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Exponential developments of quantum dots ecosystem for solar energy conversion and photocatalytic reactions: From photoanode design to renewable energy applications

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Abstract

Quantum dot-sensitized solar cells (QDSSCs) present a promising approach for advancing solar energy conversion due to their tunable optical properties, quantum confinements and superior charge carrier dynamics. This review explores recent innovations in photoanode materials, focusing on the integration of functional quantum dots such as CdS, CdSe, PbS, and other novel QD materials like nickel phosphide, plasmonic, carbon/graphene, hexagonal-boron nitride, and black phosphorus, etc. Several studies show that optimally configured QDSSCs can reach power conversion efficiencies (PCE) of up to 8.6% in systems sensitized with PbS/CdS QDs on ZnO nanorods, marking significant advancements in light harvesting and energy conversion capabilities. Notably, core-shell architectures such as TiO_2-SiO_2 have been shown to enhance light scattering and optimize electron transfer pathways, resulting in PCEs of approximately 3.6%, a substantial increase over conventional designs. The review highlights the design of photoanodes with enhanced surface area, structural diversity, and light absorption, emphasizing the role of multi-band energetics, inter-band transitions and composite interactions. Additionally, this review offers insights into how optimized photoanode morphologies and QD coupling can mitigate surface charge recombination, enhance catalytic activity, and elevate green hydrogen production. By addressing key developments in material engineering, this work aims to guide future research towards more efficient and sustainable energy technologies.

Keywords: photoanode materials, solar energy, plasmonic, carbon/graphene, hexagonal-boron nitride.