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Improving the efficiency of copper-dye-sensitized solar cells by manipulating the electrolyte solution

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The use of a copper(i) dye, bearing a 2,9-dimesityl-1,10-phenanthroline and a 6,6'-dimethyl-2,2'-bipyridine-4,4'-dibenzoic acid, was investigated in DSSCs with various electrolyte solutions based on two different redox mediators, namely the common I^-/I_3^- couple and an interesting copper electron shuttle. The experimental results provide evidence of the importance of the redox mediator concentration and the crucial role of additives such as 4-*tert*-butylpyridine and lithium bis(trifluoromethanesulfonyl)imide in the performance of sustainable "full-copper" DSSCs, consolidating the way to DSSCs with Earth-abundant components.

Introduction

Since the discovery of Grätzel-type dye-sensitized solar cells (DSSCs) as a convenient way for the conversion of solar energy to electrical energy,¹ there has been a phenomenal amount of work to improve their photoconversion efficiency (η).² In particular, a lot of effort has been devoted to optimize the sensitizer^{3–8} and the redox mediators.^{8–13} Except for a few organic or zinc(ii) porphyrin-sensitized solar cells which reach up to 14% efficiency,^{14–16} the best photovoltaic performances (*ca.* 11% efficiencies) have so far been achieved with ruthenium complexes such as *cis*-di(thiocyanato)bis(2,2'-bipyridine-4,4'-dicarboxylate)Ru(ii) and the related doubly deprotonated complex (N719)¹⁷ with the iodide/triiodide couple (I^-/I_3^-) as the electrolyte.^{18,19} Cyclometalated ruthenium complexes represent good alternatives for application in DSSCs, due to their higher stability.^{20–28} However, a drawback of these sensitizers is the scarcity of ruthenium in the Earth's crust and its high cost. For this reason, in the last few years, an exponential amount of work has been dedicated to the use of dyes based on Earth abundant metals such as environmentally-friendly copper(i) complexes in combination with the I^-/I_3^- redox mediator.^{6–8,29–39} Their photoconversion efficiencies are still lower than the values obtained for state-of-the-art ruthenium(ii) dyes, but it is important to point out that the dye structures and dye/electrolyte combinations in the ruthenium-based

DSSCs have been optimized for almost 30 years, whereas copper-based DSSCs are still in their infancy and, with systematic tuning of the dye and electrolyte components^{6–8,35–37} and with the use of co-sensitization,³⁸ enhanced performances are progressively being attained.

The actual 4.66% record efficiency, corresponding to a remarkable 63% relative efficiency (η_{rel})⁴⁰ with respect to a N719-sensitized control cell set at 100%, was obtained with a copper(i) complex having as an anchoring ligand a 4,4'-dicarboxylic acid-6,6'-dimesityl-2,2'-bipyridine and, as an ancillary ligand, a 4,4'-bis(*N,N* diethylaminestyryl)-6,6'-dimethyl-2,2'-bipyridine, using the I^-/I_3^- redox mediator.³⁹ It should be pointed out that this record value was reached with unmasked cells³⁹ and therefore could be overestimated. In fact, masking the cells is crucial in order to have accurate values of photoconversion efficiency.⁴¹

Besides, the long term incompatibility of copper complexes with I^-/I_3^- , due to the low solubility of CuI,^{42,43} and the problems related to this redox couple,⁸ led to the preparation of iodine-free copper(i) solar cells. The use of [Co(2,2'-bipyridine)₃]^{2+/3+} as a redox couple was the first important step towards the development of this kind of DSSC.⁴⁴ In parallel, the fact that Cu⁺²⁺ mediators can outperform both iodine-based and Co-based electrolytes in combination with various dyes^{45–50} along with the ability of Cu mediators to solve the thermodynamic and kinetic dichotomies of the device operation^{51–53} were the springboard for the development of "full-copper" DSSCs.^{54,55} A promising photoconversion efficiency (2.06% corresponding to 38.1% relative to N719 set at 100%, masked cells⁴¹) was reached with a copper(i) dye, bearing one 4,4'-dimethoxy-6,6'-dimethyl-2,2'-bipyridine and a phosphonic acid anchor, and a copper redox mediator bearing two 4,4'-dimethoxy-6,6'-dimethyl-2,2'-bipyridines.⁵⁵ In parallel,

