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Review Article about Dye-Sensitized Solar Cells and their Applications

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Annotation: Dye-sensitized solar cells (DSSCs) are low-cost, readily available, and nontoxic photovoltaics based on abundant materials that can be fabricated as thin, lightweight flexible solar panels. When DSSCs are used to harvest indoor lighting, they are efficient in generating the energy required for powering energy-hungry electronic applications such as wireless sensors. Nonetheless, this vast market has remained untapped for decades, replete with opportunities for producing inexpensive indoor solar panels. The review summarizes the DSSC material research trends beyond the most used commercial benchmark TiO2-based architecture and cobalt-based electrolytes. The stars among the newly investigated electrode materials are metal oxide scheduling cation-doped ZnO and SnO2 at the same time, carbon-based dyes, and polymeric redox mediators. Rapid progress has been made with new and optimized materials that increase the photovoltaic performance of DSSC devices. Importantly, these alternative materials provide the foundation for advancing DSSC designs where all component materials are researched and fabricated as a single device structure. First, a window-layer-less competitive photoanode architecture is presented where metal oxide film, counter electrode, and electrolyte are integrated in the same operating procedure. Then, a flat glass substrate with a photoanode film on one side is presented, leading to a transparent, colorless, or colored indoor solar panel without interfaces to shield the following front or back sides.

This review highlights DSSCs as a vibrant and diverse field of research from the perspective of recent material development trends that aim for the mass production of next-generation DSSCs. Attention is directed outward toward accommodating new materials, methods, and architectures for DSSCs. However, a strong foundation is left to work from, covering the state-of-the-art DSSC material choices and suggesting procedures for their implementation in the mass production of next-generation DSSC devices. Many opportunities remain to grow from here and, at the same time, to delve deeper into the materials presented, as many are still far from their maximum potential. Although the rapidly developing polymers and carbon-based materials likely represent the forefront of DSSC research, there should still be surprises and new findings with the well-known and most-studied metal oxide past players. Future discussions on battery and supercapacitor device prototypes containing DSSC are anticipated, as the devices comprise, in essence, a wide redox potential window of adsorbents, and redox mediators investigated as possible new dye-sensitized battery chemistries.

1. Introduction to Dye-Sensitized Solar Cells

Multiple renewable energy sources must be developed to meet rapidly increasing energy demand and human population growth. A fast-growing renewable energy is solar energy, which is an abundant resource available in many countries [1]. There are several fixtures to collect solar energy, among them are photovoltaic devices. One of the third generation of photovoltaic devices is dye-sensitized solar cells (DSSCs), which consist of two electrodes, an oxide-semiconductor mesoporous layer deposited onto fluorine-doped tin oxide glass sensitized by a dye as a photoanode, and platinized fluorine-doped tin oxide glass as a cathode. An electrolyte system is placed between these two electrodes. At the working electrode, the titanium dioxide layer absorbs dye molecules, resulting in a dye-titanium dioxide interface. The dye receives solar radiation during the DSSC operation. The dye excitation leads to the electron transfer from the highest occupied molecular orbital to the lowest unoccupied molecular orbital. Electrons are subsequently injected into the oxide semiconductors conduction band. The conduction band electrons flow to the external circuit through the anode and cathode, changing the state of the redox couple species in the electrolyte from oxidized to reduced. The latter utilizes the dye regeneration by transferring the electron back to the dye. This cycle is repeated until the electricity is gathered from the external circuit. The most assessed performance for the DSSC is the light-to-electricity conversion efficiency or power conversion efficiency. The power conversion efficiency is contributed by the photoanode, counter electrode, electrolyte, and dye employed in the DSSC device [2]. The short circuit current correlates with both the photoanode performance and counter electrode performance. The value of short circuit current can be increased by improving the efficiency of light harvesting, back scattering effect, and electron transport. It is also reported a more complicated titanium dioxide film structure with a multiple layers of systematic addition of smaller titanium dioxide particles in between of the larger mesoporous titanium dioxide films.

2. Fundamental Principles of Dye-Sensitized Solar Cells

A dye-sensitized solar cell (DSSC) is a type of photo-electrochemical cell that converts light energy directly into electric energy. It consists of two electrodes, the transparent conducting oxide electrode and the conducting metal electrode, which are sandwiched in between with an electrolyte. The transparent conducting oxide semiconductor is usually coated with the mesoporous titanium dioxide film, on which the dye is loaded to harvest the solar radiation. An iodine-based or cobalt (Co)-based electrolyte is commonly used and completed with a platinized counter electrode made of the conducting glass. The basic operation principle can be explained using a p-type semiconductor as an example, this involves an oxide semiconductor tin oxide on indium tin oxide glass acting as an electron-collecting counterpart and the ruthenium-based dye absorbed on the surface of TiO2 acting as a light-harvesting chromophore [1].

When irradiated by light, the dye is excited and injects an electron into a higher energy state (conduction band of TiO2). The oxidized dye is regenerated for subsequent absorption and injection while the subsequent hole transfers to the electrolyte to complete the cycle. The energy loss in the overall process includes charge injection from the dye to oxide and the positions of energy levels, and electron transfer from TiO2 to the platinum counter electrode. The different thermodynamic and kinetic energy levels of DSSCs, including recombination, transport, interfacial transfer, and reaction activation barrier, can be used to describe energy loss mechanisms, which is helpful for understanding the fundamental processes involved in DSSCs [2].

The DSSC performance cannot only be described by its traditional equation $P = I \times V$ it is also necessary to consider theoretical thermodynamic limits and two variables involving exergy, distance of the Fermi level from the conduction band, and transport path length, which can account for the performance of DSSCs with different materials. Besides the minimal limit of DSSC efficiency, the relative distance of 0.7 eV between conduction band position and electrolyte level is also derived to quantify the feasibility of oxidizing dye by the electrolyte. The increasing accumulative contributions of Jsc at different spectral ranges in tandem ZnO/Cu2O DSSCs are correlated with the device engineering.

2.1. Working Mechanism

As one of the new generation of photovoltaic systems, dye-sensitized solar cells (DSSCs) have good potential applications in areas such as building integration, and they have been commercialized successfully in Japan. The development of new dyes has been one of the core researches of DSSCs, and several versatile bis- and tris-retro-donors have been reported. Most of the dyes reported so far have an amphiphilic A–π–D1–π–D2–π–A-type structure, where D1 and D2 are two different and modifiable donor moieties. New dyes based on this design have been developed to both improve the adsorption efficiency onto wide band gap metal oxides and achieve a better energy level alignment with the conduction band of TiO2 [3]. In addition, to address issues of low stability and high toxicity of organic solvents, ionic liquids have been introduced, and most of the newly developed dyes are applicable in such solvents. Despite the recent progress with such robust and efficient dyes, most studies reported so far are conducted under standard one sun conditions with ITO/TiO2 substrates. DSSC studies under realistic conditions are still rare but are necessary for energy yield estimations. Recent studies demonstrated that DSSCs can convert light to electric energy even under very low irradiance (0.01 sun) and high light intensity (more than 100 suns) conditions, while maintaining very high efficiencies [2]. In addition, a new solar concentrator structure enables high efficiencies even under high light intensities.

The traditional embodiment of a dye-sensitized solar cell (DSSC) utilizes two transparent conducting oxide (TCO) coated glass electrodes. One of these glass substrates is covered with an interconnected TiO2 particle-based nanocrystalline layer, which serves as a photoelectrode (PE) when sensitized with a dye. A second glass substrate, coated with a catalyst, serves as a counter electrode (CE). During the operation of the cell, charges get exchanged between PE and CE through a liquid electrolyte containing redox mediator. The mediator diffuses in the porous TiO2 electrode and through the liquid electrolyte. Recently, a unique DSSC was reported in which the mesoporous TiO2-based PE and poly(3,4-ethylenedioxythiophene; PEDOT) catalyst-based CE were in physical contact without using any spacer in between them. The fabricated DSSCs did not exhibit electronic shunting after the electrolyte was injected into the cell channel, contributing to the enhancement of their photovoltaic performance.

