Supplementary Materials for

Lead-adsorbing ionogel-based encapsulation for impact-resistant, stable, and lead-safe perovskite modules

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Supplementary Methods:

Fabrication of MA$_{0.7}$FA$_{0.3}$PbI$_3$ perovskite solar modules and solar cells: The devices were fabricated according to our previous reports. Patterned ITO glass substrates (1.5 cm × 1.5 cm for solar cells, and 13.0 cm × 8.5 cm for solar modules) were first cleaned by ultrasonication with soap, DI water and IPA, and then UV-ozone treated for 15 min before use. All perovskite solar devices were prepared by blade-coating at room temperature inside a fume hood. The hole-transporting PTAA layer with a concentration of 3.3 mg mL$^{-1}$ dissolved in toluene was blade-coated onto ITO glass substrates at a speed of 20 mm s$^{-1}$. The gap between blade-coater and ITO substrates was 150 µm. The perovskite precursor solutions (2.5 M MAPbI$_3$ and 1.67 M FAPbI$_3$) were prepared separately by dissolving corresponding organic halides and lead iodide in 2-ME and stored in a N$_2$-filled. Before blade-coating, the MAPbI$_3$ and FAPbI$_3$ precursor solutions were mixed and diluted to a 1.37 M MA$_{0.7}$FA$_{0.3}$PbI$_3$ solution, and 1.35 mg mL$^{-1}$ BHC, 0.83 mg mL$^{-1}$ n-dodecylammonium iodide, 0.27 mg mL$^{-1}$ LP, 0.14% v/v MAH$_2$PO$_2$, 1.40 mg mL$^{-1}$ p-F-PEAI, 2.8% v/v DMSO were added into the precursor solution as additives. Subsequently, the precursor solution was blade-coated onto the PTAA-covered ITO glass substrates with a gap of 250 µm at a movement speed of 20 mm s$^{-1}$. The N$_2$ knife worked at 20 psi during blade-coating. After that, the perovskite films were annealed at 120 °C for 5 min in air. The solar cells were completed by thermally evaporating C$_{60}$ (30 nm, 0.2 Å s$^{-1}$), BCP (6 nm, 0.1 Å s$^{-1}$) and 100 nm copper (1 Å s$^{-1}$). The fabrication of mini-modules followed the same procedure of the solar cells. Laser scribing was performed twice before and after electrode deposition to complete the module fabrication. The fabricated modules have 10 subcells, and each subcell has a width of 6.5 mm. The total scribing line width was 0.4-0.6 mm, giving a geometry filling factor of 90-94%.

Fabrication of FA$_{0.92}$Cs$_{0.08}$PbI$_3$ perovskite films for solar cells: The FA$_{0.92}$Cs$_{0.08}$PbI$_3$ perovskite was prepared by dissolving FAPbI$_3$ and CsPbI$_3$ with a ratio of 1 : 0.09 in a mixture solution of 2-ME and DMSO. Before blade-coating, methylammonium chloride (MACl), phenylethylammonium chloride (PEACl), and cesium iodide(CsI) were added into the solution as additives at molar percentages of ~1.5%, ~0.15%, and ~0.3% to Pb$^{2+}$, respectively. Subsequently, the precursor solution was blade-coated onto the PTAA-covered ITO glass substrates with a gap of 250 µm at a movement speed of 20 mm s$^{-1}$ with the assistant of an N$_2$ knife. The as-coated film was annealed at 150 °C in air for 2-5 mins.

Supplementary Notes 1

The estimated material cost for the ionogel layer: Combining the estimated usage for 100 µm thick ionogel (~60 g TPDP m$^{-2}$; ~40 g AA m$^{-2}$; ~0.1 g MBAA m$^{-2}$; ~0.1 g AIBN m$^{-2}$) and quotation of raw materials from industrial vendors with large amount ($845 for 10 kg TPDP; $300 for 1000 kg AA; $8 for 1 kg MBAA; $5 for 1 kg AIBN), the cost could be calculated to be ~5.08 $ m$^{-2}$, which is still more expensive than commercialized EVA (~1.1 $ m^{-2}$) and POE (~1.7 $ m^{-2}$) films (obtained from Firstpv company report). The unit price might be reduced if the ionogel could be industrialized as EVA or POE. It should be noted that it is much cheaper compared to Bynel or Surlyn (119.2 $ m^{-2}$) and below half of the reported self-healing polymer (12.3 $ m^{-2}$). The unit price for Bynel or Surlyn is first quoted from the vendor of 200 mm × 300 mm for $28.1, which is then estimated by a discount of 90% of unit price when doubling the order amount. For 500 m$^2$
Bynel or Surlyn order, the unit price is 119.2 $ m^{-2}. The cost for the self-healing polymer is obtained from the reference².

