Tetrahedron Letters 55 (2014) 1635–1639

Contents lists available at ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Production of three radical cations from a single photon using a photo acid generator

Kazuo Tanaka[a], Wataru Ohashi[a], Hiroshi Okada[a,b], Yoshiki Chujo[a,*]

[a] *Department of Polymer Chemistry, Graduate School of Engineering, Kyoto University, Katsura, Nishikyo-ku, Kyoto 615-8510, Japan*
[b] *Matsumoto Yushi-Seiyaku Co., Ltd, 2-1-3, Shibukawa-cho, Yao-City, Osaka 581-0075, Japan*

ARTICLE INFO

Article history:
Received 4 December 2013
Revised 15 January 2014
Accepted 22 January 2014
Available online 28 January 2014

Keywords:
Photo acid generator
Radical
Tetrathiafulvalene
Photoreaction
Amplification

ABSTRACT

Efficient generation of the organic radicals is a fundamental technology for preparing the spintronic materials. In this Letter, we present the chemical reaction of the three radical generation from a single photon. A photo acid generator which can release the multiple acid molecules via the automatic amplification mechanism was synthesized. The synthesized acid generator immediately released methanesulfonic acid by UV irradiation. Due to the amplification system, a maximum of three acid molecules can be produced from the single acid generator. In addition, the release of acid is induced by UV irradiation and automatically proceeds until the release of three acid molecules is finished. Finally, by employing the acid-catalyzed radical generation of tetrathiafulvalene, we also demonstrate the efficient radical generation triggered by UV irradiation in the polymer film.

Introduction

Corresponded to development in spintronics, the robust materials involving the spin sources have been strongly desired to prove the theoretical predictions and apply the material functions for the practical devices. In particular, organic radicals based on the small molecules and polymeric materials have attracted much attention as a spin source because of the diversity of molecules and the tunable properties.[1,2] To expand the applicability of the organic radical species, the fundamental technologies for the facile generation and the restrictedly control of the amount of the radical species are required. To satisfy the demands for the control of the generation, we have reported that the gradient materials with the radical concentration can be obtained in the polymer matrices with the photo-acid generator.[3,4] Based on the acid-catalyzed radical generation via intermolecular electron transfer between tetrathiafulvalenes (TTF),[5] variable radical concentrations can be realized in the polymer films simply by changing the light-irradiation time. Because of various advantages in the photoreaction such as the minimum requirement to additives and time- and site-specificity, chemically-active species can be localized based on the preprogrammed design in the material. However, because of the intrinsic strong light-absorbing ability of TTF cation radical in the UV and visible region, the efficiency of the photoreaction was suppressed.[6] The further elaboration for progress of the transformation of TTF to the radical cation is necessary.

Photo acid generators are valid for the modification of the polymer-based materials.[7] As a practical example, on the fabrication of the integrated circuits, photo acid generators are used to prepare the patterning at the substrate by mixing to the resist materials.[7] Triggered by light irradiation, photo acid generators can play a role in the creation of the different polarity regions. For the improvement of the reaction yield, conventional photo acid generators can produce the acid species via the self-amplification system.[8] After the initial release of acid via the photoreaction, another photo acid generator can release acid via the acid-catalyzed reaction. As a result, releasing rates should be drastically enhanced, and finally all acid generators can be consumed. Such self-catalytic mechanism can significantly contribute to the improvement of the reaction yields. Whereas, the regulation of the reaction rate and amounts of the acid species are difficult in the self-catalytic system. It is expected that the restricted control of the acid generation involving the amplification mechanism is promised to contribute not only to the efficient radical generation with TTF in the materials but also to the precise regulation of the amount of the radical species in the materials.

Herein, we present the photo acid generator for the efficient production of TTF radical cation. Our acid generator can absorb UV light and subsequently release the acid molecule. In particular, this acid generator can automatically produce a maximum of three acid molecules without assistance of the released acids. Finally, we demonstrate the acid generation can proceed not only in the

---

* Corresponding author. Tel.: +81 75 383 2604; fax: +81 75 383 2605.
E-mail address: chujo@chujo.synchem.kyoto-u.ac.jp (Y. Chujo).