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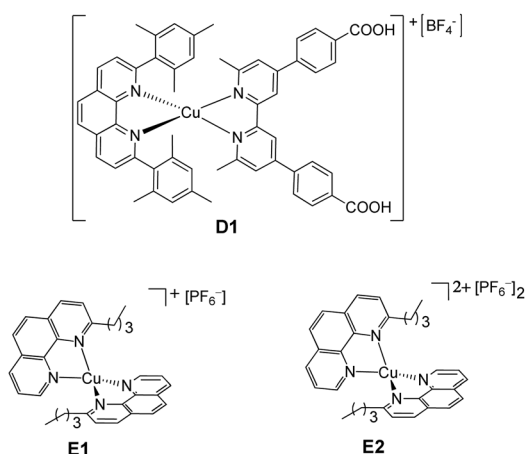


Chart 1 Chemical structures of the investigated dye (**D1**) and copper-based redox mediators (**E1/E2**).

we found that the use of a heteroleptic copper dye (**D1**, Chart 1), bearing one 2,9-dimesityl-1,10-phenanthroline and a 6,6'-dimethyl-2,2'-bipyridine-4,4'-dibenzoic acid anchoring ligand, in combination with a homoleptic copper(I/II) complex bearing two 2-*n*-butyl-1,10-phenanthrolines (**E1/E2**, Chart 1) as an electron shuttle, allows a fair photoconversion efficiency (1.4% corresponding to 16% η_{rel} , masked cells⁴¹) to be reached although lower than that obtained with the conventional Γ^-/I_3^- couple as the electrolyte.^{54,56} These first examples of full-copper solar cells^{54,55} open a new route for cheap and environmentally friendly DSSCs. Now, effort should be devoted to improve their photoconversion efficiency.

In the present work, we focus our attention on DSSCs based on **D1** as a dye and **E1/E2** as a redox mediator, investigating the effect of both the electrolyte solution concentration and the addition of 4-*tert*-butylpyridine and lithium bis(trifluoromethanesulfonyl)imide.

Experimental

Synthesis of copper complexes

The dye and the redox mediators were prepared as we previously reported.⁵⁴

Fabrication and evaluation of solar cells

TiO₂ electrodes were prepared by spreading (doctor blading) a colloidal TiO₂ paste (20 nm sized; "Dyesol" DSL 18NR-T) onto a conducting glass slide (FTO, Hartford glass company, TEC 8, with a thickness of 2.3 mm and a sheet resistance in the range of 6–9 $\Omega \text{ cm}^{-2}$) that had been cleaned with water and EtOH, treated with a plasma cleaner at 100 W for 10 min, dipped in aqueous TiCl₄ solution ($4.5 \times 10^{-2} \text{ M}$), at 70 °C, for 30 min, and washed with ethanol. After the first drying at 125 °C for 15 min, a reflecting scattering layer containing >100 nm sized TiO₂ ("Solaronix" Ti-Nanoxide R/SP) was bladed over the first TiO₂ coat and sintered until 500 °C for 30 min. Then the glass coated TiO₂ was dipped again into a freshly prepared aqueous

TiCl₄ solution ($4.5 \times 10^{-2} \text{ M}$), at 70 °C for 30 min, washed with ethanol and heated once more at 500 °C for 15 min. At the end of this operation, the final thickness of the TiO₂ electrode was in the range of 8–12 μm , as determined by SEM analysis. After the second sintering, the FTO glass coated TiO₂ was cooled at about 80 °C and immediately dipped into a methanol solution ($1.5 \times 10^{-3} \text{ M}$, previously prepared and maintained in a dry N₂ atmosphere) of the dye at room temperature for 24 h. The dyed titania-glasses were washed with EtOH and dried at room temperature under an N₂ flux. Finally, the excess of TiO₂ was removed with a sharp Teflon penknife. A 50 μm thick Surlyn spacer (TPS 065093-50 from Dyesol) was used to seal the photoanode and the platinized FTO counter electrode. Then the cell was filled up with the desired electrolyte solution (see the details reported in Table 1). The photovoltaic performance

Table 1 Main PV parameters of DSSCs based on the copper dye **D1** (in the presence of a 4 × 4 mm² square opening black mask)

