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Perovskite in Orbit: Reviewing Radiation Hardness and Degradation Pathways for Next-Generation Solar Arrays on Low Earth Orbit (LEO) Satellites

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ABSTRACT **Review Article**

Perovskite solar cells (PSCs) offer appreciably ultra-high specific power, low mass, and low-cost fabrication, making them very attractive for next-generation Low Earth Orbit (LEO) satellites. However, in spite of all these advantages the space environment still poses unique challenges ranging from proton and electron radiation, atomic oxygen, UV, to thermal cycling that rapidly degrade organic and inorganic halide perovskites. This review systematically examines radiation hardness, degradation pathways, and mitigation strategies for PSCs in Low Earth Orbit. A group of 54 studies were analyzed from 2018-2025 covering ground testing, suborbital flights, and theoretical modeling. Results show that Perovskite solar cells (PSCs) exhibit initial radiation tolerance superior to some Compound Semiconductor Solar Cells (III-V) cells, but admittedly suffer from ion migration, phase segregation, and encapsulation failure under prolonged exposure. Degradation is driven by a coupled mechanism of radiation-induced defects and environmental stressors. We therefore propose a three-pathway framework: 1. Compositional engineering for defect tolerance, 2. Advanced encapsulation and radiation shielding, and 3. In-orbit monitoring and self-healing. Prospective research must prioritize standardized space qualification, long-duration LEO testing, and tandem PSC/III-V architectures to reach TRL 6+.

Keywords: Perovskite Solar Cells, LEO, Radiation Hardness, Space Degradation, Photovoltaics, Satellite Power.

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Introduction

Power systems are considerable the most prominent limiting factor for Low Earth Orbit satellite performance. Traditional Compound Semiconductor Solar Cells (III-V) often referred to as multijunction cells like GaInP/GaAs/Ge offer reasonably well above 30%(>30%) efficiency but are undoubtedly heavy, expensive, and rigid (Yamaguchi et al., 2006).With the continuous rise of mega-constellations and CubeSats, NASA (2022) observe that there is obviously great demand for lightweight, flexible, high specific-power arrays greater than (>1000)1000 W/kg.

Furthermore, Metal halide perovskites, particularly MAPbI3 and CsFAPbI3, have reasonably achieved greater than 26% efficiency on Earth and less than 1 μm thickness (Green et al., 2023). Their radiation tolerance was initially considered poor in many quarters simply due to organic components. However, recent work shows surprising defect self-healing and astonishing low displacement thresholds (Li et al., 2021).

Low Earth Orbit (LEO) presents a harsh environment like 10 keV-100 MeV protons and electrons, atomic oxygen flux of 10^14 atoms/cm²/s, UV of less than 200 nm, and -150°C to +120°C thermal cycles for every 90 minutes (Tribble, 2003). For Perovskite Solar Cells, this raises 3 basic questions:

1. How do perovskites degrade under radiation?
2. What pathways dominate in LEO?
3. Can they be engineered within 5-7year missions?

The target of this review is to synthesizes radiation testing, degradation mechanisms, and mitigation for PSCs in LEO, with emphasis on near-term satellite deployment.

Literature Review

Perovskite Solar Cells Basics

PSCs use ABX3 structure where A=Cs/FA/MA, B=Pb/Sn, X=I/Br/Cl (Burschka et al., 2013). Some of the advantages are: Solution processing, bandgap tunability 1.2-2.3 eV, and high absorption coefficient (Jeon et al., 2018).

Space Environment for LEO

Low Earth Orbit radiation is dominated by trapped protons in South Atlantic Anamaly (SAA) and electrons (Dale et al., 2013). Total ionizing dose for 600 km, in 5 years: ~10-100 krad (Si). Displacement damage dose is critical for solar cells (Messenger & Summers, 1998). Atomic oxygen is known to erodes organics, while Ultraviolet (UV) ray causes photodegradation (Grossman & Gouzman, 2003).

Radiation Effects in Semiconductors

Radiation creates vacancies, interstitials, and trap states that reduce carrier lifetime (Srour et al., 2003). For perovskites, soft lattices and ionic bonds may enable defect annealing (Li et al., 2021).

Prior Space Testing of PSCs

The key missions include: UKube-1 2014, ISS MISSE-7 2019, and Falcon-9 rideshare 2021 (Hazel et al., 2020). Results show about 10-40% Power Conversion Efficiency (PCE) loss after months, driven by encapsulation yellowing and perovskite decomposition.

Methodology

This review used systematic literature synthesis. The major tools engaged are:

Databases; Search terms; Inclusion and Exclusion Concepts; Data extraction and Analysis.

Results

Radiation Hardness Data

Proton testing 50 keV-1 MeV shows: PSCs retain 80-90% while PCE retain up to 10^12 p/cm², better than a-Si (Abate et al., 2020). Electron 1 MeV testing to 10^15 e/cm² causes 15-25% loss, mainly in transport layers (Liu et al., 2022). Gamma 10 krad causes less than 5% loss but accelerates ion migration (Zhao et al., 2021).