0040-4039/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tetlet.2014.01.092

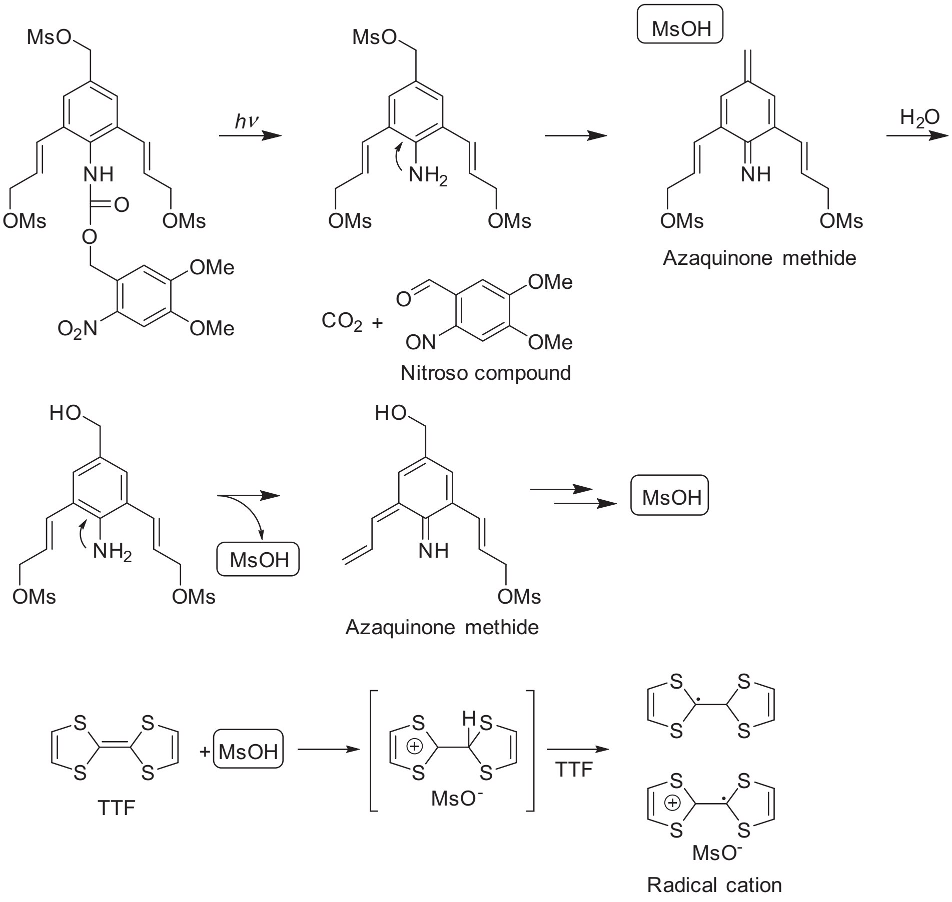
solution but also in the film states, resulting in the generation of the TTF radical cation. This is the first example, to the best of our knowledge, to offer the amplification of the radical production from a single photon.

