

Journal Pre-proofs

Review

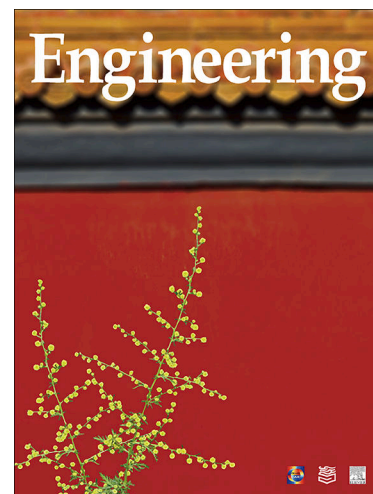
Advancing Perovskite Solar Cell Reliability for Extreme Space Environments

EQ Han, Jung-Ho Yun, Lianzhou Wang

PII: S2095-8099(25)00735-0
DOI: <https://doi.org/10.1016/j.eng.2025.09.031>
Reference: ENG 2152

To appear in: *Engineering*

Received Date: 17 March 2025
Revised Date: 11 September 2025
Accepted Date: 30 September 2025



Please cite this article as: E. Han, J-H. Yun, L. Wang, Advancing Perovskite Solar Cell Reliability for Extreme Space Environments, *Engineering* (2025), doi: <https://doi.org/10.1016/j.eng.2025.09.031>

This is a PDF of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability. This version will undergo additional copyediting, typesetting and review before it is published in its final form. As such, this version is no longer the Accepted Manuscript, but it is not yet the definitive Version of Record; we are providing this early version to give early visibility of the article. Please note that Elsevier's sharing policy for the Published Journal Article applies to this version, see: <https://www.elsevier.com/about/policies-and-standards/sharing#4-published-journal-article>. Please also note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company

Frontiers of Extreme Manufacturing—Review

Advancing Perovskite Solar Cell Reliability for Extreme Space Environments

EQ Han ^{a,b}, Jung-Ho Yun ^{b,*}, Lianzhou Wang ^{a,c,*}

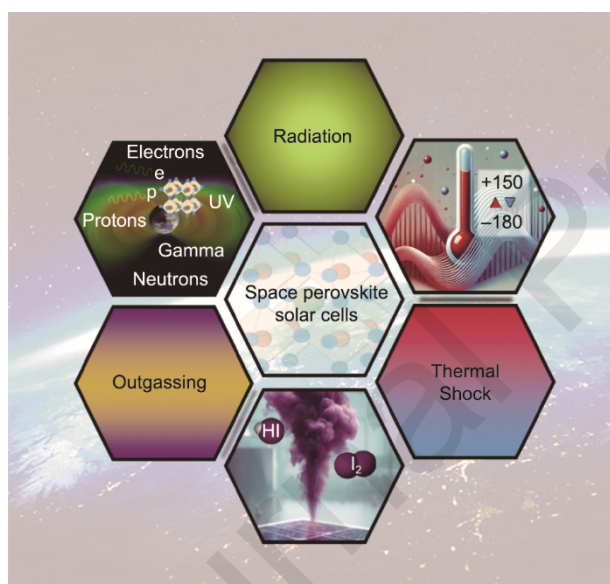
^a Nanomaterials Centre, School of Chemical Engineering, Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Brisbane, QLD 4072, Australia

^b Air & Environment Energy Nexus Lab, Department of Environmental Science and Engineering, College of Engineering, Kyung Hee University, Gyeonggi-do 17104, Republic of Korea

^c Department of Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hong Kong 999077, China

* Corresponding authors.

E-mail address: jungho.yun@khu.ac.kr (J.H. Yun), lianzhou.wang@polyu.edu.hk (L. Wang)



Abstract: Making space exploration more accessible requires affordable power-generation solutions for commercial applications, in which photovoltaics (PVs) play a pivotal role. Metal halide perovskite (MHP) solar cells have emerged as one of the most promising technologies for low-cost space PVs owing to their high power conversion efficiency, outstanding power-to-weight ratio, and cost-effectiveness compared to the commonly used triple-junction III-V solar cells. Perovskite solar cells (PSCs) offer multiple advantages: They are lightweight, solution-processable, and can be fabricated on flexible substrates for expandable solar panels. They also demonstrated significant resilience to various types of cosmic radiation, including electrons, protons, ultraviolet light, and gamma rays. However, despite their strengths, PSCs still lag in long-term stability compared to silicon and III-V cells, especially under extreme space conditions, such as significant temperature variation in a high-vacuum environment, making stability enhancements essential for extended space applications. This review discusses the challenges and potential of PSCs for space use and highlights their high radiation tolerance, thermal stress, and outgassing. We present an overview of the current qualification tests for space-grade solar cells and propose a qualification evaluation of thin-film solar cells for space applications, which is critical for evaluating their reliability in terms of long-term performance in extreme space environments.

Keywords: Perovskite solar cells; Stability; Extreme condition; Space applications

1. Introduction

Since the launch of Sputnik 1 in 1957, the field of space exploration has advanced significantly, driven by the desire for humanity to uncover the mystery of the Universe. Over the decades, thousands of spacecraft have been deployed for various purposes, including studying Earth's atmospheric and geological phenomena, exploring solar systems, and observing distant galaxies, stars, and exoplanets. Additionally, the development of orbiting laboratories, such as the International Space Station (ISS), has enabled various studies under unique conditions, such as microgravity [1]. However, one of the most critical challenges in spacecraft design is the ability to withstand harsh space environments [2].

Unlike the Earth's surface, where the atmosphere provides protection against radiation and stabilizes the temperature, space presents extreme conditions that necessitate the use of highly durable materials in spacecraft construction. Given the high costs associated with launching and maintaining space vehicles, which range from thousands to tens of thousands of dollars per kilogram (kg), minimizing replacement and maintenance is crucial. Among spacecraft components, power generation and electronic systems are particularly vital because they ensure energy supply and operational functionality, including communication with ground stations [3].

To satisfy the increasing energy demands of modern spacecraft, which often require several kilowatts (kW) of continuous power, photovoltaic (PV) technologies have emerged as a potential solution because of the abundance of solar energy in space, along with the scalability and modularity of PV systems, as shown in Fig. 1(a) (ISS) [4]. Although nuclear energy is sometimes viewed from a concerning perspective when it comes to safety [5], its limited historical adoption in space missions is largely driven by cost, policy, and public acceptance factors. Programs such as Nuclear Engine for Rocket Vehicle Application (NERVA) [6,7] have demonstrated technical viability. More recently, the National Aeronautics and Space Administration (NASA, USA) has actively employed radioisotope thermoelectric generators (RTGs), as shown in Fig. 1(b), and initiated the development of nuclear propulsion systems for long-duration, deep-space missions [8]. These developments reflect the complementary role of nuclear power, particularly in missions where solar flux is limited. Meanwhile, PV technology remains the primary power source for near-Earth missions such as satellites in low Earth orbit (LEO) and the ISS, as shown in Fig. 1(a). The ISS is powered by four large solar arrays covering approximately 27 000 square feet and can generate up to 120 kW of electricity [4,9]. However, for space operation to be feasible, PV technologies must meet the requirements of radiation tolerance, high specific power (W/g), lightweight form factors, and long-term operational efficiency under extreme environmental stressors [10,11].

Currently, silicon and multi-junction (MJ) III-V solar cells (MJ III-V SCs) dominate the market for space applications. To qualify as a space PV technology, it is essential to evaluate both the beginning-of-life (BOL) and end-of-life (EOL) performances under defined proton or electron irradiation conditions, typically characterized by specific energies and fluences. Figs. 1(c) and (d) represent the simulated annual proton and electron fluences as a function of particle energy for various orbital altitudes [12]. Companies like Azur Space manufacture some of the most efficient solar cells, including triple- and quadruple-junction devices [13]. For instance, Azur Space's AlInGaP/AlInGaAs/InGaAs/Ge solar cell (thickness: $(110 \pm 12) \mu\text{m}$) starts with a PCE of 31.8% at the BOL and decreases to 28.7% and 20.1% at EOL after prolonged exposure to 1 MeV electron irradiation with fluences of 1×10^{15} and $1 \times 10^{16} \text{ e}^- \cdot \text{cm}^{-2}$, respectively [14]. Similarly, a silicon-based cell (Si cells, thickness: $(130 \pm 30) \mu\text{m}$) from the same manufacturer initially achieves a PCE of 16.9% but declines to 12.5% after 1 MeV electron irradiation with $1 \times 10^{15} \text{ e}^- \cdot \text{cm}^{-2}$. Despite their high efficiency, these devices are rigid, thick, and relatively heavy, with specific power values of approximately 0.4 W/g for MJ III-V SCs and 0.38 W/g for Si cells [15,16] that are not suitable for compact and light spacecrafts such as Cube-sat. Additionally, it should be noted that in actual space environments, protons generally induce more severe degradation in silicon solar cells than electrons, primarily due to their significantly greater mass and resulting displacement damage. Therefore, careful selection of the radiation source is important to ensure that EOL performance is evaluated under conditions representative of the intended space environment.

Given these challenges, the research on alternative materials for space PV applications has intensified (Fig. 1(e)) [9]. Cu(In, Ga)Se₂ (CIGS) solar cells have emerged as promising candidates owing to their high radiation resistance and lightweight nature [17], which boast a specific power of approximately 3 W/g [18,19], which is approximately 7 to 9 times lighter per W than that of MJ III-V and Si SCs. CIGS can be manufactured on flexible substrates using cost-effective processes [20], making them highly adaptable to different spacecraft designs. However, their performance under 1 Sun AM1.5G ground-laboratory scale measurement, 23.64% attractive on-earth application [21,22], needs to be enhanced to supply spacecraft with reliable power. A recent study on a CIGS tandem device achieved a certified PCE of 22.8% with a specific power of 6.15 W/g when a wide-bandgap (WBG) metal halide perovskite (MHP) photoabsorption layer was employed as the top cell of the tandem device [23]. MHPs have gained attention for terrestrial PV applications because of their exceptional optoelectronic properties [24,25]. Perovskite solar cells (PSCs) have achieved PCEs of 27% [22], competing with well-established technologies such as silicon, CIGS, and cadmium telluride (CdTe) solar cells. Their structure is based on the general formula ABX₃, where the A site is a monovalent cation such as methylammonium (MA⁺), formamidinium, FA⁺, Cs, or Ru; site B is a divalent metal cation such as lead (Pb) or tin (Sn); and X is a monovalent halogen anion (I⁻, Br⁻ or Cl⁻) that allows for tunability in composition, leading to enhanced efficiency and stability [26–28].

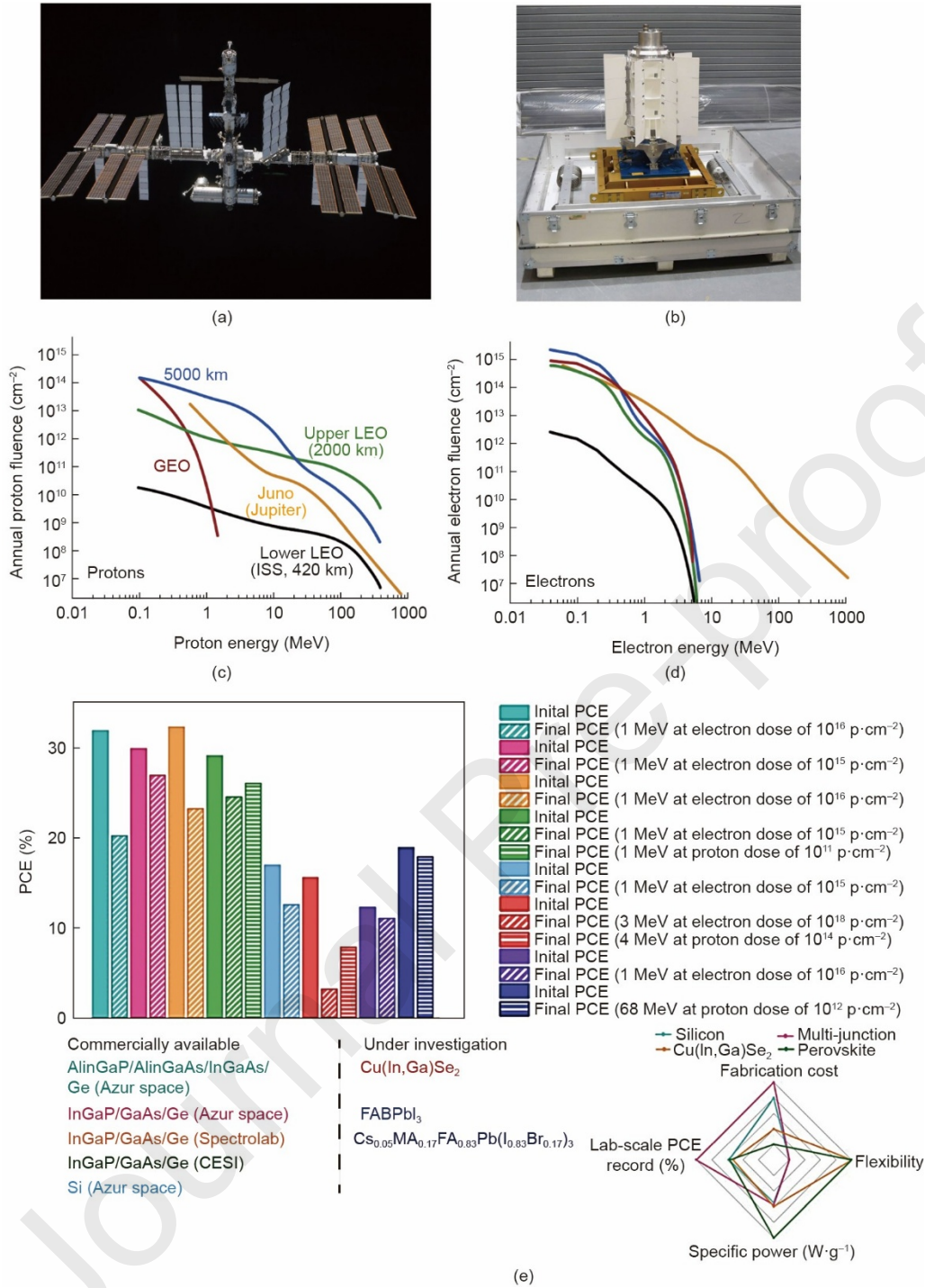


Fig. 1. (a) Solar arrays of the ISS image. Reproduced from Ref. [4] with permission. (b) Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for NASA's Mars 2020 rover. Reproduced from Ref. [8] with permission. (c, d) Annual (c) proton and (d) electron fluences simulated using SPENVIS (Company, Country) are plotted by energy for various orbital altitudes: ISS (420 km, black), upper-LEO (2000 km, green), 5000 km (blue), GEO (red), and Jupiter orbit (yellow). Reproduced from Ref. [12] with permission. (e) Comparison of solar cells available for space application, presenting compiled data from various literature sources with different irradiation conditions. Due to variations in particle type, energy, and fluence, the comparisons are not direct but intended to qualitatively illustrate the radiation response across PV technologies. Reproduced from Ref. [9] with permission.