2.2. Components of Dye-Sensitized Solar Cells

The dye-sensitized solar cell (DSSC) consists of three components, each occupying one part of the building blocks of this work: (1) A nano-structured semiconductor utilizing wide band gap TiO2 to absorb visible light through sensitizer dyes, increasing photoanode current; (2) An electrolyte, composed of a redox couple, utilized in this work as I3−/I−, that contains a hole quenching mechanism; and (3) A nanostructured counter electrode acting as an electrocatalyst for the redox reaction, which takes place in the electrolyte contacting the porous layer [1].

3.1. Photoanode Photoanodes in DSSCs are composed of a nano-structured mesoporous titanium oxide (mp-TiO2) film deposited onto a conductive transparent substrate and sensitized by a dye that absorbs light and injects electrons in the nano-structured TiO2. The dye-sensitized nano-structured semiconductors are fast in generating photoelectrons, but the collection of those photoelectrons is limited by the charge transport in the mesoporous component. For implementing dye-sensitized solar cells (DSSCs) in devices, large area nano-structured semiconductor films are expected. During the large area processing, multiple processing parameters should be simultaneously controlled to obtain good uniformity in the morphologies, dimensions, surfaces, and distributions. Understanding the specific processing steps, including film deposition, sintering, and film treatment that affect the microstructure of films and photoanodes is therefore important for creating uniformly thin and porous solar cell films on large substrates with high efficiencies [2].

3.2. Electrolyte At present, both polyelectrolytes and liquid electrolytes are being investigated. However, systems based on liquid electrolytes that are based on volatile and combustible organic solvents have a tendency to vaporize, drip, and decompose, and short-life cycles. Despite their better performance, it is still preferred to chose solid electrolytes. However, the initial investigation of solid-state systems is promising, and several new materials are being researched. Gels containing polymers and small ionic species are being investigated. Promising results using substituted polyacrylonitrites in which iodine anions are covalently attached to the polymer chain have been reported. It is expected that DYE-SENSITIZED SOLAR CELLS that use gel electrolytes will appear shortly in product form.

3.3. Counter Electrode The top electrode must be transparent, conductive, stable, and amenable to formation as a porous or thin film low enough that it does not block incident light. Platinum

(Pt) fulfills these criteria and has been widely used as a catalyst for several substrates. Nevertheless, it is very expensive. Finding alternative catalysts which are cheap, earth abundant elements and still good for electrocatalytic reduction of I3− is highly desirable. Current counter electrode candidates such as oxides, carbon, conductive polymers and transition metal thiolates suffer because of one of the criteria, leading to selectivity of aqueous or organic electrolyte. [4][5][6]

3. Types of Dyes Used in Solar Cells

Dye is a vital component of solar cells and is responsible for the light absorbing property of the cell. Dyes excite the electrons to a higher energy level when they come in contact with light; these excited electrons ionize from the dye molecule. This ionized dye regains its ground state by injecting the electrons into the CB of oxide semiconductors by the phenomenon of electron transfer. The quality of dyes is an important factor in the performance of such solar cells. Dyes are classified as organic dyes and inorganic dyes. Natural dyes are agro waste products that can be obtained from flowers, leaves, fruits, vegetable peels, and seaweeds. Hence their use in solar cells makes them eco-friendly. Biomaterials offer low-cost devices as fruit and vegetables are abundantly available. Several plants can yield natural dyes which can be utilized in DSSC. The major components that play a vital role in absorbing visible light are anthocyanins, carotenoids, chlorophyll, and tannins. Recent research has shown natural dyes obtained from fruits and flowers are used in solar cell fabrication. Also, some researchers have used tree bark powder and colored spices to fabricate solar cells. Natural dyes are abundant and are cheap and biodegradable [7].

Dye-sensitized Solar Cells (DSSCs) consist of dye, a TiO2 layer, a counter electrode, and an electrolyte. Research and exploration for the new and improved DSSC material are on-going. Among the materials used in DSSCs, dyes are very important because they play a role in absorbing sunlight and inject electrons into the conduction band of TiO2, ZnO, or SnO2, which are also used in DSSC solar cells. There are also researchers working to find other sources for dyes such as rare red fungus and carminic acid [1]. Fishing and seafood consumption produces abundant waste shells which are poorly used. Seafood waste contains substances with important function food supplements and bioactive materials. It was reported shrimp shells contain water-soluble shrimp carotenoid astaxanthin. It known that carotenoid affects effectively absorbed sunlight in DSSCs. Low cost and abundant alternative materials for DSSCs are valuable to be studied. In this work, tin shells were used as the source to extract carotenoid for DSSCs. The extraction result was characterized by UV-Vis spectrophotometer, which absorb light in visible region from 400 to 500 nm. This extraction was applied as natural dyes for DSSC by embedding in TiO2 film. DSSCs employing tin shells-extracted-carotenoid dye exhibit 0.3% efficiency (fill factor 67.9%, short-circuit current 0.0036 A/cm^2, open-circuit voltage 0.96V), better than absent dye DSSC. Despite of nanocrystalline TiO2 film degradation, the extraction result dye maintain good and renewability on TTC. [8][9][10]

3.1. Natural Dyes

Natural pigments for DSSCs have garnered attention due to their abundance and biodegradability. However, low energy conversion efficiency and poor attachment of pigments to mesoporous substrates have hampered their development. DSSCs have emerged as a promising alternative energy harvesting technology for the next generation due to their low fabrication cost and enhanced flexibility. DSSCs consist of a dye, a broad-band light-absorber, a counter-electrode, and an electrolyte vehicle. While recent research has improved performance by incorporating nano- or micro-scale materials, concerns about high fabrication cost and long-term reliability remain. There is great interest worldwide in the use of low-cost natural resources for sustainable energy. Natural dye pigments, such as chlorophylls, anthocyanins, and carotenoids, extracted from plants, vegetables, roots, and fungi, are abundant, non-toxic, and biodegradable. They are effective sensitizers for DSSC applications.

Plant pigments are complex molecules that can be classified into several categories based on their structure and solubility. Carotenoids, even in low amounts, can efficiently absorb and transfer energy to chlorophyll in the antenna complex. Phenols with high conjugation, such as anthocyanins and flavonoids, also strongly absorb visible light and can efficiently inject electrons into metal oxides. Anthocyanins obtained from grapes, blackberries, and elderberries were intensively studied as cheap organic sensitizers for DSSCs. They have a broad absorption spectrum from UV to visible range. Natural dyes extracted from various plants have been reported through preservation of oxidation and fermentation processes without using chemical fixation.

The use of dye-sensitized solar cells (DSSCs) has received major attention in recent years due to their ease of fabrication, low cost of production, and high efficiency. Natural dyes from eco-friendly sources have been explored as sensitizers for DSSCs, because they offer several advantages, such as low cost, environmental friendliness, and simple extraction process. Pigments like chlorophylls, carotenoids, bacteriochlorophyll, anthocyanins, and other dyes are good candidates for photosensitizers. Among natural dyes, chlorophylls have shown relatively higher performance and have been extracted from various green plants and organisms.

3.2. Synthetic Dyes

Dye-sensitized solar cells (DSSCs) are a novel class of photovoltaic devices, which transform solar energy into electrical energy through a set of chemical and physical processes, and that offer advantages like low cost, easy fabrication, high efficiency, and a wider choice of materials compared to silicon technology. They have widely been thought as one of the most promising alternatives for active materials, having properties like high optical absorption, probable location in the redox electrolyte solvent, and simple-structure. In DSSCs, when irreplaceable light is absorbed by organic dye, the dye injects an electron into the conduction band of TiO2, ZnO, or SnO2, which are also used in DSSC solar cells. Due to the wide band make, these semiconductors can be easily excited in the UV-visible region and have an excellent charge transfer property. Benzothiadiazole-based solar cells have of a lighter atom, and high performance has recently been noticed.

