REVIEW SUMMARY

SOLAR CELLS

Challenges for commercializing perovskite solar cells

Yaoguang Rong*, Yue Hu*, Anyi Mei*, Hairen Tan, Makhsud I. Saidaminov, Sang Il Seok†, Michael D. McGehee†, Edward H. Sargent†, Hongwei Han†

BACKGROUND: Perovskite solar cells (PSCs) have attracted intensive attention because of their ever-increasing power conversion efficiency (PCE), low-cost materials constituents, and simple solution fabrication process. Initiated in 2009 with an efficiency of 3.8%, PSCs have now achieved a lab-scale power conversion efficiency of 23.3%, rivaling the performance of commercial multicrystalline silicon solar cells, as well as copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) thin-film solar cells. Thousands of articles related to PSCs have been published each year since 2015, highlighting PSCs as a topic of intense interest in photovoltaics (PV) research. With high efficiencies achieved in lab devices, stability and remaining challenges in upscaling the manufacture of PSCs are two critical concerns that must be addressed on the path to PSC commercialization.

ADVANCES: We review recent progress in PSCs and discuss the remaining challenges along the pathway to their commercialization. Device configurations of PSCs (see the figure) include mesoscopic formal (n-i-p) and inverted (p-i-n) structures, planar formal and inverted structures, and the printable triple mesoscopic structures. PCEs of devices that use these structures have advanced rapidly in the case of small-area devices (~0.1 cm^2). PSCs are also attracting attention as top cells for the construction of tandem solar cells with existing mature PV technologies to increase efficiency beyond the Shockley-Queisser limit of single-junction devices.

The stability of PSCs has attracted much well-deserved attention of late, and notable progress has been made in the past few years. PSCs have recently achieved exhibited lifetimes of 10,000 hours under 1 sun (1 kW/m^2) illumination with an ultraviolet filter at a stabilized temperature of 55°C and at short-circuit conditions for a printable triple mesoscopic PSCs. This irradiation is equivalent to the total irradiation of 10 years of outdoor use in most of Europe. However, within the PSC community, standard testing protocols require further development. In addition, transparency in reporting standards on stability tests needs to be improved; this can be achieved by providing both initial photovoltaic performance and normalization parameters.

The upscaling of PSCs has also progressed steadily, leading to PSC mini-modules, standard-sized modules, and power systems. PV companies have set out to manufacture large-area PSC modules (see the figure), and a 110-m^2 perovskite PV system with screen-printed triple mesoscopic PSC modules was recently debuted. Studies of these increased-area modules and systems will promote the development of PSCs toward commercialization. PSC research is expanding to cover fundamental topics on materials and lab-sized cells, as well as to address issues of industrial-scale manufacturing and deployment.

OUTLOOK: The PV market has been continuously expanding in recent years, bringing opportunities for new PV technologies of which PSCs are promising candidates. It is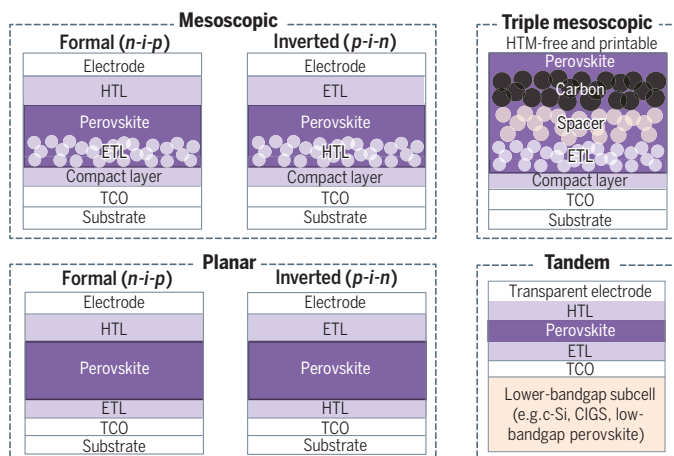 imperative to achieve a low cost per watt, which means that both efficiency and lifetime need improvement relative to current parameters. The efficiency gap between lab cells and industrial modules has seen impressive reductions in crystalline silicon; PSCs must similarly enlarge module areas to the panel level and need to achieve lifetimes comparable to those of legacy PV technologies. Other improvements will need to include industry-scale electronic-grade films, recycling methods to address concerns regarding lead toxicity, and the adoption of standardized testing protocols to predict the operation lifetime of PSCs. Modules will need to endure light-induced degradation, potential-induced degradation, partial-shade stress, and mechanical shock. The field can benefit from lessons learned during the development of mature PV technologies as it strives to define, and overcome, the hurdles to PSC commercial impact. ■

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Configurations and application demonstration of PSCs. PSCs have been developed in various device configurations, including mesoscopic, planar, triple mesoscopic, and tandem structures. Recently, a 110-m^2 perovskite PV system with printable triple mesoscopic PSC modules (3600 cm^2 for each) was launched by WonderSolar in China.

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Challenges for commercializing perovskite solar cells

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Perovskite solar cells (PSCs) have witnessed rapidly rising power conversion efficiencies, together with advances in stability and upscaling. Despite these advances, their limited stability and need to prove upscaling remain crucial hurdles on the path to commercialization. We summarize recent advances toward commercially viable PSCs and discuss challenges that remain. We expound the development of standardized protocols to distinguish intrinsic and extrinsic degradation factors in perovskites. We review accelerated aging tests in both cells and modules and discuss the prediction of lifetimes on the basis of degradation kinetics. Mature photovoltaic solutions, which have demonstrated excellent long-term stability in field applications, offer the perovskite community valuable insights into clearing the hurdles to commercialization.