The next generation of space exploration will demand substantial advancements in power generation, as missions explore deeper into space and rely on highly sophisticated scientific equipment, electric propulsion, and life-support systems. To address growing power demands, the aerospace industry is exploring high-

voltage systems (300–600 V) to enhance efficiency while reducing the volume and mass of the power distribution hardware [29]. In this context, PSCs have emerged as promising candidates for space PVs owing to their light weight, mechanical flexibility, low-cost processing, and exceptionally high specific power (up to 50.4 W/g) [30]. One of the most compelling advantages of PSCs for space applications is their exceptionally high specific power (W/g). This characteristic is particularly critical for small satellite platforms, such as CubeSats and microsatellites, where mass and volume constraints are stringent. The ultrathin and lightweight nature of PSCs enables efficient power generation without the burden of heavy support structures, making them attractive for future low-cost, mass-efficient space applications. These features make PSCs particularly attractive for applications in which mass and adaptability are critical. Although nuclear energy systems such as RTGs and nuclear propulsion technologies (NTPs) are mature and indispensable for deep-space missions and high-power applications, space PV systems remain highly relevant for a broader range of missions, particularly those in Earth's orbit, lunar surface operations, and short- to medium-duration missions where solar flux is sufficient. Rather than being mutually exclusive, nuclear and solar power systems are complementary, and the optimal choice depends on mission-specific factors, such as mission duration, distance from the sun owing to light absorption by PV systems, and the operational environment.

To employ PSCs in space missions, PSCs must be overcome. Factors such as long-term stability in extreme radiation environments, thermal fluctuations, and vacuum-induced degradation require further intensive research and advancement, although the space environment is free of water and oxygen, which cause degradation of the perovskite active layer. However, the promising attributes of perovskites suggest that they could play a pivotal role in the future of space PVs, offering a viable alternative to existing technologies for both near-Earth and deep-space applications. As the demand for compact, lightweight, and cost-effective satellite power systems grows, the development of reliable solar cells and reliable characterization tests for space solar cells will become crucial. Although some studies have been conducted, a well-established framework or systematic approach for the accurate evaluation of thin-film solar cells, such as perovskite or organic PV (OPV) cells is lacking. Moreover, the current qualification standards for space solar cells do not sufficiently account for the material properties and radiation response behaviors of MHP thin-film solar cells. In this study, we investigated the space environment and its impact on PSCs. In the next section, we provide an overview of international standards for space solar cells. Finally, we provide challenges, suggestions that reflect the unique characteristics of perovskites, and the prospects of PSCs for space applications.

2. Go, space-space environment

Understanding the space environment and its impact on spacecraft is crucial for the effective design and operation of solar cells for space missions. According to the NASA Marshall Space Flight Center, the space environment can be categorized into seven key components [31,32].

The first component is plasma, also known as solar wind, which consists of a continuous stream of charged particles emitted from the solar corona. This phenomenon presents a significant threat to the long-term functionality of spacecraft because it can lead to surface charging, electrostatic discharge, power loss, and short circuits in PV and electronic components. These issues can be mitigated through shielding techniques and active control of the electric potential. This factor involves the interaction between the solar wind and the Earth's geomagnetic field, which results in the formation of Van Allen radiation belts. These belts contain high-energy charged particles, with the inner belt (extending from approximately 3 200 to 16 000 km) primarily trapping protons and the outer belt (ranging from 13 000 to 38 000 km) containing high-energy electrons [33]. Spacecraft operating within these altitudes must be designed to endure prolonged exposure to radiation.

The second component, radiation, is one of the most significant threats to spacecraft. Directly ionizing particles, such as protons and electrons can cause damage by inducing ionization and defect formation in materials. Similarly, indirect ionizing radiation, including neutrons and gamma rays, can be detrimental as it may lead to the generation of secondary charged particles or cause atomic displacement due to scattering or nuclear recoil. Therefore, it is essential to quantify the fluxes and energy levels of these radiation sources. For instance, electron and proton flux levels at different altitudes around Earth's atmosphere have been

measured to range from 10^3 to 10^8 particles per square centimeter per second. Regarding indirect ionizing radiation, a space solar cell in low- and medium-Earth orbits could accumulate approximately 10 000 gray (Gy) of gamma radiation over 20 years [9]. Meanwhile, at the ISS orbit, the neutron dose can reach 2.8×10^{11} particles per square centimeter per year, with neutron energy spanning from 10^{-1} to 10^{11} eV [10,34]. To assess the resilience of space solar cells, accelerated ground-based tests simulate long-term radiation exposure by subjecting the devices to high radiation doses.

The third factor influencing spacecraft durability is thermal fluctuation, as temperatures in Earth's orbit can range from approximately -180 as to 150 °C depending on distance from Earth and solar illumination [10,35]. These extreme variations generate thermal stress that may lead to material cracking or delamination in multilayered solar cells. Consequently, thermal control systems are essential for regulating the spacecraft temperature and preventing structural degradation. Certain solar cells undergo periodic temperature-induced phase transitions in their light-absorbing layers. For instance, PSCs composed of MAPbI_3 undergo different phase transitions depending on temperature: orthorhombic below 163 K, tetragonal between 163 and 327.3 K, and cubic beyond 327.3 K [36]. Excessively high temperatures can accelerate material degradation, induce irreversible ion diffusion, and trigger metal migration, all of which adversely affect solar cell performance.

Solar cells designed for space applications were evaluated using the air mass zero (AM0) solar spectrum, which differs from the AM1.5G spectrum used on Earth and contains higher levels of ultraviolet (UV) radiation, the fourth factor [29,37]. Although terrestrial solar cells can be protected with UV filters, space-grade solar cells must balance the power-conversion efficiency with the practical limitations of additional weight, making UV protection strategies a significant design consideration. The first four factors were heavily influenced by solar activity. Variations in solar activity alter the energy and density of the emitted plasma, thereby affecting spacecraft exposure to environmental hazards.

The fifth and sixth factors, owing to the neutral atmosphere, affect spacecraft longevity primarily through atomic oxygen exposure and vacuum conditions [37]. Atomic oxygen can cause physical and chemical degradation, such as bond breakage, oxidation, and surface erosion. These effects can be mitigated using protective coatings and corrosion-resistant materials. High-vacuum conditions introduce additional challenges, including material outgassing, adhesion, cold welding, sublimation, and decomposition. These issues are particularly concerning for PSCs, as volatile materials may outgas and redeposit on the surfaces, potentially contaminating sensitive optical components. To counteract these effects, spacecraft employ pressure control and sealing strategies.

The seventh factor in the space environment is the presence of meteoroids and space debris, both of which pose collision risks that can result in structural damage, surface erosion, and changes in material properties [37]. To minimize these threats, spacecrafts are equipped with protective measures such as metallic shielding, debris recovery systems, deorbiting technologies, and laser-based debris removal.

Among the seven environmental factors shown in Fig. 2, radiation exposure is the most critical threat to the stability and longevity of space solar cells, because it cannot be entirely mitigated through shielding or spacecraft design optimization. Other environmental challenges can be addressed using effective engineering solutions. However, in the case of PSCs, radiation exposure, thermal fluctuations, and vacuum surrounding conditions are detrimental to the perovskite. Hence, it is important to understand perovskite materials and their potential and approach conventional qualification tests and characterization tests for space solar cells with different aspects to evaluate PSCs for space applications.

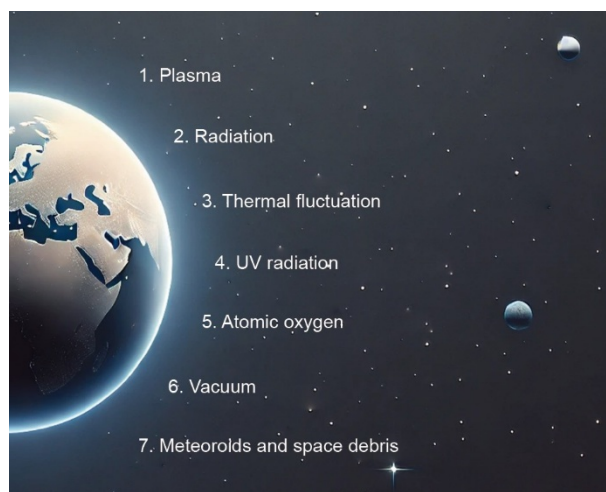


Fig. 2. Space environments characteristics. The space environment is extremely different from earth conditions, such as various radiations, vacuum, and thermal fluctuation.

3. Overview of qualification test for space solar cells

Qualification tests established by organizations such as the American Institute of Aeronautics and Astronautics (AIAA), European Cooperation for Space Standardization (ECSS), and Japan Aerospace Exploration Agency (JAXA) have long been based on the stringent requirements set for III-V semiconductors and silicon-based solar cells, which have been the standard for space applications because of their high efficiency and proven durability in harsh environments (Table 1) [38–40]. These tests ensure that the solar cells are assembled without mechanical and physical issues and can withstand extreme conditions such as radiation exposure, vacuum environments, temperature fluctuations, and mechanical stresses encountered in space missions. For the evaluation of radiation hardness, radiation tests with electron and proton irradiation were used to evaluate the electrical degradation using two methods: ① Relative Damage Coefficients (RDC) developed by NASA Jet Propulsion Laboratory (JPL) and ② Displacement Damage Dose (DDD) developed by the US Naval Research Laboratory (NRL) [38]. These methods require various radiation energies and fluences to extrapolate degradation curves. For example, in assessing the effects of electron radiation, AIAA protocols for establishing RDCs using the Equivalent Fluence methodology require the measurement of the degradation caused by 1 MeV electron exposure as a reference [38]. Additionally, to determine the energy dependence of RDCs, measurements must be performed using at least two additional electron energies within the 0.5–5 MeV range, including 1 MeV as a reference. The degradation data must include at least five fluence levels to ensure a smooth degradation curve when plotted against the logarithm of fluence. The fluence range should be selected so that the lowest fluence induces approximately 5% degradation of the solar cell's maximum power output, while the highest fluence must be at least 1×10^{16} electrons·cm⁻² at 1 MeV. The JAXA's qualification test for thermal shock, for example, minimum 5 cycles of thermal shock are conducted with a temperature range from below -186 to +140 °C and over with a minimum 30 °C·min⁻¹ rate of temperature change [40]. To evaluate outgassing, as it can cause degradation of the components of solar cell assemblies, the current test methods from AIAA, ECSS, and JAXA use the total mass loss (TML) and collected volatile condensable materials (CVCM) based on ASTM E595, where the solar cells must be composed of materials with a TML of less than 1.0% and CVCM of less than 0.1% [38–40]. To compare the testing protocols and procedures between organizations, the current testing protocols for thermal shock, radiation, and outgassing are summarized in Table 2. Although these testing protocols were originally established for inorganic solar cells, such as III-V and silicon-based devices, it should be noted that organic-based PV technologies, including PSCs and OPVs, require the development of tailored qualification protocols to ensure their suitability for space PV applications.

Table 1

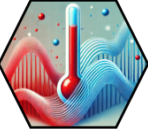
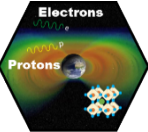
Lists of the qualification tests for the space application of solar cells from the AIAA, ECSS, and JAXA. Test protocols are based on AIAAS-111A-2014, ECSS-E-ST-20-08C Rev.2, and JAXA-QTS-2130A.

AIAA [38]	ECSS [39]	JAXA [40]
Solar cell weld or solder test	Interconnect welding	External and structure
Solar cell integration test	Visual inspection, including electroluminescence	Load current
Cell-level humidity test	Dimensions and weight	Fill factor
Electron radiation effects	Electrical performance	Reverse characteristics
Proton radiation effects	Temperature coefficient	Solar absorptance and emittance
Bend test	Diode temperature behavior	Mass
Mechanical strength	Spectral response	Dimensions
Light I-V characterization for multiple temperature	Optical properties	Thermal shock
Quantum efficiency	Humidity and temperature 1,2	Flaking of antireflection coating
Dark I-V characterization	Coating adherence	Resistance to solvents
Capacitance effects	Contact uniformity	Thermal shock and 45 angle tensile strength
Solar cell electrostatic discharge sensitivity (ESDE) test	Surface finish	Humidity resistance
Accelerated life test	Pull	High temperature vacuum
—	Electron irradiation	Radiation hardness

—	Proton irradiation	Fatigue of interconnect
—	Photon irradiation	Non-operating life
—	Diode characterization	Reverse current
—	Solar cell reverse bias test	Applications—solar cells with an interconnect
—	Thermal cycling	Applications—solar cells with a cover glass
—	Active-passive interface	Applications—solar cells without a cover glass
—	Flatness	—

Table 2

Comparison of key environmental qualification test conditions for PV devices based on AIAA S-111A-2014, ECSS-E-ST-20-08C, and JAXA-QTS-2130A standards. The table summarizes thermal cycling, radiation exposure, and outgassing requirements relevant for space applications.

Test protocols	AIAA (S-111A-2014)	ECSS (E-ST-20-08C)	JAXA (QTS-2130A)
 Thermal shock	Cold extreme: –175 to 95 °C, 2000 cycles Hot extreme: –95 to 140 °C, 20 000 cycles With active electrical bias under AM0 illumination	Temperature range: mission-specific –170 to 120 °C LEO: based on the number of eclipses per year Extreme test: –186 to 140 °C, GEO: 1000 cycles Interplanetary: full mission lifetime Vacuum required	Standard test: –170 to 120 °C, ≥ 20 cycles Extreme test: –186 to 140 °C, ≥ 5 cycles Performed in vacuum
 Radiation (electron/proton)	Electron: 0.6/1.0/5.0 MeV, up to $1 \times 10^{16} \text{ e}^- \cdot \text{cm}^{-2}$ Proton: 20 keV–3 MeV, up to $1 \times 10^{13} \text{ p}^+ \cdot \text{cm}^{-2}$ Proton for III-V cells: 1–3 MeV Proton for silicon: ~10 MeV Fluences for III-V and silicon are varies	Electron: 1–3 MeV, up to $1 \times 10^{16} \text{ e}^- \cdot \text{cm}^{-2}$ Proton: 1–10 MeV, up to $1 \times 10^{13} \text{ p}^+ \cdot \text{cm}^{-2}$ ≥ 4 combinations with 5 fluences each Must reflect actual incident direction	Electron: ~1 MeV, up to $1 \times 10^{16} \text{ e}^- \cdot \text{cm}^{-2}$ Proton: ~10 MeV, up to $1 \times 10^{13} \text{ p}^+ \cdot \text{cm}^{-2}$ Cell temperature control (< 30 °C) Angle of incidence considered

Test protocols	AIAA (S-111A-2014)	ECSS (E-ST-20-08C)	JAXA (QTS-2130A)
	TML $\leq 1.0\%$, CVCM $\leq 0.1\%$	RML $\leq 1.0\%$, CVCM $\leq 0.1\%$	TML $\leq 1.0\%$, CVCM $\leq 0.1\%$
	Test at 125 °C sample/25 °C collector	Test at 125 °C sample/25 °C collector	Test at 125 °C sample/25 °C collector
	24 h under vacuum	Performed in vacuum	Under vacuum $\leq 7 \times 10^{-3}$ Pa, 24 h
Outgassing	Based on ASTM E595	Bake-out may apply at system level	Follows ASTM E595

CVCM: collected volatile condensable materials; RML: recovered mass loss

For more detailed testing procedures, it is recommended that the official guidelines provided by each organization be consulted.

