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Journal of Fluorine Chemistry 127 (2006) 257-262



www.elsevier.com/locate/fluor

Ring-fluorinated fluoresceins as an organic photosensitizer for dye-sensitized solar cells using nanocrystalline zinc oxide

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Received 28 November 2005; received in revised form 6 December 2005; accepted 12 December 2005 Available online 30 January 2006

Abstract

Four kinds of ring-fluorinated fluoresceins and sulfofluorescein from tetrafluororesorcinol and/or tetrafluorophthalic anhydride have been synthesized and the photochemical properties of the zinc oxide nanocrystalline electrode sensitized by the ring-fluorinated fluoresceins were investigated.

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Keywords: Dye-sensitized solar cells; Fluorinated fluoresceines; Zinc oxide

1. Introduction

Much attention has been addressed to the investigation on new metal-free organic dyes such as merocyanines [1], coumarins [2], styryl [3], and indoline dyes [4], for the dyesensitized solar cells with nanocrystalline semiconductors due to the advantages, such as the wide versatility for the synthesis of organic dyes, the ease of the tuning of molecular structure, and its low cost, since Grätzel and O'Regan have been published highly efficient ruthenium complex-sensitized titanium oxide solar cells [5].

Various halogenated 9-fluoresceins have also been employed as one of the most effective metal-free organic sensitizer for the dye-sensitized solar cells [6]. However, although ring-fluorinated fluoresceines are widely used as fluorescence probes for nitric oxide and metal anion [7], only 2',7'-difluorinated fluoresceine derivative has been examined as a sensitizer for the dye-sensitized solar cell [8].

Recently, a novel method for the preparation of porous zinc oxide (ZnO), which could be used as a semiconductor for dye-

0022-1139/\$ – see front matter O 2006 Elsevier B.V. All rights reserved. doi:10.1016/j.jfluchem.2005.12.009

sensitized solar cells, has been developed [9]. During the course of our search for the suitable dyes for this porous ZnO [10], we would like to report here on the synthesis of four kinds of ringfluorinated fluoresceins including fluorinated sulfofluoresceine, the application to the dye-sensitized solar cell with the porous ZnO, and the estimation of relationship between the efficiency and the position of the fluorine atoms.

2. Results and discussion

2.1. Synthesis of ring fluorinated fluoresceins

Four kinds of ring-fluorinated fluoresceins were prepared according to literature [11]. First, 2,4-difluororesorcinol (2) was prepared in four steps from commercially available 2,3,4,5-tetrafluoronitrobenzene (1), as follows (Scheme 1): (1) nucleophilic substitution of fluorine atoms, which are activated by the nitro group, with methoxide ion; (2) reduction of the nitro group with Pd/C in EtOAc under hydrogen atmosphere (one atom); (3) hydrodediazonation of the difluorinated aniline using the combination of HNO₃ and H_3PO_2 ; (4) BBr₃-promoted deprotection of methyl ether producing difluorinated resorcinol.

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Scheme 1. Reagents and conditions: (a) 2.2 equiv, MeONa, MeOH, $4 \,^{\circ}C$ (95%); (b) 10 mol% Pd/C, one atom H₂, EtOAc, rt (95%); (c) (1) 1.05 equiv, NaNO₂, H₂O-conc HCl (v/v = 2:1) and (2) 20 equiv, H₃PO₂, rt (71%); (d) 3 equiv, BBr₃, CH₂Cl₂, rt (90%).

As shown in Scheme 2, the obtained 2,4-difluororesorcinol (2a) reacted smoothly with phthalic anhydride (3a) in the methanesulfonic acid, which acts as both a solvent and a Blønsted acid, at 80–85 °C to give the corresponding 2',4',5',7'-tetrafluorofluorescein 4a (4a') in 74% yield. Resorcinol (2b) also reacted well with commercially available tetrafluor-

ophthalic anhydride (**3b**) under the same conditions to produce the corresponding 4,5,6,7-tetrafluorofluorescein **4b** (**4b**') in 74% yield. Unfortunately, 2,4-difluororesorcinol (**2a**) did not participate well in the reaction with tetrafluorophthalic anhydride (**3b**) to give only 19% yield of the corresponding fluorescein **4c** (**4c**'). The reaction of difluororesorcinol with sulfophthalic anhydride under the same conditions produced 2',4',5',7'-tetrafluorosulfofluorescein (**4d**) in 31% yield.