Hybrid organic-inorganic perovskite solar cells (PSCs) have recently emerged as a promising photovoltaic (PV) candidate (*1*). Perovskites have a general chemical formula of AMX$_3$, in which the M metallic cations and X anions form MX$_6^{4-}$ octahedra with A cations occupying the 12-fold coordinated holes within the cavity. These materials exhibit desirable optical-electrical properties for PV devices, such as suitable and tunable bandgap, strong optical absorption, long carrier diffusion length, and high defect tolerance (*2*). The record-certified power conversion efficiency (PCE) of PSCs has recently risen to 23.3% (*3–6*) for a small-area device (~0.09 cm^2) whose active area is well below that of standard commercial crystalline silicon solar cells. Perovskite films are made using solution-based fabrication and are composed of earth-abundant materials (*7*) (Fig. 1A), but the most efficient devices rely on costly gold and organic hole-transport materials (HTMs) such as 2,2′,7,7′-tetrakis(*N*,*N*-di-p-methoxy-phenylamine)-9,9′-spirobifluorene (spiro-OMeTAD).

Although the potential for low-cost PSCs offers a promising prospect for commercializing this PV technology, a complex interplay has unfolded between the pursuit of high efficiency and other commercially viable aspects, such as long-term stability and scale-up manufacturing. This Review aims to provide an overview of recent progress toward the commercialization of PSCs.

Device configurations and performance

PSCs have a layered device structure that includes a transparent conductive oxide (TCO)–coated glass substrate, an n-type semiconductor as the electron-transport layer (ETL), a perovskite absorber layer, a p-type semiconductor as the hole-transport layer (HTL), and a back-contact (metal, TCO, or carbon) (Fig. 1B). In mesoscopic PSCs developed after investigations of dye-sensitized solar cells, the perovskite absorber sensitizes a mesoporous metal oxide layer (e.g., *meso*-TiO$_2$) used as a scaffold (*3, 8*). In planar PSCs, the perovskite layer is sandwiched between a planar ETL [e.g., compact TiO$_2$ (c-TiO$_2$), SnO$_2$, or C$_{60}$ and its derivatives] and an HTL [e.g., spiro-OMeTAD, poly(triarlyamine) (PTAA), and poly(3,4-ethylenedioxythiophene)-poly(styrene-sulfonate) (PEDOT:PSS)] (*9–12*). Depending on the sequence of depositing the ETL and HTL, the structure can be divided into formal (conventional) versus inverted architectures (*13, 14*). Notably, the design and fabrication of inverted devices is not a simple reversal from the formal device structure, and the two device structures typically require systematic development of suitable ETLs and HTLs, especially in light of the restrictions in the suitability of processing solvents. In triple mesoscopic PSCs, the perovskite is deposited on a triple-layer scaffold, made of a screen-printed mesoporous TiO$_2$ layer, a ZrO$_2$ spacer layer, and a carbon electrode (*15, 16*). Such devices use carbon electrodes to replace the noble metal back-contacts and do not require a hole-conducting layer.

The prospects of PSCs as a top-cell for constructing tandem solar cells with other PV devices—such as silicon (*17*), copper indium gallium selenide (CIGS) (*18*), and low-bandgap perovskites (*19*)—have been reviewed elsewhere (*20*). Partnership with existing mature PV technologies not only boosts their efficiency beyond the Shockley-Queisser limit of single-junction devices (*21*) but also provides access to established market channels (*22*).

Progress in the efficiency of single-junction PSCs is summarized in Fig. 1C (*3–6, 11, 15, 23–35*). The perovskite layer and charge-transporting layers are typically deposited by spin coating for small-area (<1.0 cm^2) lab cells. Enlarging the device area with current techniques to fabricate PSC modules leads to a decrease in PCE of all device structures (*8, 9, 36–45*). Screen printing, slot-die coating, spray coating, and soft-cover coating methods have been developed to fabricate intermediate-sized PSC modules on the scale of tens of square centimeters (*46*). Alternative processing strategies must be explored to achieve large-area uniform films and efficient materials utilization.

Ohmic loss due to resistance from the front transparent electrode must also be reduced. The conductivity of FTO films can, in principle, be enhanced by increasing the thickness, but this will decrease its transparency. Depositing conductive grids and/or constructing interconnected unit cells can be used to reduce resistance in large-area modules at some sacrifice to the active area of the modules (*47*). Geometrical fill factor [(GFF), the ratio between the active area and the total area of a module] can be further enhanced by enlarging the module area, since the ratio of the dead area associated with edges for encapsulation and frames can be reduced.

