

Review Article

Recent Advances in Dye-Sensitized Solar Cells

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This review describes recent advances in the research on dye-sensitized solar cells. After a brief discussion of the general operation principles and a presentation of record efficiencies, stability data and key technology drivers, current trends will be reviewed. The focus of this review is on materials development (sensitizers, nanostructured oxide films, and electrolyte), but commercialization aspects will also be briefly addressed. The review describes the most relevant characteristics and major trends in a compact way.

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1. INTRODUCTION

Dye-sensitized solar cells (DSCs) are a prominent member of the larger group of thin film photovoltaics. All thin film technologies together currently still represent less than 10% of the annual PV module sales. They are expected to gain growing market shares in the years to come because of both an ultimately higher potential for low-cost fabrication, compared with wafer-based PV technologies, and an access to new markets, where flexible and light-weight products are desired. Next to those thin film technologies, which have already made their way to the marketplace, that is, amorphous and microcrystalline Si as well as CdTe and CI(G)S, others are still in the precommercial phase. Among the latter, dye-sensitized solar cells are the most advanced and they are currently on the verge of commercialization with—among others—a recent announcement of a manufacturing facility of significant capacity (25 MW) in the course of 2007 in Cardiff, Wales.

After a brief discussion of the general operation principles and a presentation of record efficiencies, stability data, and key technology drivers, current trends will be reviewed. The focus will be on materials development, but commercialization aspects will also be briefly addressed. This article describes the most relevant characteristics and the major trends in a compact way. Reviews including more extensive and complete descriptions of the field are referred to in the text.

2. OPERATION PRINCIPLES AND STRUCTURE

Dye-sensitized solar cells operate differently from other types of solar cells in many ways with some remarkable analogies to the natural process of photosynthesis. Therefore, this system has repeatedly been described in terms of artificial photosynthesis since the interest in DSCs took off with the landmark publication by O'Regan and Grätzel in the early 1990's [1]. Like the chlorophyll in plants, a monolayer of dye molecules (sensitizers) absorbs the incident light, giving rise to the generation of positive and negative charge carriers.

In more detail, the different steps of the photoconversion process can best be described in conjunction with the energy band diagram and the schematic structure of a DSC (see Figure 1).

Upon light absorption, the dye (S) is promoted into an electronically excited state (S^*) from where it injects—within femtoseconds—an electron into the conduction band of a large bandgap semiconductor film (TiO_2), onto which it is adsorbed (1). The electrons are transported through the TiO_2 film by diffusion before reaching the anode of the cell—in general an $\text{SnO}_2:\text{F}$ coated glass substrate—and the external circuit (2). The positive charges resulting from the injection process are transferred into a liquid electrolyte by reaction of the dye cation (S^+) with the reduced species of a redox couple in the electrolyte solution. This leads to the regeneration of the charge neutral state of the sensitizer (3). The most typical redox couple is I^-/I_3^- . After ionic diffusion, the carrier

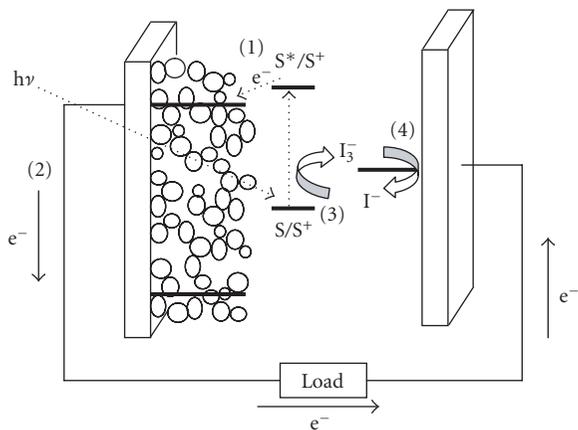


FIGURE 1: Schematic structure of a DSC, illustrating the operation principles.

of the positive charge, that is, I_3^- , reaches the cathode, where it releases its charge, thus being reduced back to I^- (4). The latter process typically requires a catalytic amount of Pt on the cathode surface. The process control is governed by kinetic competition. In optimized systems, a favorable kinetic balance [2] assures that loss mechanisms, such as the thermalization of the dye excited state and other recombination processes, are largely suppressed. Overall, the photoconversion process is regenerative; that is, there is no net change in the chemical composition of the cell.

