

Description of Functional Materials That Form the Basis of Photovoltaic and Hydrogen Energy Systems

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Abstract. Perovskite solar cells (PSCs) and organic solar cells (OSCs) have expanded the boundaries of photovoltaic energy conversion. PSCs, nearing 25.7% power conversion efficiencies (PCEs), could achieve 42-49% efficiencies in tandem devices. The fusion of perovskite with silicon and CIGS in tandem cells shows high efficiency potential. OSCs, however, provide affordable, adaptable optical features, processability, and flexibility, with the finest OSCs yielding over 18% PCEs. Despite hurdles, combining perovskite and organic semiconductors in a tandem structure, has resulted in 16% PCE and 1.63 V V_{oc} , indicating scope for improvement.

Keywords: Perovskite Solar Cells, Organic Solar Cells, Tandem Devices, Power Conversion Efficiency, Low-bandgap Materials, Silicon, CIGS, Photovoltaics, Hydrogen Energy.

Introduction

In light of the global energy dilemma, transitioning from fossil fuels to renewable energy sources has become critical. Enhancing the efficiency, cost-effectiveness, and durability of renewable energy capture and storage systems is at the forefront of this transition. In particular, the innovative materials propelling solar energy technologies, such as Photovoltaics (PV), and the burgeoning role of hydrogen as an energy vector, are essential in this context. PV energy transformation, which converts sunlight to electricity via solar cells, has progressed considerably in recent years, spearheaded by Perovskite solar cells (PSCs) and organic solar cells (OSCs) [1]. Concurrently, hydrogen energy is emerging as a compelling, environmentally friendly alternative due to its high energy potential. PSCs and OSCs have notably expanded PV energy transformation capabilities. PSCs are nearing top power conversion efficiencies (PCEs) of 25.7% under standard solar conditions, whereas OSCs provide affordable, adjustable optical properties and mechanical flexibility, making them versatile for numerous applications [2]. This paper offers a detailed exploration of the functional materials underpinning PV and hydrogen energy systems. We aim to provide an encompassing perspective on the theoretical foundation, existing technologies, and materials within these fields. Our discussion accentuates recent progress, innovations, and case studies, allowing for a comparative analysis of functional materials utilized in PV and hydrogen energy systems. We also anticipate future trends and research directions, offering potential research pathways to stimulate innovation in this sector [3]. We commence with an outline of PV and hydrogen energy, providing a theoretical backdrop and current technologies and materials overview. We then scrutinize novel materials, their properties, and recent breakthroughs, focusing primarily on PV, followed by a similar analysis for hydrogen energy. We then conduct a comparative examination of the functional materials within these domains. We identify the primary strengths and weaknesses of these materials, laying the groundwork for a discussion on future trends and research directions. We conclude with a recapitulation of central points and final reflections on the sector's status. This exploration of functional materials for PV and hydrogen energy provides an insightful perspective for researchers and engineers working in renewable energy technology [4]. It could guide future research and technological advancement, possibly leading to more efficient, affordable, and robust energy harvesting and storage systems [5].

Photovoltaics and Hydrogen Energy: An Overview

The photovoltaic effect, where light exposure causes materials to produce electricity, is used in photovoltaics (PV) like silicon-based solar cells. Hydrogen energy sources, on the other hand, utilize hydrogen's electrochemical reactions in fuel cells for power generation, producing only water as a byproduct. Challenges exist in both sectors, including efficiency, cost, and sustainability. Alternative solutions like perovskite solar cells (PSCs) and organic solar cells (OSCs) show promise in PV, achieving power conversion efficiencies up to 25.7%, despite stability and efficiency concerns. Hydrogen energy heavily relies on fuel cells and electrolyzers, with ongoing efforts to find cost-effective and durable alternatives to traditional platinum-group metal catalysts. Despite advancements, challenges persist in efficiency, durability, and scalability of these technologies. Continued focus on functional materials development is key to overcoming these issues for a sustainable energy future.

Functional Materials in Photovoltaics

The emergence of innovative materials such as perovskites and organic semiconductors has revolutionized photovoltaic technology. The adaptability of perovskites and the solution processability of organic semiconductors, paired with their high absorption coefficients and effective exciton transport, have pushed the efficiency boundaries of photovoltaics. Significant progress has been made using these materials. Notably, perovskite solar cells (PSCs) have demonstrated power conversion efficiencies (PCEs) rivalling those of traditional monocrystalline silicon cells. Furthermore, the integration of perovskite with silicon or organic semiconductors in tandem architectures has resulted in even greater efficiencies. Advancements in interfacial materials and manufacturing processes also promise to mitigate surface recombination and facilitate the production of flexible and lightweight cells. Case studies further illuminate the potential of these materials. A notable example includes a 16% PCE demonstrated by a tandem solar cell comprising perovskite and organic semiconductors. Another achievement by the NREL is the record 29.15% efficiency in a perovskite-silicon tandem solar cell. These successes underscore the significant potential of these material combinations, however, overcoming challenges related to stability, scalability, and environmental impact remains crucial for the future success of these promising photovoltaic materials.