Stability of PSCs

One challenge in comparing stability among PSCs resides in the use of a range of nonstandard testing protocols within the PSC community (*48*). For shelf-life stability tests in the dark, PSCs are encapsulated or unencapsulated, and aspects of the ambient environment (e.g., atmosphere, humidity, and temperature) vary (*49*). Indoor light stability tests use different light sources (*50*), such as an AM1.5 xenon lamp with or without an ultraviolet (UV) filter, a metal-halide lamp, a sulfur plasma lamp, a halogen lamp, or a UV-free light-emitting diode lamp. Outdoor tests with encapsulated devices (*51*), thermal stability tests (*52*), thermal cycling tests (*53*), and others (*54*) have also been reported. Transparency in reporting standards on stability tests needs to be improved in the perovskite PV community. Some reports present normalized results without providing initial PV parameters. Such reports risk obscuring the fact that the devices under test for stability are often much less efficient than the devices with the best or even average performance. Thus, it is necessary to present the original PV data and the normalization parameters. We urge the community to develop and then follow standardized protocols to enable accelerated

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tests and to predict the lifetime of PSCs on the basis of degradation kinetics specific to the cell components (48). The well-established standards [e.g., International Electrotechnical Commission (IEC) 61215 or 61646] in mature crystalline silicon and inorganic thin-film PVs can be deployed by the PSC community, and additional protocols to test the reliability of PSCs can also be advanced.

Here we summarize dominant causes of instability in PSCs on the device level. One source of instability is the chemically active charge-transporting material and interfacial degradation. The TiO₂-based ETL, which is widely used in high-performing cells, causes photocatalytic degradation under UV illumination. Replacing TiO₂ with other UV-stable materials (e.g., BaSnO₃) (Fig. 2A) (55) or inserting an interfacial modifier (e.g., CsBr, Sb₂S₃, or Cl atoms) (Fig. 2, B and C) (9, 56, 57) between the ETL and the perovskite absorber can improve stability. Commonly used organic HTMs such as spiro-OMeTAD, poly(3-hexylthiophene) (P3HT), and PTAA encounter thermal or moisture instability in their doped forms. Substituting the organic HTM with inorganic materials (Fig. 2, D and E), inserting

buffer layers between perovskite and HTM, and deploying suitable encapsulation can improve stability (49). Metal electrodes such as Au, Ag, and Al have stability issues as well. Ag and Al electrodes suffer from corrosion by ion migration in perovskite, resulting in an apparent color change and PCE decay (58, 59). Even relatively inert Au diffuses across the organic HTM layer at temperatures exceeding 70°C, leading to an irreversible performance loss (60). Interfacial layers such as Cr, MoOₓ, and reduced graphene oxide have been introduced to prevent metal diffusion and thus improve long-term stability (49, 61). Replacing the metal electrodes with indium tin oxide (ITO) can also improve stability by providing an unreactive electrode and creating a barrier layer that keeps moisture out and retains volatile components of perovskite (17, 53).

Triple mesoscopic PSCs based on TiO₂/ZrO₂/carbon/mixed-cation perovskite have passed relatively harsh lifetime testing conditions. With initial efficiencies of 10 to 12%, the PSCs and modules exhibited negligible performance loss after illumination under an unfiltered Xe lamp for 1000 hours (Fig. 2, F and G). The devices also exhibited acceptable stability in thermal stability tests at

85° to 100°C for 2160 hours and in outdoor stability tests in Jeddah, Saudi Arabia, for 168 hours and Wuhan, China, for 720 hours (51, 62, 63). Improved stability in triple mesoscopic PSCs was enabled by removal of unstable components (such as organic HTM and metal electrodes) (64) and incorporation of bulky organic ligand [5-ammoniumvaleric acid (5-AVA)] to form mixed-cation perovskites (5-AVA)ₓ(MA)₁₋ₓPbI₃, where MA is methylammonium (16).

Devices using low-dimensional perovskites in which some or all cations are replaced by large organic ligands exhibited greater stability over long-term operation against moisture and light soaking, as compared with 3D perovskite devices (65–67) (Fig. 3, A and B). However, the large ligands impede charge-transfer transport and sacrifice efficiency (35, 68) (Fig. 3C). Alternatives such as shorter-chain cations (69) and conjugated cations (35) can potentially increase efficiency without sacrificing stability.