The key to efficient light harvesting is the high surface area of the porous TiO_2 film. While a single monolayer of dye molecules on a flat TiO_2 film can typically absorb not more than a negligible fraction of the incoming light, the nanostructured TiO_2 films provide enough surface area for more than 1000 dye monolayers. Typical maximum extinction coefficients of the dye between $1\text{--}2 \cdot 10^4 \text{ M}^{-1} \text{ cm}^{-1}$ allow for quantitative light harvesting over a broad range of the dye absorption spectra. The open porosity of these films allows the liquid electrolyte to fill all pores of the film. The nanocomposite geometry thereby ascertains the required contact of every dye molecule to both the TiO_2 as well as the electrolyte phase, and the extracted current is the sum of all active molecular charge generators (dye molecules), connected in parallel.

The operating principles and the nanocomposite nature of DSCs bring about some unique features. Unlike any other type of solar cells, charge generation takes place exclusively at the interface, where the charges are separated—the TiO_2 /dye/electrolyte interface—with obvious advantages for the initial charge separation efficiency. Also, the processes of light absorption and charge transport are separated. The dye molecules only absorb the light and generate the charge carriers, while charge transport occurs in the TiO_2 and the electrolyte. This implies the absence of minority carrier recombination, and hence a relatively high tolerance for impurities. More in-depth descriptions of operation principles and loss mechanisms in DSCs can be found in other recent review papers [3–6].

3. STATE-OF-THE-ART DEVICE PERFORMANCE AND STABILITY

The best device today with a size of more than 1 cm^2 is listed with a certified efficiency of 10.4% under standard test conditions (1000 W m^{-2} , AM1.5, 298 K) in the solar efficiency tables [7], published regularly in *Progress in Photovoltaics: Research and Applications*. On smaller device areas, higher efficiencies have been reported, as also indicated in the solar efficiency tables in *Progress in Photovoltaics* under “notable exceptions.” Entries into the main table require a minimum size of 1 cm^2 .

In Table 1, a selection of representative benchmark efficiency data from the past years is shown, including also results from devices $< 1 \text{ cm}^2$.

Currently, the efficiency is limited primarily by two factors:

- (1) nonoptimized I_{SC} arising from the absorption spectrum of the dyes which does not extend far enough into the near infrared range of the optical spectrum;
- (2) nonoptimized V_{OC} arising from undesirable dark currents due to interfacial electron back transfer of injected electrons to the redox electrolyte.

Research is ongoing on both of these limitations as will be discussed in Section 5.

Long-term stability is a key parameter for any type of solar cells. For a proper assessment of stability, it is generally helpful to differentiate between intrinsic and extrinsic factors [14], where intrinsic factors are related to the solar cell under the condition of a perfectly closed/sealed system, while extrinsic factors are related to degradation processes induced by potential diffusion of molecules into or out of the solar cell. Penetration of water and oxygen and escape of solvent molecules are typical examples for extrinsic factors. In the early development stage of DSC technology, the quality of device sealing was sometimes not appropriate in laboratory test cells, leading to leakage of the volatile nitrile-based solvents, typically used for the electrolytes. While this type of problems is occasionally still considered as a challenge for the technology, most research groups with longer experience, including industrial labs, seem to have overcome them by improved sealing technologies [11]. Due to the direct relevance to the manufacturing of commercial products, little is published on processing issues though [15–17].

Good results on overall system stability have been reported since several years [18], including recent publications demonstrating excellent stability characteristics under laboratory test conditions at temperatures as high as 85°C in the dark and 60°C under illumination [19–21].

These good results need to be confirmed under real outdoor conditions in order to ascertain an appropriate correlation with the published stability data obtained under laboratory test conditions.

Information, available about outdoor field testing, is too scarce to be representative, but it suggests that further work on stability may be required despite the described progress [22, 23].

TABLE 1: Record efficiencies of DSC of various device sizes.