4. PSCs for space

4.1. PSCs

There has been a significant focus on MHP-based solar cells in recent years as promising candidates for low-cost PV applications. Since the first demonstration of viable devices achieving approximately 3.8% efficiency in 2009 [41], PSCs as shown in Fig. 3 have undergone rapid advancements, reaching approximately 27% efficiency in single-junction configurations [22]. This substantial improvement over a relatively short period highlights its potential as next-generation PV technology. One of the primary reasons for this rapid progress is the exceptional optoelectronic properties of perovskite materials, including high charge-carrier mobility, tunable bandgap, and tolerance factors [42–45]. These characteristics contribute to their remarkable power conversion efficiency [46], positioning them as strong competitors of conventional Si-based PVs. In addition, their low-temperature fabrication through solution-based or vapor-phase deposition methods allows for cost-effective and scalable manufacturing [47,48]. Perovskite thin films offer another crucial advantage: They are lightweight and have a flexible device architecture. As they can be processed using solution- or vapor-phase deposition, they are compatible with flexible substrates, leading to the development of lightweight, compact, and mechanically flexible solar modules. These properties make perovskite-based solar cells particularly attractive for wearable electronics, portable power sources, and space applications where mass and volume constraints are critical.

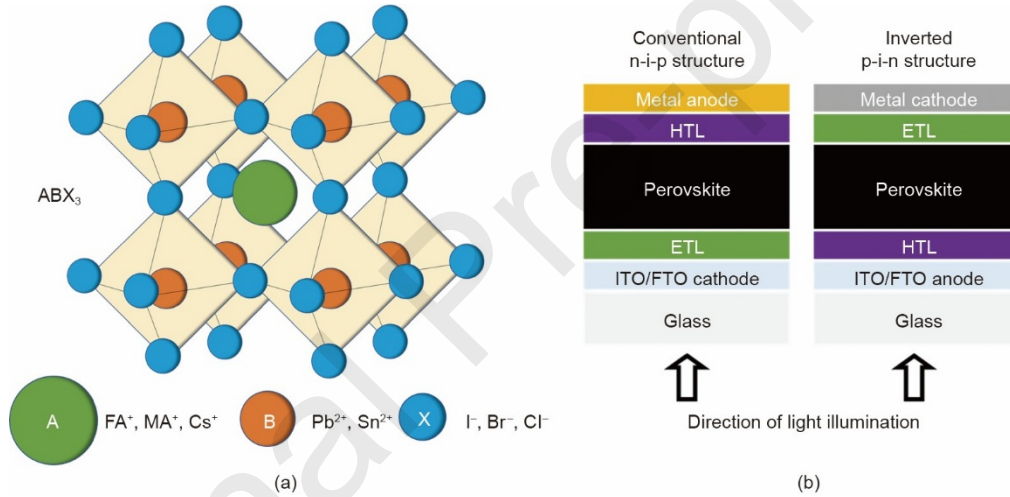


Fig. 3. (a) Typical perovskite crystal structure with chemical formula ABX_3 and (b) PSC device structures. Left-side stacking design is conventional n-i-p structure where ETL is a buried layer, and right-side stacking design is inverted p-i-n structure where HTL is a buried layer under the perovskite layer. ITO: Indium Tin Oxide; FTO: Fluorine-doped Tin Oxide.

Despite their remarkable progress, stability remains a major challenge hindering the widespread commercialization [49] as well as space application of PSCs [9,12]. These materials are sensitive to environmental factors such as moisture, oxygen, heat, and UV exposure, which can lead to their degradation over time. Water and oxygen are free in space in LEO. Researchers are actively working on strategies to improve long-term operational stability, including compositional engineering, encapsulation techniques, and improved interfacial-layer designs. In addition, perovskites have significant potential for use in MJ solar cells, where higher efficiencies can be achieved by incorporating multiple absorber layers with complementary bandgaps. These tandem architectures are expected to enhance light harvesting not only under standard terrestrial conditions (1 Sun, AM1.5G) but also under the AM0 solar spectrum encountered in space environments [50,51]. For instance, of WBG PSCs, the use of bication thiocyanate salts (1-butyl-3-methylimidazolium thiocyanate, BMI-Th, and lead thiocyanate, $Pb(SCN)_2$) in WBG perovskites (1.65 eV) has been shown to enhance tolerance to photo-induced and thermal degradation [52], while ionic liquid-modified interfaces of perovskite (1.67 eV) can mitigate ion migration and defect formation by introducing a methoxyethyl group to the piperidinium [53]. WBG perovskite-narrow-bandgap (NBG) perovskite tandem structures have been demonstrated to be an effective way to enhance performance, further reaching efficiency limits. Their bandgap tunability, ranging from 1.4 to 2.3 eV, makes them ideal candidates for both top-cell and bottom-cell applications in tandem solar configurations [54]. In addition to all-perovskite

tandem solar cells, the WBG perovskite photoactive layer can also be configured with crystalline silicon or CIGS bottom cells because WBG perovskite/tandem architectures enable greater spectral coverage and improved overall power conversion efficiency [50,51,55,56]. With continuous advancements in stability, fabrication techniques, and tandem architectures, PSCs remain at the forefront of next-generation PV technologies, promising high-efficiency, low-cost, and scalable solutions for renewable-energy applications.

4.2. PSCs under extreme space conditions

4.2.1. Radiation hardness

Space radiation can affect the dielectric properties of a spacecraft. Ionizing radiation includes protons, high-energy electrons, gamma rays, X-rays, and neutrons, which have sufficient energy to ionize atoms by removing tightly bound electrons. In contrast, non-ionizing radiation, such as UV, visible light, infrared (IR), microwaves, and radio waves, lacks the energy required for ionization but can still cause molecular excitation or heating. This radiation can impact PSC materials. When materials are exposed to high-energy particles, such as proton and electron radiation, atomic displacements create defects in perovskite structures, such as ion vacancies and interstitials, which become recombination centers. Various studies have been conducted to understand the relationship between the radiation impact and perovskite materials, as well as to evaluate the performance changes after irradiation.

Electrons are high-energy particles in space that cause both ionizing and displacement damage to MHPs. Miyazawa et al. [57] in 2018 reported the effects on electron irradiation (1 MeV with $1 \times 10^{16} \text{ e} \cdot \text{cm}^{-2}$ fluences) on MAPbI₃ PSCs (FTO/TiO₂/MAPbI₃/P3HT/Au) as shown in inset of Fig. 4(a). The damage induced by electron radiation was minimal, as the devices maintained $99\% \pm 4\%$ of their initial J_{sc} , $97\% \pm 3\%$ of their initial V_{oc} , and $93\% \pm 13\%$ of their initial PCE. Although their PCE were relatively low, the external quantum efficiency (EQE) spectrum shown in Fig. 4(a) was slightly reduced after electron irradiation. Song et al. [58] in 2020 reported similar results for V_{oc} and FF with a device exceeding 20%; however, the J_{sc} decreased significantly. After electron irradiation, while V_{oc} and FF maintained nearly 90% of their initial values after electron irradiation (1 MeV with 1×10^{13} for low and $1 \times 10^{15} \text{ e} \cdot \text{cm}^{-2}$ for high dose of fluences), J_{sc} dropped to 70% of its initial values because of darkening of the glass substrates, leading to a 40% drop in PCE after irradiation (Figs. 4(b) and (c)) [58]. The reduction in the transmittance of the substrate hindered the absorption of light by the perovskite photoabsorption layer. Moreover, the large carrier diffusion length ($> 1 \mu\text{m}$) of the thin-film perovskite layer contributes to enhanced radiation tolerance because the photogenerated carriers can still diffuse effectively and support power generation despite the presence of radiation-induced defects and traps [57–61]. It is worth noting that soda-lime glass becomes center-colored when exposed to radiation, implying that selecting suitable substrates can prevent darkening. These results imply the high tolerance of PSCs to electron irradiation.

Beyond preserving the performance, further enhancement of the resistance of perovskites to electron radiation requires a deeper understanding of the mechanisms by which electron radiation affects it. Xia et al. [59] investigated the mechanism of electron beam (EB) damage in perovskite thin films (MAPbI₃, FAPbI₃, and CsPbI₃) using cathodoluminescence (CL) spectroscopy. Two mechanisms were proposed to explain the changes observed in the CL peaks. As shown in Fig. 4(d), the observed CL signal changes can be explained by two primary damage mechanisms: defect formation from irradiation damage and phase transformation due to electron-beam heating. The broadening and quenching of the excitonic CL peak ($\sim 1.6 \text{ eV}$ for MAPbI₃) result from nonradiative defect formation, likely caused by high-energy electron irradiation displacing atoms in the perovskite lattice. This knock-on displacement generates Frenkel-type defects, where displaced ions move to interstitial sites, potentially forming nonradiative recombination centers that reduce the CL intensity. Meanwhile, the appearance of new high-energy CL peaks suggests the formation of an intermediate phase due to EB heating, particularly under high voltage, strong beam current, or prolonged exposure. They also found CsPbI₃ shows stable behavior under EB irradiation, indicating better thermal stability. Dang et al. [60] investigated the mechanism of EB in the decomposition of inorganic perovskites (CsPbX₃, X = I, Br). As shown in Fig. 4(e), they suggest degradation mechanism that CsPbBr₃ nanocrystals undergo radiolysis, where electron-stimulated desorption causes partial bromine loss and partial reduction of Pb²⁺ to Pb⁰. The resulting Pb⁰ atoms diffuse and aggregate, forming high-contrast particles, a phenomenon previously observed by multiple research groups. This diffusion process was enhanced by elevated temperatures and

EB exposure. In the initial stages, Pb nanoparticles remain epitaxially bound to the CsPbBr₃ lattice. However, with continued irradiation, they transition into Pb crystals, leading to local amorphization and the eventual disruption of the CsPbBr₃ lattice.

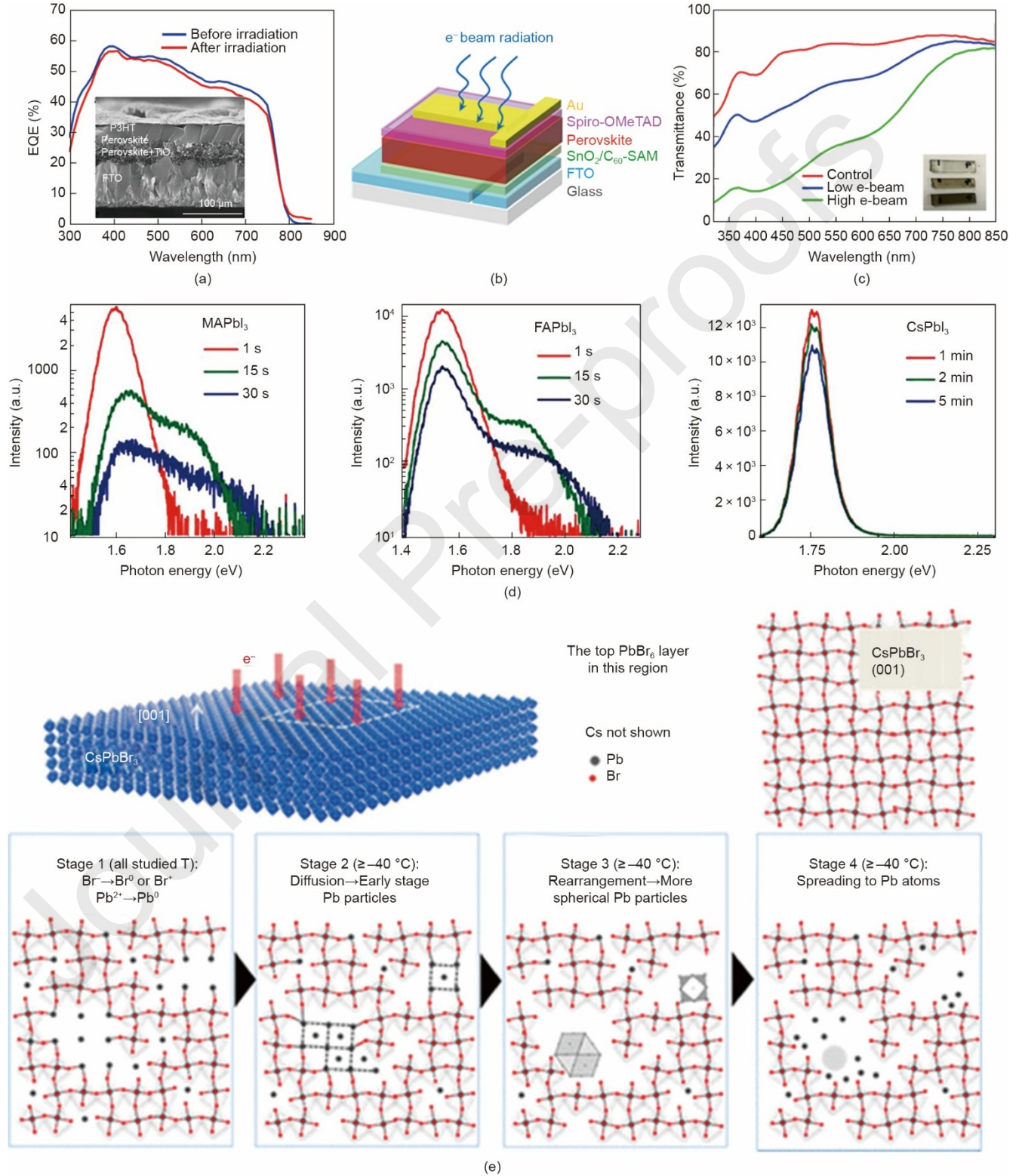


Fig. 4. Electron radiation effect on PSCs. (a) Photocurrent EQE spectra pre- and post-irradiation of 1 MeV electron with fluence of $1 \times 10^{13} \text{ e}^- \text{ cm}^{-2}$ and cross-section SEM image of the device inset. Reproduced from Ref. [57] with permission. (b)

Device structure of a PSC for electron irradiation test with 1 MeV and 1×10^{13} to 1×10^{15} e $\cdot$ cm $^{-2}$ fluences, and (c) transmittance spectra of pre- and post-irradiation with inset photo of colored glass. Reproduced from Ref. [58] with permission. (d) Cathodoluminescence (CL) spectra of MAPbI $_3$, FAPbI $_3$, and CsPbI $_3$ from left to right of pre- and post-irradiation of 15 kV electrons for various times. Reproduced from Ref. [59] with permission. (e) Illustration of CsPbBr $_3$ under electron irradiation (80/200 keV) and decomposition stages after irradiation. Reproduced from Ref. [60] with permission.