Protecting interfaces and grain boundaries—sites where degradation may begin—can slow decomposition. Small-molecule additives such as thiophene, pyridine (70), urea (71), phenyl-C₆₁-butyric acid methyl ester (PC₆₁BM) (72), and quaternary
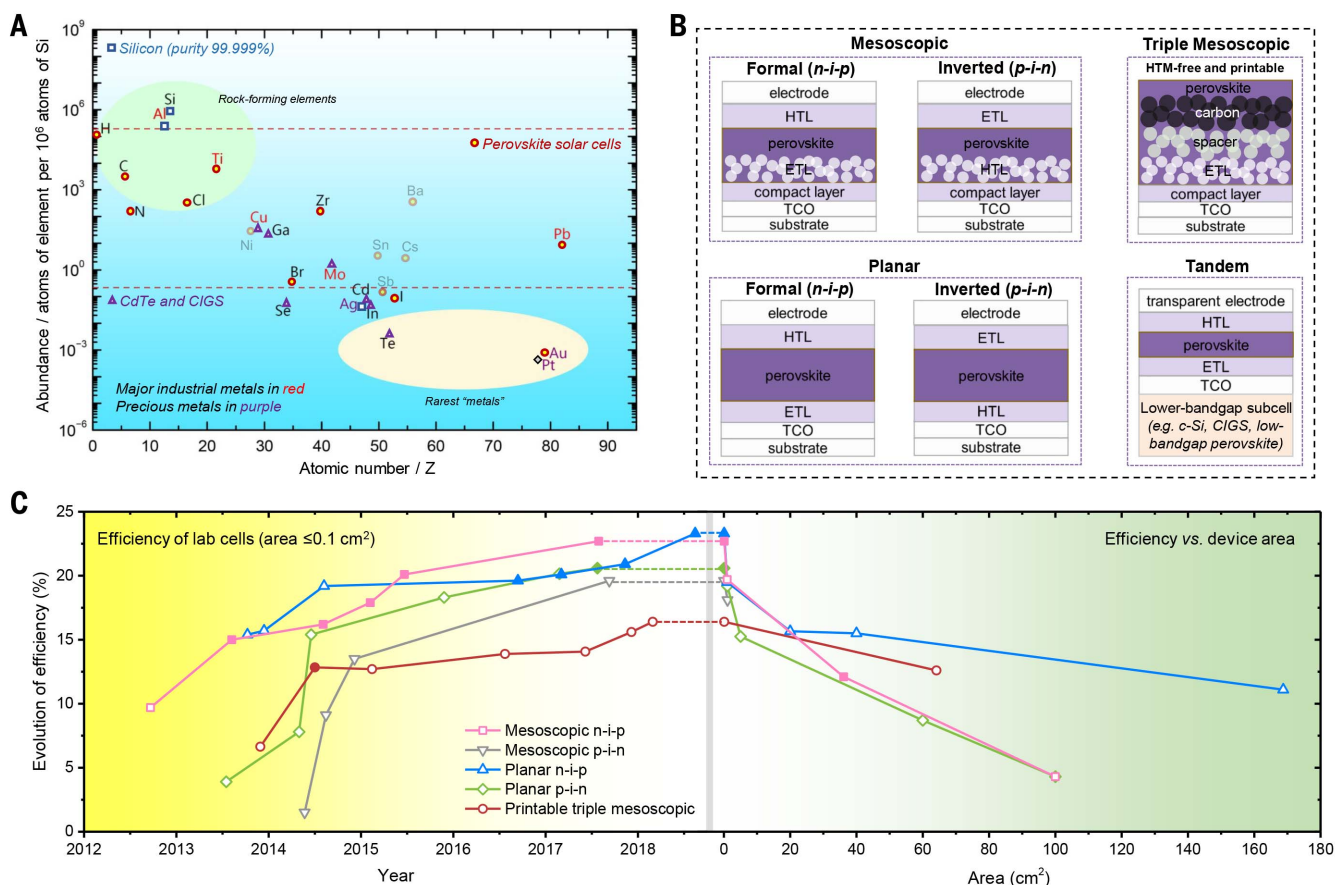

Fig. 1. Chemical elements used in different solar cells, device configurations and efficiencies of PSCs. (A) Atom fraction of elements used for different types of solar cells. The major elements for silicon solar cells are denoted by blue squares, PSCs by red circles, and CdTe and CIGS thin-film solar cells by purple triangles. Ni, Sn, Cs, Ba, and Sb elements are labeled in semitransparent color, as they have been used in PSCs but not in the mainstream architectures. Major industrial metals and precious metals are categorized according to Goldschmidt classification (7). (B) Four device configurations of PSCs: mesoscopic structure, planar structure, triple mesoscopic structure, and tandem structure with lower-bandgap subcell. (C) Evolution of the best-reported lab-cell (≤0.1 cm²) efficiencies and large-area (≥1.0 cm²) device efficiencies. Solid symbols represent certified efficiencies; hollow symbols denote uncertified efficiencies.

ammonium halide (73) have demonstrated improved stability. The hydrophilic side interacts strongly with perovskites, and the hydrophobic side faces outward to protect the surface of perovskites from moisture. In addition, formamidinium (FA$^+$) or Cs$^+$ was used to replace the MA$^+$ cation (74, 75), and Cl$^-$, Br$^-$, or SCN$^-$ replaced the I$^-$ anion (76), yielding various perovskites with a series of tolerance factors (77). This result tunes the Pb–I bond and the perovskite crystal systems influencing the formation energy and changes the inherent stability of perovskites.

Upscaling and future applications

Recently, several PV companies have set out to manufacture large-area PSC modules. Microquanta Semiconductor (China) obtained a PCE of 17.4% for a rigid perovskite mini-module with an active area of 17.8 cm^2 (Fig. 4A). Solliance (the Netherlands) developed 169-cm^2 perovskite modules with a GFF of 90% using laser ablation to define the cells that exhibited a total efficiency of 10% and an active area efficiency of 11.1% (41). The processing steps were carried out at temperatures below 120°C and are compatible with flexible substrates and a roll-to-roll process (Fig. 4B). Saule Technologies (Poland) used inkjet printing to fabricate perovskite solar modules on flexible substrates, which allows the design of free-form patterns (Fig. 4C). Greatcell Solar (previously Dyesol, Australia) has achieved 12% conversion efficiency in 10 cm by 10 cm modules and is committed to full-scale production in 2019 (78). p-OLED (China) and Solaronix (Switzerland) are also engaging in the upscaling of PSCs by providing chemicals and equipment around the world.

Oxford PV (United Kingdom) and Tandem PV (formerly Iris PV, United States) seek to use perovskites to upgrade the performance of silicon solar cells by fabricating high-efficiency perovskite-Si tandem cells. Recently, Oxford PV announced a record-certified PCE of 27.3% for 1-cm^2 perovskite-Si tandem solar cells (79). Huazhong University of Science and Technology (HUST) in China initiated the upscaling of printable triple mesoscopic PSCs and has achieved efficiency >10% with an area of 100 cm^2 (Fig. 4D). A 7.0-m^2 solar panel was assembled with these cells in early 2015 (51). Recently, a 110-m^2 perovskite PV system with screen-printed triple mesoscopic PSC modules (3600 cm^2 for each) was launched by WonderSolar (Fig. 4E) (80).

