Integrated Photo‐rechargeable Batteries: Photoactive Nanomaterials and Opportunities

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Abstract: The demand for fossil fuels has been increasing over the last few decades but will one day be depleted and researchers are now using biomass to alleviate the fuel crisis. This paper concentrates on a range of current devices with intrinsic solar energy collection, conversion and storage properties, different classes of cells as well as their areas of application and recent research advances. Nanomaterials, meanwhile, are key to making significant progress in the study of photovoltaic electrodes for solar rechargeable batteries, and this paper describes seven currently commonly used semiconductor and nanomaterials. This not only alleviates the severe environmental pollution and greenhouse effect caused by fossil fuels, but also makes a significant contribution to the sustainability of human existence.

Keywords: Photo-rechargeable battery, Nanomaterial, Photoactive.

1. Introduction

For the past few decades, fossil fuels have been used to facilitate daily human life. But as the world's population grows, so does the demand for fossil fuels, which are a non-renewable resource that will one day be exhausted. Research data suggests that in the future mankind can rely on fossil fuels to diversify its energy sources, converting non-renewable energy sources into renewable ones such as photovoltaic (PV), hydroelectric, wind, thermal and biomass. Researchers are now harnessing solar energy and applying it to solar energy storage cells, thus alleviating the fossil fuel crisis.

These renewable energies can be used in providing a greener and safer energy source for mankind and, most importantly, they are sustainable, which means that they will never run out. On the other hand, as the burning of fossil fuels brings about severe environmental pollution and the greenhouse effect, the consumption of renewable energy sources can largely reduce the ecological problems caused by fossil fuels, which makes a great contribution to the sustainability of human existence.

2. Solar-charged electrochemical energy storage: state of the art

2.1 Converting and storing solar energy

Researchers have now developed a range of devices with intrinsic solar energy collection, conversion and storage properties [1]. In practice, however, due to fluctuating conditions, solar cells need to be combined with storage devices to balance energy supply and demand [2]. Experiments have shown that the weight and volumetric energy density of a battery are key parameters for its use in real-life devices. Therefore there are currently several methods of calculating specific energy (weight) and energy density (volume) applicable to the different stages of battery development: (i) materials exploration, (ii) electrode design, and (iii) cell-level engineering. These calculations help to establish a fair and robust method to compare energy metrics [3-4].

2.2 Photovoltaic cells combined with rechargeable batteries

Photovoltaics (PV) is a renewable energy source that converts sunlight into electricity through the photovoltaic effect and has become one of the most widely used energy sources due to its high efficiency and green nature [5-7]. By 2020, the cost of producing photovoltaic energy has fallen to less than $0.05 per kilowatt hour, compared to $0.05 per kilowatt hour for fossil fuels and $0.03 per kilowatt hour for coal [7]. As photovoltaic technology is increasingly researched and developed, the future of solar energy will be cheaper and more capable of meeting human needs than fossil energy.

Current researchers have classified photovoltaic cells into five different types based on raw materials and operating principles [8], namely silicon solar cells, thin-film solar cells, dye-sensitised solar cells, organic solar cells and chalcogenide solar cells [9,10]. Silicon-based solar cells dominate due to their high efficiency of approximately 25% [11,12]. The second generation of photovoltaic cells, known as solar thin film cells, is made up of multiple

layers of photovoltaic materials and although it is cheap to produce, it is inefficient and contains toxic substances, which can lead to environmental pollution and ecological damage [13]. For the third generation of photovoltaic cells (including organic solar cells, dye-sensitised solar cells and chalcogenide solar cells), although they have shown their superior performance on a research scale, they nevertheless still lag behind other generations of solar cells due to limitations in stability, efficiency, reproducibility and scalability.

