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Recent Advances in Photovoltaic Sustainable Solar Sensing Energy Conversion

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Extended Abstract

Introduction

The rapid growth of global energy consumption, together with increasing environmental concerns and climate change, has intensified the demand for sustainable and renewable energy technologies. Solar energy conversion via photovoltaic (PV) systems represents one of the most viable solutions due to its cleanliness, abundance, and scalability. Silicon-based photovoltaic cells currently dominate the commercial market owing to their material abundance and favorable electronic properties; however, their high fabrication cost and complex surface processing significantly limit large-scale economic deployment. Consequently, extensive research has focused on alternative photovoltaic materials and advanced device architectures that offer reduced cost, enhanced efficiency, and improved long-term stability.

Among emerging photovoltaic technologies, perovskite solar cells (PSCs) have demonstrated extraordinary progress, achieving power conversion efficiencies exceeding 23% within a short period. Despite these remarkable advances, PSCs suffer from intrinsic instability under moisture, ultraviolet radiation, high temperature, and ion migration. In parallel, copper-based chalcogenides such as Cu_2FeSnS_4 (CFTS) have gained attention as low-cost, earth-abundant absorber materials with suitable bandgaps and high absorption coefficients. Furthermore, graphene, with its exceptional electrical, optical, and mechanical properties, has emerged as a multifunctional material capable of enhancing efficiency and stability in next-generation solar cell devices.

Methods

This work presents a comprehensive and structured analysis of advanced photovoltaic materials and architectures, focusing on silicon-based solar cells, CFTS-based systems, and perovskite solar cells integrated with graphene. Various fabrication and synthesis techniques reported in the literature are examined, including nanostructuring and heterojunction engineering in silicon photovoltaics, chemical and physical synthesis routes for CFTS nanomaterials (hot-injection, microwave-assisted, solvothermal, hydrothermal, reflux, and mechanochemical methods), and planar and mesoscopic device configurations in PSCs.

Particular emphasis is placed on interfacial engineering, dimensional control (0D–3D nanostructures), encapsulation strategies, and electrode material selection. The role of graphene as an electrode, charge transport layer, and protective coating is analyzed in terms of its influence on charge extraction, recombination suppression, moisture resistance, and thermal stability. Stability enhancement strategies addressing humidity exposure, UV irradiation, high-temperature operation, and ion migration are systematically reviewed.

Results and Discussions

The analysis reveals that nanostructured silicon heterojunction and tandem configurations significantly improve light absorption, carrier transport, and quantum efficiency; however, the high cost of silicon wafer processing remains a critical limitation. CFTS-based photovoltaic materials demonstrate promising optoelectronic properties, including suitable bandgaps, enhanced conductivity, and low toxicity, while offering scalable and cost-effective fabrication routes. In addition to photovoltaic performance, CFTS nanostructures exhibit multifunctionality through photocatalytic and antibacterial activities.

Perovskite solar cells exhibit superior power conversion efficiency compared to conventional photovoltaic technologies, supported by favorable electronic structures and low-temperature processing. Stability challenges are substantially mitigated through mixed-dimensional and two-dimensional perovskite structures, compositional engineering, optimized tolerance factors, and advanced encapsulation techniques. The integration of graphene into PSC architectures yields notable improvements in device efficiency and durability by enhancing charge transport, suppressing metal diffusion, and providing hydrophobic and thermally stable protective layers. Graphene-modified PSCs retain over 90% of their initial efficiency under prolonged exposure to humidity and elevated temperatures, outperforming conventional device configurations.

Conclusion

Future photovoltaic technologies are expected to rely on synergistic integration of low-cost absorber materials, advanced nanostructures, and multifunctional two-dimensional materials. While silicon-based photovoltaics will remain relevant, their economic limitations motivate the transition toward alternative systems such as CFTS- and perovskite-based solar cells. Graphene and related two-dimensional materials offer a promising pathway to simultaneously enhance efficiency, stability, and device lifetime, addressing key bottlenecks in perovskite solar cell commercialization.

Continued progress in material engineering, interface optimization, and encapsulation strategies—supported by data-driven approaches such as machine learning and intelligent optimization algorithms—will be essential for achieving scalable, durable, and high-performance solar energy systems. The convergence of perovskite photovoltaics with graphene-based materials positions this technology as a strong candidate for next-generation sustainable energy conversion.

Keywords: Solar sensing, graphene, photovoltaic devices, perovskite solar cells

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