Proton radiation is also an ionizing radiation, which is 2000 times heavier than electrons and can cause the degradation of PSCs, as ionizing radiation is known to impact electronic devices by inducing defect formation. In 2016, Lang et al. [62] investigated the proton radiation hardness of PSCs (glass/ITO/PEDOT:PSS/MAPbI $_3$ /PC61BM/BCP/Ag where PEDOT:PSS is Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate), PC61BM is Phenyl-C61-butyric acid methyl ester, and BCP is Bathocuproine) with an inverted structure by exposing devices to 68 MeV of proton radiation up to 1.02×10^{13} p $\cdot$ cm $^{-2}$ as shown in Fig. 5(a). In Fig. 5(b), 40% reduction in J_{sc} was observed at proton doses of 10^{12} and 10^{13} p $\cdot$ cm $^{-2}$, respectively, while V_{oc} and the fill factor remained stable. They found that the perovskite absorber can endure proton doses up to 10^{12} p $\cdot$ cm $^{-2}$, nearly three orders of magnitude higher than the damage threshold of crystalline silicon (c-Si). They measured the internal quantum efficiency (IQE) as shown in Fig. 5(c) to observe the effect of the decrease in the light-absorption capability of the PSCs. After proton irradiation ceases, the perovskite undergoes a self-healing process, leading to J_{sc} recovery. After 10 days, V_{oc} and FF improved significantly compared with those of the reference devices. Later, Lang et al. [63] studied the radiation hardness of a triple-cation-based perovskite (Cs $_{0.05}$ MA $_{0.17}$ FA $_{0.83}$ Pb(I $_{0.83}$ Br $_{0.17}$) $_3$) with 20 and 68 MeV proton irradiation from the substrate side. As 1 mm of substrate can shield radiation penetration into perovskite for low-energy protons such as 10 MeV, they employed 20 MeV, 68 MeV, and 1 GeV of proton energy, which are sufficient to penetrate the substrate, to investigate the radiation hardness of perovskite (Figs. 5(d) and (e)). They found that 68 MeV proton irradiation caused a slight decrease in all PV parameters while 20 MeV proton irradiation had no detrimental effect, as shown in Figs. 5(f) and (g). To explain why 68 MeV protons create more recombination centers than 20 MeV protons, they analyzed the nuclear scattering energy loss using SRIM simulations. The results show that 20 MeV protons lose four times more energy to nuclear scattering but cause fewer primary knock-ons, with energy loss primarily affecting the inorganic framework at higher proton energies. For the 68 MeV protons, the increased collision cascades displaced more iodine (I) and lead (Pb) atoms, preventing them from returning to their original lattice positions. Recently, Kirmani et al. [64] suggested the mechanisms of radiation-induced degradation of perovskite devices (glass/ITO/SnO $_2$ /perovskite/Spiro-OMeTAD/Au) and healing by applying dual irradiation dosing of low proton energies, 0.06 MeV and 1.0 MeV (Figs. 5(h) and (i)). They systematically tuned the ionization or non-ionization energy loss (IEL or NIEL) to investigate irradiation scenarios (Fig. 5(j)). By systematically increasing the ionization energy loss (IEL) of incident protons, they obtained direct evidence of defect healing through electronic ionization. Defects induced by low-energy protons (0.06 MeV) were partially healed when the device was exposed to an optimal dose of higher-energy protons (1.0 MeV).

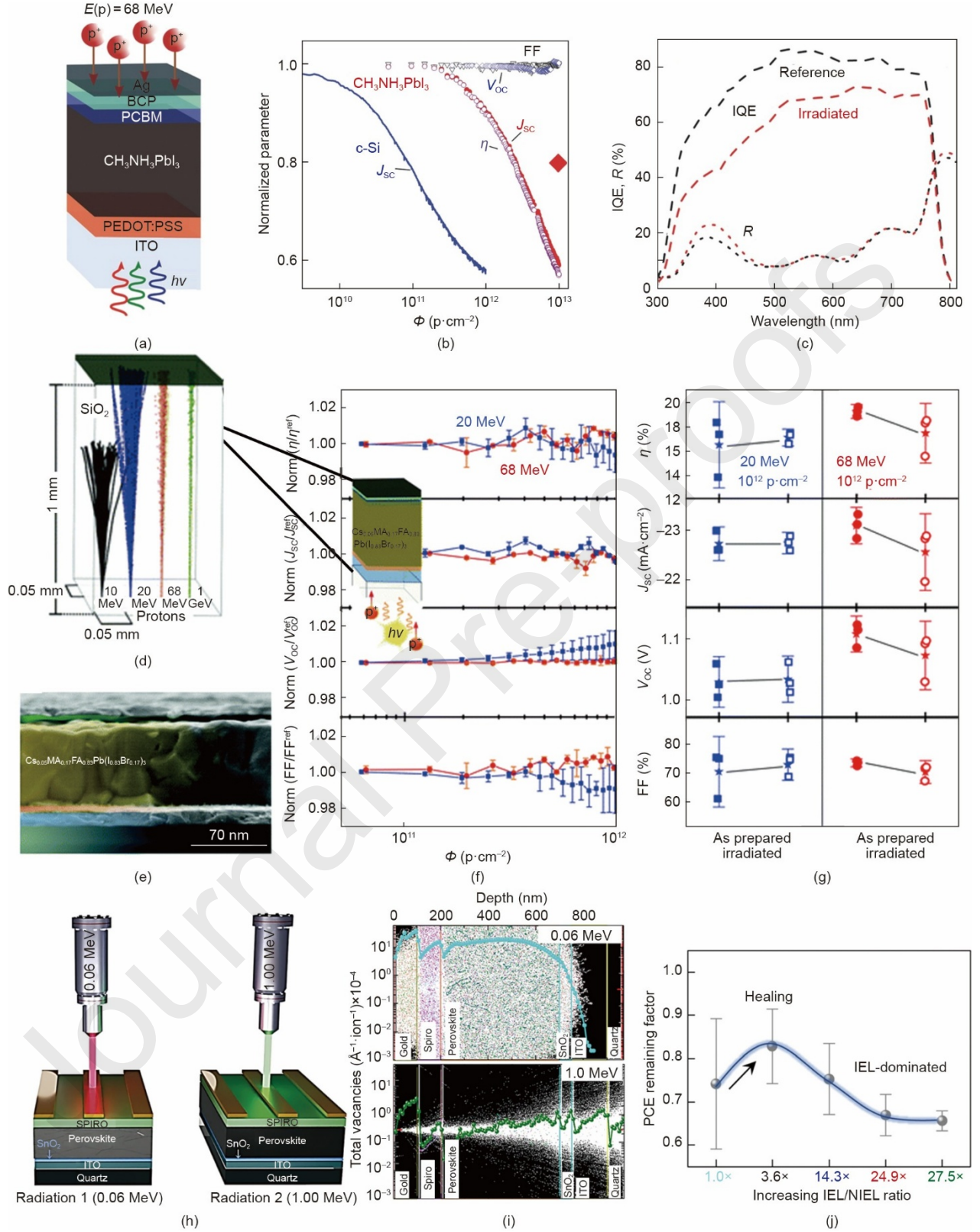


Fig. 5. Proton radiation effect on PSCs. (a) Structure of tested device for 68 MeV proton irradiation. (b) Normalized PV parameters (V_{oc} , J_{sc} , and FF) with x-axis of proton dose, Φ , and (c) IQE and reflectance (R) of the reference device (black) and the proton-irradiated device (red). Reproduced from Ref. [62] with permission. (d) SRIM simulation image of 10, 20, 68 MeV and 1 GeV proton radiation through the SiO_2 quartz, (e) cross-section SEM image of tested device, (f, g) the evolution of η (efficiency), J_{sc} , V_{oc} , and FF in $\text{Cs}_{0.05}\text{MA}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.83}\text{Br}_{0.17})_3$ solar cells during 20 and 68 MeV proton irradiation is shown as a function of accumulated proton dose (Φ), normalized to non-irradiated reference devices. Data was obtained from *in situ*

J–V measurements under halogen lamp illumination and (f) statistical analysis of PV parameters before and after irradiation at $\Phi = 10^{12}$ p·cm⁻² with 20 or 68 MeV protons, measured under simulated AM1.5G conditions. Reproduced from Ref. [63] with permission. (h) Schematic image of single (0.06 MeV) and dual dose (1.0 MeV) of proton radiation on n-i-p PSC device, (i) SRIM simulation images of ion vacancy profiles, (j) PCE remaining factor curves of PSCs with proton irradiation with various IEL/NIEL scenarios. Reproduced from Ref. [64] with permission.

A significant number of gamma rays are inevitably generated when galactic cosmic rays, primarily composed of protons and alpha particles, interact with the structural nuclei of spacecraft. Over 20 years of space missions, spacecraft are expected to accumulate approximately 1000 krad of gamma radiation [65–67]. This presents a challenge to the long-term stability of perovskite materials for space applications. In this regard, Yang et al. [66] found that hybrid perovskites are stable under exposure to continuous light and total accumulated dose of 2.3 Mrad gamma-ray irradiation for 1535 h, and the devices maintained 96.8% of initial performance. As expected, they found that gamma radiation induced center coloring in the substrates, leading to a reduction in transmittance, (Figs. 6(a)–(c)) and suggested that gamma-ray exposure displaces ions in the perovskite crystal, creating ion vacancies that contribute to the initial degradation [65]. However, these vacancies can migrate back to their original lattice positions because they represent a thermodynamically lower-energy state, facilitating a self-healing process (Fig. 6(d)) [65]. Center-colored substrates after gamma radiation have also been reported by Yang et al. (Fig. 6(e)) [66]. As reported in their study, even after 500 krad of gamma irradiation, the SEM images of the perovskite films remained dense and uniform as shown in Fig. 6(f). Boldyreva et al. [67] conducted the gamma ray resistance of various perovskite compositions (MAPbI₃, MAPbBr₃, Cs_{0.15}FA_{0.85}PbI₃, Cs_{0.1}MA_{0.15}FA_{0.75}PbI₃, CsPbI₃, and CsPbBr₃) at doses ranging from 10 to 1000 krad. They claimed that MAPbI₃-based solar cells were the most stable against gamma radiation owing to the self-healing process of MAPbI₃. In MAPbI₃, fast defect healing is primarily driven by the reversible formation of volatile species, radical chemistry induced by ionizing radiation, their easy diffusion within the active layer, and the passivating effect of iodine as a Lewis acid. Other perovskite materials did not generate significant amounts of volatile species at low temperatures, making the gas-phase healing ineffective (Fig. 6(g)).

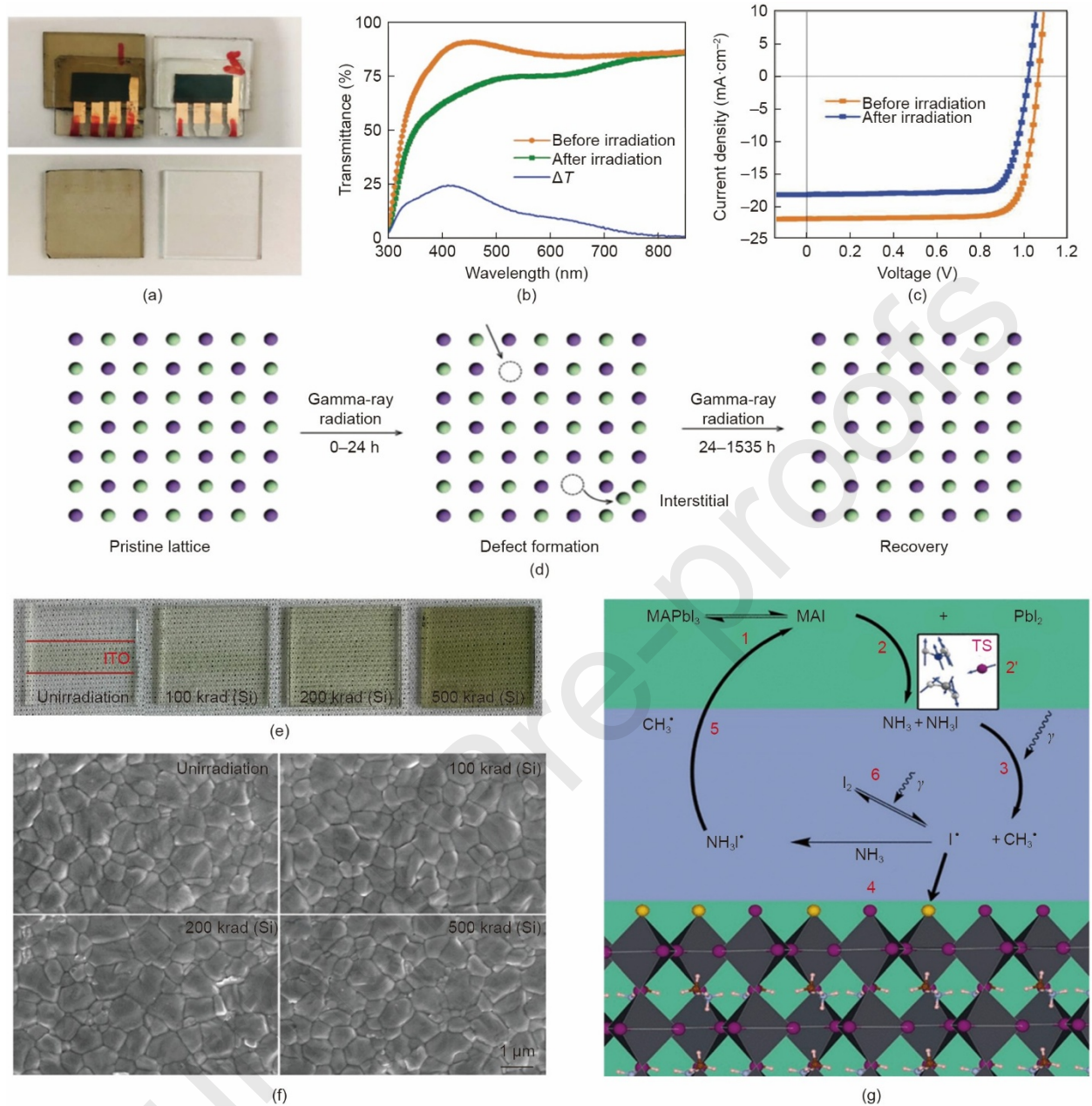


Fig. 6. Gamma ray radiation effect on PSCs. (a) Device pictures of (right) before and (left) after 2.3 Mrad of gamma ray irradiation; (b) transmittance spectra changes; (c) J–V curves of the perovskite device before and after irradiation test; (d) illustration of self-healing mechanism of perovskites under gamma ray irradiation. Reproduced from Ref. [65] with permission. (e) Actual substrate images and (f) top-view of SEM images of perovskite films under gamma rays with various dose. Reproduced from Ref. [66] with permission. (g) Illustration of healing mechanism of MAPbI_3 decomposition based on theoretical calculations, where the green background represents a solid state and the blue background denotes the gas phase. Reproduced from Ref. [67] with permission.