	Dye	Electrolyte	J_{SC} , mA cm ⁻²	V_{OC} , mV	FF	η , %	η_{rel}^a , %
1	N719	Γ^-/I_3^- ^b	15.17	659	68.7	6.87	100%
2	D1	Γ^-/I_3^- ^{c,d}	6.17	670	73.9	3.05	44.4%
3	D1	Γ^-/I_3^- ^{c,e}	6.41	648	73.0	3.03	44.1%
4	D1	0.085 M E1	4.06	606	63.9	1.57	22.9%
		0.0085 M E2					
		0.05 M LiTFSI ^{f,g}					
5	D1	0.085 M E1	3.69	708	62.7	1.64	23.9%
		0.0085 M E2					
		0.05 M LiTFSI ^f					
		0.14 M <i>t</i> BuPy					
6	D1	0.038 M E1	4.35	630	63.1	1.73	25.2%
		0.0038 M E2					
		0.022 M LiTFSI ^f					
7	D1	0.038 M E1	2.88	725	59.9	1.25	18.2%
		0.0038 M E2					
		0.022 M LiTFSI ^f					
		0.062 M <i>t</i> BuPy					
8	D1	0.085 M E1	5.77	622	70.1	2.51	36.5%
		0.0085 M E2					
		0.1 M LiTFSI ^f					
		0.28 M <i>t</i> BuPy					
9	D1	0.038 M E1	4.98	543	66.2	1.84	26.8%
		0.0038 M E2					
		0.1 M LiTFSI ^f					
		0.28 M <i>t</i> BuPy					
10	D1	0.085 M E1	2.22	705	56.0	0.88	12.8%
		0.0085 M E2					
		0.1 M LiTFSI ^f					
		0.28 <i>t</i> BuPy					
		0.26 M MBIPF ₆ ^h					

^a Relative efficiency with respect to an **N719**-sensitized control cell set at 100%. ^b 0.6 M *N*-methyl-*N*-butylimidazolium iodide, 0.03 M iodine, 0.1 M guanidinium thiocyanate, and 0.5 M *t*-BuPy in a 15/85 (v/v) mixture of valeronitrile/acetonitrile. ^c 0.26 M *N*-methyl-*N*-butylimidazolium iodide, 0.01 M LiI, 0.017 M iodine, and 0.28 M *t*-BuPy in a 15/85 (v/v) mixture of valeronitrile/acetonitrile. ^d By working with 0.65 M *N*-methyl-*N*-butylimidazolium iodide, 0.025 M LiI, 0.04 M iodine, and 0.28 M *t*-BuPy, the PV parameters are: $J_{\text{SC}} = 6.1 \text{ mA cm}^{-2}$, $V_{\text{OC}} = 592 \text{ mV}$, FF = 71, and $\eta = 2.5\%$. ^e 0.025 M guanidinium iodide is present. ^f LiTFSI is lithium bis(trifluoromethanesulfonyl)imide; all the electrolyte solutions containing the **E1/E2** redox couple are in acetonitrile. ^g By working with 0.17 M Cu(I), 0.017 M Cu(II) and 0.1 M LiTFSI in acetonitrile, the PV parameters are: $J_{\text{SC}} = 3.8 \text{ mA cm}^{-2}$, $V_{\text{OC}} = 593 \text{ mV}$, FF = 61, and $\eta = 1.4\%$. ^h MBIPF₆ is [*N*-methyl-*N*-butylimidazolium][PF₆].



of the cells was measured with a solar simulator (Abet 2000) equipped with a 300 W xenon light source; the light intensity was adjusted with a standard calibrated Si solar cell ("VLSI Standard" SRC-1000-RTD-KG5); the current–voltage characteristics were determined by applying an external voltage to the cell and measuring the generated photocurrent with a "Keithley 2602A" (3A DC, 10A Pulse) digital source meter. For a given complex and configuration, at least four different devices were made and characterized on different days; the difference between the average and the highest or lowest efficiency values was usually lower than 5%. The PV parameters were calculated taking into account the values of the active areas (generally in the range 13–15 mm²) measured by microphotography. In the case of masked devices, a black mask with a 4 × 4 mm² square opening, realized with a cutting plotter, was carefully placed over the devices making sure to completely leave the photoanodes uncovered. IPCE measurements were performed in the DC mode in the 300–900 nm region with a Bentham PVE300 instrument equipped with a xenon QTH lamp, a TMc300 monochromator and a Stanford SR830 DSP amplifier.