2.3 Photo-charge or photo-assisted charge

Photo-charge cells enable an effective combination of solar energy collection and energy conversion/storage functions, offering a potential solution for the large-scale utilisation of unlimited and cost-effective solar energy and alleviating the limitations of conventional energy storage devices. Solar energy can not only be stored directly during the charging process, enabling various photo-assisted/ photo-charged rechargeable batteries, but also in certain devices to improve the discharge performance through the photovoltaic effect. Several integration/combination strategies have been developed by researchers for direct conversion and/or solar energy storage[14,15]. Depending on the electrode number used, the different device structures can be classified as 1) two-electrode, 2) three-electrode, and 3) T-type systems.

2.4 Working principle of the photo-assisted rechargeable metal batteries

In general, rechargeable batteries work by using visible light to induce charge storage and release on demand. Photoelectrochemical (PEC) systems provide a method of converting light energy into electricity or chemical fuel through an electrochemical reaction. The key to a photoelectrochemical cell is the electrolyte used and the semiconductor photoelectrode where the redox chemistry occurs [16]. In contrast, the PEC system of semiconductor photoelectrodes works on the principle of charge separation occurring upon excitation by photon energy and the formation of a region of space charge at the semiconductor-electrolyte interface. The key to self-charging lies in the ability of the material itself to generate photoelectrons and thus excite charge transfer in the dark on demand [17].

2.5 Photo-assisted rechargeable lithium metal batteries

Although graphite has proved to be the best and most reliable substance used to date for making cathodes, it holds a limited number of ions. Researchers have been hoping to replace graphite with lithium metal foil, which can hold more ions, but typically lithium metal foil reacts adversely with the electrolyte, which can lead to overheating and even combustion. Lithium metal batteries (LMBs) are batteries that use lithium metal as the negative electrode, and the cathode material that goes with it can be oxygen, monolithic sulphur, metal oxides and other substances. Lithium metal batteries were primary batteries when they were first proposed in 1912, but after a century of development, the technology is now well suited to the dissolution and deposition of lithium metal during the charging and discharging process, i.e. secondary batteries. Recent researchers have used nanostructured halloysite nanotubes (NHNT) to create high-performance polyvinyl alcohol composite diaphragms (OPVA/NHNT diaphragms), which can effectively improve the electrochemical performance and safety of lithium metal batteries while reducing the overall production cost of lithium metal batteries.

2.6 Photo-assisted rechargeable Li-ion intercalative electrodes

Since Sony commercialised the first lithium-ion battery with $LiCoO_2$(LCO)-graphite insertion chemistry in 1991, there have been many developments of new electrode materials [20-22]. Current researchers have used intercalation techniques to modify the "shuttle" effect and multiplicity performance of lithium batteries.

Tong et al. explored the application of different hydrated metal ion intercalated layered vanadium-based electrode materials in battery cathode materials by preparing LVO nanosheets synthesized by hydrothermal method after wet mixing of LiOH-H_2O and V_2O_5, and investigated their electrochemical performance and energy storage mechanism. This novel design will have important theoretical and practical implications[23].

2.7 Photo-assisted rechargeable lithium-ion batteries

The most commonly used batteries today are based on metal anodes, of which lithium, zinc and sodium are the most representative examples of anode materials. Of these, lithium-based materials are most commonly used as solar rechargeable batteries[24-27]. The main advantage of using lithium is its large theoretical energy density and, in addition, due to its small size, lithium ions can be easily inserted into other nanomaterials without changing their structure[28,29].

Designing lithium-ion batteries (LIBs) is key to portable devices and mobile electrical devices, which currently exist mainly in areas such as electric vehicles [30-32]. The fast charging and self-powering of batteries is therefore an important but challenging key technology. With the depletion of fossil fuels and global energy depletion, people are forced to look for new and renewable sources of energy, but without efficient energy storage the full use of energy cannot be achieved, so modern devices are placing additional demands on existing LIB technology to meet the fast-paced society and emerging needs, especially in terms of power density and charging rates [33-37].

Wang et al. designed a lithium-ion battery with photoelectric charging (photo LIB), using LiV2O5 as the photocathode, which can be light-assisted fast charging and photo-assisted [38]. The device achieves the highest full-spectrum light energy conversion efficiency to date of 9 % in pure light charging mode, demonstrating an efficient self-powered mode. The results show that reversible vanadium charge transfer and Li+ insertion in V_2O_5 under light conditions can improve the performance.