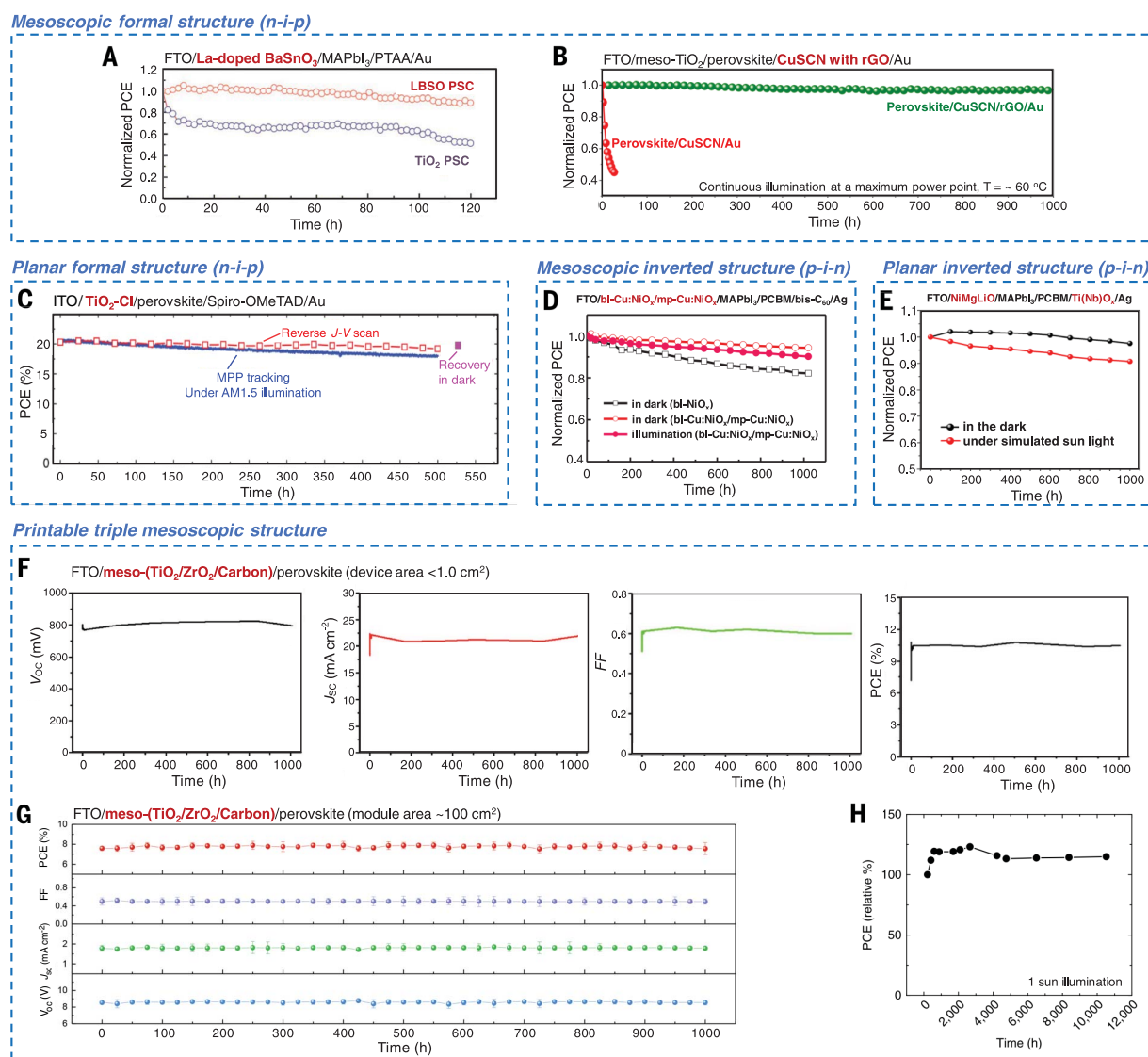Various device architectures and manufacturing processes are the subject of research and

Fig. 2. Summary of operational stability for PSCs with various device architectures. Mesoscopic formal structures (n-i-p) with organic (**A**) and inorganic (**B**) HTLs. [Reproduced from (61) with permission] (**C**) Planar formal structure (n-i-p). MPP, maximum power point; J, current density; V, voltage. (**D**) Mesoscopic inverted structure (p-i-n). [Reproduced from (8)

with permission] (**E**) Planar inverted structure (p-i-n). [Reproduced from (30) with permission] (**F** to **H**) Printable triple mesoscopic structure. Relatively stable devices have been reported for all structures by using appropriate charge-transporting materials, perovskite, and electrodes. OC, open circuit; SC, short circuit; FF, fill factor. [Reproduced from (51, 65) with permission]

development. As yet, it is unclear which architecture or fabrication method will become dominant. At large scales, it is still challenging to control morphology and obtain uniform perovskite thin films by using either solution- or vacuum-based deposition techniques (*81–83*). The crystal growth of the perovskite absorber in solvents varies as a result of different evaporation rates at different locations. When the concentration of the precursor solution deposited on a large-area substrate varies, ion migration may occur and may lead to inhomogeneous crystallization. For PSCs in typical mesoscopic or planar structures, the thickness of the perovskite layer is on the order of several hundred nanometers. Pinholes in perovskite films lead to direct contact between the ETL and HTL and cause current leakage and voltage loss for the modules. Al-

though slot-die coating has proved to be an effective method for depositing perovskite thin films on large scales, further optimizations on the compositions of the precursors and crystallization process are required.