Results and discussion

We prepared, with the HETPHEN synthetic method,⁵⁷ the copper(i) dye **D1** (Chart 1) bearing one 2,9-dimesityl-1,10-phenanthroline, where the mesityl groups provide enough steric hindrance to avoid the formation of homoleptic complexes and prevent geometric changes on going from Cu(i) to Cu(ii),⁵⁸ and a 6,6'-dimethyl-2,2'-bipyridine-4,4'-dibenzoic acid, chosen as the anchoring ligand because of its particular ability to anchor the dye on the titania surface.^{31,54} The performance of **D1** in DSSCs was investigated with various electrolyte solutions based on two different redox mediators, namely the common I[−]/I₃[−] couple and the recently reported copper electron shuttle E1/E2 (Chart 1).⁵⁴

Dye-sensitized solar cells were prepared using FTO glass coated TiO₂ sensitized with **D1** as the photoanode, a platinized FTO as the counter electrode and an electrolyte solution containing I[−]/I₃[−] or E1/E2 as the redox couple (see Experimental). The results of the investigated fully masked thin film DSSCs are presented in Table 1 together with those obtained with the Ru(ii) benchmark **N719**. In addition to the absolute photoconversion efficiency (η), Table 1 reports the efficiency relative to a cell based on the **N719** dye and the I[−]/I₃[−] electrolyte set at 100% (η_{rel}). Fig. 1 shows the current density vs. voltage curves of the devices under AM 1.5 simulated solar illumination with a power light intensity of 100 mW cm^{−2}.

It turned out that the masked dye-sensitized solar cell, based on **D1** as the dye and containing I[−]/I₃[−] as the redox shuttle, has a 3.05% photo-conversion efficiency (Table 1, entry 2). This performance is remarkable for such a simple dye.

Remarkably, the DSSC based on **D1** as the dye and I[−]/I₃[−] as the redox shuttle (entry 2) has a photoconversion efficiency much higher than that previously reported by using the same 4-*tert*-butylpyridine concentration but a 2.5 times more con-



Fig. 1 Current density–voltage characteristics of masked DSSCs in the presence of **D1** as the dye and various electrolytes.

centrated electrolyte solution based on the same redox shuttle ($\eta = 2.5\%$; $\eta_{\text{rel}} = 28\%$, masked cell),⁵⁶ due to an increase of J_{SC} , V_{OC} , and FF. This result is of particular interest, showing that it is possible to improve the DSSC efficiency by simply manipulating the electrolyte solution concentration. Addition of guanidinium iodide doesn't have a significant effect on the photo-conversion efficiency since the observed increase of J_{SC} is perfectly balanced by the corresponding decrease of V_{OC} (compare entries 2 and 3).

These results prompted us to study the effect of the electrolyte solution concentration on "full-copper" DSSCs. We recently reported that substitution of the I[−]/I₃[−] redox couple with the E1/E2 couple leads to a lower but still good efficiency ($\eta = 1.4\%$; $\eta_{\text{rel}} = 16\%$), by working with 0.17 M Cu(i), 0.017 M Cu(ii) and 0.1 M LiTFSI in acetonitrile.⁵⁶ In the present work, we found that dilution by a factor of two leads to an enhancement of J_{SC} , FF and V_{OC} affording a higher photo-conversion efficiency (Table 1, entry 4; $\eta = 1.57\%$, $\eta_{\text{rel}} = 22.9\%$). Further dilution, up to a factor of 4.5 with respect to the original concentration, leads to an even better performance (entry 6, $\eta = 1.73\%$, $\eta_{\text{rel}} = 25.2\%$), due to a simultaneous increase of J_{SC} and V_{OC} . The increase of the short-circuit photocurrent observed upon dilution of E1/E2 can be attributed to the less competitive light harvesting of E1 ($\lambda_{\text{max}} = 452$ nm (ref. 54)) with the dye **D1** ($\lambda_{\text{max}} = 478$ nm (ref. 54)). IPCE measurements (Fig. 2) supported this interpretation; in fact, devices derived from entry 4 and entry 6 are very similar and differ only in the 400–480 nm region, where in the presence of a more diluted electrolyte, a slightly higher external quantum efficiency was measured accordingly with the corresponding J_{SC} . In both cases, addition of 4-*tert*-butylpyridine (in a molar ratio 2.8, with respect to LiTFSI, (entries 5 and 7) produces a significant increase of V_{OC} (about 100 mV), but the corresponding lower J_{SC} and FF lead to a similar (entry 5, $\eta = 1.64\%$, $\eta_{\text{rel}} = 23.9\%$, to be compared with entry 4) or lower (entry 7, $\eta = 1.25\%$, $\eta_{\text{rel}} = 18.2\%$, to be compared with entry 6) efficiency.