This study provides new avenues for integrating energy conversion and storage into practical applications.

2.8 Photo-assisted rechargeable lithium-oxygen batteries

Lithium-oxygen batteries have attracted a lot of attention in the electric vehicle sector due to their ultra-high theoretical energy density (~3560 $Whkg^{-1}$), which far exceeds that of conventional lithium batteries (~387 $Whkg^{-1}$). The overall discharge/charge reaction of Li-ox batteries (with a theoretical potential of 2.96 V) involves the reversible formation and decomposition of Li-O_2 [39]. However, the high charge overpotential severely limits further cell development due to the insolubility and poor conductivity of Li-O_2. The current researchers can effectively solve this problem by integrating light through the photovoltaic effect, efficiently achieving the conversion and storage of the anode energy. Recent research has shown that the use of photocathodes in combination with lithium-oxygen cells can effectively reduce the charge overpotential by absorbing solar energy, thereby increasing the energy efficiency of the cells.

2.9 Photo-assisted rechargeable lithium-sulfur batteries

Compared to the currently popular lithium-ion batteries, lithium-sulfur (Li-S) batteries are considered to be one of the most promising candidates for portable electric devices and electric vehicles as an emerging energy storage device due to their ultra-high energy density (2600 $Whkg^{-1}$), high safety and low cost[40]. Zhou and coworkers proposed a lithium-sulphur hybrid cell consisting of a lithium anode, an organic electrolyte and a Pt/CdS-containing cell[41]. By absorbing solar energy, the photoexcited pores of Pt/CdS can oxidise the discharge products, thus allowing a reproducible photo-charging process without external electrical input. However, the reaction produces by-products that cannot be used secondarily, and this continuous consumption and relatively slow charging and discharging efficiency has led to the slow replacement of such cells.

However, the commercialisation of lithium-sulphur batteries has been hampered to some extent by a number of problems of its own. The main problems of lithium-sulphur batteries are twofold: 1) the lithium polysulphides (LiPSs) formed during the discharge process tend to dissolve into the electrolyte and are deposited across the semi-permeable membrane onto the surface of the negative lithium metal, which not only leads to capacity degradation but also hinders the further charging and discharging process; 2) the insulating properties of the active substance sulphur and the discharge products lead to poor multiplier performance. Researchers are now using calcium titanite cells to improve on lithium-sulphur batteries, and these hybrid cells exhibit good photo-charging capabilities.

2.10 Photo-assisted rechargeable Lithium-Iodine2 batteries

Among a variety of batteries, lithium-iodine (Li-I) batteries, which usually consist of a lithium anode and an iodine-based calcium solvate (I^-/I^{3-}), have a high theoretical potential and capacity (211 $mAhg^{-1}$) and are a promising type of large-scale energy storage battery. In 2015, Yu et al. reported the first example of a photosensitive Li-I cell with a three-electrode structure using dye-sensitized titanium dioxide photoelectrodes[42]. To meet the practical needs of light-assisted charging cells, researchers have investigated the application of new carbon materials in lithium-ion battery anode materials and fuel cell cathode oxygen reduction electrocatalytic materials, and explored excellent photoelectric electrodes with low cost, good visible light absorption and good electrolyte stability.

2.11 Photo-assisted rechargeable metal zinc batteries

Not only to solve the problem of energy shortage and consumption, but also to eliminate the main obstacle to modern electronic product design - the flexible battery, researchers have recently developed rechargeable zinc ion batteries (ZIBs) in addition to the continuous improvement of lithium batteries, which have the advantage that zinc metal anodes have a better stability during cycling [43,44]. As a result, zinc metal is easier to use as an anode material, thus simplifying the design of the battery [45,46].