Dye*	Surface area (cm ²)	η (%)	V _{OC} (V)	I _{sc} (mA/cm ²)	FF (%)	Reference
N-719	<1 cm ²	11.2	0.84	17.73	74	[8]
N-749	0.219	11.1	0.736	20.9	72	[9]
N-749	1.004	10.4	0.72	21.8	65	[10]
N-719	1.31	10.1	0.82	17.0	72	[11]
N-3	2.36	8.2	0.726	15.8	71	[12]
N-749	26.5 (submodule)	6.3	6.145	1.7	60	[13]

*N-719, N-749, and N-3 are codes for molecular structures (see Section 5.1).

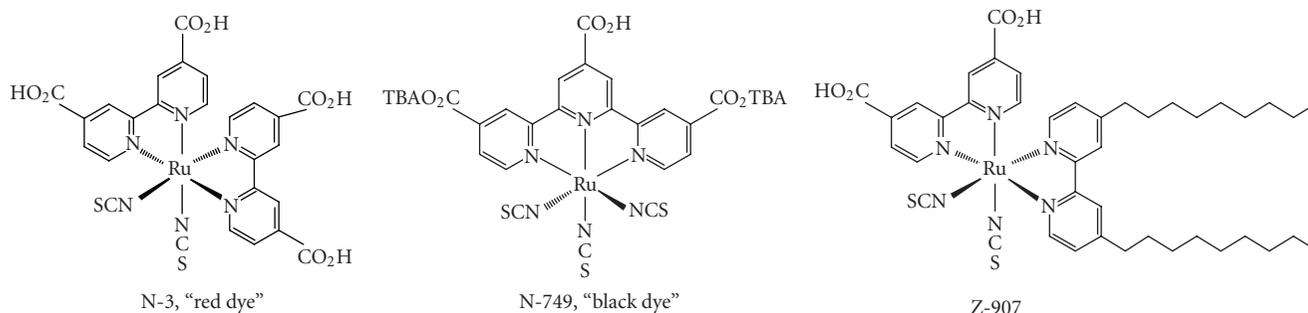


FIGURE 2: The three most frequently applied ruthenium polypyridyl complexes.

4. KEY TECHNOLOGY DRIVERS

Based on low-cost and abundant materials, the expected manufacturing costs for DSCs are among the lowest of all PV technologies. Module costs of 1 €/Wp or less seem feasible [11]. Moreover, a favorable energy payback time of less than 1 year is foreseen [24] based on the relatively low-energy input for the processing of DSC modules (moderate processing temperatures below 600 °C and absence of high-vacuum steps). Furthermore, preliminary work on life cycle analysis reveals excellent sustainability characteristics [24], achieved among others because of the use of abundant, nontoxic materials in the production as well as during the processing. The electricity generation of DSCs is remarkably good in diffuse daylight and remains practically unchanged with increasing temperature. This is important in view of the constantly changing operating conditions of solar cells which may be exposed to variations in temperature, angle of incidence, or shading by clouds. A comparison between DSCs and crystalline Si modules under outdoor conditions in Japan resulted in a 10–20% higher kWh/kWp output of the DSC modules over the testing period of 6 months [23], underlining the good average performance under changing operating conditions.

The easy tunability of DSC technology in terms of colors and transparency grade as well as the possibility of processing on foils leaves a lot of rooms for product innovations in new markets. A number of products particularly for low-power applications in mobile electronics, for instance, mobile phones or laptops, are in development (see, e.g., www.g24i.com).

5. STATE-OF-THE-ART MATERIALS AND CURRENT DEVELOPMENT TRENDS

There is an active materials research on practically all components of DSC devices. In this section, the most commonly applied materials are first presented, followed by a discussion of desirable improvements. The current R&D trends will be presented in a generic form with some selected illustrative examples.

5.1. Dyes/sensitizers

Three dyes can be considered as the backbone of currently applied sensitizers in DSC. All of these dyes are ruthenium-based metal-organic complexes with the general formula RuL_xL'_ySCN_z, where L and L' are polypyridyl ligands; they are readily available commercially and show excellent efficiency levels up to 11%. The molecular structures of these dyes are shown in Figure 2. Because of the complex chemical nomenclature, they are most often referred to with trivial names as indicated in Figure 2 (N-3 and N-749, which are commonly also called red and black dyes and Z-907). There is a widely used variant of the N-3 dye, which differs from it only in the degree of protonation (trivial name: N-719). The black dye shows the broadest absorption range up to 900 nm.