As the air density decreases with increasing altitude, especially in LEO, the intensity of the UV rays increases. UV rays can cause more damage in space than on Earth, accelerating the UV-induced degradation of solar cells by breaking down molecular chains. In particular, the UV instability of PSCs has been reported [68–70], causing the irreversible decomposition of perovskite materials with the generation of halide gases. Leijtens et al. [71] demonstrated the UV stability of PSCs with compact $\text{TiO}_2/\text{Al}_2\text{O}_3$ nanoparticles under 1 sun illumination for over 1000 h. A similar method was used to improve the mitigation of UV-sensitive TiO_2 layers by introducing an interlayer between the TiO_2 and perovskite layers [72]. The effects of the SiO_x

interfacial layer included decreased photocatalytic activity, as confirmed by photoelectrochemical measurements, improved perovskite crystallinity, and enhanced electron transport performance. Farooq et al. [73] compared the stabilities of UV-A (360–380 nm) and UV-B (310–317 nm) with those of various ETL (SnO_2 , compact- TiO_2 , electron-beam TiO_2 , and nanoparticle- TiO_2). UV-B radiation is detrimental to PSCs, regardless of the ETLs. It was also confirmed that an additional luminescence downshifting (LDS) layer can recover up to $0.3 \text{ mA}\cdot\text{cm}^{-2}$ photocurrent. In this regard, our group mitigated UV sensitivity by doping the downshifting phosphor Eu (Eu^{3+}) into TiO_2 [74], leading to improved J_{sc} and UV stability, maintaining 75% of the initial PCE under UV light (365 nm) for 500 h under ambient conditions.

In addition to protons, electrons, and gamma rays, other ionizing radiations, such as X-rays and neutrons, can affect the solar cell performance and stability of PSCs.

X-ray exposure has been reported to induce surface defects and increase trap densities, leading to reduced carrier lifetime and PV performance. Fig. 7(a) shows that the increase in X-ray irradiation (9 keV to 30–40 nm (FWHM) with a flux of $2.6 \times 10^8 \text{ photon}\cdot\text{s}^{-1}$) times for 0–800 s on perovskite causes a reduction in the concentration of iodide and lead, suggesting that the degradation of photocurrent in PSCs is primarily determined by the radiation dose deposited within the perovskite layer over the interaction volume [75]. Dai et al. [76] reported that X-ray-induced degradation (under 90 and 250 Gy, 30 and 60 min dwell time with a dose rate of $450 \text{ mGy}\cdot\text{s}^{-1}$, respectively) in PSCs is attributed to the generation of secondary electrons, which facilitate the formation and migration of mobile iodide (I^-) ions as illustrated in Fig. 7(b), indicating that the degradation behavior under X-ray exposure closely resembles that observed with direct EB irradiation. They also investigated the light intensity dependence of the healing effect, observing that 1 sun illumination induced higher temperatures and enhanced ion migration, resulting in a faster recovery rate compared to 0.05 sun illumination. Interestingly, although X-rays can degrade perovskite materials, their excellent X-ray absorption and charge transport properties enable their application as efficient X-ray detectors [77–79]. However, owing to their non-ionizing yet highly penetrative nature, neutrons mainly cause permanent displacement damage by interacting with atomic nuclei, resulting in lattice disruptions and long-term device degradation [77,80,81]. Paterno et al. [77] reported that the damage from fast neutrons, attributed to atomic displacements in the perovskite layer, can be partially offset by neutron-induced shallow traps. However, these traps functioned as dopants, enhancing the open-circuit voltage and suppressing the leakage current under simultaneous light and neutron irradiation (Figs. 7(c) and (d)). Although studies on neutron effects on PSCs are relatively few, early investigations suggest that PSCs show moderate resistance; however, further systematic evaluation is needed, particularly for space applications where the neutron flux can be significant (Fig. 7(e)) [77,82].

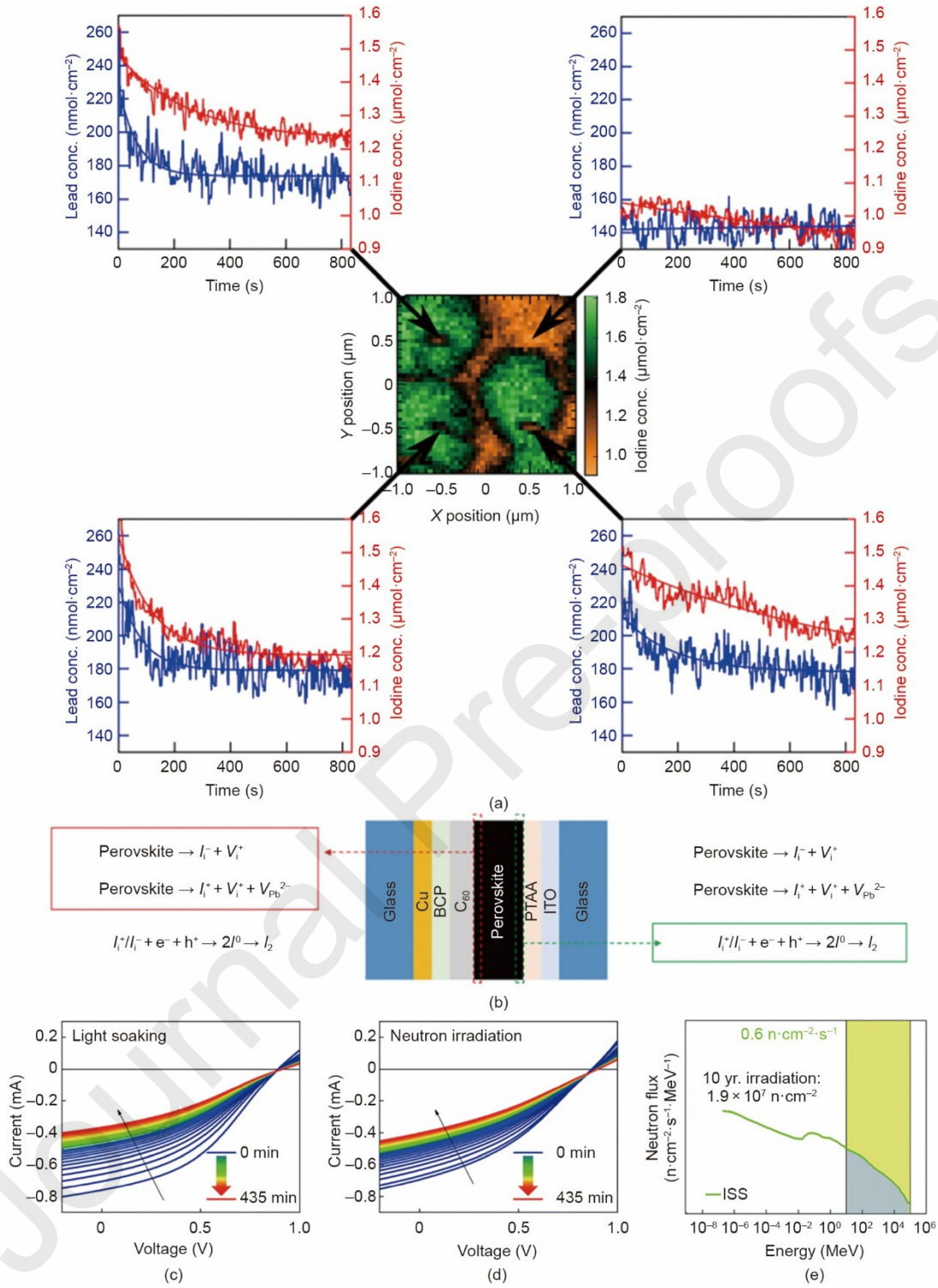


Fig. 7. (a) X-ray induced decrease of the concentrations of iodine and lead with X-ray dwell times. Reproduced from Ref. [75] with permission. (b) Suggested damage revolution in the PSCs. Reproduced from Ref. [76] with permission. (c) Neutron energy spectrum estimated flux on the ISS, and evolution of the I-V curves under (d) extended light illumination and (e) light/neutron irradiation. Reproduced from Ref. [77] with permission.

As discussed above, various types of radiation generally have a negative impact on PSC performance, although some studies have reported healing effects under certain conditions. In this context, and given the

high costs associated with space missions, it is essential that solar cells comply with qualification standards established by international agencies such as AIAA, ECSS, and JAXA. However, these tests were originally developed for III-V solar cells with relatively thick device architectures ($> 110 \mu\text{m}$). In contrast, thin-film technologies such as OPVs and PSCs typically feature much thinner active layers ($< 0.5 \mu\text{m}$), for which conventional radiation tests may not accurately capture their degradation mechanisms or operational behavior. In fact, high energy protons above 0.5 MeV can penetrate the perovskite layer and cause 1000 times less non-ionizing energy loss (NIEL) than low energy protons (0.05–0.15 MeV) [12]. The primary effect of NIEL is to cause the atom displacement by knocking atoms out of their lattice position, leading to structural defects, while ionizing energy loss (IEL) is the energy loss through ionization, where electrons are ejected from atoms, causing charge trapping, increased leakage currents, and performance degradation. As demonstrated by Kirmani et al. [64], the ratio of IEL to NIEL is important for understanding the mechanisms of radiation-induced degradation and the healing effects of PSCs. Using lower proton energy to evaluate PSCs ideally applies to thin-film solar cells with lower LEO. Given the potential applications of thin-film solar cells, including PSCs, in deeper spaces where the fluences of higher proton energy increase, the impact of high-energy protons should also be considered, although high-energy protons can fully penetrate solar cell devices without stopping. Another factor that should be considered is the direction of incident radiation. This is because the single-junction PSCs achieve their highest performance when illuminated by the substrate. In space environments, this corresponds to the direction facing the sun, which is the primary direction of radiation exposure. Therefore, considering the direction of radiation incidence during ground testing is crucial for accurately assessing the radiation hardness and overall performance of PSCs in space applications. In particular, it is important to avoid unwanted degradation at the charge transport layer (CTL) interfaces before radiation reaches the perovskite photoabsorber because the radiation energy decreases more when passing through high-density materials, such as metal oxides or metals, than when passing through organic materials [83,84]. When radiation is incident from the top electrode side, n-i-p structured PSCs typically employ organic hole transport layers such as Spiro-OMeTAD or Poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA), whereas p-i-n structures use electron transport layers like C_{60} or PCBM as the front-facing layer. In both cases, the CTL is first exposed to radiation, which can lead to the degradation of the charge extraction capability owing to radiation-induced damage in the organic CTL materials. From a broader perspective, healing effects have been reported as an inherent behavior in perovskite materials under certain conditions, such as light soaking or mild thermal activation. Nevertheless, even when such partial recovery occurs, it is essential to establish comprehensive proton and electron irradiation protocols, including proper calibration using the DDD and RDC methodologies, which account for both degradation and recovery behaviors, to accurately estimate the EOL performance of PSCs.

4.2.2. Thermal fluctuation

PSCs are also known for their relatively poor thermal stability, which presents a significant challenge for their deployment in space. On Earth, thermal fluctuations primarily occur in a cyclic manner, that is gradual heating and cooling over time. However, in space, temperature variations are far more extreme and rapid, often reaching shock levels, compared to simple cycles. For instance, solar panels on satellites and spacecrafts can experience temperature swings of several hundred degrees Celsius within minutes as they move in and out of direct sunlight. This type of thermal shock can cause severe structural and chemical degradation of the PSCs, leading to material delamination, phase segregation, and irreversible device failure. Unlike traditional Si or III-V solar cells, which have been extensively tested and optimized for space-grade thermal endurance, perovskites remain largely unproven under these conditions, raising concerns regarding their long-term viability.