2.2. Absorption, emission, and electroproperties of fluorinated fluoresceins

The UV–vis absorption, fluorescence spectra, and electroproperties of fluorinated fluoresceins (4) as well as fluorine-free fluorescein as a reference in phosphite buffer solution (pH 9.18) are listed in Table 1.

The absorption maxima (λ_{max}) of **4** and fluorescein were observed between 490 and 525 nm. The emission maxima (λ_{em})



Scheme 2. Reagents and conditions: (a) MeSO₃H, 80-85 °C.

Table 1 Properties of fluorescein and fluorinated fluoresceines 4

Entry	Dye	$\lambda_{max}(\epsilon)~(nm)^a$	$\lambda_{em} \left(nm \right)^a$	$E_{\rm red} ({\rm V})^{\rm b}$	$E_{\rm ox} ({\rm V})^{\rm b}$
1	Fl	490 (69300)	517	-1.77	0.70
2	4a	508 (75600)	535	-1.63	0.76
3	4b	508 (71200)	531	-1.68	0.76
4	4c	525 (75100)	550	-1.39	0.92
5	4d	515 (63200)	537	-1.35	1.02

 a Measured in buffer (pH 9.18) solution at the concentration of $1\times 10^{-5}\ mol\ dm^{-3}.$

^b vs. SCE in MeCN.

of **4** and fluorescein were around 515 and 550 nm. Both absorption and emission maxima shifts to the longer wavelength in the following order (4c > 4a = 4b > fluorescein) by increasing the number of a fluorine atom. Their molar absorption coefficient (ε) were in the range of 69,200–75,600 nm.

As shown in Table 1, the reduction (E_{red}) and oxidation potential (E_{ox}) of the dyes 4 are also described. Electrochemical measurements of the dyes 4 in DMSO gave the only oxidation potential. Therefore, the E_{red} of 4 is calculated using by the equations using λ that means crossing point of the absorption point and emission spectra [12], as described below.

 $E_{\rm ox}$ (V versus Ag in acetonitrile)

 $= E_{ox} (V \text{ versus Ag in DMSO}) + 0.22 V ,$ $E_{ox} (V \text{ versus SCE in acetonitrile})$ $= E_{ox} (V \text{ versus Ag in acetonitrile}) - 0.16 V,$ $\Delta E = hc/\lambda,$

 $E_{\rm red}$ (V versus SCE in acetonitrile)

 $= E_{\rm ox} (V \text{ versus SCE in acetonitrile}) + \Delta E$

Fig. 1 illustrates the energy diagram in a system of ZnO solar cell with fluoresceins **4** in tetrabutylammonium iodide and iodine solution.

The E_{ox} and E_{red} correspond to HOMO and LUMO energy levels, respectively. The E_{red} of the dyes are negative enough to inject electrons into the conduction band of ZnO. On the other hand, the energy gap between E_{ox} of the dyes and the electrolyte triiodide/iodide (I_3^-/I^-) was small.

Table 2

Photochemical properties of fluorinated fluoresceines 4b on ZnO



Fig. 1. Schematic energy diagram of semiconductors, fluorinated fluorescein 4, and electrolyte (I_3^-/I^-) .

2.3. Preparations of ZnO solar cell

Detailed procedures for the preparation of nanocrystalline ZnO film electrodes have been reported in the previous report [9]. After drying thus prepared film at 150 °C for 1 h, the film was immersed in the solvent (5 ml) of the dyes 4 (500 μ mol dm⁻³) under the described conditions in Tables 2 and 3.

2.4. Photovoltaic performance of DSSCs with the fluorinated fluoresceins **4**

As shown in Table 2, an effect of the solvents on an adsorption of the dye **4b** on the ZnO was observed.