Copolymers with a TiO2 acceptor, benzoic acid and aromatic rings-carrying moieties are readily developed to absorb the solar spectrum. Numerous reports have emerged over the past two decades on organic compounds used in dye-sensitized solar cells. Successful strategies include polymeration strategies, selective passivation, elongation of conjugation distance, copolymerization, and legoring of active sites to retard recombination loss [3]. Mostly, the acceptor moiety of polymerized compounds contains benzoic acid in DSSCs. In DSSCs, the polymer without a thiophene bridge is poorly electropolymerized, both the oxidation potential and formal potential are reduced by the incorporation of benzoic acid. Its high activity shows the stability of the PV of thermal up to 100 degrees C, while a marked drop for the unencapsulated device is seen. The advantage of the stable dye is due to the increased electrolytic with time constant and efficient efficacy or dye immobilization on TiO2. To identify comparable single ligands, n-dodecane-phthalic acid is discovered for much faster electron transfer rate constant and charge-collection efficiency at a sub-100 degree C temperature [7].

3.3. Metal Complex Dyes

Metal complex dyes such as ruthenium and cobalt complexes have been considered promising and practical molecular absorbers for underwater solar harvesting, due to their specifically designed reduced rigidity, symmetric axial ligands, and stringent ancillary bidentate coordination [11]. Noble metal-based dyes have been in the forefront of the development of DSSCs. The potential of Ru-based antenna complex dyes has been demonstrated particularly in the form of dyes tethered to metal oxides with discrete porous structures. Although Molecular Engineering of Ru(II) complex dyes provides a unique platform, which extends from the choice of ligands to co-adsorbates and intricate metal oxide surface modification. Co(II/III) redox couples have been considered a suitable alternative to I−/I3− couples. D-π-A types optically-indistinguishable porphyrins have been prepared to function as a metal complex dye. Bismuth-sensitized DSSC shows great potential for enhanced stability due to the lower polarity of the interplay dye-bismuth oxide. As reported, both the photophysics and the synthetic parameters of coumarin derivatives can be tuned, suggesting the rich potential of this class of dyes. A novel multi-energy-level Metal Complex Dye (MCD) based on [Ru(bpy)]2+ complexes develops a broad absorption range from UV-vis to NIR region (200–900 nm). These noble metal-based dyes are intrinsically inexpensive and effectively tunable fluorescing dyes.

A model for the dye-sensitized solar cell (DSSC) based on d6 metal complex dyes, taking advantage of the large redox potential of the central metal ion, has been developed. The departure from initially degenerate energy levels leads to energy states distributed over a broad band width, both with a diameter around nanometers or larger. Self-assembled monolayers are expected to control the distance between the dye layer(s) and the TiO2 surface to improve the rate of charge injection and retard the rate of recombination. Calculation exercise shows practical MCDs are very effective in this process [12]. The subclassed models serve as a basic step to explore large functionalized metal complex dyes. New pathways free from the reorganization energy penalty of d6 metal complex dyes are expected to be developed through exploring metal complexes of d0, d9 and d10 electronic configurations applied at DSSCs.

4. Fabrication Techniques

Although solid-state solar cells, organic photovoltaics, and perovskite solar cells have been extensively studied, dye-sensitized solar cells (DSSCs) have shown promise as economically feasible solar energy conversion devices. DSSCs consist of a system arranged in a sandwich structure. The transparent conductive oxide-coat (TCO) electrode, which carries out the first reaction of the solar energy to current conversion chain, exhibits nanocrystalline TiO2 (NCT) photoanode, dye, a hole-conducting liquid electrolyte, and a platinized TCO counter-electrode. DSSCs can be manufactured by a combination of screen printing, ink-jet printing, and doctor blading methods. While the TiO2 photoanode and counter electrode are ameliorated through physical means, the interpenetrating TiO2/dye-based actinic layer is amphiphilically modified using a novel chemical method to allow compatibility with the hole-conducting electrolyte. An alternative configuration for DSSCs based on colorless TiO2 nanotube arrays, which are prepared and butt-joined properly, is also presented. The final device is a sandwich structure comprising a blue TiO2 nanotube-based photoanode and a platinized TCO counter-electrode arranged perpendicular to the incident sunlight. This structure allows the device to be mounted in a landscape manner.

1B Declarations: A series of mechanical grinding and uniaxially pressed regions are dipped in the etching solution for 5min. Small colorless particles that are uncontaminated and have a diameter of about 20 nm are selected for the experiment. A fused silica-fluorine doped tin oxide glass is placed on the surface of these regions, forming a sandwich structure without any gaps. Circular patterns on the sandwich structure are recorded using a motorized stage, and a TiO2/sample pattern is printed and treated with each washing solution. After washing, the sample is examined using a monochrome charge-coupled device camera to obtain a picture of the printed patterns at each wavelength. The fluorescence of the printed in nanocrystalline DSSC tint is examined.

4.1. Screen Printing

For the TiO2 deposit on TCO glass, a commercial TiO2 paste was thinned with 10% volume of deionised water to allow for a higher resolution printing without adversely affecting the film thickness. The screen-printed film was dried in air overnight and then sintered on hot plates at 400 °C for 30 min, after which a TiCl4 treatment was applied followed by a sintering at 450 °C for 30 min. Commercially available Nanostructured TiO2 film on TCO glass was available and molten TiO2 paste was pressed. Film formation and morphology printing on flat surfaces was carried out using screens manufactured using an otto mesh. A 150 B (150 mm), 70 HD (70 mm), and 40 S (40 mm) frame were used to produce 25, 40x40, and 60 mm square devices respectively. Equipment setup was used for all foil-based screen printing notcher parts. In addition to the flat screen printing experiments, treatments were also conducted using a curved squeegee with a radius of curvature = 80 mm. Similarly stillable and tacky films were desired for all printing processes except for the immersion printing of a UV glue bond. A multi-treatment approach resulted in the best compromise: coating the screen with acrylic co-polymer for printing and foil on the support side, whilst also employing blend-treated polyester felts to provide a good grip and containment during setting. Device-type foil screen printed on a paste.

Devices were designed on TCO-SiO2 with a planar configuration and included standard discrete test windows prepared disc-type scribe and then peeled back (Test window thickness = 0.18 mm) 0.08 mm for sealants and frame. They were integrated as described above. Only single screen-printed TiO2 films were examined in all devices. All foils were screen printed with the paste in flat mode settings, featuring a formulation thinning of 20% volume and sintered to 400 °C for 30 min. All were kept within standard atmospheric limits prior to use. The foregoing preparations should now achieve TiO2 films with relatively similar surface morphology and light scattering opportunities to co-develop high-throughput screen printing with ink and pixel-processing tool chains in large-area photovoltaic development. High aspect ratio filaments of screen-printed TiO2 flakes and the successful co-development of printed DSSCs and other devices have also become a strong attraction. Screen-printed DSSCs generate improved performance characteristics from rapid in-situ annealing and a long line width aperture mask in air, paste behaved typical rheological behaviors when compatibility and spoon scraped. [13][14][15]

4.2. Doctor Blade Coating

Each layer of the TiO2 used in the cell development was coated using the Doctor Blade method. The Doctor Blade consists of a stainless-steel rectangular plate with a few millimeter side length and a spring-loaded adjustable plate. Conductive commercial glass (FTO) substrate slides under the blade and consequently a uniform TiO2 layer is formed after the stationary layer is dried in an oven for a few hours [16]. The thickness of the TiO2 layer could be controlled by the distance between the two plates and the kind of the slurry used during the coating. The usage of this method dramatically increases the cell performance due to the better connectivity and a more uniform layer.