Results and discussion

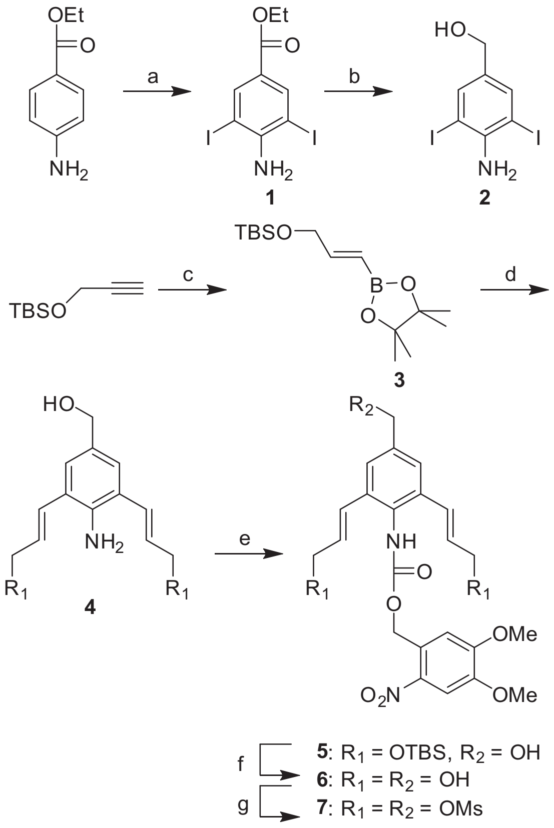
The photo acid generator **7** was designed to release three equivalents of methanesulfonic acid from the single photon (Scheme 1). By UV irradiation, the *o*-nitrobenzyl ether moiety is released, followed by the generation of the amino group. Electron donation of the amino group can tandemly facilitate the release of the mesyl groups, resulting in the formation of the azaquinone methide skeleton. Subsequently, the mesyl groups at the side chains are released after the restoration of the amino group by employing residual water. Finally, three mesyl groups can be produced from a single molecule of **7**. TTF can be protonated, followed by the formation of the radical cation via the intermolecular electron transfer.[9] Based on this reaction sequence called 'self-immolative mechanism', the multiple radical cations can be generated.[10] Although the neutral radical could be decomposed immediately, the TTF radical cation can exist in the solution and films and show the characteristic absorption band in the visible regions. The synthesis of **7** was performed as outlined in Scheme 2. The intermediates and compound **7** were prepared from commercially available materials according to the previous reports.[11,12] The deprotection of the *tert*-butyldimethylsilyl (TBS) group was conducted in 1 wt % HCl/THF to prohibit the degradation of the carbamate group by tetrabutylammonium fluoride (TBAF).[13] When the reaction of **6** with mesyl chloride was conducted at room temperature or 0 °C, chlorination occurred instead of mesylation to aryl alcohol and benzyl alcohol.[14] The total value of the peak integration in the ^{1}H NMR spectrum of **5** was corresponded to the theoretical value. At 120 °C, the peak pattern was once simplified, and the same spectrum was reversibly detected after cooling to 25 °C. These data represent that in the synthesis of compound **5** the *cis* isomer was also generated.[15]

Initially, to check the photo reactivity of the compound **7**, the time-course of the spectrum change in UV–vis absorption of **7** was examined with variable time of UV irradiation (Fig. 1). By increasing UV irradiation time, the absorption band around 350 nm assigned as the nitro group decreased.[16–18] In addition, the absorption band around 400 nm increased. These data mean the generation of the nitroso compound which is the degradation product from *o*-nitorobenzyl ether in the photoreaction. Within 30 min, the starting material was consumed. From these results, it was indicated that **7** can be activated by UV irradiation.

Next, the production of acid from **7** was investigated. To detect the existence of acid molecules, TTF was used as an indicator. It is known that TTF derivatives can be immediately transformed to TTF radical cation in the presence of acid via the intermolecular electron transfer,[19,20] leading to characteristic absorption bands at 434 nm and 579 nm from the TTF radical cation.[4,21] Based on these changes in the optical properties, the amount of TTF radical cation can be evaluated quantitatively.[4] Significantly, by adding TTF to the sample, the amount of the released acid can be estimated at this moment. After UV irradiation, the TTF/acetonitrile solution was added to the photoreacted mixtures and measured UV–vis absorption spectra (Fig. 2). Significant absorption bands with the peaks at 434 nm and 579 nm were observed from the UV-irradiated sample.



Scheme 1. Plausible mechanism for the production of TTF cation radical with photo acid generator **7**.



Scheme 2. Synthesis of **7** Reagents and condition: (a) I_2, Ag_2SO_4, ethanol, rt, 30 min, 69%; (b) diisobutylaluminium hydride, THF, 0 °C → rt, 1 h, 70%; (c) pinacol borane, Schwartz's reagent, triethylamine, 65 °C, 16 h, 95%; (d) $Pd(OAc)_2$, $P(PH_3)_3$, K_3PO_4, **2**, dioxane, water, 85 °C, 3 h, 67%; (e) 4,5-dimethoxy-2-nitrobenzylchloroformate, dichloromethane, sat. $NaHCO_3$ aq, water, rt, 2 h, 63%; (f) 1 wt % HCl/THF, rt, 30 min, 87%; (g) MsCl, triethylamine, DMF, −40 °C, 1 h, 86%. TBS = *tert*-butyldimethylsilyl, Ms = methanesulfonyl.