Among the solvent examined, such as toluene, acetonitrile, ethanol (EtOH), and dimethylformamide (DMF) under the same conditions, the value of the solar-light-to-electricity conversion efficiency (η) were not so different and the order is the following EtOH > DMF > acetonitrile > toluene (entries 1–4). Amount of the adsorbed dyes **4b** on the surface of ZnO increased, accompanied by the decrease of the polarity of the

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Entry	Solvent	Solvent polarity ^a	Immersion conditions	IPCE ^b (%)	$J_{\rm sc}^{\ c}$ (mA cm ⁻²)	$V_{\rm oc}{}^{\rm d}$ (V)	$f\!\!f^{\mathbf{e}}$	η^{f} (%)	Dye loading (nmol cm ⁻²)
1	PhMe	0.0135	80 °C, 1 h	18	1.42	0.41	0.49	0.28	66
2	MeCN	0.2744	80 °C, 1 h	21	1.58	0.42	0.55	0.36	49
3	EtOH	0.2886	80 °C, 1 h	23	1.70	0.47	0.57	0.45	32
4	DMF	0.3055	80 °C, 1 h	21	1.48	0.51	0.58	0.43	18
5	EtOH	0.2886	rt, 24 h	25	1.84	0.51	0.59	0.55	28

^a Lippert values (Ref. [13]).

^b IPCE: incident photon-to-current conversion efficiency.

^c J_{sc} : shortcircuit photocurrent density.

^d $V_{\rm oc}$: open circuit photovoltage.

^e *ff*: fill factor.

^f η : solar-light-to-electricity conversion efficiency.

Table 3

Entry	Dye ^a	IPCE ^b (%)	$J_{\rm sc}^{\rm c}$ (mA cm ⁻²)	$V_{\rm oc}{}^{\rm d}$ (V)	$f\!f^{\rm e}$	η^{f} (%)	Dye loading (nmol cm ⁻²)	$J_{\rm sc}$ per mol (10 ⁷ mA mol ⁻¹)
1	Fl	38	2.40	0.51	0.58	0.71	36	6.7
2	4 a	18	1.77	0.44	0.62	0.48	32	5.5
3	4b	25	1.84	0.51	0.59	0.55	28	6.6
4	4c	3	0.24	0.44	0.53	0.06	6	4.0
5	4d	20	1.17	0.47	0.57	0.31	21	5.6

Photochemical properties of fluoresceins and fluorinated fluoresceines 4 on zinc oxide

^a Dyes were adsorbed on zinc oxide in EtOH at rt for 24 h.

^b IPCE: incident photon-to-current conversion efficiency.

^c J_{sc} : shortcircuit photocurrent density.

^d $V_{\rm oc}$: open circuit photovoltage.

^e *ff*: fill factor.

f η : solar-light-to-electricity conversion efficiency.

solvents. Immersion at lower temperature for a prolonged time slightly increased the all photochemical properties (entry 5).

Action-photocurrent spectra, UV-vis absorption spectra of thin film of fluorinated fluorescein **4b**/ZnO under the best immersion conditions (EtOH, rt, 24 h), and that in EtOH are shown in Fig. 2.

Absorption maximum (λ_{max}) of **4b**/ZnO is shifted to longer wavelength and the absorption peak is slightly broadened, compared with its corresponding absorption peak in EtOH. The observation can be attributed to the formation of the dimer and/ or aggregate of the dye molecule on the surface of ZnO. The action-photocurrent spectrum resembles the absorption band of **4b** on ZnO. This result indicates that the photocurrent is generated by the injection of electrons from the adsorbed fluorinated fluorescein **4b** into the conduction band of ZnO.

Photocurrent-photovoltage (I-V) curve of **4b** is appeared in Fig. 3.

The shortcircuit photocurrent density $(J_{\rm sc})$ and open circuit photovoltage $(V_{\rm oc})$ of **4b** were observed at 1.84 mA cm⁻² and 0.51 V, respectively. The fill factor (*ff*) was calculated to be 0.62 and the solar-light-to-electricity conversion efficiency (η) was calculated to be 0.59, respectively, using the equations described below.

$$ff = P_{\text{max}}/(V_{\text{oc}}J_{\text{sc}}), \qquad \eta = (V_{\text{oc}}J_{\text{sc}}ff)/P_{\text{in}}$$

In these equations, P_{max} and P_{in} stand for the largest output power of solar cells and the input power, respectively. Other

dyes' ff and η were also calculated by measuring the *I*–*V* curve of other dyes **4** and fluoresciene. The performance characteristics of ZnO cells with fluorinated fluoresceines **4** as well as fluoresceine as a reference are summarized in Table 3.