Despite the promising characteristics of PSCs, including their high efficiency and lightweight properties, there is currently a lack of comprehensive research addressing their behavior under extreme thermal shock. Most studies focused on terrestrial thermal cycling tests (Fig. 8(a)) with and without encapsulation [85–88]. Due to the multi-stacking nature of PSCs, thermal cycling tests induce delamination of the layers, as shown in Fig. 8(b) [88]. Meanwhile, Li et al. [89] conducted the rapid thermal cycling tests of PSCs between -60°C and 80°C with a rate of 20°C per minute. After 120 rapid thermal cycles, the devices with β -poly(1,1-difluoroethylene) (β -pV2F) additives in perovskite maintained over 90% of their initial efficiency (Figs. 8(c) and (d)). This stability is attributed to the strain-buffering and lattice-stabilizing effects of β -pV2F, which forms a self-assembled polymeric layer around the perovskite crystals. This layer reduces friction and

mitigates lattice strain during thermal cycling, enabling the perovskite to endure stress more effectively. Another work with a thermal cycling test based on ISOS-T-3 (-40 to -80 °C, N₂, 6 hours per cycle) for perovskite solar cells has been reported to understand mechanical stress of perovskite films after conducting thermal cycling fatigue [85]. They added *n*-octylammonium iodide with an alkyl $(\text{CH}_2)_n$ ($n = 8$) linker into perovskite precursors to minimize the residual internal stress. They found that even after 100 thermal cycling tests, the perovskite films containing an optimal amount of OAI exhibited improved structural integrity as shown in Figs. 8(e) and (f). Additional XRD results in Fig. 8(g) further demonstrated that the OAI-containing perovskite films maintained good crystallinity and thermal stability even after 200 cycles compared to control. The authors attributed this behavior to the OAI molecules that stabilized the buried interface and grain boundaries by buffering local stress accumulation, thereby mitigating mechanical degradation and fracture. The temperature range used in these studies is also relevant for ground-based applications. However, temperature in space can rise up to 125 °C in LEO and the proposed current testing protocols of thermal cycling are ① -95 to 140 °C and -175 to 95 °C for hot extreme test and cold extreme test from AIAAS-111A-2014 [38], ② -170 to 120 °C for vacuum thermal cycling from ECSS-E-ST-20-08C Rev.2 [39], and ③ -170 to 120 °C for thermal shock from JAXA-QTS-2130A [40]. Although recent reports revealed that perovskites decompose at a high temperature exceeding 250 °C [90,91], the space environment is complex and can lower the trigger point of the decomposition of perovskite. In this regard, this gap must be addressed before PSCs can be considered reliable options for space missions. The instability of the perovskite crystal structure under extreme heat or cold stress, coupled with its known susceptibility to decomposition, makes it imperative to develop improved material formulations, encapsulation strategies, and thermal management techniques specifically designed for space applications. In fact, because thermal shock tests with/without vacuum are extremely expensive to conduct in laboratory-scale testing owing to the price of equipment with rapid temperature changes, there is an obstacle to accessing the evaluation of PSCs. One of NASA internal articles uses relatively mild thermal cycling testing conditions, -55 and 125 °C for 35–100 cycles on their solar cells [92]. Therefore, it is ideal to develop an inference test that can reflect a similar level of thermal stress with or without vacuum conditions as well as to design solar cell structures by considering lattice strains and the coefficient of thermal expansion (CTE) between multi-stacked layers, including encapsulations, to avoid lattice mismatches and delamination by thermal stress, thereby accelerating the degradation of PV performance [93,94]. The main challenge arises from the lattice mismatch-induced strain, which generates significant tensile stress, promotes ion migration, and deteriorates charge carrier mobility, resulting in poor device performance and stability. Therefore, improving the thermal resilience of PSCs for space applications should be considered from various perspectives.

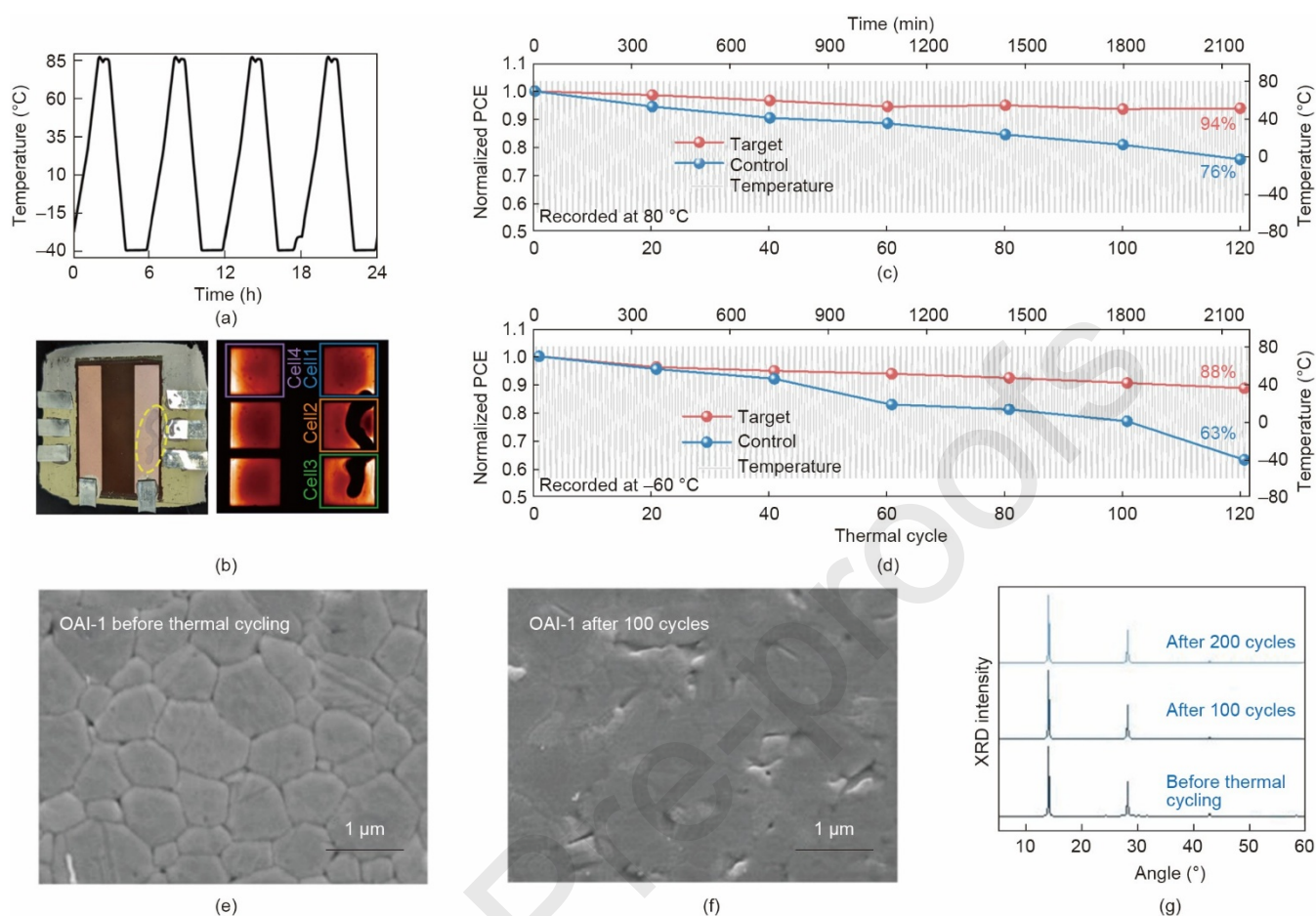


Fig. 8. Thermal cycling of PSCs. (a) Thermal cycling temperature profile and (b) device image after thermal cycling test. Dash-circled area indicates delamination of device and electroluminescence (EL) image (right-side). Reproduced from Ref. [88] with permission. (c, d) PCE evolution of control and target PSCs recorded at (c) 80 and (d) -60 °C under thermal cycling between -60 and 80 °C. Rapid thermal cycling was performed at a 20 °C $\cdot$ min $^{-1}$ ramp rate, with a 2 min waiting period at extreme temperatures for thermal equilibrium. The cycle starts at room temperature, heats to 80 °C, cools to -60 °C, and returns to room temperature, completing each cycle in 18 min. Reproduced from Ref. [89] with permission. (e–g) Show SEM top-view images of the fractured buried interface of the perovskite thin films before and after 100 cycles of thermal cycling test (-40 to 85 °C) and (g) X-ray diffraction peaks of perovskite films before and after 100 and 200 cycles of thermal cycling test. Reproduced from Ref. [85] with permission.

4.2.3. Outgassing

The space exists in vacuum devoid of air and atmospheric pressure [95–99]. PSCs face significant challenges related to outgassing, particularly because of the volatile nature of their halide components and because they are accelerated without encapsulation as shown in Fig. 9(a) [100]. One of the most concerning issues is the decomposition of iodide into iodine gas (Fig. 9(b)) [95–97], which occurs under illumination. This degradation pathway not only reduces the efficiency and stability of solar cells, but also poses a risk in enclosed spacecraft environments, where outgassed iodine can interact with and potentially damage sensitive electronic and optical components [98,99]. While this problem is already well known under standard terrestrial conditions, it is expected to become even more severe in a space vacuum. In the absence of atmospheric pressure, volatile species have an even lower activation energy barrier for sublimation, meaning that iodine and other gaseous by-products can be released at a much higher rate, accelerating the degradation of PSCs and contaminating the surrounding spacecraft materials.

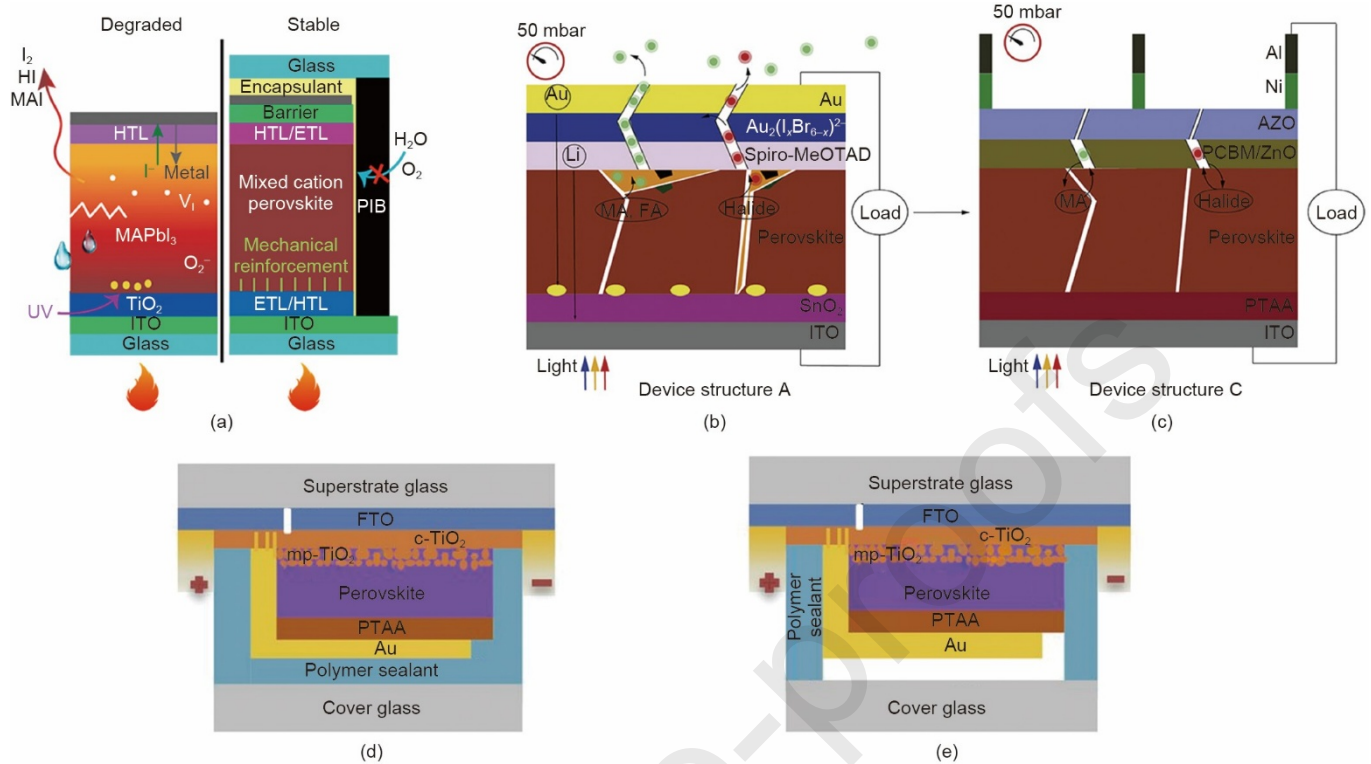


Fig. 9. Outgassing effect of PSCs. (a) Illustrations of outgassing of I₂, HI, and MAI gases from an unencapsulated device and a stable encapsulated device. Reproduced from Ref. [100] with permission. (b, c) Illustrations depicting the impact of device structure on OHP transformation and ion migration under vacuum and illumination. Device structure A, Li⁺, Au, I⁻, and Br⁻ migrate and accumulate, accompanied by slow MHP outgassing, whereas device structure C with encapsulation remains unaffected. Reproduced from Ref. [96] with permission. (d, e) Illustrations of two different encapsulation methods to suppress outgassing of decomposition perovskite. Gas chromatography was used for verification of gas compositions. Reproduced with permission from Ref. [101].

To mitigate these issues, one approach could involve suppressing volatile halides with more stable compositions or incorporating encapsulation strategies that effectively suppress outgassing (Figs. 9(c)–(e)) [87,96,101,102]. In addition to halide instability, organic-based CTLs such as PEDOTP: PSS, P3HT, PTAA, spiro-OMeTAD, 2PACz, and 4PACz, which are commonly used in PSCs, present another outgassing concern. Many PSC architectures incorporate organic hole and electron transport layers owing to their superior charge selection and blocking abilities and their ability to form high-quality interfaces with the perovskite absorber [103]. However, in vacuum, these organic layers may undergo outgassing, releasing small organic molecules or volatile decomposition products. This is particularly problematic in space applications where stringent material selection criteria are in place to prevent the contamination of spacecraft optics, thermal radiators, and other mission-critical surfaces. Organic compounds that exhibit significant outgassing behavior can lead to unwanted deposition on optical lenses, solar panels, or other exposed equipment, degrading performance over time. Additionally, alternative charge transport materials, such as metal oxides, may offer a more promising solution than organic layers. These materials, including tin oxide (SnO₂), titanium dioxide (TiO₂), or nickel oxide (NiO_x), are not only more resistant to outgassing but also exhibit excellent stability under radiation and thermal stress, making them better suited for space environments. However, such modifications must be carefully optimized to maintain the high efficiency and scalability of PSCs, as the performance of PSCs with all-inorganic CTLs is far inferior to that of PSCs with organic CTLs [104–106]. Developing low-outgassing and space-qualified encapsulation technologies requires a combination of advanced material designs, perovskite devices, and comprehensive vacuum stability testing to ensure long-term reliability in space missions.

5. Conclusion and outlooks

PSCs have demonstrated potential for space applications because of their high efficiency, light weight, and radiation hardness. However, several key challenges must be addressed before PSCs can be widely used in long-term space missions. Most importantly, to obtain reliable PSCs for space applications, standardized testing protocols must be adopted. While the existing qualification standards set by the International Electrotechnical Commission (IEC) [107] were originally designed for Si-based PVs, emerging initiatives such as the International Summit on Organic PV Stability (ISOS) are working toward tailored stability assessments for PSCs [108]. Benchmarking this approach for assessment is required to adequately evaluate PSCs in space. Future research directions are recommended to reflect the characteristics of PSCs and advance their applications in space.

(1) Radiation hardness testing should consider appropriate radiation energy with fluence depending on the mission goals and the incident direction of radiation exposure depending on the structure (single-junction or MJ) of the PSCs. Radiation tolerance can be improved by compositional engineering (e.g., all-inorganic or 2D/3D hybrid structures) and incorporation of radiation-absorbing buffer layers.