Desirable improvements

The primary goal of R&D on sensitizers is further progress in efficiency. Issues with respect to robustness, sustainability, and cost are also of relevance, though. For improvements in current output, an extension of the absorption range of DSCs

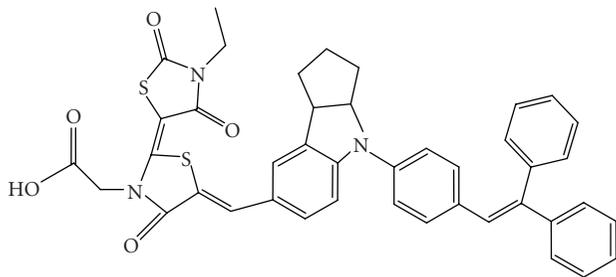


FIGURE 3: Organic sensitizer D-149.

towards longer wavelengths from currently 800–900 nm to 900–1000 nm is required.

Moreover, dyes with enhanced molar absorption coefficients are attractive for efficient light harvesting with thinner TiO_2 layers. This can lead to an efficiency boost of DSC concepts, which depends so far on such thin layers (particularly solid state- but also ionic liquid-based systems) and generally to improved V_{OC} independent of the type of system.

With regard to sustainability and cost, organic dyes may be advantageous.

Assessment of current trends

An impressive number of new sensitizers are being developed in recent years. Many of the new dyes are derivatives of the N-3 molecule with various chemical modifications on one of its two bipyridyl moieties while leaving the rest of the molecule unchanged. This work has led to sensitizers with improved molar absorption coefficients [25], referred to in the literature as the “K-series” [26–28], as well as to the discovery that hydrophobic side chains (like in Z-907) can be beneficial for long-term stability [29]. This latter effect is assigned to the inhibition of H_2O adsorption to the TiO_2 surface. Dyes in which the carboxylic acid functions are replaced by phosphonic acid functions [30, 31] may also be advantageous for long-term stability because of the stronger adsorption of these groups to the TiO_2 surface.

On the other hand, efforts to further extend the spectral absorption range of the sensitizer beyond that of the “black dye,” published for the first time in 1997 [32], have not been successful yet, which is why record efficiencies have remained unaffected by this research thus far. The coadsorption of several dyes in “dye cocktails,” following this same goal, has shown to be conceptually applicable [33, 34], but it needs further elaboration. The development of tandem concepts is another promising route. A significantly enhanced absorption range and improved efficiency (15%) could be achieved by the combination of a DSC top cell with a CIGS bottom cell [35]—approaches based on DSCs exclusively are under development [36, 37].

Next to the systematic development of improved ruthenium complexes, there is also a significant number of publications on purely organic dyes with increasingly good photovoltaic performance [38–40]. This trend is driven among others by the argument of potentially lower cost. The best results thus far have been obtained with the indoline dye D-149

[41, 42], shown in Figure 3. Such dyes may become a viable alternative to ruthenium complexes in case further favorable characteristics, also on long-term stability, can be achieved.

Rather, a sideline of current research but with potential significance for new markets (decorative applications) is the development of sensitizers with different colors, such as green Zn phthalocyanine complexes [13, 43].

Another innovative research line is the replacement of molecular sensitizers by semiconductor quantum dots, for example, PbS [44]. This approach, which is still in its infancy, may profit from the very high absorption cross-sections of quantum dots as well as from the recently discovered phenomenon of impact ionization (creation of multiple excitons by excitation with a single photon when the photon energy is three times higher than the bandgap) [45]. To date, reaching competitive levels of overall conversion efficiency by sensitization with quantum dots has remained a major challenge though. A notable exception is a related approach based on a nanocomposite structure consisting only of TiO_2 and CuInS_2 . Here, the CuInS_2 assumes the functions of sensitizer and hole conducting medium at the same time, and an overall efficiency of up to 5% has been published for this all solid-state approach [46, 47].

5.2. Nanostructured oxide films

The most extensively applied and successful material by far is the high bandgap semiconductor TiO_2 (bandgap: 3.2 eV). The often translucent nanocrystalline layers consist of interconnected colloidal particles in the size range of 15–30 nm with a layer thickness typically between 5 and 15 μm . The surface area enhancement (often also referred to as roughness factor) of such layers is on the order of 100/ μm^2 and the porosity is between 50 and 70% [48]. The best photovoltaic performances have been obtained using layers with enhanced haze and by application of a TiCl_4 posttreatment [49]. Enhanced haze is achieved by introduction of scattering centers (large TiO_2 particles) inside [9, 48] or on top of the film with the smaller particles [42]. The colloidal TiO_2 materials are prepared by a hydrothermal sol-gel method in acidic or basic aqueous media [48, 50] and the layers are generally applied by industrially relevant processes such as screen-printing. For a quantitative removal of organic additives (binders and dispersants) after printing, processing temperatures between 450 °C and 550 °C are typically required during the annealing of the films. An SEM image of a typical TiO_2 film is shown here in Figure 4.

Desirable improvements

For liquid electrolyte-based cells, the currently applied TiO_2 layers are already fairly optimized with respect to surface area, film thickness, porosity, and optical properties (haze).

On the other hand, cells in which the liquid electrolyte is replaced by solid-state hole conductors suffer from insufficient pore filling—a problem which might be relieved by other microstructures with more easily accessible pores, for example, by the use of linear pore geometries.

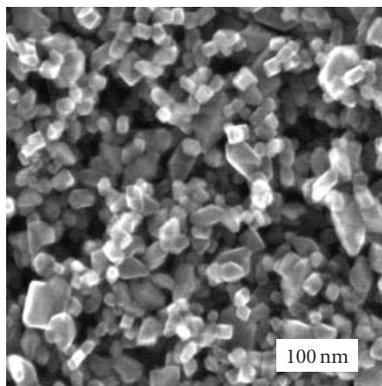


FIGURE 4: SEM micrograph of a nanocrystalline TiO_2 film (view from the top).

In general, the development of low-temperature processes without compromising system efficiencies is an attractive goal, particularly in order to make processing on polymer substrates possible.

Further improvements in V_{OC} —also for electrolyte-based systems—could be obtained if ways are found to hamper interfacial recombination by chemical or physical surface engineering.

Assessment of current trends

Efforts to replace TiO_2 as the material of choice for DSC have been plentiful, however, until now without convincing success [51–54]. The search for another material is motivated primarily by higher electron mobilities to reduce the electron transport resistance—this is the case of ZnO —or by higher bandgaps, as in SnO_2 . The latter aims at avoiding any absorption of UV photons by the oxide, which can potentially give rise to degradation processes by strongly oxidizing valence band holes. While DSC devices have been successfully prepared with a number of different oxides, including ZnO [51], SrTiO_3 [53], SnO_2 [54], and Nb_2O_5 [52], the achieved device performances are at best half of those published for TiO_2 -based devices. Considering in addition the excellent chemical stability of TiO_2 , its large abundance, and nontoxicity, the probability of finding a more appropriate material can be considered as being quite small.

One recent trend is the application of ultrathin insulator layers like Al_2O_3 [55] or MgO [56] on TiO_2 . Such coatings were found to slow down the interfacial recombination kinetics. While this approach needs further elaboration, clear benefits have typically only been observed for solid-state systems [57, 58], in which the interfacial recombination kinetics can limit the performance. For electrolyte-based systems on the other hand, no clear benefits were found as long as TiO_2 was used as a photoanode material [54].

A very recent development is the application of ordered TiO_2 microstructures [59–61]. Only some months ago, one of the major limiting factors of such materials, that is, the insufficient total surface area, has been overcome by the successful preparation of TiO_2 nanotubes with roughness fac-

TABLE 2: Typical current solvent-based electrolyte compositions (ACN = acetonitrile, VN = valeronitrile, MPN = 3-methoxypropionitrile, PMII = 1-propyl-3-methylimidazolium iodide, GuSCN = guanidinium thiocyanate, TBP = tert-butylpyridin, NBB = 1-butyl-1H-benzimidazol.).

	High η	Robust
Solvent	ACN:VN (3/1)	MPN
Iodide compound	1 M PMII	1 M PMII
Iodine	0.03 M I_2	0.15 M I_2
Additive 1	0.1 M GuSCN	0.1 M GuSCN
Additive 2	0.5 M TBP	0.5 M NBB
Efficiency	10.5% ($<1 \text{ cm}^2$)	9% ($<1 \text{ cm}^2$)

tors up to >1000 , as required for efficient light harvesting in DSC [62]. In this work, a noncertified overall efficiency of almost 7% was published for an electrolyte-based cell. However, considering the excellent performance of the “standard” colloidal TiO_2 layers in electrolyte cells, this approach as well may be beneficial primarily for solid-state devices, where a facilitation of pore-filling is possible.

Low-temperature preparations of TiO_2 films are pursued since several years ($T < 200^\circ\text{C}$) and with increasingly good results in terms of DSC performance on flexible substrates. The processing of the oxide layer at low temperature is essential in view of cost-effective production on conductive plastic foils. Methods for the fabrication of low-temperature oxide films include pressing and electrophoresis [63, 64] as well as low-temperature chemical sintering [65, 66] or electrodeposition [67]. Nevertheless, the best flexible system to date—on a titanium foil—still applies a high-temperature sintering step for the TiO_2 layer ($\eta = 7.2\%$). [68].

5.3. Electrolytes/molecular hole conductors

The record conversion efficiencies up to 11%, reported in Section 3, are typically achieved with liquid electrolytes based on acetonitrile—a low-viscosity volatile solvent—and by using comparatively low iodine concentration. These high-efficiency electrolytes are not at the same time optimized for achieving the best long-term stability characteristics, for which other electrolyte formulations with less volatile solvents or ionic liquids as well as higher iodine concentrations are more appropriate. These latter electrolytes are often referred to as robust electrolytes in the literature and their application leads to a lower-efficiency output in the range of 7–9%. Next to the redox-active species and solvents, the electrolytes contain typically some additives. The function of these additives is in most cases to reduce the dark current by coordination to the TiO_2 surface, thus improving the V_{OC} of the solar cells. Table 2 compares the compositions of a widely used high-efficiency electrolyte and a popular robust electrolyte; both are used in conjunction with a sensitizer from the K-series (see Section 5.1) and coded K-77 in this case [21].

Desirable improvements

The predominant technological drivers for the current work on electrolytes are aspects related to robustness, environmental sustainability, and processability for module concepts. As an example of processability, the replacement of the corrosive iodine-based electrolyte could facilitate module production on larger areas by avoiding the necessity to apply protective coatings to metallic current collector grids. Concerning system robustness and sustainability, the replacement of volatile solvents is expected to be beneficial. Full solid-state versions in which the electrolyte is completely replaced by a solid material will have clear advantages for interconnection schemes on the level of module fabrication.

Furthermore, the goal to further improve the efficiency is also an important motivation for the work on electrolytes, for instance, by the search for new additives for the suppression of interfacial recombination. This could lead to gains in V_{OC} .

Assessment of current trends

One current research direction is the development of non-corrosive electrolytes. The most promising results so far have been obtained with the Co(II)/Co(III) redox couple with external quantum efficiency values up to 80% [69] and overall efficiencies up to 4% at full sun illumination and 8% at 1/10 sun illumination [70]. The amount of research going on in this direction is surprisingly limited considering the obvious benefits which could be achieved. This may in part be explained by the impeccable functioning of the I^-/I_3^- couple, in which a negatively charged ion carries the positive electrical charge. The resulting electrostatic repulsion between the electron in the TiO_2 and the hole on the I_3^- ion may be advantageous for the slow interfacial recombination kinetics (in the millisecond time domain). A further probable factor in the context of these favorably slow kinetics is the involvement of two electrons in the recombination reaction ($I_3^- + 2e^-_{TiO_2} \rightarrow 3I^-$).

Several research groups currently investigate the use of ionic liquids instead of organic solvents in liquid electrolytes. Ionic liquids are a new class of materials with a number of attractive properties for application in DSCs, such as high stability, negligible vapor pressure, nonflammability, as well as excellent environmental compatibility. On the other hand, overall power conversion efficiencies obtained with ionic liquids are so far considerably lower than those obtained with organic solvent electrolytes, typically in the range of 4–7.5% (on device areas $< 1\text{ cm}^2$) [71–74]. This is due to diffusion limited current output in these systems caused by their more viscous nature. Viscosity values are higher by a factor of 10–100 than in acetonitrile-based electrolytes [42]. If these limitations can be overcome, ionic liquids may well turn out to be an attractive alternative to the liquid electrolytes based on volatile solvents. The most frequently studied class of ionic liquid materials is 1-methyl-3-alkylimidazolium iodide (see Figure 5).