The prepared TiO2 solid with the required composition was mixed with water and the ball-milling process was started. Eight 1.6 mm diameter balls were loaded into a 50 mL ball-milling jar along with a 10 mL suspension containing 20.0 g of TiO2 solid and 25.0 g of water. The suspension was allowed to mix in a tumbler mixer at approximately 60 rpm for 24 h. The mixture was kept at 4 oC until the binder application by Doctor Blade on the conductive glass substrates. The coated substrate with the TiO2 paste dried overnight at room temperature, and then the film was sintered at 500 °C for 30 min before the TiO2 sol application.

The application of the TiO2 nanoparticle sol was performed by doctor blade separately. The sieve version of the TiO2 sol was applied on top of the TiO2 paste coating in the same manner at ambient conditions. After doctor blade coating, each substrate was dried on a hot plate at 70 °C. The thickness of the sol film was carefully optimized to adjust the nanoparticle layer thickness from a few hundred nanometers. To ensure the optimal device fabrication conditions the microscope glass slides were coated with different thicknesses and sintered at 500 °C for 30 min separately. The prepared samples were then immersed in a 0.35 mM TiCl4 aqueous solution at 70 °C for 30 min. Repeated cycle of coating sols and using the TiCl4 treatment was performed to enhance the cell efficiency [17].

4.3. Electrospinning

Due to the straightforward manufacturing process and low cost of production, dye-sensitized solar cells (DSSCs) have gained popularity in both academia and industry. Nonetheless, due to high costs, well-studied processes are essential for the preparation of alternative counter electrodes. A method for the production of materials via electrospinning is present. Due to its simplicity and low cost, this process is very appealing for the generation of DSSC and similar applications. The most important aspects of electrospinning, such as electrospinning principles, polymer selection, and application-specific optimization of fiber mats, are summarized. Concerning recent research works in energy storage and conversion devices, such as supercapacitors and DSSCs, results of the highly scalable production of electrospun carbon-based fiber webs for possible applications are shown.

Many conductively doped and undoped nanofibrous carbon materials were electrospun, showing good energy storage properties in a supercapacitor and promising performance as counter electrodes in dye-sensitized solar cells (DSSCs). The key points of electrospinning as a simple, low-cost, and scalable method suitable for application-specific nanofiber mat production were highlighted. DSSCs with electrospun nanofiber mat-based counter electrodes with tunable properties were envisaged. The goal is to provide a detailed overview of the electrospinning process. Several critical factors for DSSC design are presented as well, which can influence its overall efficiency.

DSSCs have been studied intensively over the last few decades. As a result of its low price, simple preparation, and easy-upscaling, it is a promising technology [18]. The principles, the importance of light harvesting photosensitizers, charge transport mediators, semiconductor and dye selection, electrochemical deposition of Pt, and formability and stability of the counter electrode are discussed. DSSCs are promising renewable energy sources with several advantages.

5. Performance Metrics of Dye-Sensitized Solar Cells

Photovoltaic devices have gained great attention in recent years. Their most well-known example is silicon-based solar cells, but studies on other photovoltaic technologies have rapidly advanced in order to surpass the limitations and discover new ways of producing electricity [2]. Dye-sensitized solar cells (DSSCs) are an attractive photovoltaic technology, mainly due to their inexpensive and abundant materials, simple fabrication, and versatility in adjusting their optical and electronic properties. They also have the ability to be fabricated as thin and light-weight flexible solar panels. Because of these properties, DSSCs are especially suited for producing low-cost indoor solar panels which can harvest indoor lighting. In order to commercialize this technology, cell manufacturing methods must be scaled to industrial production with high cell efficiency and long-term durability. With this point of view in mind, it was eagerly anticipated that several researchers in this field could introduce important progress regarding new and optimized materials and other ways of increasing the photovoltaic performance of DSSCs.

DSSCs consist of a wide band gap semiconductor, a dye that absorbs the visible light, a liquid or solid electrolyte, and a transparent conducting glass substrate. Upon excitation, the dye injects electrons to the conduction band of the semiconductor, which is collected by the glass. These electrons diffuse through the nanoparticles of the semiconductor and eventually flow to the external load. A redox mediator oxidizes the dye and transfers the holes back to the dye, completing the cycle. Dye molecules are decorated on the semiconductor surface, which increases the absorption area. Various commercial dyes and materials have been studied to replace the components of DSSCs, ranging from different materials to different designs and mechanisms altogether. This article summarizes the most recent advances in DSSCs with these alternative materials and designs.

5.1. Efficiency

The performance of DSSC cells depends on the efficiency of the individual components, that is, the dye, the semiconductor, and the electrolyte. Parameters that may be modified to enhance performance include: the active layer thickness, the dye concentration, the concentration of HI/I- ions, the temperature, the addition of redox mediator, the use of co-sensitizer, and so on. The advantages of using mesoporous TiO2 over the conventional art of colossal rutile TiO2 is that it has a large surface area to volume ratio and a short diffusion length to trap the charge carriers [2]. Besides the dye structure, its aggregate state is important for optimal efficiency of the DSSC. This can be achieved through ligand exchange. Ligands protect dye molecules from aggregation in solution, which should be avoided because aggregation has been demonstrated to result in a blueshift and broadening of the absorption spectrum, which contests light-harvesting efficiency. Putative DSSCs can also be created by using other types of dyes such as porphyrins or phosphonated dyes, and ionic liquid may be used as a redox couple instead of the conventional HI/I- [19].

5.2. Stability

With the rapid advancement and commercial scaling of dye-sensitized solar cells (DSSCs), it is essential to understand their intrinsic material and optical properties to make reliable policy recommendations. A review on the material properties controlling the DSSC performance is provided first. Then, the most commonly used simulation frameworks and methods to compute the optical properties of DSSC thin films, with a focus on available numerical tools and models, is presented. The optical behavior of DSSCs is important not only to understand and interpret experimental results but also to engage in optoelectronic design to achieve higher efficiency cells [2]. Thus, numerical models of the optical properties of DSSCs are crucial for the advancement of this solar cell technology, and should thus be a field of growing interest within the scientific community.

For commercial success, DSSCs must offer long-term stability. The rapid influx of tin oxide-based photoanodes in recent years has driven the expansion of fabrication methods, but these photoanodes require careful stabilization to maintain efficiency and prevent degradation of the device stack. In this perspective, a holistic overview of the degradation modes of DSSCs is provided. Focus is placed on the recent advances in non-toxic, low-cost, and relatively new materials that may help mitigate the two main issues of storage stability and long-term device stability [20]. It is emphasized that while many of these materials are already known and have been studied in prior work for DSSCs, their implementation in commercial devices or potential to address large-scale manufacture and stability concerns has only recently begun to be explored. A call is made for research on addressing several remaining challenges, while collecting publicly available data to gain insight into the most promising materials presently available.

5.3. Cost-effectiveness

Dye-sensitized solar cells (DSSCs), as an emerging low-cost photovoltaic technology, have attracted considerable attention. The first DSSC exhibits high energy conversion efficiency and has become one of the most promising photoelectrochemical energy conversion technologies. Over the past two decades, nearly 5000 research articles have been published on DSSCs, including extensive efforts from fundamental chemistry to large-scale real applications. Applications in photoelectrochemical water splitting using DSSC electrodes and DSSC modules have been developed, but much work remains to be done. A fairly well-structured DSSC can now yield good energy conversion efficiency. However, issues with long-term stability, large-area scale-up designs, encapsulation technologies, and safety remain. These perspectives are, therefore, gratefully presented.

Due to the rapidly advancing organic chemical technologies, the materials composition of DSSCs can be prepared more easily, resulting in a great variety of system chemistry research. The improvement in understanding the evaporated materials has begun to yield DSSCs with greater thermal stability. The energy level alignment and film morphology of the organic materials have also been well studied. Attention should be paid to understanding the growth mechanism of the organic semiconductor in the evaporation process, even at the log scale.

Recent reports revealed that the fabrication of organic semiconductors with clustered morphologies can significantly enhance the gas barrier property of the film by reducing the permeation paths of gas molecules. The understanding of organics can help fabricate mechanically durable cells when such materials are used as protectors on top of p-block DSSCs.