(2) Thermal shock needs to be conducted with rapid temperature changes of $30\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ to reflect space thermal fluctuation, extended to consideration of the difference of CTE between layers. In this regard, the thermal stability may be enhanced through robust encapsulation, low-CTE substrates, and phase-stable perovskite compositions.

(3) To minimize the outgassing effect caused by external stresses such as vacuum, atomic oxygen, and thermally induced degradation, it is important to find an ideal MHP composition, replace CTLs with less volatile materials such as metal oxides, and encapsulate them to reduce the volatilization of halides or organic gases.

Although there are no standard qualification tests for space PSCs meeting the current space-grade qualification standards set by organizations such as AIAA, ECSS, and JAXA, these standards are crucial in ensuring the feasibility of PSCs for demanding space applications. Additionally, more realistic simultaneous stress tests incorporating radiation exposure under illumination and thermal cycling will provide a better approximation of real-space operating conditions [109]. One particularly promising approach for space-based PSCs is that of Sn-based perovskites. While Sn perovskites suffer from the rapid oxidation of Sn^{2+} to Sn^{4+} in the presence of oxygen issues on Earth [28], the oxygen-free vacuum of space could significantly mitigate this degradation pathway, allowing them to retain structural and electronic stability over extended periods in space. Another advantage is that their low-bandgap characteristics ($\sim 1.5\text{ eV}$) make them well-suited for tandem solar cells optimized for the AM0 solar spectrum, particularly in Pb-Sn hybrid configurations [28,110]. In the meantime, an innovative direction for PSC, which is difficult for other solar cells to carry out, is the in-space manufacturing of PSCs, a concept explored by NASA and the National Renewable Energy Laboratory (NREL) [111]. Technologies under development [112], such as on-orbit printing, vapor deposition, and laser scribing, can enable the fabrication of ultrathin, large-area solar arrays directly in space. By reducing the need for extensive launch costs and the risk of launch failure, this approach can dramatically reduce costs and support self-sustaining solar power solutions for lunar bases and deep-space missions. A 1 MW solar array could be fabricated in orbit using only 12 kg of condensed absorber material, significantly lowering launch expenses while maintaining high energy efficiency. This is not only limited to single-junction PSCs but is also extended to all-perovskite MJ tandem solar cells, with low-bandgap Sn-based or Sn/Pb-mixed PSCs as the bottom cell and WBG PSCs as the top cell. This in-space-supplied PSCs technology can accelerate the construction of the Lunar Base and Habitat, and further space exploration.

Acknowledgments

This work was supported by the Global STEM Professorship Scheme of the Hong Kong government, a National Research Foundation (NRF) of Korea grant funded by the Korean government (MEST) (RS-2023-00257494 and RS-2024-00333809), the Korea Institute of Energy Technology Evaluation and Planning (KETEP), the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (20224000000260).

References

- [1] Vailati A, Šeta B, Bou-Ali MM, Shevtsova V. Perspective of research on diffusion: from microgravity to space exploration. *Int J Heat Mass Transf* 2024;229:125705.
- [2] Pearson SD, Clifton KS. NASA's Space Environments and Effects (SEE) program: contamination engineering technology development. In: *Proceedings of the Optical System Contamination*; 1999 Jul 18–23; Denver, CA, USA. Bellingham: SPIE; 1999. p. 4–14.
- [3] Zhang W, Sun C, Liu K, Shen W, Wu Y, Yao L, et al. Technical challenges of space solar power stations: ultra-large-scale space solar array systems and space environmental effects. *Sp Sol Power Wirel Transmission* 2024;1(2):69–87.
- [4] NASA. Station assembly elements [Internet]. Washington, DC: NASA; 2025 Jun 6 [cited 2025 Jun 7]. Available from: <https://www.nasa.gov/international-space-station/international-space-station-assembly-elements/>.
- [5] El-Genk M. Chapter 26—Safety guidelines for space nuclear reactor power and propulsion systems. In: Pelton JN, Jakhu RS, editors. *Space safety regulations and standards*. London: Elsevier; 2010. p. 319–70.
- [6] NASA. Nuclear rockets [Internet]. Washington, DC: NASA; C2025 [cited 2025 Jun 7]. Available from: <https://www.nasa.gov/rocket-systems-area-nuclear-rockets/>
- [7] Thomas D. Nuclear thermal propulsion – Progress and potential. *J Space Saf Eng* 2024;11(2):362–73.
- [8] NASA. Mars 2020's MMRTG. Report. Washington, DC: NASA; 2020.
- [9] Romano V, Agresti A, Verduci R, D'Angelo G. Advances in perovskites for photovoltaic applications in space. *ACS Energy Lett* 2022;7(8):2490–514.
- [10] Verduci R, Romano V, Brunetti G, Yaghoobi Nia N, Di Carlo A, D'Angelo G, et al. Solar energy in space applications: review and technology perspectives. *Adv Energy Mater* 2022;12(29):2200125.
- [11] Xu G, Cai P, Tu Y, Kong H, Ke Z, Li Y, et al. Calibration for space solar cells: progress, prospects, and challenges. *Sol RRL* 2024;8(6):2300822.
- [12] Kirmani AR, Durant BK, Grandidier J, Haegel NM, Kelzenberg MD, Lao YM, et al. Countdown to perovskite space launch: Guidelines to performing relevant radiation-hardness experiments. *Joule* 2022;6(5):1015–31.
- [13] Guter W, Dunzer F, Ebel L, Hillerich K, Köstler W, Kubera, et al. Space solar cells – 3G30 and next generation radiation hard products. *E3S Web Conf* 2017;16:03005.
- [14] AZUR SPACE. 1.5 million cells in space without any failures. Heilbronn: AZUR SPACE; [cited 2025 March 1]. Available from: <https://www.azurspace.com/index.php/en/products/products-space/space-solar-cells>.
- [15] Kaltenbrunner M, Adam G, Głowacki ED, Drack M, Schwödauer R, Leonat L, et al. Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air. *Nat Mater* 2015;14(10):1032–9.
- [16] Hu Y, Niu T, Liu Y, Zhou Y, Xia Y, Ran C, et al. Flexible perovskite solar cells with high power-per-weight: progress, application, and perspectives. *ACS Energy Lett* 2021;6(8):2917–43.
- [17] Lin TY, Hsieh CF, Kanai A, Yashiro T, Zeng WJ, Ma JJ, et al. Radiation resistant chalcopyrite CIGS solar cells: proton damage shielding with Cs treatment and defect healing via heat-light soaking. *J Mater Chem A* 2024;12(13):7536–48.
- [18] Kawakita S, Imaizumi M, Yamaguchi M, Kushiya K, Ohshima T, Ito H, et al. *In-situ* measurement of degradation of Cu(In,Ga)Se₂ thin film solar cells during electron and proton irradiations. In: *Proceedings of the Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference*, 2002; 2002 May 19–24; New Orleans, LA, USA. Piscataway: IEEE; 2002. p. 978–81.
- [19] Kaltenbrunner M, White MS, Głowacki ED, Sekitani T, Someya T, Sariciftci NS, et al. Ultrathin and lightweight organic solar cells with high flexibility. *Nat Commun* 2012;3:770
- [20] Boukourt NEI, Loureiro AG, Abushattal A. Efficiency improvement of ultrathin CIGS solar cells. *Sol Energy* 2024;282:112935.

- [21] Keller J, Kiselman K, Donzel-Gargand O, Martin NM, Babucci M, Lundberg O, et al. High-concentration silver alloying and steep back-contact gallium grading enabling copper indium gallium selenide solar cell with 23.6% efficiency. *Nat Energy* 2024;9(4):467–78.
- [22] NREL. Best research-cell efficiencies chart [Internet]. Golden: NREL; 2025 [cited 2025 March 1]. Available from: <https://www.nrel.gov/pv/cell-efficiency.html>.
- [23] Jeong I, Lee TK, Van Tran H, Hwang I, Hwang J, Lee A, et al. Flexible and lightweight perovskite/Cu(In,Ga)Se₂ tandem solar cells. *Joule* 2024;9(3):101794.
- [24] Han E, Lyu M, Choi E, Zhao Y, Zhang Y, Lee J, et al. High-performance indoor perovskite solar cells by self-suppression of intrinsic defects via a facile solvent-engineering strategy. *Small* 2024;20(4):2305192.
- [25] Han E, Yun JH, Maeng I, Qiu T, Zhang Y, Choi E, et al. Efficient bifacial semi-transparent perovskite solar cells via a dimethylformamide-free solvent and bandgap engineering strategy. *Nano Energy* 2024;131(Part A):110136.
- [26] Zhang C, Baktash A, Steele JA, He D, Ding S, Penukula S, et al. Post-synthetic interstitial metal doping for efficient and stable 3D/2D heterostructured perovskite solar cells. *Adv Funct Mater* 2024;34(24):2315897.
- [27] Saliba M, Matsui T, Domanski K, Seo JY, Ummadisingu A, Zakeeruddin SM, et al. Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance. *Science* 2016;354(6309):206–9.
- [28] He D, Chen P, Hao M, Lyu M, Wang Z, Ding S, et al. Accelerated redox reactions enable stable tin-lead mixed perovskite solar cells. *Angew Chem Int Ed Engl* 2024;63(4):e202317446.
- [29] McMillon-Brown L, Peshek TJ. Chapter five—perovskite solar cells: background and prospects for space power applications. In: Bailey SG, Hepp AF, Ferguson DC, Raffaele RP, Durbin SM, editors. *Photovoltaics for Space*. Amsterdam: Elsevier; 2023. p. 129–56.
- [30] Jia C, Li Z, Wan Z, Jiang Z, Xue J, Shi J, et al. Ultra-thin perovskite solar cells with high specific power density based on colorless polyimide substrates. *Nano Energy* 2024;131(Pt A):110259.
- [31] Finckenor MM, de Groh KK. A researcher's guide to: space environmental effects. Report. Washington, DC: NASA. 2020.
- [32] Bedingfield KL, Leach RD, Alexander MB. Spacecraft system failures and anomalies attributed to the natural space environment. Report. Washington, DC: NASA; 1996.
- [33] Wrbanek JD, Wrbanek SY. Space radiation and impact on instrumentation technologies. Report. Washington, DC: NASA; 2020.
- [34] Armstrong TW, Colborn BL. Predictions of secondary neutrons and their importance to radiation effects inside the international space station. *Radiat Meas* 2001;33(3):229–34.
- [35] Schneider TA, Vaughn JA, Wright KH, Phillips BS. Space environment testing of photovoltaic array systems at NASA's Marshall Space Flight Center. In: *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*; New Orleans, LA, USA, 2015 Jun 14–19. Piscataway: IEEE; 2015. p. 1–6.
- [36] Singh S, Li C, Panzer F, Narasimhan KL, Graeser A, Gujar TP, et al. Effect of thermal and structural disorder on the electronic structure of hybrid perovskite semiconductor CH₃NH₃PbI₃. *J Phys Chem Lett* 2016;7(15):3014–21.
- [37] Lu Y, Shao Q, Yue H, Yang F. A review of the space environment effects on spacecraft in different orbits. *IEEE Access* 2019;7:93473–88.
- [38] AIAA S-111A-2014: Qualification and quality requirements for space solar cells (AIAA S-111A-2014). USA standard. Reston: AIAA; 2014.
- [39] ECSS-E-ST-20-08C Rev.2: Photovoltaic assemblies and components. European standard. Noordwijk: ECSS; 2023.
- [40] JAXA. Database of JAXA Qualified EEE Parts and Materials [Internet]. Tokyo: JAXA; c2025 [cited 2025 Jun 7]. Available from: <https://ssl.tksc.jaxa.jp/eeepitnl/en/>.
- JAXA, SOLAR CELLS, HIGH RELIABILITY, SPACE USE, GENERAL SPECIFICATION FOR. JAXA, JAPAN AEROSPACE EXPLORATION AGENCY, 2004.

- [41] Kojima A, Teshima K, Shirai Y, Miyasaka T. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *J Am Chem Soc* 2009;131(17):6050–1.
- [42] Filip MR, Eperon GE, Snaith HJ, Giustino F. Steric engineering of metal-halide perovskites with tunable optical band gaps. *Nat Commun* 2014;5(1):5757.
- [43] Li Z, Yang M, Park JS, Wei SH, Berry JJ, Zhu K. Stabilizing perovskite structures by tuning tolerance factor: formation of formamidinium and cesium lead iodide solid-state alloys. *Chem Mater* 2016;28(1):284–92.
- [44] Kiermasch D, Rieder P, Tvingstedt K, Baumann A, Dyakonov V. Improved charge carrier lifetime in planar perovskite solar cells by bromine doping. *Sci Rep* 2016;6(1):39333.
- [45] Turren-Cruz SH, Saliba M, Mayer MT, Juárez-Santisteban H, Mathew X, Nienhaus L, et al. Enhanced charge carrier mobility and lifetime suppress hysteresis and improve efficiency in planar perovskite solar cells. *Energy Environ Sci* 2018;11(1):78–86.
- [46] Zheng Y, Li Y, Zhuang R, Wu X, Tian C, Sun A, et al. Towards 26% efficiency in inverted perovskite solar cells via interfacial flipped band bending and suppressed deep-level traps. *Energy Environ Sci* 2024;17(3):1153–62.
- [47] Wang Z, Lyu M, Zhang BW, Xiao M, Zhang C, Han E, et al. Thermally evaporated metal halide perovskites and their analogues: film fabrication, applications and beyond. *Small Methods* 2025;9(2):2301633.
- [48] Weerasinghe HC, Macadam N, Kim JE, Sutherland LJ, Angmo D, Ng LWT, et al. The first demonstration of entirely roll-to-roll fabricated perovskite solar cell modules under ambient room conditions. *Nat Commun* 2024;15(1):1656.
- [49] Siegler TD, Dawson A, Lobaccaro P, Ung D, Beck ME, Nilsen G, et al. The path to perovskite commercialization: a perspective from the United States solar energy technologies office. *ACS Energy Lett* 2022;7(5):1728–34.
- [50] Yoon W, Song Z, Chen C, Scheiman D, Yan Y. 21.1% efficient space perovskite/Si four-terminal tandem solar cells. In: *Proceedings of the 2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*; 2020 Jun 15–Aug 21; Calgary, AB, Canada. Piscataway: IEEE; 2020. p. 1552–6.
- [51] Lang F, Jošt M, Frohna K, Köhnen E, Al-Ashouri A, Bowman AR, et al. Proton radiation hardness of perovskite tandem photovoltaics. *Joule* 2020;4(5):1054–69.
- [52] Bae MS, Chang YH, Lee W, Moon CS, Kim SW, Kim HS, et al. Bication thiocyanate salts for advanced performance of wide-band gap perovskite solar cells. *Energy Fuels* 2023;37(6):4608–15.
- [53] Bae MS, Chang YH, Li MQ, Kim SW, Lee W, Bae JJ, et al. Enhanced chemical interaction between ionic liquid and halide perovskite to improve performance of perovskite solar cells. *Mater Today Energy* 2024;43:101593.
- [54] Liu Z, Lin R, Wei M, Yin M, Wu P, Li M, et al. All-perovskite tandem solar cells achieving >29% efficiency with improved (100) orientation in wide-bandgap perovskites. *Nat Mater* 2025;24(2):252–9.
- [55] Jošt M, Köhnen E, Al-Ashouri A, Bertram T, Tomšič Š, Magomedov A, et al. Perovskite/CIGS tandem solar cells: from certified 24.2% toward 30% and beyond. *ACS Energy Lett* 2022;7(4):1298–307.
- [56] Tockhorn P, Sutter J, Cruz A, Wagner P, Jäger K, Yoo D, et al. Nano-optical designs for high-efficiency monolithic perovskite–silicon tandem solar cells. *Nat Nanotechnol* 2022;17(11):1214–21.
- [57] Miyazawa Y, Ikegami M, Chen HW, Ohshima T, Imaizumi M, Hirose K, et al. Tolerance of perovskite solar cell to high-energy particle irradiations in space environment. *iScience* 2018;2:148–55.
- [58] Song Z, Li C, Chen C, McNatt J, Yoon W, Scheiman D, et al. High remaining factors in the photovoltaic performance of perovskite solar cells after high-fluence electron beam irradiations. *J Phys Chem C* 2020;124(2):1330–6.
- [59] Xiao C, Li Z, Guthrey H, Moseley J, Yang Y, Wozny S, et al. Mechanisms of electron-beam-induced damage in perovskite thin films revealed by cathodoluminescence spectroscopy. *J Phys Chem C* 2015;119(48):26904–11.
- [60] Dang Z, Shamsi J, Palazon F, Imran M, Akkerman QA, Park S, et al. *In situ* transmission electron microscopy study of electron beam-induced transformations in colloidal cesium lead halide perovskite nanocrystals. *ACS Nano* 2017;11(2):2124–32.
- [61] Stranks SD, Eperon GE, Grancini G, Menelaou C, Alcocer MJP, Leijtens T, et al. Electron-hole diffusion lengths exceeding 1 micrometer in an organometal trihalide perovskite absorber. *Science* 2013;342(6156):341–4.