The toxicity of the solvents used to prepare perovskite films and other charge-transport layers merits further study and adaptation: Solvent-free deposition methods (*37*, *82*) and solution-based deposition approaches that use reagents with lower toxicity (*84*) warrant further development. For industrial-scale production, rigorous enclosures that prevent contact between operators and solvents are required, as are recycling and tail-gas–treating units.

In addition to addressing the concerns regarding stability and mass production, a thorough life cycle assessment, including evaluation of mate-

rials, production processes, and environmental impact, should be performed. The lead contained in PSCs has given rise to toxicity concerns. The amount of lead contained in PSCs is below that produced annually by the coal industry when it generates an equivalent amount of electricity (*85*) and is roughly equivalent to that already contained in a 1-cm-thick layer of natural soil (~0.3 to 1.2 g m^{-2}) with the same area (*86*, *87*). Nevertheless, lead in PSCs is more soluble in water and thus can move more readily through the biogeochemical cycle. Therefore, replacing Pb with other nontoxic elements to develop Pb-free PSCs will generate interest if comparable performance can be achieved. It may also be optional to develop additives that immediately convert water-soluble lead compounds into insoluble complexes upon destruction of a large perovskite solar power plant.
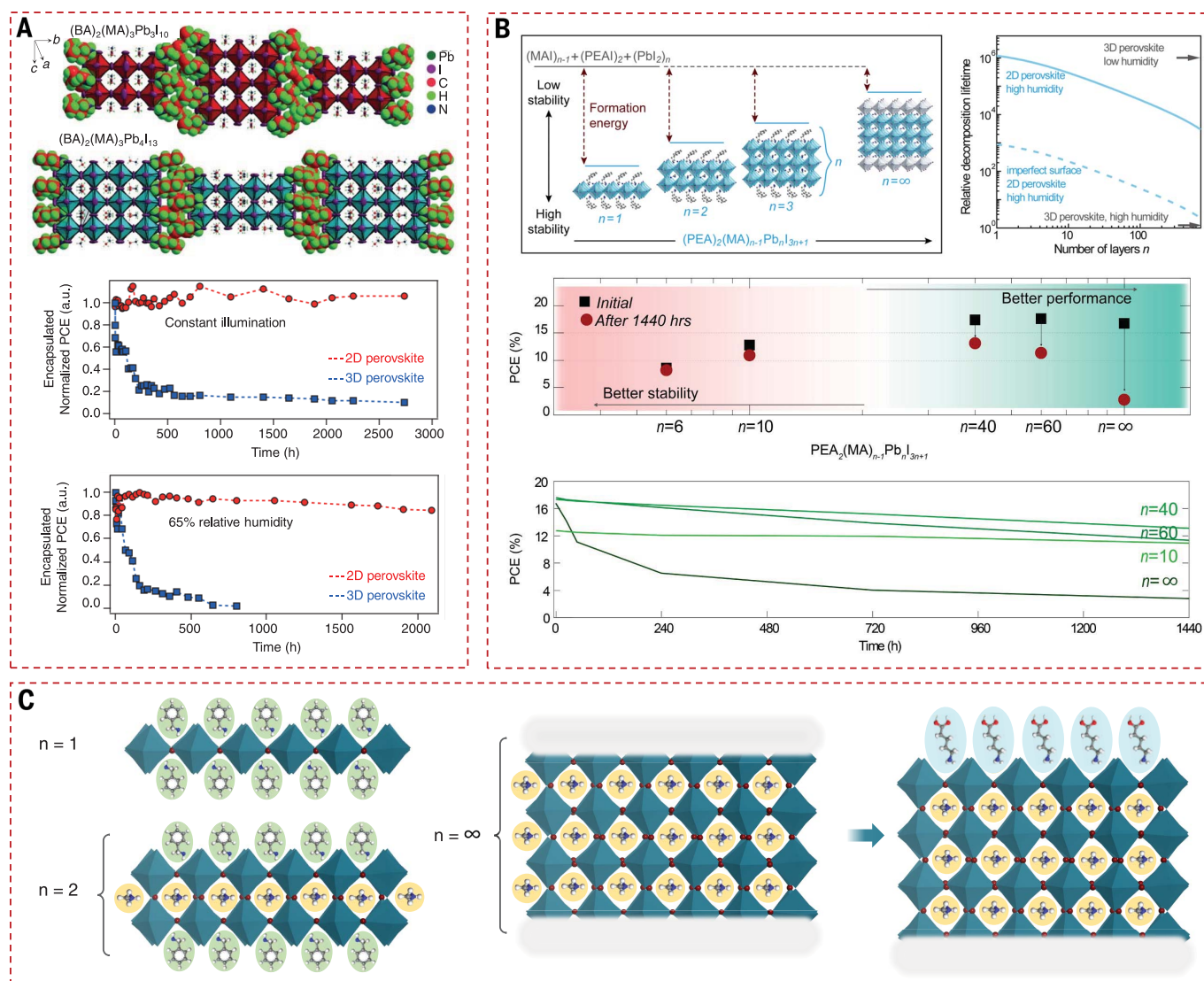