This type of battery has a zinc anode, a metal oxide cathode and a solid polymer electrolyte. The cathode and anode are located on either side of the cell and the zinc ions flow from the anode to the cathode in the electrolyte to initiate a chemical reaction that continuously generates electricity. Because zinc is not very active in the environment and can be as small as a few hundred microns (the broad band of two hairs), these ultra-miniature batteries could be used in digital smart tags, for example to check the freshness of food. the Imprint team has produced a lithium battery that could be used in flexible sensors, especially for devices that are worn on the human body or even implanted inside the body, making zinc batteries a safer option.

Buddha uses photo-assisted zinc ion cells (hv-ZIBs), where the electrodes consist of layers of grown zinc oxide and molybdenum disulfide [47]. These are able to collect solar energy and store it in the corresponding material, while at the same time alleviating the need for solar cells or power converters. Experimental results demonstrate a capacity retention of up to 82% after 200 cycles, a photocathode with a light-to-charge conversion efficiency of 1.8% and a capacity increase of up to 38.8% in the presence of light.

2.12 Photo-assisted rechargeable metal sodium batteries

Sodium ion batteries are more suitable as large-scale energy storage devices, which have three advantages: 1) sodium has better safety properties as an energy storage material compared to lithium; 2) sodium is abundant in

the earth's reserves, with 2.4% of crustal species of metallic sodium; and 3) sodium is cheap. For the first time, researchers have now embedded a titanium dioxide (TiO_2) photoelectrode into the positive electrode of a new sodium ion battery to achieve efficient conversion and storage of solar energy. The light-assisted rechargeable sodium ion battery utilizes an aqueous Na_2SO_4 anode electrolyte and NaI cathode electrolyte as the active substances for the negative and positive electrodes respectively, and the TiO_2 photoelectrode is embedded in the positive electrolyte as the solar energy conversion and storage primitive. When the battery is charged under simulated solar illumination, the TiO_2 photoelectrode is excited by light to produce electrons and holes, and the discharge process of the battery is similar to that of a conventional sodium ion battery. The ultra-low charging potential plateau is significantly lower than the discharging potential plateau, resulting in an energy conversion efficiency of 190%, equivalent to a saving of nearly 90% of the input power. The research results provide a new idea for the development of low-cost, high-safety performance photoelectric conversion and storage devices, while promoting the practical application of photo-assisted batteries.

2.13 Pioneering works on bifunctional electrodes

Photovoltaic cell (PE) is one of the key factors in the development of high performance and is often the limit to overall efficiency. The choice of materials and design of structures is therefore crucial for efficient conversion and storage of solar energy[48]. The PE can consist of a simple semiconductor or a photovoltaic cell. In a photovoltaic cell, the PE is part of the energy conversion unit and works independently of the storage system. In an integrated two-electrode photovoltaic cell, the PE is a bifunctional photovoltaic cell because it has to fulfil two purposes: to obtain energy from the sun/sunlight; and to store the obtained energy by chemical means. The storage of energy by means of a redox reaction/ion transfer electrolyte requires efficient charge transfer between the PE and the electrolyte, which are closely related to the nanostructure of the material[49,50]. Researchers can now more easily tune the band gap and electronic band structure of nanomaterials by changing their size and doping [51].

3. Photo-induced mechanisms

3.1 Basic concepts in photo-batteries

A photovoltaic cell is a semiconductor element that generates an electric potential in the presence of light. It is a component that generates an electric potential in response to the irradiation of light. It is generally used for photoelectric conversion, photoelectric detection and light energy utilization. There are many types of photovoltaic cells, commonly used are selenium photovoltaic cells, silicon photovoltaic cells and thallium sulphide and silver sulphide photovoltaic cells.

Photovoltaic power generation is a technology that uses the photovoltaic effect of semiconductors to convert light energy directly into electricity. The key component of this technology is the solar cell. Solar cells are connected in series and then encapsulated and protected to form a large area solar cell module, which is then combined with power controllers and other components to form a photovoltaic power generation device. The advantages of photovoltaic power generation are fewer restrictions, safety and reliability, no noise and low pollution.