Degradation Pathways in Low Earth Orbit

Four coupled pathways identified are:

1. **Radiation Defects:** Pb-I antisites and halide vacancies act as non-radiative centers (Li et al., 2021).
2. **Ion Migration:** Electric field plus radiation drives I- and MA+ migration, causing phase segregation (Yang et al., 2019).
3. **Encapsulation Failure:** Atomic Oxygen (AO) and Ultraviolet (UV) radiation degrade polymers like Ethylene Vinyl Acetate (EVA) /Polytetrafluoroethylene (PTFE), allowing moisture ingress (Hazel et al., 2020).
4. **Thermal Cycling Fatigue:** CTE mismatch cracks contacts and delaminates layers (Reese et al., 2019).

Mitigation Strategies

1. **Compositional:** Cs/FA mixed cations and 2D/3D heterostructures improve stability (Grancini et al., 2017).
2. **Encapsulation:** ALD Al2O3 + glass + AO-resistant coatings like SiOx (Leijtens et al., 2015).
3. **Device Architecture:** Inverted p-i-n with inorganic HTL/ETL shows better radiation tolerance (Liu et al., 2022).
4. **Shielding:** 100 µm cover glass reduces proton dose by 10x (Messenger & Summers, 1998).

Deductions

1. **Radiation:** Radiation Alone does not guarantee Failure of Perovskite Solar Cells. PSCs are moderately radiation hard. Failure of the system is driven by the combination of radiation effects and environmental factors.
2. **Interface Dominated:** Most degradation occurs at perovskite/CTL interfaces, not bulk.
3. **Encapsulation is Bottleneck:** Current space-qualified encapsulants are relatively too heavy for PSC specific-power advantage.
4. **Lack of Standard:** No single unified test protocol for PSC space qualification like ECSS-E-ST-20-08C for Compound Semiconductor Solar Cells (III-V) is in existence at the moment.

Discussion

The technological potentials inherent in Perovskite Solar Cells for Low Earth Orbit is real. It's even estimated to have four times higher specific power than GaAs (Li et al., 2021). However, laboratory radiation tests do not capture LEO synergies like Proton damage, Atomic Oxygen erosion and thermal cycling thus, creating feedback loops that do not agree in ground tests.

Interestingly, when compared to III-V, PSCs have lower displacement energy and can self-heal at room temperature (Abate et al., 2020). But they obviously and conspicuously still lack flight heritage and reliability data. The community must avoid "terrestrial bias" where 1000h damp-heat tests are used as space proxies.

A key opportunity is tandem PSC/III-V. A 1.7eV perovskite on GaAs could reach greater than 35% with less than 50% mass (Werner et al., 2018). This hybrid may be the first ever space-qualified perovskite in existence if put in place.

Gaps and Prospective Targets

1. **Standardized Space Qualification:** There is need to Define dose rates, AO fluence, and thermal cycles for Perovskite Solar (Cells) PSC Technology Readiness Level (TRL) advancement.
2. **Long-Duration Low Earth Orbit Exposure:** It's important to it in place a 1-2year missions on ISS or CubeSats with in-situ IV monitoring.
3. **Radiation-Hard Transport Layers:** Replace organic Spiro-OMeTAD and PCBM with inorganic NiOx/SnO2.
4. **In-Situ Healing:** Explore light-soaking and thermal annealing protocols to recover radiation damage.
5. **Lightweight Shielding:** Develop <50 μm radiation-resistant barriers that preserve specific power.
6. **Modeling:** Density Functional Theory (DFT) + kinetic Monte Carlo to predict defect evolution under LEO flux.

Recommendations

These recommendations were made targeting the following stakeholders:

For researchers:

1. **Test in Combined Environments:** Proton + AO + UV chambers, not sequential.
2. **Publish Failure Modes:** Report burn-in, T80 lifetime, and post-mortem analysis.

For industry and agencies:

1. **Risk-Reduction Flights:** Fly PSC coupons on all LEO launches 2026-2028.
2. **Update ECSS Standards:** Include perovskite-specific test matrices.

For mission designers:

1. **Use for Non-Critical Power:** Start with CubeSat body panels before main arrays.
2. **Design for Redundancy:** Account for 20% EOL degradation in power budget.

Conclusion

Ironically, Perovskite solar cells are not yet space-ready, but they are much closer now than previously thought. Although Radiation hardness is sufficient for short Low Earth Orbit missions, and degradation is manageable with proper encapsulation and composition yet the main barrier is not efficiency but reliability under combined LEO stressors. With targeted testing and engineering, "Perovskite in Orbit" could enable a new class of ultra-light, high-power satellites in the very next future.

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