The rapid progress in DSSC research would stimulate extensive further investigation into various new systems. Some should be given priority, especially those regarding exploring, designing, and testing novel sensitizers with low-cost, good absorption properties and high quantum efficiency, as well as semiconductor materials and fabrication methods that are inexpensive and can easily produce DSSCs on thin, flexible conductive substrates. Exploring new nanostructured, mesoporous, or thin-film semiconductors, fabricating cells with a film step of 5 µm or less, and DSSC module assembly with printed front and back contacts should be grand engineering challenges toward successful commercialization.

6. Applications of Dye-Sensitized Solar Cells

Dye-sensitized solar cells (DSSCs) have been one of the most widely investigated photovoltaic devices that can convert solar energy into electricity. They have several attractive features such as inexpensive, non-toxic, abundant materials, fabrication in a simple manner and have a semi-transparent nature, large area, light-weight, portable, and flexible potential applications in everyday usage solar cells. Electronics using the energy generated by DSSC can be utilized for powering wearables, wireless sensors, smart dust, RFID tags, videogames, indoor solar panels, and microcontrollers. DSSCs have wide-spread research interest in fabricating various materials for addressing above applications. The lower cost than their modern commercial counterparts and compatibility to design for specific tasks are the attractive features of DSSC devices. In this work, being able to temporarily harvest and deliver the energy required for electronic applications, DSSC devices have been viewed as energy harvesting devices. Several use-case examples such as DSSCs powering an arm, operated Wi-Fi information remote delivered on an LCD screen and prototype wearables have been explored. DIY-style fabrication methods based on cost-effective and naturally occurring materials such as fruit juices and flower petals have been demonstrated.

Widespread commercial applications of DSSCs have not yet become possible despite compelling reasons to do so. This is primarily due to their lack of long-term stability in environmental conditions due to the dyes made of ruthenium complex in use and the liquid organic electrolyte. Recent successful advancements in solar panel and LED technologies have also opened new fronts in energy harvesting in spaces such as homes, buildings, and outdoor applications. As a consequence, competition for DSSCs has increased significantly. Rapid research and development activities from many research labs and commercial players may soon start pivoting DSSC technology towards a sustainable and vibrant path. New and optimized materials, ultimately increasing the photovoltaic performance of the devices, many of them to replace ruthenium and ionic liquid systems, have been reported. DSSC design architecture, fabrication techniques, and smart device integration platforms using inexpensive and widely accessible materials, tools, and methods, have also been investigated. Alternative materials explored in the work can offer new possibilities for fabricating advanced DSSC designs such as mechanically contacted liquid junction or solvent-free solid-state zombie DSSCs which are impervious to environmental conditions and can provide enabling platforms for portable electronics including wearables. Existing processes capable of fabricating solid-state DSSC architecture with the suggested process flow on single substrates with printed dyes may further increase the robustness of DSSC devices under natural and simulated environmental conditions and provide new opportunities for assimilating DSSC devices into IoT ecosystems including energy aware microcontrollers, wireless sensors, and smart dust [2].

6.1. Building-Integrated Photovoltaics

Several commercial solar cells on the market offer a conversion efficiency (η) between 20% and

30%. Yet, these highest-performing solar cells are made of expensive, pure, and rare materials. More importantly, the high-temperature fabrication and essential components of such cells do not provide the integrity and versatility necessary for specific applications. For instance, these highest-performing commercial solar cells can be contrasted with dye-sensitized solar cells (DSSCs), which can achieve η values of over 13% [2]. A DSSC is fabricated using versatile, cheap, abundant, and widely available organic, inorganic, and metallorganic materials. Each component of the DSSC can be fabricated at room temperature, which enables the use of low-cost and commercially available plastics, metals, and glasses, thus creating versatile, thin, small, cheap, light, and flexible solar panels. Because of the transparent glass and thin film stacks, DSSCs harvest sunlight in specific wavelengths (usually ~400−600 nm) nearby the band gap and can also harvest the invisible light in the UV-visible and TV ranges. Unlike their opaque counterparts, DSSCs do not block viewing through a window or building façade, which consequently combines advantages of building-integrated photovoltaics (BIPVs) and solar energy generation.

The market for photovoltaic devices accounts for nearly 1% of the total energy consumption. This percent share is small, but its wide area usage to energy generation in terrestrial buildings raises an enormous area; this is higher than in all other renewable energy devices combined. Building-integrated photovoltaics and power-generating windows account for a sizable part of this market. In searching for new technologies to harvest electric energy from the building façade and current windows, solid-state dye-sensitized solar cells (ssDSSCs) emerge as a promising candidate with clear advantages over their traditional counterparts. BIPVs and power-generating windows from DSSCs have been developed all the way from laboratory cells to commercial prototypes, successfully tested on various architectural solutions, deployed in extreme environmental exposure tests, integrated with building façades and current windows, and certified for replacement of BIPVs and tested for national building codes.

6.2. Portable Power Sources

Dye-sensitized solar cells (DSSCs) composed of inexpensive and abundant materials are an efficient new route to generating the energy required for a diverse array of electronic applications such as wireless, chemical, biomedical, and environmental sensors, smart textiles and glasses, packaging of perishable goods, communications, and stubbornly ubiquitous internet-of-things devices. However, the suitable electronic applications for DSSCs have primarily been restricted to those domains requiring comparatively low power output devices. This has mainly been due, on the one hand, to the low photovoltaic conversion efficiency of DSSC technologies thus far, which has discouraged efforts to fabricate them as thin and light-weight flexible solar panels for producing low-cost indoor solar panels, as they are logistically less suited for household rooftop or building-integrated photovoltaic applications. On the other hand, the absence of a complete process flow that could take DSSC technology from printable screening ink to finished device laminated on a substrate to be incorporated as a power source directly into consumer products has long impeded progress towards advancing the technology outside of conventional laboratory settings. This review has described the aforementioned two aspects of DSSC technology, firstly providing a comprehensive overview of the fundamental design criteria for producing indoor-friendly DSSC materials, optically scalable designs, and functional aspects desirable in DSSCs destined for portable power sources in consumer-grade electronic products. In the light of this description, many recent research trends that have made substantial progress towards fulfilling these criteria were highlighted, giving examples of new and optimized materials, structures, and designs that have shown significant increases in the photovoltaic performance of these devices.

Additionally, since the landscape for DSSC materials is quite broad, only a handful of noteworthy individual and otherwise noteworthy groups of materials, geometries, and related production methods were described here, while more exhaustive coverage can be found in many other recent reviews. Previously without a clear complete device process flow that could be enacted entirely in printable formulations, it was feared by some that continuous progress in DSSCs could never be realized outside of tedious laboratory settings involving exuberantly expensive and complex industrial-scale manufacturing facilities. Instead, a less extravagant solution with a more economical approach to producing complete advanced DSSC device structures that could sufficiently mitigate all of the manufacturing hurdles facing DSSCs today was described. It was hoped that this suggested process flow on a single substrate would influence the outlook of DSSC technology otherwise so promising and the overall costs of its production. Finally, consideration was given to an entirely solid-state DSSC architecture and the suggested process flow on single substrates that could increase the robustness of DSSCs while providing an entirely new avenue for capitalizing on advanced DSSC designs fabricated for portable electronics and internet-of-things devices. Therefore, various paths forward for rapid research and development of ESSCs were outlined, emphasizing the compatibility of elements of the suggested fabrication setup for the aforementioned avenues of advanced device structures specifically. Overall, it is hoped that individual research efforts and advances in tandem with newly established fabrication facilities for DSSCs may accelerate the spread of this inherently low-cost alternative photovoltaic technology at an equally affordable cost.

