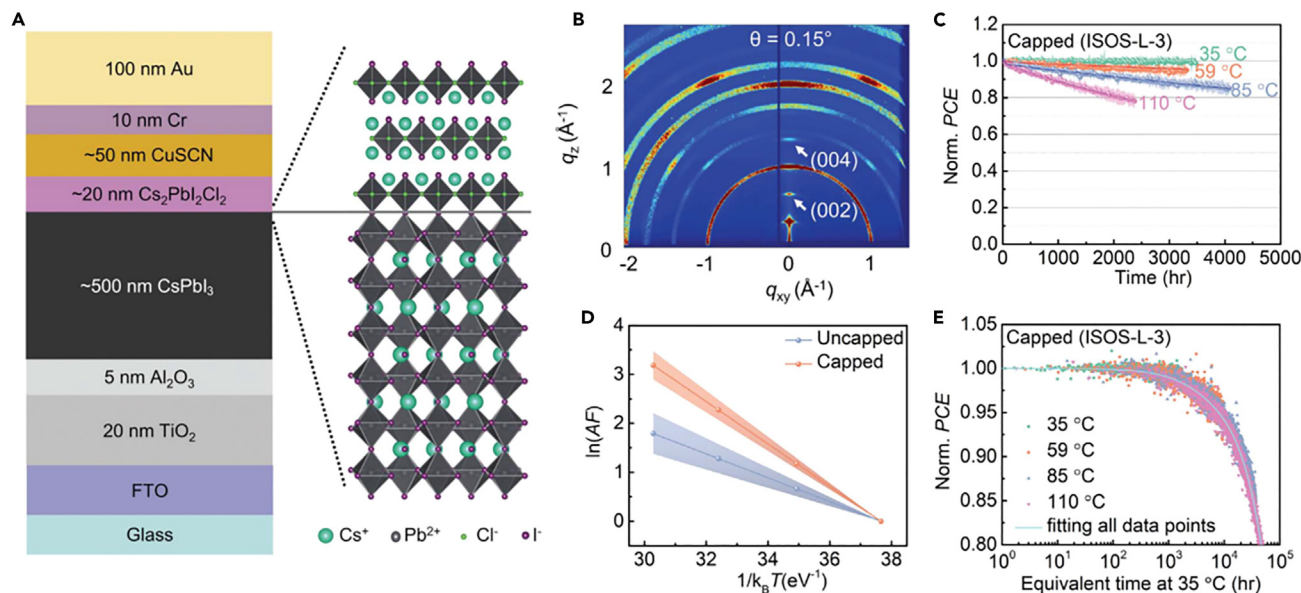


Figure 1. Illustration and characterization of two-dimensional $\text{Cs}_2\text{PbI}_2\text{Cl}_2$ capped device architecture and accelerated aging of PSCs

(A) Representation of the device architecture and crystal structure of 2D $\text{Cs}_2\text{PbI}_2\text{Cl}_2$ and 3D CsPbI_3 layer.

(B) GIWAXS patterns of 2D $\text{Cs}_2\text{PbI}_2\text{Cl}_2$ capped perovskite film at an incident angle of 0.15° .

(C) Operational stability of 2D $\text{Cs}_2\text{PbI}_2\text{Cl}_2$ capped PSCs under thermal stress.

(D) Natural logarithm of AF versus $1/k_B T$.

(E) A plot of the normalized PCE of capped PSCs versus the equivalent aging time at 35°C .

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perovskites enhanced the PCE from 14.9% to 17.4% via surface passivation.

To evaluate the stability of 2D-capped PSCs, the authors carried out MPP tracking under continuous 1-sun illumination at four different temperatures, 35°C , 59°C , 85°C , and 110°C , and $\sim 65\%$ relative humidity, aligned with the ISOS-L-3 protocol. They found that 2D-capped devices retained their initial performance for over 3,500 h of continuous operation at 35°C . Performance degradation was observed at high temperatures, with a T_{80} (time to reach 80% of the initial performance) of 2,100 h at 110°C . The authors sought to calculate the acceleration factor, the means to relate the lifespan in accelerated tests with that projected under milder field operating conditions. They analyzed the time-dependent degradation of the PCE at different temperatures and found a biexponential pattern in PCE degradation, characterized by two distinct decay constants: k_{fast} and k_{slow} . The constants follow a simple Arrhenius

relationship with temperature: the activation energy E_a in the Arrhenius equation can be derived for each decay constant across the entire temperature range. The authors then calculated an acceleration factor (AF) of 24.2 at 110°C . This corresponds to a T_{80} of 51,000 h at 35°C , a more than five-year device stability under continuous 1-sun illumination at 35°C .

These findings highlight the promise of all-inorganic PSCs and suggest that a principal degradation mechanism accounts for performance change across temperatures ranging from 35°C to 110°C . Using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), and scanning electron microscope (SEM), the authors identified this as morphological and structural changes in the CuSCN layer, induced by iodide diffusion from the perovskites. Further investigation revealed that the 2D capping layer suppresses ion migration, thereby stabilizing the CuSCN layer and enhancing the operating stability of the device.

This study is a milestone in establishing ISOS protocols as a methodology for assessing long-term stability under reference conditions and is relevant to future PSC industrialization. Accelerated aging offers insights into the mechanistic picture of degradation in PSCs. Specifically, this work links the deterioration of CTLs to the intrinsic stability of all-inorganic PSCs, underlining the importance of interface passivation, which sets the stage for continued progress.

The accelerated aging approach will benefit from further use in outdoor testing. Challenges remain for stability evaluation of more efficient PSCs that rely on organic cations and CTLs, as their degradation pathways tend to be more complex. In such scenarios, it is unlikely that a single Arrhenius equation would be sufficient for the determination of acceleration factors. Beyond intrinsic degradation, extrinsic factors, such as encapsulation and interconnections within modules, also impact device stability. This requires the rational

selection of ISOS protocols for more thorough evaluation at both the device and module levels.

Overall, as PSCs strive to reach a level of stability suitable for commercial use, a multidisciplinary approach to durability science—one uniting material design, advanced characterization, device engineering, and mechanistic understanding—will guide further stability enhancement. The strategy will support deployment in a wider range of optoelectronic devices, including light-emitting diodes, photodetectors, and quantum information.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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Controllable thermal energy storage by electricity for both heat and cold storage

Xiaoxue Kou¹ and Ruzhu Wang^{1,*}

Beyond heat storage pertinent to human survival against harsh freeze, controllable energy storage for both heat and cold is necessary. A recent paper demonstrates related breakthroughs including (1) phase change based on ionocaloric effect, (2) photoswitchable phase change, and (3) heat pump enabled hot/cold thermal storage.

Along with the ambitious targets and commitments toward carbon neutrality, the unstable game of supply and demand, exacerbated by the high share of renewable energy, is of great concern. As heating and cooling ac-

count for about 50% of total energy consumption (according to the International Energy Agency, IEA), the pivotal role of thermal energy storage is most clearly brought to the fore. More attention has long been paid to heat storage

pertinent for human survival against harsh freeze, while less has been paid to cold storage to counter hyperthermia. The advent of climate change, involving global warming and extreme weather leading to heat exposure, as well as mankind's pursuit of thermal comfort, are driving a boom in the demand for cold storage.

Globally, about 33% of households utilize both heating and cooling every year (78% in Europe, 56% in North America, and 80% in China) (IEA).

¹Institute of Refrigeration and Cryogenics, MOE Engineering Research Center of Solar Power and Refrigeration, Shanghai Jiao Tong University, Shanghai 200240, China

*Correspondence: rwang@sjtu.edu.cn
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