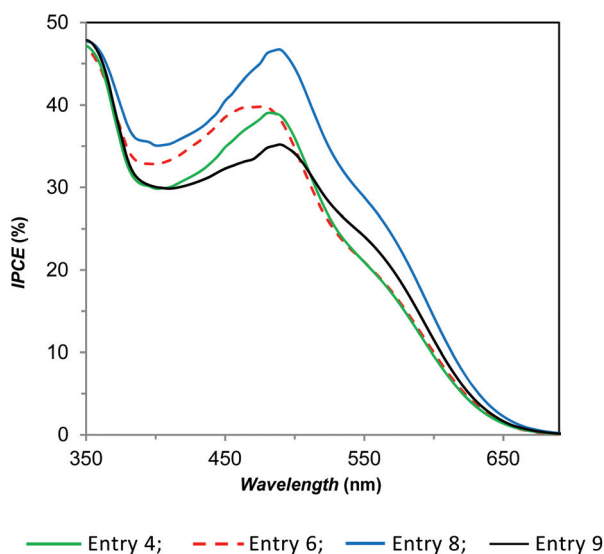


Fig. 2 IPCE characteristics of selected DSSCs in the presence of **D1** as the dye and various electrolyte compositions.

However, surprisingly, by keeping the same **E1/E2** concentration as in entry 4 and adding LiTFSI and *t*-BuPy, maintaining the 1 : 2.8 molar ratio but with a double concentration, we obtained a significant increase of all the photovoltaic parameters (J_{SC} , V_{OC} , and FF), and in these conditions, a much higher efficiency is reached (entry 8, $\eta = 2.51\%$, $\eta_{rel} = 36.5\%$). We observed the same effect also in the presence of **E1/E2** where the concentration decreased by a factor of 2.3, but with this setting, we recorded an increase only for J_{SC} and FF, while V_{OC} decreased by almost 100 mV (entry 9 *versus* entry 6); consequently, the growth in efficiency was lower compared to entry 8. The corresponding IPCE data, which agree with the current density/voltage measurements, are shown in Fig. 2. Finally, the addition of [*N*-methyl-*N*-butylimidazolium][PF₆] (MBIPF₆/**E1** = 3, molar ratio), into our powerful electrolyte solution, produced a noteworthy growth of the V_{OC} , but also an important loss in J_{SC} and FF, so the efficiency was reduced to about one-third with respect to our best result (entry 10, $\eta = 0.88\%$, $\eta_{rel} = 12.8\%$). This result shows the negative effect of MBIPF₆ in the optimization of the electrolyte solution for efficient “full-copper” DSSCs.

Remarkably, the simultaneous increase of the molar ratio LiTFSI/**E1** (in the range 1.2–2.6) and *t*-BuPy/**E1** (in the range 3.3–7.4) has a positive effect on the performance of the cell, allowing, to our knowledge, the best absolute efficiency (entry 8, $\eta = 2.51\%$) reported up to now for a “full-copper” solar cell to be reached. It has been reported that 4-*tert*-butylpyridine can have a negative effect on the Cu-mediated redox couple bearing bipyridine or phenanthroline ligands with methyl groups adjacent to the nitrogen donor atoms.^{59–62} In fact, contrary to Cu(I) species, the Cu(II) counterparts tend to accept 4-*tert*-butylpyridine as the ligand. It appeared that the so-formed penta-coordinated Cu(II) species have higher reorganization energies for the charge recombination process,

causing lower recombination rates; they shift the electrolyte potentials to more negative values and cause higher diffusion resistances of the Cu complexes.⁶² In contrast, our results show that the presence of 4-*tert*-butylpyridine can have a positive influence on the performance of “full-copper” DSSCs. Therefore, future work should be devoted in order to better understand the role of this Lewis base.

Conclusions

In this work a heteroleptic copper(I) sensitizer bearing one 2,9-dimesityl-1,10-phenanthroline and a 6,6'-dimethyl-2,2'-bipyridine-4,4'-dibenzoic acid, **D1**, was used in DSSCs with the common I[−]/I₃[−] redox couple or the copper(I)/copper(II) couple. Very good efficiencies were reached. It appeared that the composition, as well as the molar ratios between the various components of the electrolyte solutions, play a crucial role in the performance of the DSSCs. Upon dilution of the redox shuttle, there is an increase of the short-circuit photocurrent. Such an observation can be attributed to the less competitive light harvesting of the diluted electrolyte with respect to the dye. Manipulation of the electrolyte solution by using an adequate quantity of LiTFSI and *tert*-butylpyridine allows to improve the performance of “full-copper” DSSCs to be greatly improved. Remarkably, for masked cells based on the same copper(I) dye **D1**, the best absolute efficiency reached with the copper(I)/copper(II) redox shuttle ($\eta = 2.51\%$) is 82% the best efficiency reached with the problematic I[−]/I₃[−] couple ($\eta = 3.05\%$), confirming the great potential of “full-copper” DSSCs and consolidating the way to DSSCs with Earth-abundant components.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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