3.2 Dependence on the electrode architecture

3.2.1 Influence of the electrode thickness

Lithium-ion batteries (LIBs) have become the most attractive source of power in today's pure or hybrid electric vehicles, but the fact remains that there is still range anxiety, insufficient fast charging capability and a range of safety issues. Reducing the proportion of materials that are not electrochemically active is a good way to increase the energy density of a battery. For example, the electrode composition can be changed by reducing the proportion of active binders and conductive agents, which can be disguised as an increase in electrochemically active material content. Studies have shown that at low multipliers there is little difference in capacity between electrodes and little difference in voltage plateau. When the electrode thickness is greater, the voltage plateau increases and decreases slightly during charging and discharging, which indicates greater polarisation for thicker electrodes.

3.2.2 Influence of the porous network

Combining electrodes, diaphragms, collectors and even graphite cathodes of similar area capacity, the researchers found that reducing porosity results in higher battery capacity at lower magnifications, however, as charge and discharge magnifications increase, electrodes with higher porosity exhibit superior performance due to the faster transfer kinetics and mass transfer characteristics of higher porosity electrodes at higher magnifications. Therefore, while reducing the contact resistance and effective lithium ion diffusion rate in the electrolyte, reducing the porosity of the electrode will increase the specific resistance and charge transfer resistance of the cell.

3.3 Role of the electrolyte

Electrolyte chemistry plays an important role due to the high reactivity of the electrode-electrolyte interface and the corresponding layered oxides to high states of charge (SOC). The electrolyte composition can therefore be adapted to promote a more stable cycle[52]. By comparison, it was found that the electrolyte generally uses about 7 mol/l of KOH solution (there is also a certain amount of NaOH instead of KOH), but of course a small amount of other components such as LiOH are added to

the electrolyte, but some impurities such as carbonates, chlorides, sulphides, etc. are required.

4. Photoactive nanomaterials working as bifunctional photoelectrodes

4.1 Dye-sensitized photoelectrodes

Gratzel Cells introduced the third generation of solar cells in 1988, known as dye-sensitised solar cells (DSSCs).DSSCs are photoelectrochemical solar cells consisting of a glass substrate, a transparent conductor, a semiconductor material, a dye, an electrolyte and a cathode in a five component structure [53,54]. In the past two decades, academic research on dye-sensitised solar cells (DSSCs) has shown tremendous progress. Researchers have indicated that dye-sensitised solar cells hold promise as one of the alternative options to replace conventional silicon-based photovoltaics. The DSSC works in four basic steps: photon absorption, electron injection, carrier transport and current collection. The advantage of DSSC is that it can achieve better performance through low material cost and simple fabrication [55,56]. However, DSSC glass substrates have limitations due to their stiffness, high mass and expensive nature [57,58].

Since dyes are primarily responsible for the absorption of light in the system, the researchers wanted a dye whose absorption covered a wide range of wavelengths in the visible region and even extended into the near infrared (NIR) part. Equally important, given the lifetime of the device, the dye should be thermally stable and have strong interfacial binding to the metal oxide [59,60]. Xu et al. designed a composite formed by TiO2/N719 dye/Cu2S to be used as a photocathode in a solar rechargeable Li-S cell [61]. By depositing cuprous sulphide on the dye, a bifunctional PE was created that could collect light and store it.

4.2 Transition metal oxide-based semiconductors

Transition metal oxide cathodes tend to have intrinsically low conductivity, which can lead to inhomogeneous charge distribution in the electrode [62]. To mitigate the potential charge inhomogeneity and electrode composition, coating methods using conductive polymers or carbonaceous substances have been intensively investigated. Layered oxide materials remain the current cathode of choice for lithium-ion batteries, particularly in the automotive sector, where a number of low cobalt and high nickel compositions are ready for commercialisation. In order to mitigate the effects of the harmful degradation processes of nickel-rich compositions, research has shown that strategies to introduce electrochemical activity, stabilise the entry of cations into the structure and apply stable surface coatings have proven to be successful in extending cycle life.