An alternative approach for the replacement of volatile electrolytes is the addition of gelators to solvent-based elec-

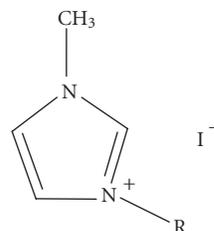


FIGURE 5: General molecular structure of a typical ionic liquid.

trolytes, leading to the formation of quasisolid gel electrolytes. A considerable number of articles have appeared on this topic in recent years. Systems with efficiencies in the range of 4–6% [75–78] have been published, with some including promising stability data [79].

A more “radical” and fundamentally different approach is the replacement of the electrolyte by a solid-state mediator. Practical preparation issues are substantially more challenging than for all liquid-based approaches though. It is not evident to fill all the nm-sized pores of the TiO_2 films with another solid and to achieve a similarly quantitative and intimate interfacial contact with the dye molecules as can be achieved with a liquid. This is one of the reasons why rather thin TiO_2 layers of only 2–3 μm are typically employed in solid-state devices leading to limitations in light absorption.

Next to this, the interfacial charge recombination dynamics—for electrons in the TiO_2 with holes in the mediator—are reported to be faster by a factor of about 10 compared with liquid electrolytes [80]. Special attention to interface engineering is thus required, a topic which has only been addressed in a preliminary fashion so far [28, 81, 82]. Considering these two major challenges, pore filling and recombination kinetics, the results obtained in various groups with efficiencies up to $>4\%$ [83, 84] are promising. The best material so far investigated is the amorphous organic hole conductor spiro-OMeTAD [85] followed by crystalline Cu(I) compounds, CuSCN [86] and CuI [87]. The amorphous state seems clearly to be more appropriate for the pore-filling requirements, which is also consistent with the observation of improved device performance by the addition of a crystal inhibitor in systems based on crystalline CuI as mediator [88]. In terms of pore-filling, the development of more sophisticated deposition techniques is desirable; the methods applied so far, spin-coating and “solution-casting,” are not suited well enough. Self-assembly concepts—similar to the one successfully applied ever since for the monolayer formation of the dye molecules on the TiO_2 surface—could prove to be helpful in this context.

6. COMMERCIALIZATION

Currently, DSC technology is on the verge of commercialization, a view which is supported by the growing number of patents in this field (>300 in 2005) as well as by the recently started organization of a series of conferences dedicated specifically to the topic of industrialization of DSC (DSC-IC, www.dyesol.com/conference). A large number of

commercial companies are active in the field, presenting first module prototypes at conferences or selling DSC-specific materials and production equipment. Commercialization ambitions take place on several continents with a certain focus in Asia (Japan). Relevant names are IMRA-Aisin Seiki/Toyota, Sharp, Toshiba, Dai Nippon, Peccell Technologies (all in Japan), Dyesol (Australia), Konarka (US), G24i (UK), and Solaronix (Switzerland). G24i has announced a DSC module production of 25 MW capacity in 2007 in Cardiff, Wales (UK), with extension plans up to 200 MW by the end of 2008 (<http://www.g24i.com>). Various module types are developed by these companies, including flexible light-weight designs on plastic or metal foils as well as glass-based modules. The products envisaged by the producers cover a broad range of low- and high-power applications from charging units for mobile electronics (phones and laptops) and colorful decorative elements to electric power producing glass tiles for facade integration in buildings.

7. CONCLUSIONS AND OUTLOOK

DSC technology currently develops very dynamically. Progress has been made on various aspects, including efficiency, stability, and commercialization. Record efficiencies have reached more than 11% on small device areas ($< 1 \text{ cm}^2$) and more than 6% on relevant submodule areas—for the most robust systems, these values are lower. Further improvements are probable; they depend critically on systematic and successful materials research. Stability data under laboratory test conditions from the last years are encouraging; field-testing is now required to confirm these results under real outdoor conditions on the module level.

These developments have fuelled an active commercial interest in the past few years.

With its attractive features, like low-cost potential, good performance under typical changes in operating conditions (temperature and illumination conditions), and application variability, the appearance of the first commercial products in the marketplace seems close.

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