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Solar Energy Harvesting: Innovations in Photovoltaic Materials

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ABSTRACT

Solar energy utilisation, mostly via photovoltaic (PV) technology, offers a hopeful resolution to worldwide energy issues arising from the limited availability of fossil fuels and the ecological harm they do. This review investigates new advancements in photovoltaic materials, highlighting their significance in surpassing the constraints of conventional silicon-based technology. The paper analyse the progress made in organic photovoltaics, quantum dot-sensitized solar cells, and perovskite solar cells, emphasising their capacity to achieve very high efficiency, low cost, and scalability. This paper also examines the use of nanostructured materials into hybrid systems, with a specific emphasis on their capacity to improve energy conversion efficiency and promote stability. The review continues by acknowledging the obstacles related to long-term stability, manufacturing, and cost, and suggests future avenues for research and development to enhance the feasibility and ubiquity of solar energy as an energy technology.

Keywords: Solar energy harvesting, Photovoltaic materials, Organic photovoltaics (OPVs), Quantum dot-sensitized solar cells (QDSSCs), Perovskite solar cells (PSC).

INTRODUCTION

The rising energy demand and its environmental consequences are crucial issues. Fossil fuel-based sources cause damage through emissions and climatic changes. Addressing this requires sustainable concepts. Photovoltaic technologies produce electrical energy from sunlight with zero emissions. Solar energy has enormous potential but faces challenges in large-scale implementation [1]. There is still a need for low-cost, scalable, and nanostructured materials to effectively harvest solar energy. Moreover, the efficient separation of the two critical components in such devices (e-h pairs and excitons) is another challenging factor in developing low-cost nanostructured devices. As a result of this unique combination of challenges and opportunities, a multidisciplinary research approach involving various aspects ranging from material science, chemistry, physics, and device physics is crucial to develop promising materials and devices for solar energy harvesting applications. The scope of the book chapter is to introduce the fundamental concepts on the growing importance of solar energy harvesting and emerging new classes of nanostructured materials for PV applications [2].

IMPORTANCE OF RENEWABLE ENERGY SOURCES

In recent years, renewable energy sources have been increasingly seen as the electricity generation solution for the future. Renewable energy, here meaning energy sourced from renewable natural sources, provides an alternative to fossil fuel burning. This has been chosen as the solution for many reasons, including the fact that fossil fuel is a finite energy source, large burning quantities lead to toxic greenhouse gas emissions, and international geopolitics could potentially impact energy supply for many countries dependent on fossil fuel imports [3]. Renewable energy may be available in many forms, such as photovoltaic materials, solar thermal, wind, tidal, hydroelectric & wave, geothermal, and biomass. Photovoltaic materials convert light energy into usable electric energy through the photovoltaic effect. This effect consists of semiconductor materials where the absorption of light leads to an excitation of electrons, creating free mobile charge carriers, thus forming a voltage difference and generating usable electricity [4]. Throughout the years, great advancements in the technical and commercial performance of renewable energy resources have been made. The global new investment in renewable electricity capacity has surpassed investment in fossil fuel electricity generation. It is expected for similar trends to continue globally, especially in developing countries, where high understanding of the additional social and economic benefits of RES exists [5]. The World Energy Council estimates that within the years 2004–2030, the global primary energy demand will increase by approximately 48%. An international sharing of technologies and financial investments in renewable energy sources leads to mutual interest and benefits. Clean energy solutions could prevent climate change, leading to a more stable environment where countries can develop economically, helping to raise living standards and improve the quality of life for many [6]. Energy demand is expected to continuously grow as economies develop, and energy resource dependency and long-term availability of fossil fuels are questioned. The depletion of fossil fuel reserves does not mean the depletion of the potential to extract fuel from deposits. It determines a time-scale rather than an absolute value. This time-scale for fossil fuels to run out is often quoted from a few decades up to several centuries, depending on consumption estimates and availability of resources. The renewable energy potential is at least an order of magnitude larger than current consumption amounts of energy from fossil fuels [7].

FUNDAMENTALS OF PHOTOVOLTAIC MATERIALS

The operation of photovoltaics relies on photoelectric absorption, electron-hole pair separation and transport. A comprehensive overview of materials and device engineering challenges for each materials class is provided in the following chapters. Organic photovoltaic systems rely on blends between electron-donating and electron-accepting layers, with considerations for compatibility and performance optimization. Hybrid devices use porous or nanoparticle morphologies, raising questions about processing and dielectric properties. Fullerene-free systems broaden absorbance and energetics, but raise questions about excited state behavior. Inorganic semiconductor photovoltaic devices use doped nanocrystalline metal oxides as an electron transport layer, with impact on device efficiency and questions about excited state fate at interfaces [8]. Silicon wafer-based technologies dominate the photovoltaic market, but alternative materials and device architectures offer lower cost and energy return. Colloidal nanocrystal quantum dots show promise as photocurrent harvesters in LED devices. Questions remain about electron fate at dielectric interfaces and transport of multiple-excitation photons. Several materials enable high-throughput manufacturing, with some commercially available. Further work is needed to improve absorption efficiency. Organic photovoltaics also offer potential. Overall, researchers and engineers face opportunities, challenges, and considerations [9].