Fig. 3. Strategies to improve the stability of perovskite absorbers.
(**A**) Encapsulated PSCs based on 2D Ruddlesden-Popper perovskites exhibit much-reduced degradation under constant AM1.5G illumination and high relative humidity. BA, butylammonium; a.u., arbitrary units. [Reproduced from (*67*) with permission] (**B**) Improved stability of PSCs by tuning the dimensionality of the perovskite absorber. [Reproduced from (*68*) with permission from American Chemical Society] (**C**) By taking advantage of the hydrophobicity of large cations, the stability of perovskites can be effectively improved by tuning dimensionality. Protecting the interfaces and grain boundaries of perovskites is another way to slow down the degradation.
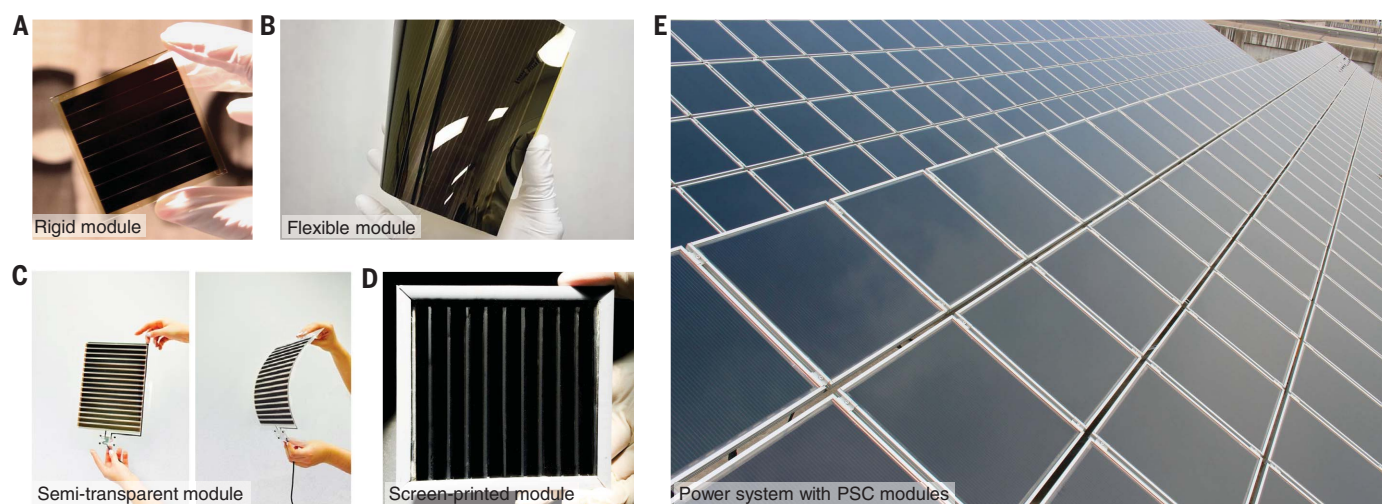
Fig. 4. Perovskite solar modules. (**A**) Rigid perovskite mini-module. [Courtesy of Microquanta Semiconductor] (**B**) Roll-to-roll processed flexible module. [Courtesy of Solliance Solar Research] (**C**) Semitransparent module fabricated via an inkjet printing technique. [Courtesy of Saule Technologies] (**D**) Screen-printed module developed by Wuhan National Laboratory for Optoelectronics at HUST. [Reproduced from (*51*) with permission] (**E**) Power system with printable triple mesoscopic PSC modules. [Courtesy of WonderSolar]

Life cycle assessment of perovskite tandem solar cells has also raised concerns regarding the environmental impact of gold and spiro-OMeTAD (because of solvent use) (*88*). Therefore, development of HTL-free and noble-metal–free PSC architectures that do not compromise PCE is a topic of growing interest.

When lead is used in PSCs, the recycling of perovskite modules is required. Experience and lessons from the CdTe PV industry offer hints for the treatment and recycling of lead and cadmium in absorbers. Perovskite solar panels also include frames, glasses, synthetic materials (e.g., HTMs), encapsulation materials [e.g., ethylene vinyl acetate (EVA)], and other materials, that require further development of recycling strategies. One proposed procedure is to remove the layers of PSCs by using adhesive tape and via immersion of the substrate in different organic solvents. PbI_2 can then be recycled from the perovskite solar panel after recrystallization (*89*). For specific devices such as the printable triple mesoscopic structure, the device scaffold can be reused by washing away the perovskites and reloading them (*90*). In situ recycling of PSCs through a methylamine gas posttreatment has also been reported (*36*). For silicon solar cells, recycling efficiency can reach impressive values of 85%, which is important given that up to 78 million tons of waste will be generated by silicon solar panels by 2050 (*91*). More than 95% of the glass and all-external aluminum frames can be reused. The remaining materials are incinerated to evaporate the encapsulation plastic, and the silicon can be melted again for manufacturing new silicon modules.

Reliability concerns for perovskite solar modules

For commercial PV technologies, international standards such as "Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval" (IEC 61215) and "Thin-film ter-restrial photovoltaic (PV) modules—design qualification and type approval" (IEC 61646) have been established and released by the IEC. Specific endurance tests must be passed before the modules are put into field applications. These tests determine the electrical and thermal characteristics of the modules and are needed to show that the modules are capable of withstanding prolonged exposure in climates described in the scope. The actual lifetime expectancy of the modules so qualified still depends on the design, installation, and environment conditions under which they operate.

