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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

^aShanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, 201800, Shanghai, China. E-mail: yifan.zheng@siofm.ac.cn; shaoyuchuan@siofm.ac.cn^bCenter of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, 100049, Beijing, China^cBeijing Institute of Spacecraft Environment Engineering, Beijing 100094, China^dScience and Technology on Power Sources Laboratory, Tianjin Institute of Power Sources, Tianjin, 300384, China

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Reinforcement, 1999* **Heaven and Earth:Vol. 16, USAS:Civilian Uses of Near-Earth Space** Dorinda Dalmeyer,Kosta Tsipis,1997-01-01 Near earth space which extends to geosynchronous orbits where satellites remain faithfully over a fixed spot on the ground does not lend itself to romantic fantasies of science fiction It is a working place from which services can be delivered with ease and efficiency Meteorology seismic and crop yield predictions environmental monitoring communications of all sorts guidance and navigation medical and educational services treaty verification and photographic reconnaissance news gathering scientific observation across the entire electromagnetic spectrum prospecting remote sensing and monitoring of human activities are all in a day s work for near earth space Global cellular telephony only a few years ago the exclusive privilege of comic book heroes is becoming a space based commonplace Planes that land in fog and cars that find their way in the labyrinthine streets of Tokyo guided from space are beyond a near horizon Space is delivering its promise This volume describes many of these activities and their prospects for changing the way we live communicate and travel on this Earth **Lunar Science** Yann-Henri Chemin,2022-08-25 There are still many open scientific questions about the moon including whether humans will one day be able to live there This book looks at the history of the moon s orbit and the prospects of in situ lunar science the radiation impact on the lunar surface the resistance of settlement materials on the moon under the conditions of protecting humans on site and the preparation of humans for space missions JBL Audio Engineering for Sound Reinforcement John M. Eargle,Chris Foreman,2002-05-01 Book This up to date book comprehensively covers all aspects of speech and music sound reinforcement It is roughly divided into four sections Section 1 provides the tutorial fundamentals that all audio engineers will need discussing subjects such as fundamentals of acoustics psychoacoustics basic electrical theory and digital processing Section 2 deals with the fundamental classes of hardware that the modern engineer will use such as loudspeaker systems and components microphones mixers amplifiers and signal processors Special attention is given to digital techniques for system control and to audio signal analysis Section 3 deals with the basics of system design from concept to final realization It covers topics such as basic system type and speech intelligibility site survey user needs analysis and project management Section 4 discusses individual design areas such as sports facilities large scale tour sound systems high level music playback systems for the theater religious facilities and other meeting spaces The book is written in an accessible style but does not lack for ample amounts of technical information It is truly a book for the 21st century **Developments in the Formulation and Reinforcement of Concrete** Sidney Mindess,2014-01-23 Concrete is the most widely used construction material in the world This important book summarises the wealth of recent research on improving qualities such as durability and sustainability as well as the emergence of a new generation of specialist concretes for particular applications A number of chapters discuss new types of concrete such as autoclaved aerated concrete high strength concrete sprayed concrete fibre reinforced concrete lightweight concrete self

compacting concrete foamed and polymer concrete together with their characteristics and applications Other chapters review the development of concrete especially suited for particular conditions such as radiation protection hot weather and underwater conditions as well as the increasingly important area of recycling With its distinguished editor and international team of contributors Developments in the formulation and reinforcement of concrete is a standard reference for civil and structural engineers Summarises a wealth of recent research on improving qualities such as sustainability and durability Discusses new concrete types together with their characteristics and applications Reviews the development of concrete especially suited to particular conditions such as hot weather and under water **AI Knowledge Transfer from the**

University to Society José Guadix Martín, Milica Lilic, Marina Rosales Martínez, 2022-01-18 AI Knowledge Transfer from the University to Society Applications in High Impact Sectors brings together examples from the Innovative Ecosystem with Artificial Intelligence for Andalusia 2025 project at the University of Seville a series of sub projects composed of research groups and different institutions or companies that explore the use of Artificial Intelligence in a variety of high impact sectors to lead innovation and assist in decision making Key Features Includes chapters on health and social welfare transportation digital economy energy efficiency and sustainability agro industry and tourism Great diversity of authors expert in varied sectors belonging to powerful research groups from the University of Seville with proven experience in the transfer of knowledge to the productive sector and agents attached to the Andalusian TECH Campus Astronomy Alton Biggs, 2002