TYPES OF PHOTOVOLTAIC MATERIALS

Photovoltaic materials, such as solar cells, can be classified into three generations: first-gen or conventional cells, second-gen or contemporary cells, and third-gen cells, including organic or hybrid cells. First-gen cells are further categorized as monocrystalline, polycrystalline, and thin-film (amorphous) cells. These are primarily made of silicon and account for 90% of global solar cells. Mono-Si cells have a high conversion efficiency of 24.4% and around 40% module efficiency. Poly-Si cells have approximately 22% lab efficiency and 17% commercial efficiency. Thin-film first-gen cells, based on amorphous silicon (aSi) technology, have about 11% efficiency for commercial use. The drawback of these cells is the high energy consumption in Si wafer fabrication. Despite their market dominance, there are ongoing efforts to develop novel, cost-effective solar cells [10]. Second-generation solar cells are classified into emerging technologies such as dye-sensitized solar cells (DSSCs) and organic photovoltaics (OPVs). These solar cells are inexpensive, which makes them contemporary solar cells. DSSCs have the highest energy conversion efficiency of 14.3% for lab-prototype cells, while OPVs have a maximum solar energy conversion efficiency of 6.8% for lab-prototype cells. These second-generation solar cells are low-cost, easy to fabricate, and lightweight, which makes them compatible for indoor solar energy harvesting, especially for low-light conditions. However, these solar cells have two main disadvantages: low stability and limited operating lifetime (3-5 years). Third-generation solar cells are classified into quantum-dot-sensitized solar cells (QDSSCs), another emerging technology. QDSSCs are based on the heterojunction or nanostructured approach using semiconductor nanocrystals or quantum dots (QDs) as light-harvesting electron transfer materials. The QDs are composed of cadmium-tellurium, lead-sulfide, silicon, lead-selenide, tin-selenide, etc. They possess unique optical and electronic properties such as impurity-free band-gap tuneability, high photoluminescence and quantum yield efficiency, and excellent electron-hole or exciton dissociation capability, which are useful in enhancing the solar energy conversion efficiency of solar cells. Although QDSSCs were invented in 1983, efforts are underway to improve their energy conversion efficiency [11].

RECENT INNOVATIONS IN PHOTOVOLTAIC MATERIALS

Considerable attention has once again turned to the sun, which is seen as the most promising natural source of energy. As a result, significant efforts in research and development have been made to construct more efficient photovoltaic materials for the conversion of solar energy into usable chemical fuels. While several materials, including Si, GaAs, and CdTe, have laid the groundwork and achieved commercial success, the need for inexpensive materials to make photovoltaics economical and accessible on a larger scale still continues to be a challenge [12]. Recent advances in energy harvesting using naturally abundant photovoltaic materials such as organic compounds and materials rooted in earth-abundant elements have sparked interest for alternative energy materials and devices. This focus for materials to dismantle the current energy infrastructure reproducibly on a global scale has also paved the groundwork for a different class of energy harvesting materials based on nanostructured materials. However, producing similar nanostructured materials from disparate global sources economically in mass remains a grand challenge for energy harvesting technology [13]. Nevertheless, organic photovoltaics composed of carbon-based semiconductors have gained wide interest in academia and industry, spurred by the potential for reduced material and energy costs through the economies of scale that such roll-to-roll processing would provide. Amidst recent advancements for cost-effective materials for solar energy conversion is a new class of high-performance thick film solar cells composed of synthetic metal oxides based on earth-abundant elements that have been rigorously studied and developed [14]. Will cheaply processed metal oxide materials fabricated by a rapidly scalable sol-gel and low-temperature thermal treatment route catalyze a paradigm shift in the next generation photocurrent-generating solar cells? Can new wave engineered metal oxide materials, superior to Si photovoltaics, hold the key to sustainable energy harvesting technologies? [15].

PEROVSKITE SOLAR CELLS

The invention of low-temperature, thin-film, and easy fabrication procedures for mixed-cation mixed-halide perovskite solar cells (PSCs) has attracted substantial scientific interest. Recent studies with mixed cation/mixed halide perovskite materials involving MA+, FA+, and Rb+ cations have revealed dramatic improvements in the efficiency and long-term operational stability of PSCs. Since the initial development of organic-inorganic hybrid perovskite (CH3NH3)PbI3 light-absorber material, the field of PSCs has expanded significantly. Notably, recently reported efficiencies exceeding 25% for PSCs fabricated with low-temperature solution deposition, thin-film technology, and low-cost materials demonstrate that PSCs are a very promising candidate for next-generation, cost-effective photovoltaics [16]. Despite improvements in the MAPbI3 perovskite system, its long-term stability is still a challenge, especially under high humidity. New approaches involving mixed cation/mixed halide PSCs have shown improved resistance to humidity and heat. The incorporation of variable amounts of FA+ cations into the MAPbI3 scaffold greatly stabilizes the material. A partially-adopted mixed-cation approach yields remarkable improvements and sets a new efficiency record for PSCs. This new family of materials remains stable under 1-Sun illumination, even at high temperatures [17]. More recently, mixed compositional systems involving halides have been investigated, including MA+ and FA+ cations, which generally entailed multiple fabrication steps to convert dark-grey MAPbI3 starting material into MAPb(I/Br)3 or MAPb(I/Cl)3 ternary systems. While these methods improved efficiencies and indicated time-constant thermal stability, there was no investigation of the relevant Gibbs free-energy deviations. However, a simple low-temperature approach can yield brown MAPb(I/Br)3 materials with Gfree-E = −519 meV more negative than MAPbI3. Consequently, MAPb(I/Br)3 materials are metastable in humid air containing 1.5% water vapor and sunlight, evidenced by dynamic light-scattering studies showing growth of absorbing nanocrystals on the order of ~50-200 nm within seconds [18].

CHALLENGES AND FUTURE DIRECTIONS

The need for sustainability and energy demands has led to interest in solar photovoltaics. Quasi-2D materials with perovskite structures have gained prominence in solar energy harvesting. They have properties suitable for perovskite solar cells and can enhance device performance. Challenges remain in stability, manufacturing, efficiency, and costs [19]. The best-performing thin-film technologies use thick absorbers (≥2 μm) due to their high absorption coefficients. Thin film solar cells face challenges with optical losses and low efficiency in lead halide perovskites 3-50 μm thick. The quality and uniformity of the semiconductor film and device in a module are important, as well as manufacturing challenges in bulk. Manipulating reflective and absorption properties of sunlight can create imperfections in the material. Chemical defects may have different effects in large-area, low-cost devices compared to small, high-cost electrical devices [20].

EFFICIENCY AND COST CONSIDERATIONS

The main considerations for new solar energy materials are efficiency and cost. Initially, spectrally selective materials were created with the hope of allowing solar energy into the photovoltaic part of a cell. It was later discovered that these materials needed to be chosen carefully or they would be useless. Attention then turned to improving electro-optical properties, resulting in success with materials like silicon nitride and aluminum-doped zinc oxide films. However, the introduction of wide gaps like CdS and CdTe disrupted the established structure [21]. These materials did not match well with the conduction band of the substrate, which meant that they rapidly "poured" charge into the semiconductor for nearly 100% internal quantum efficiencies. The structure by necessity drove a 1-D analysis, which required a more light-harvesting, and again more speculatively activated, electro-optical structure. Following this early opportunity, a parallel interest in specialized complex dielectric inserts like as-SiNx:Fe that was hoped might "design" the spectral response more favorably was attempted but largely failed. Meanwhile, further experimental studies indicated clearly the need for good surface field formation in an electro-optical context to realize widely anticipated 30% device efficiency limits. Despite all this, the field remained easy to convince that better and more complex dielectric designs unveiled would somehow contribute competitively against the massively complex but very successful NASA IR analysis while basically not analyzing periodic or more complex thin film designs at all [22]. Wasteful attempts at complex designs led to unnecessary complexity and possible loss of compatibility. SLAC pilfered Wisconsin's work and claimed it added technical expertise. The need for an electro-optical approach was advised but ignored. Ambitious designs were proposed, disregarding previous attention given to shortening conduction paths. Manufacturers continued with SLAC, hoping it would support their efforts [23]

CONCLUSION

The field of photovoltaic materials has witnessed remarkable advancements, with new materials and technologies emerging to address the limitations of traditional silicon-based solar cells. Organic photovoltaics, quantum dot-sensitized solar cells, and perovskite solar cells offer promising pathways to achieving higher efficiency, lower costs, and greater scalability. However, significant challenges remain, particularly in the areas of long-term stability, manufacturing complexity, and overall cost-effectiveness. Continued research and development in nanostructured materials and hybrid systems are essential to overcoming these barriers and realizing the full potential of solar energy as a sustainable and ubiquitous energy source. By addressing these challenges, the future of solar energy harvesting looks increasingly bright, with the potential to play a central role in meeting global energy needs

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