At present, silicon and inorganic thin-film PV modules have demonstrated exceptionally high levels of reliability in field applications and are able to provide a warranty of 25 years, and the solar panels can maintain a power output ≥80% of their initial output after 25 years. Notably, the lifetimes of such PV modules are not only predicated by accelerated aging tests but also have been verified by statistical results obtained with modules under actual outdoor operating conditions (*92*, *93*).

For PSCs, the instability associated with the perovskite absorber and additional instabilities associated with materials interfaces are among the critical hurdles to practical application. The light-soaking test for PSC mini-modules (active area ~50 cm^2) has now been increased to 10,000 hours, but this test has also utilized UV-filtered lamps. The total irradiation is equivalent to the integrated solar irradiation for ~10 years in much of Europe. With rigorous device design and proper encapsulation, PSCs (active area ~1 cm^2) have passed the dark damp heat test for 1000 hours, as described in IEC design qualification testing protocol 61215. These results have principally been obtained on small-sized lab devices that are below the area of commercial solar cells. Up to now, there exist no reports of PSCs nor perovskite modules that pass the IEC design qualification-testing protocols for crystalline silicon and thin-film terrestrial PV modules. Thus, it will be crucial to develop PSCs and modules (with proper encapsulation) that meet IEC standards for reliability.

In addition to heat and irradiation, mechanical shock may also influence the stability of PSCs. Perovskites have a low fracture energy, and their thermal expansion coefficient is more than 10 times that of glass and TCOs—this may lead to delamination during temperature cycling. Cells passed industry-standard tests involving 200 cycles between −40°C and 85°C when encapsulants with a moderate Young's modulus, such as EVA, were used to help relieve strain in the solar cells. It remains important to ensure that full-sized panels, in which the perovskite layers have been scribed, remain durable during temperature cycling (*53*).

In practical applications, cells are exposed to high-voltage stress compared to ground since they are connected both in series and in parallel. PSCs should be assessed through the use of potential-induced degradation (PID) testing protocols, and it is noteworthy that other commercial PV technologies (such as inorganic thin-film PVs) have been more prone to PID than is c-Si (*94*). For silicon solar cells, PID is a reliability concern with varied failure mechanisms, including irreversible ones (such as electrochemical corrosion and sodium ion damage) and reversible ones (due to the accumulation of static charge on the surface of cells). For PSCs, ion migration (*95*) and charge accumulation (*96*) are present in cells and lead to the anomalous photocurrent hysteresis effect. Ion migration may lead to severe PID and works against the long-term reliability of modules. It is thus crucial to develop a method to suppress ion migration in PSCs. In future studies, PID testing for PSCs will be required to ensure long-term module reliability.

Partial-shade stress tests remain another topic requiring in-depth studies for perovskite modules:

In PV systems, shaded cells will be under reverse bias, owing to the operation of other cells. IEC 61215 describes partial-shade stress tests to quantify permanent performance loss (*97*, *98*). PSCs have much lower breakdown reverse bias than crystalline silicon and inorganic thin-film solar cells: A reverse-bias breakdown occurs in PSCs between –1 and –4 V (*99*). In addition, local heating as a result of partial shading may lead to damage or even decomposition of perovskites because organic-inorganic hybrid perovskites are usually not temperature tolerant. It is important for the perovskite community to carry out further studies of partial-shade stress and increase understanding of behavior under reverse bias, as well as to find the means to improve durability under these conditions, possibly by interconnecting bypass diodes within monolithic modules.

Perspective

PSCs can be produced from low-cost materials via a simple fabrication process. PSCs have achieved major advances in efficiency, obtaining high efficiencies in lab cells, and will continue to advance in maturity as stability is enhanced. In general, PSCs feature both a low materials cost and a short energy payback time (<0.22 years) (*88*, *100*).

At present, the major challenge for PSCs is to achieve long-term stability on the module level and to ensure durable outdoor operation. It is necessary for the perovskite PV community to develop a consensus on the stability measurement protocols and release standardized testing protocols within the community. New protocols should be designed to accelerate the aging process under operation conditions and effectively predict the lifetime of PSCs. Although the degradation of the perovskite absorber caused by moisture or oxygen in ambient air can be inhibited by appropriate encapsulations, the performance decay induced by illumination and heat should be addressed through the construction of stable materials and interfaces. Compositional engineering efforts should aim to maximize formation energies and will likely benefit from emerging machine learning algorithms and robotized synthesis.

A loss in efficiency is observed when PSC area increases (*81*). With continued efforts from the research and industrial communities toward scaling-up of PSCs, we expect that the efficiency gap between lab cells and industrial modules will be minimized and will achieve a level comparable to that of other PV technologies. Cost per kilowatt-hour is dominated by the efficiency and lifetime of solar panels. The abundant low-cost raw materials and simple processing for PSCs indicate pathways to reduce production cost below the level for conventional PV technologies. In the long run, the lower production cost can provide a more sustainable reduction in total module cost, thus making PSCs commercially competitive.

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Science

Challenges for commercializing perovskite solar cells

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The road ahead for perovskites

The high power conversion efficiencies of small-area perovskite solar cells (PSCs) have driven interest in the development of commercial devices. Rong *et al.* review recent progress in addressing stability, how to allow mass production, and how to maintain uniformity of large-area films. They note that lifetimes exceeding 10,000 hours under 1 sun (1 kW/m^2) illumination have been reported for printable triple mesoscopic PSCs.
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