Supplementary Notes 2

**Ionogel based encapsulation of perovskite modules (structure C):** The structure of ionogel based encapsulation is PDMS/Ionogel/perovskite devices on ITO glass/POE/Ionogel/glass cover. The top 300 µm-thick PDMS layer has two functions: 1. light anti-reflection to enhance device efficiency; 2. protect the ionogel from ambient contaminant. The 100 µm-thick ionogel between PDMS and ITO glass is to provide mechanical impact resistivity and lead adsorbing capability on the top side. POE layer is to separate ionogel and perovskite devices before curing because the uncured ionogel would damage perovskite devices. The POE layer also provides encapsulation to the devices. Ionogel between POE and bottom 1.1 mm heat-strengthened glass cover further enhances mechanical integrity and lead adsorbing capability from the bottom side.
Fig. S1. Chemical structures of materials used in PAA ionogel.

monomer: AA
covalent crosslinker: MBAA

ionic liquid: TPDP
thermo-initiator: AIBN
Fig. S2. Mechanical properties of ionogels. (a) tensile curve of ionogel, (b) tensile curve of self-healed ionogel.
Fig. S3. Images of ionogels. (a) pristine and (b) under stretching. Photo credit: Meixiang Wang, North Carolina State University.
Fig. S4. Adhesion of glass with ionogel to metal balls after broken and storage in ambient for 85 days. Photo credit: Xun Xiao, University of North Carolina Chapel Hill.
**Fig. S5. Material costs of various encapsulants.** Prices for EVA, POE and Bynel or Surlyn are quoted from industrial vendors. Self-healing polymers cost is from reference². Materials cost for ionogel is calculated based on quotation from raw material vendors and usage as described. The price is applied as quoted without further negotiation.
Fig. S6. Lead adsorption kinetics fitted by pseudo-first-order model with equation of

$$\ln(q_e - q_t) = \ln q_e - kt.$$
Fig. S7. Adsorption isotherm fitted with Langmuir model \( \frac{c_e}{q_e} = C_e \times \frac{1}{q_{max}} + \frac{1}{K_L q_{max}} \).
Fig. S8. Statistic results of device parameters for small cells (a-c) and modules (d-f).
Fig. S9. Temperature evolution for one cycle in thermal cycling test.
Fig. S10. Water dripping test results for damaged modules with different structures.
Fig. S11. Reducing lead leakage scheme under extreme damage.
**Fig. S12.** Lead leakage status under impact test. Broken modules with structure A (a), B (b) and C (c) images after destructive impact and soaking in DI water for a certain time. Photo credit: Xun Xiao, University of North Carolina Chapel Hill.
Fig. S13. Lead leakage status under severe hail test of 8 metal ball shots per module.
Table S1. Isotherm parameters of pseudo-second-order model.

|                  | Pesudo-first-order |                        | Pesudo-second-order |                        |
|------------------|--------------------|------------------------|---------------------|------------------------|
| q_e (mmol/g)     | K_1 (min^{-1})     | R^2                    | q_e (mmol/g)        | K_2 (g mmol^{-1} min^{-1}) | R^2       |
| 1.18             | 0.69               | 0.839                  | 1.46                | 1.64                   | 0.927     |

Movie S1.
Ionogel adhesive test with metal balls.

Movie S2.
Bare glass, and glass with ionogel attached were hit by a metal ball (8.36 g, diameter of 0.5 inch) dropped from a height of 2 m.

Movie S3.
Encapsulated perovskite modules with various encapsulation methods were hit by a metal ball (64 g, diameter of 1 inch) dropping from a height of 2 m.

Movie S4.
Extreme loading with a car on encapsulated perovskite films.