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Advancements in radiation resistance and reinforcement strategies of perovskite solar cells in space applications

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Perovskite solar cells (PSCs) hold great promise for space photovoltaics (PV) due to their impressive PV performance, excellent power-to-weight ratio, and cost-effectiveness. However, the environment in space presents numerous challenges for solar cells, especially cosmic radiation. PSCs have shown remarkable resistance to various forms of radiation, such as electrons, protons, ultraviolet, and γ -rays. Nevertheless, their stability in space applications still lags behind that of crystalline silicon (c-Si) and gallium arsenide (GaAs) cells. To facilitate the application of PSCs in space, it is vital to enhance their long-term stability. This mini-review examines the radiation resistance of PSCs, explores the mechanisms behind radiation-induced damage, and proposes potential strategies to bolster their resistance to radiation and reinforce overall stability.

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1. Introduction

Metal halide perovskites (MHPs) are semiconductor materials known for their exceptional properties, allowing them to be widely utilized across various industries. These materials typically exhibit direct-transition semiconductor behavior, characterized by a high absorption coefficient and a low exciton binding energy, resulting in excellent PV performance. Furthermore, MHPs display efficient carrier transport rates, long carrier lifetimes, and significant diffusion lengths, enabling effective transfer of electrons and holes with minimal recombination.¹ Perovskite solar cells (PSCs) utilizing MHPs as the absorbing layer have emerged as examples of third-generation solar cells. A significant milestone in the development of PSCs was achieved in 2009 when Miyasaka *et al.* replaced the absorbing material in dye-sensitized solar cells with perovskite, resulting in a photovoltaic conversion efficiency (PCE) of 3.8%.² Since then, PSCs have garnered significant attention, and their PCE has experienced rapid growth, as depicted in Fig. 1(A).^{3–6} Currently, single-junction PSCs have achieved a certified PCE of 26.14%,⁷ steadily approaching the Shockley–Queisser efficiency limit of 33.7%.⁸

The high light absorption coefficient of MHPs allows for a significant reduction in the thickness of the absorption film to just a few hundred nanometers, providing PSCs with a high power-to-weight ratio (Fig. 1(B)). In comparison, traditional c-Si cells possess a ratio of less than 1 W g^{−1} due to their thicker light-absorbing layer.⁹ Triple-junction III–V semiconductor cells achieve a ratio of roughly 3 W g^{−1} through their densely fabricated structure. In contrast, flexible single-junction PSCs can reach an impressive ratio of 23–29 W g^{−1}, while multi-junction PSCs can surpass even that, reaching an outstanding ratio of 79–83 W g^{−1}.^{10–12} Based on the above comparison, the PSCs are undoubtedly better suited to meet the needs of spacecraft for lightweight energy systems. However, the long-term stability of PSCs remains the main obstacle to their pragmatic applications. Moisture can lead to hydrolysis in MHPs, while oxygen molecules can interact with photogenerated electrons in the conduction band, resulting in the formation of superoxide (O₂[−]) and accelerating the decomposition of MHPs.¹³ If PSCs can be utilized in a space environment devoid of moisture and oxygen, these two prominent factors will be negligible, making PSCs very promising for space deployment.

While plenty of current studies on PSCs have been conducted for ground applications, there is a lack of studies focusing on their suitability in space. The space environment poses challenges due to its complexity and variability, subjecting PSCs to harsh conditions such as extreme radiation, ultra-high vacuum, and severe temperature fluctuations.¹⁴ Moreover, the exorbitant cost of space flight makes it practically impossible to repair or replace PSCs once they are deployed in space. Therefore, PSCs must exhibit long-term stability and reliability to ensure the safety of spacecraft. Fortunately, research has

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Table of Contents Reinforcement Radiation From Space Answers

1. Understanding the eBook Reinforcement Radiation From Space Answers
 - The Rise of Digital Reading Reinforcement Radiation From Space Answers
 - Advantages of eBooks Over Traditional Books
2. Identifying Reinforcement Radiation From Space Answers
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Reinforcement Radiation From Space Answers
 - User-Friendly Interface
4. Exploring eBook Recommendations from Reinforcement Radiation From Space Answers

- Personalized Recommendations
- Reinforcement Radiation From Space Answers User Reviews and Ratings
- Reinforcement Radiation From Space Answers and Bestseller Lists
- 5. Accessing Reinforcement Radiation From Space Answers Free and Paid eBooks
 - Reinforcement Radiation From Space Answers Public Domain eBooks
 - Reinforcement Radiation From Space Answers eBook Subscription Services
 - Reinforcement Radiation From Space Answers Budget-Friendly Options
- 6. Navigating Reinforcement Radiation From Space Answers eBook Formats
 - ePub, PDF, MOBI, and More
 - Reinforcement Radiation From Space Answers Compatibility with Devices
 - Reinforcement Radiation From Space Answers Enhanced eBook Features
- 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Reinforcement Radiation From Space Answers
 - Highlighting and Note-Taking Reinforcement Radiation From Space Answers
 - Interactive Elements Reinforcement Radiation From Space Answers
- 8. Staying Engaged with Reinforcement Radiation From Space Answers
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Reinforcement Radiation From Space Answers
- 9. Balancing eBooks and Physical Books Reinforcement Radiation From Space Answers
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Reinforcement Radiation From Space Answers
- 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
- 11. Cultivating a Reading Routine Reinforcement Radiation From Space Answers
 - Setting Reading Goals Reinforcement Radiation From Space Answers
 - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Reinforcement Radiation From Space Answers

- Fact-Checking eBook Content of Reinforcement Radiation From Space Answers
- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
- 14. Embracing eBook Trends
 - Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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