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ERDA Energy Research Abstracts United States. Energy Research and Development Administration,1977 Radiological Issues for Fukushima's Revitalized Future Tomoyuki Takahashi,2016-01-12 This book overviews environmental issues 4 years after the Fukushima nuclear accident covering a wide range of areas related to radiation and radioactivity The topics discussed are necessary to make clear the relationship between the results of research and Fukushima s revitalized future The chapters are divided into four parts Part 1 presents the identification of radionuclides in soil and migration of radionuclides in the terrestrial environment Part 2 describes the safety decontamination system and treatment of radioactive waste Part 3 explains the development of the system of measurement of environmental radiation and evaluation of external exposure and Part 4 discusses the identification of radionuclides in farm products control of root uptake identification of decreasing radionuclides by food processing and evaluation of internal exposure Since the accident at the Tokyo Electric Power Company s Fukushima Daiichi nuclear power station in 2011 gradual steps have been taken toward environmental recovery in the area However there are still many issues that need to be tackled in order to achieve the full revitalization of Fukushima These issues encompass many different disciplines such as economics psychology and sociology In this kind of situation the role of science in relation to radiation and radioactivity is especially important This book aims to contribute to planning countermeasures against nuclear disasters in the future It will be of particular interest to governmental officials who are engaged with the Fukushima nuclear accident researchers including those in international sectors who are interested in radiological issues and those who

need comprehensive and reliable information about the Fukushima accident *ERDA Energy Research Abstracts* ,1977

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Knorr,2009-08-25 Connect students in grades 4 and up with science using Learning about Atoms This 48 page book covers topics such as the development of the theory of the atom atomic structure the periodic table isotopes and researching famous scientists Students have the opportunity to create a slide show presentation about elements while using process skills to observe classify analyze debate design and report The book includes vocabulary crossword puzzles a quiz show review game a unit test and answer keys **Radiation Control for Health and Safety Act of 1967** United States. Congress. Senate.

Committee on Commerce. Subcommittee on Surface Transportation,1968 *Space-Age Acronyms* Reta C.

Moser,2012-12-06 Acronym agglomeration is an affliction of the age and there are acronym addicts who in their weakness find it impossible to resist them More than once in recent months my peers have cautioned me about my apparent readiness to use not only acronyms but abbreviations foreign isms codes and other cryptic symbols rather than common ordinary American words Many among us though either have not received or have chosen to ignore such advice As a consequence what we write and speak is full of mystery and confusion It is then for the reader and listener and for the writer and speaker that Reta C Moser has compiled this guide Its effective application to the art of communication is urged Such use should help avoid many of the misunderstandings involving terminology which occur daily Although such misunderstandings are certainly crucial in humanistic and social situations they are often of immediate import and the trigger to disaster in scientific technical and political situations Some 15 000 acronyms and 25 000 definitions are provided a 50 and 47 percent increase over the 1964 edition with due credit to Miss Moser s diligence in making the compilation and with the acknowledgment that the acronymical phenomenon is very much with us This edition like the first is certain to be of value to writers librarians editors and others who must identify and deal with acronyms *Energy Research and Development and Small Business: how much? How much more from small business? How soon?* United States. Congress. Senate. Select Committee on Small Business,1975 **Energy Research and Development and Small Business** United States. Congress. Senate. Select Committee on Small Business,1975 Oncology Rehabilitation E-Book Deborah Doherty,Chris Wilson,Lori

Boright,2022-07-23 Coverage of physical therapy patient management includes acute care outpatient and multidisciplinary clinical settings along with in depth therapeutic management interventions Content on the continuum of cancer care addresses the primordial primary secondary tertiary and quaternary stages in prevention and treatment Focus on clinicians includes the professional roles responsibilities self care and values of the oncology rehabilitation clinician as an integral member of the cancer care team Information on inseparable contextual factors helps in dealing with administrative infrastructure and support advocacy payment and reimbursement of rehabilitation as well as public policy Evidence

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The Power of Agentic AI: Redefining Human Life and Decision-Making

C. Kishor Kumar Reddy, Shenson Joseph, Herat Joshi, Srinath Doss, Mariya Ouaisa, 2025-09-26 This book explores how autonomous AI systems are reshaping human decision making across various industries and society The book delves into the concept of Agentic AI AI systems that can act independently and make decisions without human intervention Unlike existing literature that speculates about superintelligent systems this book offers practical insights into how current AI systems are already transforming sectors like health care finance and law It highlights the growing impact of these technologies on professional roles and governance offering a balanced view of both the opportunities and challenges presented by AI autonomy The book's findings show that Agentic AI enhances decision making by improving efficiency accuracy and scalability However it also presents ethical concerns related to accountability transparency and the shifting nature of human responsibility in AI mediated environments It emphasizes the need for robust ethical frameworks and governance structures to ensure that AI systems align with human values By focusing on real world applications and current AI technologies the book provides actionable insights for decision makers helping businesses policymakers and technologists navigate the evolving AI landscape It offers a roadmap for understanding the present day capabilities of autonomous systems and prepares professionals for the ethical and operational challenges of integrating these technologies Readers will gain a comprehensive understanding of how Agentic AI is poised to redefine human life and decision making making it essential for anyone interested in the future of technology ethics and innovation Unlike traditional AI which typically requires human supervision or input Agentic AI introduces the concept of autonomy AI systems that can act learn and make decisions independently This paradigm shift challenges the conventional human centered approach to decision making positioning AI as a true partner in complex cognitive tasks The book also explores the ethical and societal implications of AI autonomy in ways that extend beyond typical discussions

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