- [62] Lang F, Nickel NH, Bundesmann J, Seidel S, Denker A, Albrecht S, et al. Radiation hardness and self-healing of perovskite solar cells. *Adv Mater* 2016;28(39):8726–31.
- [63] Lang F, Jošt M, Bundesmann J, Denker A, Albrecht S, Landi G, et al. Efficient minority carrier detrapping mediating the radiation hardness of triple-cation perovskite solar cells under proton irradiation. *Energy Environ Sci* 2019;12(5):1634–47.
- [64] Kirmani AR, Byers TA, Ni Z, VanSant K, Saini DK, Scheidt R, et al. Unraveling radiation damage and healing mechanisms in halide perovskites using energy-tuned dual irradiation dosing. *Nat Commun* 2024;15(1):696.
- [65] Yang S, Xu Z, Xue S, Kandlakunta P, Cao L, Huang J. Organohalide lead perovskites: more stable than glass under gamma-ray radiation. *Adv Mater* 2019;31(4):1805547.
- [66] Yang K, Huang K, Li X, Zheng S, Hou P, Wang J, et al. Radiation tolerance of perovskite solar cells under gamma ray. *Org Electron* 2019;71:79–84.
- [67] Boldyreva AG, Frolova LA, Zhidkov IS, Gutsev LG, Kurmaev EZ, Ramachandran BR, et al. Unravelling the material composition effects on the gamma ray stability of lead halide perovskite solar cells: MAPbI₃ breaks the records. *J Phys Chem Lett* 2020;11(7):2630–6.
- [68] Liu R, Wang L, Fan Y, Li Z, Pang S. UV degradation of the interface between perovskites and the electron transport layer. *RSC Adv* 2020;10(20):11551–6.
- [69] Lee SW, Kim S, Bae S, Cho K, Chung T, Mundt LE, et al. UV degradation and recovery of perovskite solar cells. *Sci Rep* 2016;6(1):38150.
- [70] Huang PC, Yang TJ, Lin CJ, Wang MY, Lin WC. Unraveling the heat- and UV-induced degradation of mixed halide perovskite thin Films via surface analysis techniques. *Langmuir* 2024;40(23):11873–87.
- [71] Leijtens T, Eperon GE, Pathak S, Abate A, Lee MM, Snaith HJ. Overcoming ultraviolet light instability of sensitized TiO₂ with meso-superstructured organometal tri-halide perovskite solar cells. *Nat Commun* 2013;4(1):2885.
- [72] Ren J, Luo Q, Hou Q, Chen H, Liu T, He H, et al. Suppressing charge recombination and ultraviolet light degradation of perovskite solar cells using silicon oxide passivation. *ChemElectroChem* 2019;6(12):3167–74.
- [73] Schneider TA, Vaughn JA, Wright KH, Phillips BS. Space environment testing of photovoltaic array systems at NASA's Marshall Space Flight Center. In: *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*; 2015 Jun 14–19; New Orleans, LA, USA. Piscataway: IEEE; 2015. p. 1–6.
- [74] Chen P, Wang Z, Wang S, Lyu M, Hao M, Ghasemi M, et al. Luminescent europium-doped titania for efficiency and UV-stability enhancement of planar perovskite solar cells. *Nano Energy* 2020;69:104392.
- [75] Stuckelberger ME, Nietzold T, West BM, Luo Y, Li X, Werner J, et al. Effects of X-rays on perovskite solar cells. *J Phys Chem C* 2020;124(33):17949–56.
- [76] Dai X, Fei C, Kandlakunta P, Zhao L, Ni Z, Cao LR, et al. Origin of the X-ray-induced damage in perovskite solar cells. *IEEE Trans Nucl Sci* 2022;69(8):1850–6.
- [77] Paternò GM, Robbiano V, Santarelli L, Zampetti A, Cazzaniga C, Garcia Sakai V, et al. Perovskite solar cell resilience to fast neutrons. *Sustain Energy Fuels* 2019;3(10):2561–6.
- [78] Ou X, Gao F. Blossoms in perovskite planar X-ray detectors. *Nat Commun* 2024;15(1):5754.
- [79] Sakhatskyi K, Turedi B, Matt GJ, Wu E, Sakhatska A, Bartosh V, et al. Stable perovskite single-crystal X-ray imaging detectors with single-photon sensitivity. *Nat Photonics* 2023;17(6):510–7.
- [80] Galicia-Aragón J, François-Lacouture JL, Aguilar-Hernández F. Estimation of the fast neutron fluence in Laguna Verde RPV-Steel specimens simulating their irradiation in a TRIGA reactor. *Prog Nucl Energy* 2016;88:264–76.
- [81] Zheng J, Zeng Y, Wang J, Sun C, Tang B, Wu Y, et al. Hydrogen-rich 2D Halide perovskite scintillators for fast neutron radiography. *J Am Chem Soc* 2021;143(50):21302–11.
- [82] De Rossi F, Taheri B, Bonomo M, Gupta V, Renno G, Yaghoobi Nia N, et al. Neutron irradiated perovskite films and solar cells on PET substrates. *Nano Energy* 2022;93:106879.

- [83] Gohel A, Makwana R, Soni B. Evaluating shielding materials for high energy space radiation. *IOP Conf Series Mater Sci Eng* 2022;1221(1):012003.
- [84] Naito M, Kitamura H, Koike M, Kusano H, Kusumoto T, Uchihori Y, et al. Applicability of composite materials for space radiation shielding of spacecraft. *Life Sci Space Res* 2021;31:71–9.
- [85] Chen M, Dong Y, Zhang Y, Zheng X, McAndrews GR, Dai Z, et al. Stress engineering for mitigating thermal cycling fatigue in perovskite photovoltaics. *ACS Energy Lett* 2024;9(6):2582–9.
- [86] Dong B, Wei M, Li Y, Yang Y, Ma W, Zhang Y, et al. Self-assembled bilayer for perovskite solar cells with improved tolerance against thermal stresses. *Nat Energy* 2025;10(3):342–53.
- [87] Cheacharoen R, Boyd CC, Burkhard GF, Leijtens T, Raiford JA, Bush KA, et al. Encapsulating perovskite solar cells to withstand damp heat and thermal cycling. *Sustain Energy Fuels* 2018;2(11):2398–406.
- [88] Erdil U, Khenkin M, Bernardes de Araujo WM, Emery Q, Lauermann I, Paraskeva V, et al. Delamination of perovskite solar cells in thermal cycling and outdoor tests. *Energy Technol* 2025;13(1):2401280.
- [89] Li G, Su Z, Canil L, Hughes D, Aldamasy MH, Dagar J, et al. Highly efficient p-i-n perovskite solar cells that endure temperature variations. *Science* 2023;379(6630):399–403.
- [90] Ma L, Guo D, Li M, Wang C, Zhou Z, Zhao X, et al. Temperature-dependent thermal decomposition pathway of organic–inorganic halide perovskite materials. *Chem Mater* 2019;31(20):8515–22.
- [91] Yang W, Shi R, Lu H, Liu K, Yan Q, Bai Y, et al. Revisiting the thermal decomposition mechanism of MAPbI₃. *Phys Chem Chem Phys* 2024;26(26):17999–8005.
- [92] Finckenor MC, Carr J, SanSoucie M, Boyd D, Phillips B. Simulated space environmental effects on thin film solar array components. In: *Proceedings of the Applied Space Environments Conference 2017*; 2017 May 15–19; Huntsville, AL, USA. Washington, DC: NASA; 2017. p. 2017005334.
- [93] Wang Y, Zheng D, Wang K, Yang Q, Qian J, Zhou J, et al. Lattice mismatch at the heterojunction of perovskite solar cells. *Angew Chem Int Ed Engl* 2024;63(29):e202405878.
- [94] Shin H, Han E, Park N, Kim D. Thermal residual stress analysis of soldering and lamination processes for fabrication of crystalline silicon photovoltaic modules. *Energies* 2018;11(12):3256.
- [95] Wu WQ, Rudd PN, Ni Z, Van Brackle CH, Wei H, Wang Q, et al. Reducing surface halide deficiency for efficient and stable iodide-based perovskite solar cells. *J Am Chem Soc* 2020;142(8):3989–96.
- [96] Jiang Y, Yang SC, Jeangros Q, Pisoni S, Moser T, Buecheler S, et al. Mitigation of vacuum and illumination-induced degradation in perovskite solar cells by structure engineering. *Joule* 2020;4(5):1087–103.
- [97] Fu F, Pisoni S, Jeangros Q, Sastre-Pellicer J, Kawecki M, Paracchino A, et al. I₂ vapor-induced degradation of formamidinium lead iodide based perovskite solar cells under heat–light soaking conditions. *Energy Environ Sci* 2019;12(10):3074–88.
- [98] Wren JC, Glowa GA, Merritt J. Corrosion of stainless steel by gaseous I₂. *J Nucl Mater* 1999;265(1-2):161–77.
- [99] Zschätzsch D, Benz SL, Holste K, Vaupel M, Hey FG, Kern C, et al. Corrosion of metal parts on satellites by iodine exposure in space. *J Electr Propuls* 2022;1(1):14.
- [100] Boyd CC, Cheacharoen R, Leijtens T, McGehee MD. Understanding degradation mechanisms and improving stability of perovskite photovoltaics. *Chem Rev* 2019;119(5):3418–51.
- [101] Shi L, Bucknall MP, Young TL, Zhang M, Hu L, Bing J, et al. Gas chromatography–mass spectrometry analyses of encapsulated stable perovskite solar cells. *Science* 2020;368(6497):eaba2412.
- [102] Wang Y, Ahmad I, Leung T, Lin J, Chen W, Liu F, et al. Encapsulation and stability testing of perovskite solar cells for real life applications. *ACS Mater Au* 2022;2(3):215–36.
- [103] Krishna BG, Ghosh DS, Tiwari S. Hole and electron transport materials: a review on recent progress in organic charge transport materials for efficient, stable, and scalable perovskite solar cells. *Chem Inorg Mater* 2023;1:100026.
- [104] You J, Meng L, Song TB, Guo TF, Yang Y, Chang WH, et al. Improved air stability of perovskite solar cells via solution-processed metal oxide transport layers. *Nat Nanotechnol* 2016;11(1):75–81.

- [105] Chiang YH, Shih CK, Sie AS, Li MH, Peng CC, Shen PS, et al. Highly stable perovskite solar cells with all-inorganic selective contacts from microwave-synthesized oxide nanoparticles. *J Mater Chem A* 2017;5(48):25485–93.
- [106] Liu X, Jiang J, Wang F, Xiao Y, Sharp ID, Li Y. High photovoltage inverted planar heterojunction perovskite solar cells with all-inorganic selective contact layers. *ACS Appl Mater Interfaces* 2019;11(50):46894–901.
- [107] Holzhay P, Saliba M. A full overview of international standards assessing the long-term stability of perovskite solar cells. *J Mater Chem A* 2018;6(44):21794–808.
- [108] Khenkin MV, Katz EA, Abate A, Bardizza G, Berry JJ, Brabec C, et al. Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures. *Nat Energy* 2020;5(1):35–49.
- [109] Costa C, Manceau M, Duzellier S, Nuns T, Cariou R. Perovskite solar cells under protons irradiation: from *in-situ* IV-monitoring to root cause degradation elucidation. *Sol Energy Mater Sol Cells* 2023;257:112388.
- [110] Li C, Song Z, Chen C, Xiao C, Subedi B, Harvey SP, et al. Low-bandgap mixed tin–lead iodide perovskites with reduced methylammonium for simultaneous enhancement of solar cell efficiency and stability. *Nat Energy* 2020;5(10):768–76.
- [111] McMillon-Brown L, Luther JM, Peshek TJ. What would it take to manufacture perovskite solar cells in space? *ACS Energy Lett* 2022;7(3):1040–2.
- [112] NASA. On-orbit servicing, assembly, and manufacturing 2 (OSAM-2) [Internet]. Washington, DC: NASA; 2023 Oct 20 [cited 2025 March 1]. Available from: <https://www.nasa.gov/mission/on-orbit-servicing-assembly-and-manufacturing-2-osam-2/>.

Declaration of interests

- ☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- ☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: