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Effects of nanostructure on clean energy: big solutions gained from small features

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Abstract The increasing energy consumption and environmental concerns have driven the development of cost-effective, high-efficiency clean energy. Advanced functional nanomaterials and relevant nanotechnologies are playing a crucial role and showing promise in resolving some energy issues. In this view, we focus on recent advances of functional nanomaterials in clean energy applications, including solar energy conversion, water splitting, photodegradation, electrochemical energy conversion and storage, and thermoelectric conversion, which have attracted considerable interests in the regime of clean energy.

Keywords Clean energy · Functional nanostructures · Photocatalysis · Solar energy · Electrochemical energy conversion and storage · Thermoelectric conversion

1 Introduction

With the explosive growth of population and the threat of global warming, as well as severe pollution problems, human beings have been pushed to develop cost-effective, high-efficiency solutions to meet the ever increasing demand for clean energy. Advanced functional nanomaterials and relevant nanotechnologies are playing a crucial role in resolving some energy issues. As one of the internationally recognized and highly influential academic journals of China, *Chinese Science Bulletin* has devoted close attention to state-of-the-art clean energy-related materials. A special issue on "Advanced Materials for Clean Energy" was published in June 2014 to highlight recent advances in clean energy harvesting, conversion, storage, and utilization through artificial photosynthesis, dye-sensitized solar cells (DSSCs), perovskite solid-state solar cells, electrochemical supercapacitors, rechargeable Li-ion/Na-ion batteries, and thermoelectric materials [1–8]. Here, we summarize the recent promising applications of nanostructures in the field of clean energy (Fig. 1).

2 Photocatalysis: utilization of solar energy

Solar energy, as an important inexhaustible source of clean energy, has been investigated for several decades. Although utilizing solar energy includes many aspects, such as solar cells, photocatalytic degradation of pollution, and water splitting, they are all based on the photocatalysis process, which is the acceleration of a photoreaction in the presence of a catalyst and the absorption of solar energy by an adsorbed substrate. The photogenerated catalysis activity (PCA) depends on the ability of the catalyst to create electron–hole pairs, which is able to undergo redox reactions with other species. According to the utilization of the photoelectrons, applications of solar energy based on the photocatalysis process could be divided into the following groups.

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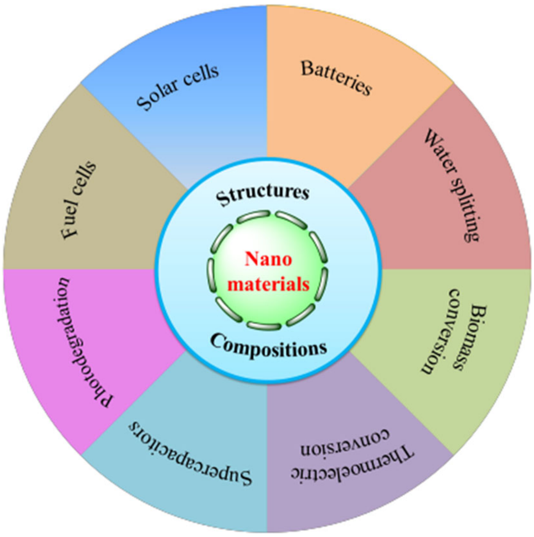

Fig. 1 (Color online) Applications of nanostructures in the field of clean energy

2.1 Solar energy conversion

Solar cells are devices that directly convert sunlight into electricity on the basis of the photovoltaic effect, for example meaning that the generated electron–hole pairs are directly used as charge carriers, representing a most promising method for utilization of solar energy. Apart from the expensive traditional p–n junction-based silicon solar cells, new prototypes of solar cells have been developed such as sandwich-like dye- or quantum-dot-sensitized solar cells, which consist of a counter electrode, electrolyte, and a photoanode [9, 10]. Usually, two basic important processes rule the performance of solar cells: (1) the excitation process, for example generation of photoelectrons by the photoelectrode under irradiation of light and (2) the transport process for the photoelectrons, including the transfer of photoelectrons from inside the photoelectrode to the surface and the transport between the electrolyte and electrodes. Nanostructures not only offer huge surface areas for excitation, but also tune the absorption of light and excitation of photoelectrons via quantum effects [11]. Moreover, the transport of photoelectrons across the interface between the photoelectrode and the electrolyte could be easily tuned by different nanostructures. Hence, the performance of solar cells could be effectively improved by nanostructures with different morphologies and compositions, such as nanowires, mesoporous materials, and monodisperse beads, as well as surface modification through nanotechnology [3, 12, 13]. Hitherto, relatively high power conversion efficiency has been realized for traditional photovoltaic devices; for example, a maximum efficiency of 19.6 % and 20.3 % has been achieved in CdTe quantum-dot solar cells [14] and $Cu(In,Ga)Se_2$ (CIGS) cells [15], respectively. Despite the high power conversion efficiency, however, their wide applications are strongly limited, either by their expensive fabrication and the rarity of their natural resources or by the high toxicity of some elements. Moreover, the risk of liquid electrolyte leakage is a big issue for long-term operation without degradation.

Another breakthrough in solar cells lies in the usage of organolead halide perovskite ($CH_3NH_3PbI_3$) as the sensitizer for high-efficiency solid-state semiconductor-sensitized solar cells [16]. More recently, a high efficiency of 15 % was achieved in $CH_3NH_3PbI_3$-sensitized hybrid solar cells by modifying the deposition of the perovskite light absorber and by increasing the conductivity of the hole transport materials [12]. The conversion occurred within the nanoporous host upon PbI_2 and CH_3NH_3I came into contact, permitting much better control over the perovskite morphology than the previously employed routes [12]. Another rapid rise in solar-to-electric power conversion efficiency to more than 18 % was achieved by incorporation of methylammonium lead bromide ($MAPbBr_3$) into formamidinium lead iodide ($FAPbI_3$) as the light-harvesting unit by optimizing phase stability, perovskite morphology, hysteresis in *I*–*V* characteristics, and overall performance as a function of chemical composition [13]. Zhang and Cai [8] have summarized the progress on organolead halide perovskite-based solar cells. It is highly likely that the conversion efficiency could be further boosted by nanotechnology, which makes it highly promising for large-scale commercialization [17].

2.2 Generation of hydrogen and oxygen by water splitting

Hydrogen gas is another highly promising source of clean energy because only water is produced by its burning. In addition, hydrogen possesses extremely low density and high combustion enthalpy, which leads to high energy density. In addition, it can be stored for later use. One of the impediments to its wide application, however, is the high cost of fabrication. Since Fujishima and Honda [18] reported groundbreaking work on the photolytic cleavage of water to H_2 and O_2 in 1972, the concept of using solar light and a suitable semiconductor catalyst to generate H_2 without emitting carbon dioxide via a photoelectrochemical water splitting process or by photovoltaic-driven electrolysis has received tremendous scientific attention [19]. The water splitting reactions only occur when the charge carriers (electrons and holes) generated in the semiconductor from absorption of light can reach the surface during their lifetime and manage to come into contact with protons or water [19]. Thus, the quality of the semiconductor photocatalyst plays a pivotal role in the water splitting.