From the adsorption amounts in Table 3, the amount of dye on ZnO film was in the following order: Fl(36) > 4a(32) > 4b(28) > 4d (21) > 4c (6). These results indicate that the acidity of the anchoring group, which is originated from the number of the fluorine atoms as well as the difference of the functional group such as a carboxy or sulfo group, has an important effect on the amount of dye on ZnO. That is: (1) the introduction of fluorine atoms in the molecules causes the increase of the acidity of the anchoring group, because of the strongest electronegativity of the fluorine atom. In fact, Sun et al. reported that pK_a (3.3) of 4,5,6,7,2',4',5',7'-octafluorofluorescein (4c) was much smaller than those of 4,5,6,7tetrafluorofluorescein (4b) (6.1) [11] and (2) pH (1.6) of sulfo group is smaller than that of carboxy one (12.6) [14]. Consequently, the desorption of the dye from the surface of ZnO seems to be faster than the absorption in the absorptiondesorption equilibrium.

As described in Table 3, the contribution of one mole of the dye molecules to the short-circuit photocurrent could also be calculated and estimated. The order is Fl (6.7) = **4b** (6.6) > **4d** (5.6) = **4a** (5.5) > **4c** (4.0).

For the fluorinated fluoresceins 4a, 4b and 4c, the introduction of fluorine atoms into 4,5,6,7-position of the



Fig. 2. Action and UV-vis absorption spectra of 4b.



Fig. 3. I-V curve of 4b.

fluorescein hardly have an influence on the short-circuit photocurrent. On the other hand, fluorine atoms at 2',4',5',7'-position slightly caused the reduction of not only the J_{sc} but V_{oc} . Highly fluorinated fluoresceins **4c** also decreased the values of the short-circuit photocurrent. In other words, as shown in Table 1, fluorination of 2',4',5',7'-position of fluorescein (**4a**: $E_{red} = -1.63$) resulted in a lowering of the E_{red} (LUMO) than that of 4,5,6,7-position (**4b**: $E_{red} = -1.68$), and further fluorination enormously lowers the E_{red} of the dye **4c** (**4c**: $E_{red} = -1.39$). That is, the photochemical properties, such as V_{oc} and J_{sc} , may have a crucial relation to the LUMO of the dyes. Fluorination of fluorescein may cause a lowering of the E_{red} (LUMO) as well as a reduction of the photochemical properties.

3. Conclusion

In summary, four kinds of ring-fluorinated fluoresceins were prepared and employed as a sensitizer for ZnO solar cell. Among the dyes, 4,5,6,7-tetrafluorofluorescein gave highest solar-light-to-electricity conversion efficiency (η), which is less efficient than that of fluorine-free fluorescein. As an anchoring group, the carboxy group is better than sulfo group.

4. Experimental

4.1. Instruments

Melting points were obtained on a Yanagimoto MP-S2 micro-melting point apparatus and are uncorrected. Infrared spectra (IR) were recorded on a Perkin-Elmer System 2000 FT-IR spectrometer using KBr. ¹H NMR spectra were measured with a JEOL α -400 (400 MHz) FT-NMR spectrometers in $CDCl_3$ or DMSO- d_6 solutions with tetramethylsilane as the internal standard. ¹³C NMR spectra were obtained on a JEOL α-400 (100 MHz) FT-NMR spectrometers in CDCl₃ or DMSO d_6 solutions. High resolution mass spectra (HRMS) were taken on a JEOL JMS-700 mass spectrometer operating at an ionization potential of 70 eV. UV-vis absorption and fluorescence spectra were taken on Hitachi U-3500 and F-4500 spectrophotometers, respectively. Electrochemical measurements of dyes were measured with a model 800 electrochemical workstation (CH Instruments, Austin, TX, USA). One-step cathode electrodeposition was taken on Hokuto-Denko HSV-100 potentiostat system. The photoelectrochemical measurements (two-electrode system) of solar cells were performed on a Bunko-Keiki CEP-2000 system (AM 1.5).

4.2. Materials

The isolation of pure products was carried out by column chromatography using silica gel (Wakogel C-200, 100–200 mesh, Wako Pure Chemical Ind., Ltd.). Analytical TLC was done on Merck precoated (0.25 mm) silica gel 60 F_{254} plates. Ten percent Pd on carbon was purchased from Merck Co. Ltd. 2,3,4,5-Tetrafluoronitrobenzene and tetrafluorosulfobenzoic anhydride were purchased from Tokyo Kasei Kogyo. Tetra-

fluorophthalic anhydride was purchased from Acros organics. All chemicals were of reagent grade and, if necessary, were purified in the usual manner prior to use. 3,5-Difluororesorcinol, 4,5,6,7-tetrafluorofluorescein, and 4,5,6,7, 2',4',5',7'-octa-fluorofluorescein were prepared according to literature [11].

4.3. Procedure for the synthesis of 2', 4', 5', 7'tetrafluorofluorescein (4a)

The mixture of phthalic anhydride (1 mmol, 0.150 g), methanesulfonic acid (10 ml), 2,4-difluoroesorcinol (2 mmol, 0.292 g) was heated at 80–85 °C for 40 h under argon. The resultant mixture was quenched with water (70 ml). The precipitate was corrected by filtration and dried under vacuum. The precipitate was purified by column chromatography on silica gel using hexane–ethyl acetate (v/v = 1/3) to give 2',4',5',7'-tetrafluorofluorescein in 74% yield (0.304 g).

Yield 74%; mp > 300 °C; $R_f 0.50$ (hexane/ethyl acetate = 1/ 3); ¹H NMR (DMSO- d_6) δ 6.50 (2H, dd, J = 11.22, 1.95 Hz), 7.38 (1H, d, J = 7.69 Hz), 7.75 (1H, t, J = 7.69 Hz), 7.81 (1H, t, J = 7.69 Hz), 8.01 (1H, d, J = 7.69 Hz), 11.2 (2H, s); ¹³C NMR (DMSO- d_6) δ 168.15 (s), 151.36 (s), 148.52 (dd, J = 240.67, 4.96 Hz), 140.58 (dd, J = 244.80, 6.62 Hz), 136.63 (d, J = 9.10 Hz), 136.25 (dd, J = 17.37, 12.41 Hz), 135.85 (s), 130.60 (s), 125.49 (s), 125.20 (s), 123.98 (s), 108.87 (d, J = 7.45 Hz), 108.24 (d, J = 21.50 Hz), 80.28 (s); ¹⁹F NMR (DMSO- d_6) δ -57.26 (2F, t, J = 11.22 Hz), -74.84 (2F, dd, J = 11.22, 1.95 Hz); HRMS (EI): m/z calcd. for C₂₀H₈O₅F₄ (M), 404.0308; found, 404.0305.

4.4. Procedure for the synthesis of 2',4',5',7'tetrafluorosulfofluorescein (4d)

The mixture of phthalic anhydride (1 mmol, 0.150 g), methanesulfonic acid (10 ml), 2,4-difluoroesorcinol (2 mmol, 0.292 g) was heated at 80–85 °C for 2 days under argon. The resultant mixture was quenched with water (70 ml), extracted with ethyl acetate (50 ml × 3 ml), dried over Na₂SO₄, and concentrated under vacuum. The precipitate was purified by column chromatography on silica gel using methanol– dichloromethane (v/v = 1/5) to give 2',4',5',7'-tetrafluorosulfofluorescein (**4d**) in 31% yield (0.136 g).

Yield 37%; mp > 300 °C; $R_{\rm f}$ 0.03 (MeOH–CH₂Cl₂ = 1/5); ¹H NMR (DMSO- d_6) δ 6.25 (2H, d, J = 12.39 Hz), 7.13 (2H, d, J = 7.59 Hz), 7.48 (1H, t, J = 7.59 Hz), 7.56 (1H, t, J = 7.39 Hz), 7.96 (1H, d, J = 7.59 Hz); ¹³C NMR (DMSO- d_6) δ 109.99 (d, J = 21.49 Hz), 113.66 (d, J = 9.04 Hz), 127.60 (s), 128.27 (s), 129.27 (s), 129.08 (s), 129.39 (s), 129.83 (s), 139.95 (s), 140.18 (dd, J = 244.07, 7.83 Hz); ¹⁹F NMR (DMSO- d_6) δ -55.44 (2F, dd, J = 19.46, 12.20 Hz), -86.28 (2F, d, J = 19.46 Hz); HRMS (FAB): m/z calcd. for C₁₉H₉ O₆F₄S (M + H), 441.0056; found, 441.0057.

4.5. Preparation of dye-sensitized solar cells with ZnO

Preparation of ZnO thin film as well as the dye-sensitized solar cells was prepared as described in the previous paper

[9,10]. Amount of dye adsorbed on ZnO thin film was evaluated from the absorbance in the solution, after being desorbed from ZnO thin film by dipping in 7N ammonia aqueous solution.

4.6. Electrochemical measurements of the dyes

Electrochemical measurements of dyes were carried out as described in the previous paper [10].

4.7. Photovoltaic measurements of solar cells

The photoelectrochemical measurements (two-electrode system) of solar cells were performed on a Bunko-Keiki CEP-2000 system (AM 1.5) with irradiation area fixed at 0.20 cm².

Acknowledgements

This work was partially supported by the Industrial Technology Research Grant Program from New Energy and Industrial Technology Development Organization (NEDO) of Japan (01B64002c). We thank Professors H. Yamanaka and T. Ishihara as well as Dr. T. Konno of the Kyoto Institute of Technology for the HRMS measurements of **4a** and **4d**.

References

 K. Sayama, S. Tukagoshi, K. Hara, Y. Ohga, A. Shinpo, Y. Abe, S. Suga, H. Sugihara, H. Arakawa, J. Phys. Chem. B 106 (2002) 1363–1371.

- [2] K. Hara, M. Kurashige, Y. Dan-oh, C. Kasada, A. Shinpo, S. Suga, K. Sayama, H. Arakawa, New J. Chem. 27 (2003) 783–785.
- [3] K. Sayama, H. Arakawa, K. Hara, S. Suga, A Shinho, Y. Oga, JP 2003-234133.
- [4] T. Horiuchi, H. Miura, K. Sumioka, S. Uchida, J. Am. Chem. Soc. 126 (2004) 12218–12219.
- [5] B. O'Regan, M. Grätzel, Nature 353 (1991) 737-740.
- [6] (a) K. Sayama, M. Sugino, H. Sugihara, Y. Abe, H. Arakawa, Chem. Lett. (1998) 753–754;
 (b) K. Hara, T. Harianaki, T. Kinashita, K. Sayama, H. Sugihara, H.

(b) K. Hara, T. Horiguchi, T. Kinoshita, K. Sayama, H. Sugihara, H. Arakawa, Sol. Energy Mater. Sol. Cells 64 (2000) 115–134.

- [7] S. Hattori, T. Hasobe, K. Ohkubo, Y. Urano, N. Umezawa, T. Nagono, Y. Wada, S. Yanagida, S. Fukuzumi, J. Phys. Chem. B 108 (2004) 15200–15205.
- [8] (a) M. Royzen, Z. Dai, J.W. Canary, J. Am. Chem. Soc. 127 (2005) 1612– 1613;

(b) K.R. Gee, Z.-L. Zhou, W.J. Qian, R. Kennedy, J. Am. Chem. Soc. 124 (2002) 776–778.

- [9] T. Yoshida, M. Iwaya, H. Ando, T. Oekermann, K. Nonomura, D. Schlettwein, D. Wöhrle, H. Minoura, Chem. Commun. (2004) 400–401 (and references cited therein).
- [10] (a) M. Matsui, H. Mase, J.-Y. Jin, K. Funabiki, T. Yoshida, H. Minoura, Dyes Pigm. 70 (2006) 48–53;
 (b) M. Matsui, Y. Hashimoto, K. Funabiki, J.-Y. Jin, T. Yoshida, H. Minoura, Synth. Met. 148 (2005) 147–153;
 (c) M. Matsui, K. Nagasaka, S. Tokunaga, K. Funabiki, T. Yoshida, H. Minoura, Dyes Pigm. 58 (2003) 219–226.
- [11] W.C. Sun, K.R. Gee, D.H. Klaubert, R.P. Haugland, J. Org. Chem. 62 (1997) 6469–6475.
- [12] R. Mosurkal, J.-A. He, K. Yang, L.A. Samuelson, J. Kumar, J. Photochem. Photobiol. A 168 (2004) 191–196.
- [13] E. Lippert, Z. Naturforsch 10a (1955) 541-545.
- [14] F.G. Bordwell, D. Algrim, J. Org. Chem. 41 (1976) 2507-2508.