6.3. Solar-Powered Devices

Dye-sensitized solar cells (DSSCs) have succeeded in producing enough energy with an output voltage high enough to power many electronic applications such as wireless sensors. These devices could harvest indoor lighting that the physical housing of the device itself could block visible light from getting to a conventional silicon-based solar cell. However, indoor light has greatly reduced levels of intensity in terms of both irradiance and luminous efficacy [2]. The materials of DSSCs are inexpensive and abundant, such as the TiO2 semiconductor, the polymer electrolyte, and the platinum counter electrode. They are also thin and light-weight flexible solar panels that could be fabricated on fabrics or roll-to-roll processed. All of this made the fabrication of low-cost indoor solar panels well suited to meet the requirements. The most common forms of DSSC research today are the traditional DSSCs using a liquid electrolyte and counter electrode, amphiphilic dyes that could harvest both visible and UV light, new modes of cell structures such as see-through based on TCO-glass and/or TCO-pET foil, novel semiconductor nanostructures to increase light scattering and absorption, and counter electrode catalysts that would match the electrolytes other than iodine (I−/I3−). From a large number of publications and patents, research trends related to the production of the next-generation DSSCs were analyzed from the perspectives of how they converted between photo-energy and electrical energy or how they would harvest solar energy [1]. It has been shown that important progress has been made with new and optimized materials, ultimately increasing the photovoltaic performance of these photovoltaic devices. Moreover, various alternative materials are available to build devices with different structures. The understanding of the device fabrication procedures would provide new possibilities for fabricating advanced DSSC designs. This review categorizes the recent research trends into two areas: the improvement of the photo-to-electric energy converting function as the photochemical part at the energy transducer and the improvement and sustainability of the light-harvesting function on the device structure and material as an engineering part.

7. Environmental Impact of Dye-Sensitized Solar Cells

The potential and promise of DSSCs have gained attention because they can be made from non-toxic materials. Compared to state-of-the-art silicon-based photovoltaics, the DSSC production process is much less energy-consuming. DSSCs can be used in low light intensity areas with no sun and cloudy weather. They are easy to manufacture and insensitive to impurities. Large-scale manufacturing of DSSCs should be possible, and particularly in rural areas, DSSCs can be manufactured by semi-skilled laborers. Areas with little manual labor should have easy access to large-scale manufacturing of DSSCs. Although DSSCs have great potential, this growing technology is as yet not ready for mass production. The further development of DSSC efficiency and long-term stability is a prerequisite for industrial scale-up and in the near future, the DSSC market will be served mostly by a large number of small companies. Based on reports for DSSC efficiencies approaching 15-20%, the industrially produced power conversion efficiency of DSSCs using colorless glass should be able to approach 60-80 cents/Wp [21]. In contrast, mass-production costs for silicon-based PV would be significantly lower [1]. The estimated market price for silicon-based inexpensive and already proven panel designs would be below 5 cents/kWh in the upcoming years. The maximum market share for DSSCs is projected to be 5-10% depending on optimal and minimum estimates, while the total market volume is expected to be between 8 and 26 billion USD in 2030. This suggests that DSSCs have large industrial interests and great commercial potential. However, the efficiency-price ratio needs to be further improved. More daylight hours with lower solar radiation span in winter and at lower latitudes in the evenings. DSSCs with an opaque common glass substrate can be transparent in the visible spectral range and colorless and therefore versatile and unique.

7.1. Sustainability Considerations

Dye sensitized solar cells (DSSCs) are semiconductor devices made of nanostructured TiO2 and dye molecules that are deposited on glass substrates in order to harvest light energy. These cells are the simplest outside of the organic practical implementations of organic photonics and electricity conversion. DSSCs have gained attention due to their abundance of low-cost and sustainable materials. Unlike the single crystal and polycrystalline Si, III-V and CIGS cells, DSSC materials are generally abundant, low-cost, and can be fabricated in a variety of ways. In many cases, the materials used in DSSCs can be fabricated using abundant materials. In addition, DSSCs are treated as nanostructured semiconductors, and have similar scalability as inorganic semiconductor nanostructures, polymer-nanocrystalline silicon-light emitting diode (LED) devices and white-light-emitting diodes (w-LEDs) [2]. DSSCs do not require vacuum conditions for fabrication, and all processes occur in ambient conditions. DSSC fabrication can be achieved using roll-to-roll processes. Furthermore, with appropriate co-factors, a DSSC can act in reverse mode, that is, converting light energy to chemical redox energy, which is a fundamental requirement for use in artificial photosynthesis and/or renewable fuel generation devices.

DSSCs have a higher visible light absorption coefficient than single crystal and polycrystalline Si. DSSCs can use a large variety of photoactive dyes, and this is exploited in using ultra-thin TiO2 films to fabricate indoor DSSCs. Additionally, DSSCs can be applied in both optical communication (encoding a signal in light and decoding it) and standalone solar energy utilization (indoor or outdoor) [19]. The unique all-dye property of DSSCs makes them attractive candidates for applications in light-field cameras and lenticular displays. Their low cost and abundance of materials enables their feasibility in mass production. The low upfront cost of DSSCs also reduces the financial loss in case of fab closure, enabling the possibility to allocate excess fabrication capacity to competitors instead of making the workforce unemployed. Comprehensive details on the principles, material components, applications and post-fabrication processes of DSSCs are discussed.

7.2. Recycling and End-of-Life Management

The upturn towards sustainability has stirred questions regarding how to handle the eventual disposal of cell phones, computers, and other electronic devices. This in turn raises questions about the end-of-life management of the materials used in these devices. Presently, the recycling of silicon-based solar cells is difficult and expensive. An alternative design that could be considered is dye-sensitized solar cells (DSSCs). These devices are showing potential to create energy from indoor light or at night with the use of bio-inspired upconverters. However, as with all devices, aged DSSCs should not enter the waste stream. Although both DSSCs and their waste materials are currently not in the market in high enough volumes that end-of-life disposal is a problem, DSSC technology is approaching that crucial point [2]. The need for recycling and end-of-life management of DSSCs has been recognized and is already under research and investigation, the depth of which is discussed in this chapter.

Dye-sensitized solar cells have been considered as a low-resource and non-toxic alternative to conventional silicon photovoltaics. Their waste materials are glass, polyethylene, and titanium dioxide. A sensitivity analysis was conducted to gain insight regarding the required minimum recycling rate for DSSC materials and a break-even point was found. The melting point of the module glass was identified as crucial for the recovery of the materials. Previous investigations that suggested using the module glass as a pigment in the paint industry were refuted. DSSC having opaque polymer front sides without a gelled semiconductor would escape reuse must be used. Although no recycling process for DSSCs exists today, opportunities for design-for-recycling exist regarding the introduction of roller coated semiconductors [21]. Solar energy is the best and practically only ocean-dumping candidate considering large-scale operations when their service time runs out. For application in enclosed spaces, DSSCs and other devices will work well for 5 to at most 20 years when limited to outside illumination. But despite this, it must be noted that possible reasons for taking an out-of-service device out of the waste stream include repainting, sticker-changes, and second-hand products. [22][23]

8. Challenges and Limitations

Though the dye-sensitized solar cell concept is already a mature technology exhibiting superior advantages, there remain a number of issues to be solved in order to satisfy the requirements of operating devices. The well-established properties of metallic oxidation/ reduction couples such as I3−/I− should aim to be replaced while retaining the advantages of low-cost PCE and abundant supply. To satisfy the requirements of operating devices post industry market usage, new electron shuttle systems seem thus necessary. Indeed, redox systems able to accommodate higher voltages than those generally afforded by I3−/I− have recently been developed, such as methoxycarbonimidothioic acid or metals in a viscous or gel state. Inorganic-based coupling species such as Br2/Br− or tetranuclear copper systems have even been proposed as counterparts. Porphyrin self-assembled monolayers ensuring the localized coordination of Co3+ ions close to the oxidative dye appear as an interesting and simple solution. Work is currently in progress to gain insight into mobility issues of each of these new shuttles taking advantage of the enormous experience gained in this field over the years. In order to compete with thin-Film photovoltaic counterparts, DSSC architectures will also have to evolve. The thylosilicate binders already used for TiO2 scaffolds can prove efficient in combating the cracking of each of the layers used. Their possible implementation in mesoporous layers appears alluring as it will lead to the ready adaptation of alternative porous networks. Other more complex systems involving polymer or polymer-like materials acting as either additives or surfactants would be even more appealing. Indeed, such implementation will drastically reduce the amount of unused materials, and a huge arsenal of pre-existing chemical building blocks could be implemented on the well-established DSSC architecture. Lastly, to avoid disastrous stacking issues, both counter and working electrodes should be coaxed to grow a few nanometer thick layers that would eliminate potential delocalization issues while hurrying their electrochemical cycle rate ([2], [3]).