The following are currently being studied by researchers: 1) titanium dioxide, a well-known n-type semiconductor with high stability, biocompatibility and high electron mobility [63]; 2) ferric oxide, an n-type semiconductor with magnetic properties. α-Fe_2O_3 is one of the most abundant metal oxides on Earth and it is thermodynamically more stable than other iron oxides [64]. It is chemically stable over a wide pH range, has a low cost and a relatively narrow band gap (2.1-2.3 eV), which facilitates light absorption in the visible spectral range; 3) tungsten trioxide is an n-type semiconductor with a band gap of 2.6-3.0 eV [65]. Tungsten trioxide is non-toxic and has good chemical and photochemical stability [66]. Tungsten trioxide nanoparticles have a high specific surface area and high electron mobility; 4) vanadium oxide, vanadium is considered to be a very abundant element in the earth's crust [67]. It has a crystal structure with different oxygen coordination sites, the most common crystal structures being vanadium dioxide and vanadium pentoxide [68]. These two materials have been used as cathode materials for lithium-ion batteries and are promising materials for photovoltaic cells with high specific capacity, energy density and good photocatalytic properties [69-71]; 5) molybdenum oxide, which, like vanadium oxide, is an n-type semiconductor. Molybdenum oxides also have light absorption in the visible range of the spectrum, and molybdenum trioxide has attracted a lot of attention in the last decades due to its non-toxicity and excellent properties in the fields of photovoltaics, energy storage, gas sensing and catalysis [72-75]; 6) cobalt oxide, which, like many metal transition oxides, can be used in photocatalysis, including secondary lithium-ion batteries [76,77]. Co_3O_4 is a p-type semiconductor with a direct band gap of 1.4-1.8 eV and an indirect band gap of 2.2 eV.

4.3 Chalcogenide-based nanomaterials

Metal-sulphur compounds are often referred to as MX_2, where X stands for elements of the VI A group (X: S, Se and Te) and M is a transition metal. MX_2 is a two-dimensional material with a large interlayer distance [78]. Due to the large interlayer spacing, interlayer van der Waals interactions are weak and metal ions can be inserted into their structure [79]. As a result, they have been used as electrodes in lithium-ion and sodium-ion batteries [80,81].

Cadmium sulphide (CdS) is the most commonly used sulphur group compound. It is an n-type II-VI semiconductor that is widely used as a photocatalyst due to its light-absorbing ability in the visible light range. It has a low cost and high electrical conductivity. In order to improve the stability and performance of cadmium sulphide, Li et al. proposed the introduction of Pt as a co-catalyst for lithium-sulphur PBATs [82]. Experimental results showed that the S_2- ions produced during discharge were oxidised to polysulphides and electrons were transferred to the nanoparticles, which would reduce the H^+ in the electrolyte and produce a valuable fuel, H_2.

4.4 Elemental-based nanomaterials

Graphite-like nanomaterials for Li-CO2 batteries. Hybrid photocathodes of silicon carbide grown on reduced graphene oxide (SiC/rGO), where the silicon carbide is synthesized in situ on the reduced graphene oxide surface [83]. Both the two-dimensional nanosheet reduced

graphene oxide and the Si-OH bonding on the surface of the silicon carbide favoured CO2 adsorption.2021, C. Jia et al. proposed 3 nm sheet-thick super-arch size silicone oxide (2.05 nm) as a photoactive material with energy storage properties, which provided impressive discharge/charge voltage retention (98 and 93%, respectively) [84].

4.5 Perovskite-based nanomaterials

Chalcogenide materials have the advantages of tunable band gap, high absorption coefficient, long exciton diffusion length, good carrier mobility and low exciton binding energy [85-87]. The power conversion efficiency (PCE) of chalcogenide solar cells has now risen rapidly to 25.5% [88]. However, point defects, luminescence or heating effects of the material lead to losses of energy and PCE of chalcogenide solar cells below the radiation limit defined by SQ theory [89].