Functional Materials for Hydrogen Energy

Hydrogen energy systems' functional materials, like catalysts, storage materials, and fuel cell conductive materials, greatly influence operational efficiency. Traditionally used catalysts such as platinum and iridium are excellent in promoting water splitting for hydrogen production. However, due to resource shortage and cost issues, alternatives like nickel, iron, and cobalt-based catalysts are being explored. Complex metal hydrides, especially those formed from light elements like lithium, boron, and aluminum, are promising for hydrogen storage due to their high capacities and enhanced kinetics via nanostructuring. In the quest for more efficient fuel cell materials, potential contenders like palladium, gold, and carbon-based materials like graphene and carbon nanotubes, along with platinum-based catalysts, are under consideration. Functional materials for hydrogen energy are witnessing remarkable innovation. One notable development is the atomically dispersed iron-nitrogen-carbon catalysts (Fe-N-C) for proton-exchange membrane fuel cells (PEMFCs), offering performance competitive to traditional platinum-based catalysts. Moreover, artificial intelligence (AI) and machine learning (ML) integration in material science accelerates the discovery and design of new materials, predicting their properties and speeding up candidate selection. Hydrogen storage advancements, particularly the development of metal-organic frameworks (MOFs) for solid-state storage, are remarkable, offering high surface areas for efficient hydrogen physisorption. Case studies reveal significant progress in this field. A synthesized Fe-N-C catalyst showed superb oxygen reduction reaction (ORR) activity and stability, reducing the need for platinum in PEMFCs. An AI-discovered new class of nitrogen-doped carbon nanotubes emerged as an efficient ORR catalyst, outperforming many non-precious metal catalysts in a PEMFC environment. Finally, a unique MOF for hydrogen storage with high storage capacity was developed, surpassing U.S. Department of Energy targets. These developments indicate important strides towards fully leveraging hydrogen's potential as a sustainable energy source.

Comparative Analysis

Functional materials serve as the cornerstone of both photovoltaics and hydrogen energy systems. In photovoltaics, the aim is to optimize efficiency and stability, with perovskite solar cells (PSCs) showcasing superior light absorption and charge mobility properties, thus promising high power conversion efficiencies. Conversely, organic solar cells (OSCs) offer flexibility through the tunable nature of organic semiconductors. Hydrogen energy systems employ unique catalysts like platinum-group metals in fuel cells to facilitate electrochemical reactions and proton exchange membranes for proton transport. However, their use in electrolyzers is hindered due to cost and scarcity. The notable strength of these functional materials in photovoltaics is their high efficiency, tunability, and processability. Yet, they face challenges concerning the stability of PSCs and the efficiency of OSCs. Hydrogen energy systems offer high-efficiency fuel cells and potential for sustainable hydrogen production as their advantages. However, they are bound by limitations such as the cost and scarcity of catalysts and issues of efficiency, durability, and scalability in electrolysis. This implies a critical need for the exploration and development of novel materials, which could mitigate these challenges and boost the performance of these renewable energy technologies.

Future Trends and Research Directions

Focusing on the future of renewable energy technologies, substantial advancements are expected in photovoltaics and hydrogen energy. We predict significant strides in resolving stability issues and enhancing efficiency in perovskite solar cells (PSCs). These developments will further solidify PSCs' role in solar energy. Organic solar cells (OSCs) are also expected to improve in light absorption, charge transport, and stability, pushing their efficiency closer to conventional solar cells. This progress will enable wider applications for OSCs, from construction to wearables. In the hydrogen energy sector, research will focus on finding affordable catalysts and improving solid-state hydrogen storage, which will enable widespread hydrogen energy adoption. In addition, water electrolysis technologies will progress, making electrolyzers more efficient and scalable for large-scale hydrogen production. These research directions will entail developing novel perovskite materials and improving electron donor and acceptor materials for OSCs.

In the hydrogen energy field, the search for new catalysts and advanced materials for hydrogen storage will be pivotal. These advancements will make renewable energy technologies increasingly efficient and affordable, promising a brighter future for renewable energy.

Conclusion

In examining the realm of photovoltaics and hydrogen energy, we explored the dynamic interplay of functional materials that underpin these technologies. From the highly efficient perovskite and flexible organic solar cells to the catalysts vital for fuel cell function and efficient hydrogen production via electrolysis, we delved into the crux of these sustainable energy avenues. However, they each bear challenges – stability for photovoltaics, and cost and efficiency for hydrogen energy systems, to name a few. Despite these hurdles, these domains are predicted to see notable progress. PSCs are expected to improve in stability, OSCs in efficiency, while fuel cells and electrolysis systems may benefit from cost-effective catalysts. Solid-state hydrogen storage and scalable electrolysis systems also represent promising areas of future research. Summarizing our discourse, the study of functional materials, crucial in photovoltaics and hydrogen energy, unveils their enormous potential to drive a sustainable energy transition. With the urgency for renewable energy adoption escalating, these materials' role is amplified. Our way forward calls for a blend of scientific prowess, creativity, collaboration, and a deep-rooted commitment to sustainability. As we continue contributing to this global mission of sustainable energy, we remain optimistic about our shared future. In essence, this conclusion is an open invitation for continued exploration, innovation, and pushing the boundaries of potential with functional materials. As we shape our sustainable energy future, our shared goal rests on the relentless pursuit of innovation in photovoltaics and hydrogen energy.

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