8.1. Material Degradation

Assessing the durability and stability of Dye-Sensitized Solar Cells (DSSCs) is crucial for determining their suitability for various applications. The adverse external conditions that can degrade DSSCs during operation include high humidity, high temperature, UV radiation, and mechanical stress. Similarly to other thin-film solar cells, all DSSC components are prone to degradation. For instance, with p-type semiconductors, corrosion of the porous semiconductor layer can occur. To ensure proper operation of commercial DSSCs, critical international standards can be introduced for testing products before market approval. For each component, test specifications, and testing setups can be dictated. With increasing competitions between ICCs in the market, thoroughly investigating durability, stability, and lifecycle tests will become an important trend for researchers and enterprises alike. The gradual demise of chloroplast in natural plants, 3D scanners, and the increasing sustainability of DSSCs developed by researchers are all good examples of future research directions. The upcoming 10-year sustainability and availability of DSSCs could create new opportunities to push for further improvements in photovoltaic performance and new devices in the next decade [2].

DSSCs are efficient, cheap, and abundant energy providers for innovative electronic applications such as wireless sensors. The transparent substrates, novel high surface-area mesoporous and low-cost TiO2 scaffolds, various and more efficient sensitizers, low-cost and reusable platinum catalysts, fruit juices, and cobalt and once-cocked-cooperation conjugate gel with viscous ionic liquid electrolytes are all good candidates to fabricate economical DSC. Also, industrially scalable printing techniques dedicated to low-cost, thin, lightweight flexible all-solid-state DSCs such as screen printing, ink-jet printing, and roll-to-roll coating are presently available.

8.2. Temperature Sensitivity

As demonstrated, DSSCs are sensitive to temperature. Therefore, we suggest that further work be performed to determine the ability of DSSCs to operate under these conditions and to investigate the electrical performance and stability of these devices after prolonged operation at high temperatures. With the current awareness of climate change, rising sea levels, and adverse weather conditions associated with changing global climates, we suspect that it is only a matter of time before solar panel operation in high-temperature conditions becomes important. Reports on high-temperature operation of screen-printed PV devices exist; however, these cells do not suffer damage under light soaking and are not based on DSSC technology.

On the other hand, in high-temperature environments, DSSCs are still very attractive in a market dominated by rigid silicon panels, provided that assembly and material compatibility are well explored. As demonstrated here, screen-printed DSSCs exhibit very good photovoltaic performance when measured at temperatures of 85 °C with a very small efficiency loss relative to room temperature, and display a speed of recovery not seen in rigid alternatives. Currently, the focus is on bench tests performed in methanol-based electrolytes. Future work will focus on real applications in high-temperature environments, most likely with a particular emphasis on the use of solid-state electrolytes/p-hole conductors.

8.3. Scalability Issues

Even though dye-sensitized solar cells can be produced in a very cost-effective way, there are still gaps between the current state of DSSC fabrication and actual large-scale production. The key issues of scalability are capacity build-up of reliable material suppliers, quality control of opto-electrical parameters, automation of production processes, and continued product development. Research has been focused on developing new materials, new designs, and new processes. New frontier applications have also been studied, including portable electronics with a potential for immediate commercial applications and interior design DSSC glasses.

Research teams have produced world-record cells, but bridging the gap to actual commercial cells capable of constant mass production with high data reliability has proved more challenging than anticipated. The competing solar technology is currently at a level that proves it is feasible to build a large factory to produce solar panels with a cost competitive with fossil fuels. Now it is more crucial than ever for DSSC technology to bridge the gap to mass production. To make any large-scale manufacturing investments, reliable industrial grade materials are needed from supplier companies. There is a limited number of potential suppliers, and it is still uncertain which of them will be able to supply materials successfully in the long term.

The overall construction of the first-generation DSSCs is relatively straightforward. There are several components: a transparent conductive anode, porous titanium dioxide coating, a dye, a hole-conducting electrolyte, and the counter electrode. There are many materials and methods from which to produce a current density in a DSSC. Therefore, it is recommended that research be directed with new designs and materials for key components so that continually higher efficiencies can be achieved. Room for improvements is rapidly diminishing unless a new path is found. It seems there is growing excitement over all-solid-state DSSCs with the potential to achieve higher efficiencies than back-to-back DSSCs, and perhaps in the future new high-voltage designs with a semiconductor solid-state pore-filling process that are compatible with glass-glass encapsulation may emerge.

9. Recent Advances in Dye-Sensitized Solar Cell Technology

Recent advances in dye-sensitized solar cell (DSSC) technology reflect an explosive research activity in the field since the conference in France. Not only academia, but also governments, industries, and public institutions from various countries are becoming more interested in DSSCs. The rapid growth in research output is witnessed from the number of publications indexed in the Web of Science, which grows every year [2]. Some 370 articles came out in 2010 on DSSCs, and since then research has increasingly moved into applied fields, such as up-scaling DSSCs in solar farms, development of building integrated photovoltaics, and commercialization. Recently, commercially available DSSCs have been developed in stationery applications for indoor use, such as mobile phones, e-books, and computers, exploiting ambient light. This is important for the scale-up of DSSCs due to their low cost along with abundant raw materials compared to the silicon photovoltaics. DSSCs are now also becoming more attractive in movable applications such as hybrid vehicles and smart windows due to their colorful nature and semi-transparency [1].

Research directions in the field of DSSCs show the large potential in further boosting performance, step further in new applied fields, and commercialize them. First, absorption spectra have to be made wider in terms of wavelengths. Second, the scratching problem in porous TiO2 films needs to be solved. Third, colored adaptive DSSCs, which can change color according to the brightness of ambient light, will be very attractive, since even usual current transparent solar cells only absorb light. Development of such totally matchless colorful adapted DSSCs would be a strong marketing strategy. Fourth, in addition to conventional glass substrates, DSSC films will become more flexible/roller-type or printed types on non heat-resistant, low-cost substrates. Fifth, DSSCs co-packed with transparent separators would be attractive. Technically and financially feasible new ideas of devices, materials, processes, and scales should come up. It should be done again, as it was done satisfactorily in the first two decades in DSSCs.

9.1. Nanostructured Materials

Nanostructured materials have a predominate role in enhancing the performance of dye-sensitized solar cells (DSSCs). A wide variety of nanostructured materials such as titania (TiO2) are used for DSSC fabrication. However, it should be noted that crystalline metal oxides, such as tungsten oxide (WO3) and zinc oxide (ZnO), that are transparent in the visible region are also opted for the counter-electrode of solar cells. The newer materials, which need to be transparent in the visible region, should possess high electron diffusion lengths (either in nanostructured or thin film form), high electrocatalytic activity, and bonding to granular nanostructured species (or porous film) of nanostructured semiconductors. Since the advent of DSSCs, TiO2 nanostructured materials have been dominant and the primary choice for photoanodes and up to a limited extent for counter electrodes [24].

Among metal oxides, semiconductors, wide bandgap ones, such as ZnO and SnO2, metal oxides having band gap in visible region, such as WO3, and conducting oxides, such as indium tin oxide (ITO) and fluorine doped tin oxide (FTO) are also examined. Highly conductive and transparent ITO and FTO films of high quality are synthesized by sol-gel and magnetron sputtering techniques. For the processing of titania pastes for producing nanostructured films, ball mill, N-methyl pyrrolidone (NMP) co-pigment, and addition of methanol have been examined. Finally, primary TiO2 nanostructured thicks of different shapes (nanoparticles as well as nanorods) and thermal treatments for conversion of brookite to anatase are discussed along with the structural and morphological study of these nanostructured materials.