Factors that affect the PCE of chalcogenide solar cells include the composition of the chalcogenide material, the charge transport material of the transport layer, and interfacial defects. These defects can cause or accelerate the degradation of chalcogenide, leading to non-radiative compounding, which affects the performance and stability of chalcogenide solar cells [90].

Current researchers have introduced several additives to improve their surface morphology and crystallinity, resulting in highly purified and smooth surface chalcogenide layers. yang et al. introduced ammonium benzene sulfonate (ABS) as a ligand molecule to reduce the defect density, which effectively retarded the crystallisation process and produced high-quality, stable chalcogenide films [91].

At present, the preparation of highly efficient, high quality and stable chalcogenide films remains the main challenge in achieving a wide range of PSC applications. At the same time, a number of mechanisms still need to be further investigated by a combination of experimental, computational and simulation means.

4.6 Organic-based photoactive materials

The main advantage of using organic-based materials in batteries is the ability to tune their physicochemical, optical and electrical properties in a simple synthesis step. Organic-based nanomaterials open up a large number of possible materials. There are examples of small organic molecules, polymers, metal organic frameworks (MOFs) and covalent organic frameworks (COFs) that have been used in rechargeable batteries [92-95].

Zhang et al. published a photocathode in a fuel-free photochemical cell (PEC) containing titanium dioxide for the water oxidation reaction [96]. This cell produces both water and oxygen, rather than carbon dioxide, which would benefit the environment.

4.7 Carbon nitride-based nanomaterials

Graphitic carbon nitride (g-C3N4) is a metal-free semiconductor that was first reported by Wang et al. in 2009 and has attracted significant attention since then [97]. Graphitized carbon nitride has the advantages of low cost, environmental friendliness, medium band gap (~2.7 eV), high redox capability, high surface activity and stable photo- and physicochemical properties [98-99]. It consists of a tri-triazine ring as a high nitrogen content building block and abundant triangular nanopores that can provide a large number of active sites for ion adsorption and redox reactions [100].

Liu et al. reported the first light-assisted rechargeable battery using g-C3N4 as a bifunctional PE [101]. Zhu et al. reported that using g-C3N4 to increase the number of active sites on its surface can help facilitate photocatalytic reactions [102]. More importantly, it can extend the light absorption range, and the experimental demonstration of the dual-electrode system yielded an energy efficiency of 92.5% after 50 cycles.

5. Challenges and outlook

The development of photoactive cells, especially integrated two-electrode configurations, is still in its infancy and presents many problems and challenges. So far, the maximum overall efficiency of a two-electrode photovoltaic cell is 9%. How to achieve an efficient and cost effective use of solar energy remains the focus of current research. Researchers are constantly improving the performance of cells by means of optimising relevant parameters such as energy conversion/storage efficiency, long-term durability, energy and power density.

However, exploring low-cost, advanced and compatible photovoltaic electrode materials while optimising the cell assembly is key to obtaining high overall efficiency, high capacity and energy density. Therefore, the development of electrolytes that are also photostable and compatible is also critical to overall stability. At the same time, nanomaterials are the key to significant progress in research on photovoltaics for solar rechargeable cells. Future generations of photovoltaic cells with high energy and photovoltaic efficiency will certainly rely on nanostructured materials.

6. Conclusions

This paper concentrates on a range of current devices with intrinsic solar energy collection, conversion and storage properties, the different classes of cells as well as their application areas and recent research advances. At the same time, nanomaterials are key to making significant progress in the study of photovoltaic electrodes for solar rechargeable cells, and this paper presents seven currently commonly used semiconductor and nanomaterials. Although the fabrication of a low-cost, stable and efficient photovoltaic cell remains a challenge, the projected growth in this field will eventually lead to a viable commercial solution. The rational use of a renewable energy source, solar energy, not only alleviates the fossil fuel crisis, but also the severe environmental pollution and greenhouse effect caused by fossil fuels, which contributes significantly to the sustainable development of human existence.

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