Among semiconductors, it has great importance to construct novel light harvesting nanostructures of TiO2, ZnO, and WO3 semiconductors, which can be interfaced at leaf-like intersection to recycle excitons of dyes at a higher rate and improve efficiency for DSSC application. Hybrid TiO2 nanotube (TNT) to TiO2 and also tunable band gap TiO2 is investigated. Among conductive attached nanostructured CEs, self-doped TiO2-C conductivity of 1 mS/cm in bath tubulance fabricated hybrid layers of TiO2-Ru based are very effective for DSSC applications. [25][26]

9.2. Hybrid Systems

Although DSSCs in their pure form have many beneficial characteristics, it can be seen that they also have several disadvantages. In particular, the ionic liquid electrolyte used in the majority of solid-state DSSCs has a significant disadvantage in terms of leakage and is quite a low density material. Cavities that exceed certain sizes appear in the porous TiO2 film, as well as possible structural imperfections. Therefore, hybrid systems were developed to minimize one material's disadvantages with the other material's benefits. Basically, in a hybrid system, either the dye or the TiO2 is in a different form (kinetic concerns, diffusion limitations). This type of device is also called Tandem or Stacked type DSSCs [2]. These devices are less common than pure DSSCs, but they are continuously being researched. Here, it will be focused on one type of hybrid DSSCs, called gel type DSSC. Such a solar module basically consists of a small number of stacks (usually two) of pure cells. Dye-sensitized solar cells (DSSCs), a third generation solar technology, have been gaining immense popularity recently due to their low-cost and simple fabrication methods [19]. DSSCs also have several additional advantages such as the ability to fabricate flexible solar panels as well as thin panels that can adhere to surfaces. Transparent DSSCs can be fabricated which can be used as building integrated photovoltaic cells. Supporting large area, large scale and flexible DSSCs has been the focus of recent research in this domain.

9.3. Advanced Dyes

The investigation of new organic dyes for DSSCs has intensified significantly owing to their rich structural diversity, environmental friendliness, and low manufacturing cost. Considerable progress has been made toward increasing the overall efficiency of organic DSSCs. A sep-pyrene-armed D-π–A dye 1 based on a diketopyrrolopyrrole unit and its derivatives were designed, synthesized, and successfully applied in DSSCs [3]. The incorporation of a new 2H-[1,2,3]triazolo[4,5-c]pyridine moiety into the D-π -A structure afforded a cyclopentadithiophene-bridged D-A-π-A (DPP-CPT2) organic sensitizer for high-performance DSSCs with a PCE (η) of 9.81%. Two new D-A-π -A organic sensitizers, featuring bis-urea-substituted dicyanovinyl thiophene, were synthesized and characterized. Structure-activity relationship studies unveiled a range of PCEs from 4.49% and 6.88%. Bi-dimensional D-A-π –D dyes were successfully synthesized and employed as sensitizers in DSSCs, leading to a maximum solar energy conversion efficiency of 4.53% and well-retained electrochemical stability. Novel D-A-π -A coumarin dyes containing low band-gap chromophores with different numbers of π-conjugated systems were prepared and applied in DSSCs. The introduction of ethylene-bridged benzothiadiazole units significantly enhances the light-harvesting performance and electron transfer ability of dendronized π -conjugated macromolecules for highly efficient DSSCs. The introduction of alkyl functional units to reduce dye aggregation on TiO2 film was studied and the alkyl-chain-length-dependent performance was evaluated. A series of new unsymmetrically substituted triphenylamine-based organic dyes were designed with two different D-π-A architectures, affording PCEs of over 5.5%. To enhance the charge recombination lifetime and lower the energy losses of organic dyes, a strategy regarding molecular design based on redox potential modulation was developed, with the goal of developing high-performance and robust organic sensitizers for DSSCs with cobalt electrolyte based devices.

10. Future Directions and Research Opportunities

Dye-sensitized solar cells (DSSCs) have become a prominent source for generating energy for electronic applications. These devices are commercially important for low-power applications since their inexpensive materials and low manufacturing costs allow them to be fabricated as thin, light-weight flexible solar panels. Furthermore, DSSCs do not suffer from efficiency degradation due to temperature and are ideally suited for low-cost indoor solar panels [2]. However, the methods of manufacturing DSSCs must be further optimized to enable high efficiency and long-term durability before they could be commercially available. Rapid development of research in the last five years in the field of so-called next-generation DSSCs is a very promising sign of progress toward that goal. Here, the most significant progress in optimizing materials for the next generation DSSCs is reported.

With these materials, more advanced types of DSSC designs can be achieved, such as mechanically contacted liquid junction or solvent-free solid-state DSSCs. The suggested process flow for producing the scaffolding and cell-structure of this design offers an even more economical approach to produce advanced device structures on a single glass substrate. It is expected to greatly influence the production costs of these devices. This more robust solid-state DSSC architecture was produced using printed dyes and a Cu redox based solid-state hole conductor. It will make them much more robust under various conditions but at the same time, open totally new opportunities for portable electronics and the internet-of-things devices. Rapid research and development from many labs and with new commercial players may enter this field and accelerate the widespread adoption of DSSC technology at an affordable cost.

The racing thermographic images showed how much improvement was achieved with the films. The only gap of the measurements for the DSSCs was regarding their efficiency to harvest near-infrared light. DSSC technology in its current form cannot be enhanced above a Power Conversion Efficiency (PCE) of 10% or harvested until now end of 15% [1]. DSSCs with a very long successful history falls behind their tiled counterparts in terms of efficiency and cost during the last year benchmarking between solar technologies. Though DSSCs have great potential, decades of research has been wasted irrespective of the improvements in many important fundamental areas that are at the core of electro chemistry, materials science, fundamental physics and engineering. Prior to fabless concept being common with companies all over the world focusing only on chip design, DSSC grid technology was initially clear hot of the Gossamer designs based on polyester meshes with equilibria output of just 1% efficiency. However, growing volumes and more than a black sheep tend to deviate the add-on ideas for newer devices. [27][28]

11. Conclusion

Dye-sensitized solar cells (DSSCs) have emerged as promising photoelectric conversion devices for use in various electronic applications, such as wireless sensors. The inexpensive and abundant materials of which they are made, in conjunction with our ability to fabricate them as thin, light-weight flexible solar panels, make DSSCs well-suited for low-cost indoor solar panels, thereby facilitating their use in large-scale applications, on surfaces such as windows and façades. During the past decade, there has been substantial activity in the field of DSSC research. The extensive literature of 2020 shows that a significant quantity of DSSC-related research progresses, primarily with the aim of improving the efficiency performance of dye-sensitized solar cell with new and optimized materials. Types of alternative materials in new potential dye-sensitized solar cell designs with a process flow for producing multi-layer LCD glass integrated DSSC devices are also discussed at the end. Important progresses made in the field of DSSC device structures and materials are presented.

High-quality, large-area DSSCs that require very inexpensive and abundant materials are reviewed. The optical transparency and electrochemical stability of photocurable polymer electrolyte glass are addressed . A range of new and improved materials are focused on either modified versions of materials already known in the DSSC field or novel materials. Overall the materials progress made in the past decade has substantially improved DSSC performance, and with further research and development efforts and by the development of new types of devices, DSSCs can become highly competitive to currently known solar cell technologies. Finally, novel devices structures for on-glass LCD integrated DSSCs with alternative materials are proposed. Offsetting current energy costs and CO2 emissions while ensuring a sustainable energy future requires radically new renewable energy sources. The establishment of an entirely new base load, readily scalable renewable energy source would essentially negate the world's dependency on fossil fuel.

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