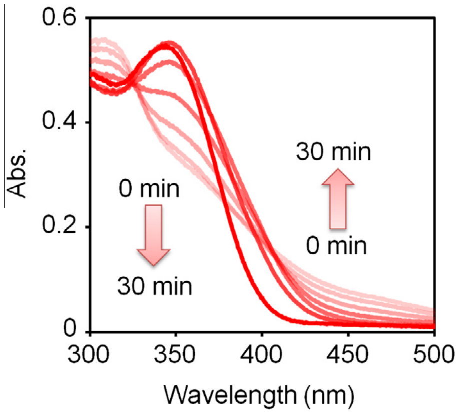


Figure 1. UV–vis spectra of 100 μM **7** solution in acetonitrile by changing UV irradiation time.

These data clearly indicate that **7** can work as a photo acid generator.

According to the reported value of the distinct molar coefficient of TTF radical cation at 434 nm, the concentrations of TTF radical cation in the samples can be estimated.[4] Figure 3 represents the time-courses of the concentration changes of TTF radical cation in the sample containing 100 μM **7** and 600 μM TTF in the acetonitrile by UV irradiation. In theoretical, the maximum concentrations of methanesulfonic acid and TTF radical cation in the sample are 300 μM. Obviously, by increasing the irradiation time, the amount of acid in the sample increased. The reaction approximately reached a plateau after 15 min irradiation. In contrast, without UV irradiation, slight enhancement was observed. These data also indicate that **7** can work as a photo acid generator. After UV irradiation for 30 min, 67 μM TTF radical cation was produced in the sample. This result represents that the same amount of acid was generated. To determine the origin of the acid generation, further analyses were performed.

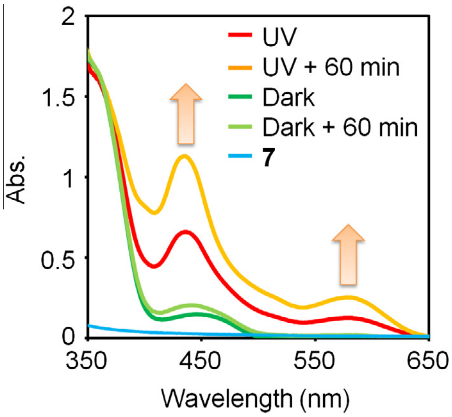


Figure 2. UV–vis absorption spectra of the reaction mixtures containing 100 μM **7** and 600 μM TTF in acetonitrile with or without UV irradiation for 15 min. The spectra represented by yellow and green lines were recorded after 1 h incubation at room temperature.

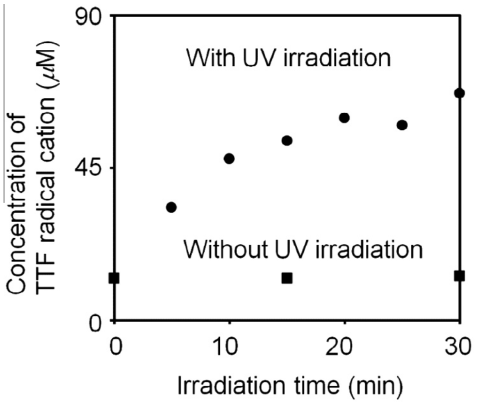


Figure 3. Time-courses of the concentration change of TTF radical cation in the samples containing 100 μM **7** and 600 μM TTF in acetonitrile. The samples were treated with or without UV irradiation at room temperature. The absorption changes at 434 nm are plotted.

The generation of TTF radical cation after UV irradiation was examined. The changes of UV–vis spectra were monitored after the photoreaction (yellow and light green lines in Fig. 2). From the sample with UV irradiation for 15 min, the increase of the absorption assigned as the generation of TTF radical cation was observed even under the dark conditions. On the other hand, the enhancement of the absorption was hardly obtained from the sample without UV irradiation. These data indicate that automatic amplification mechanism can work as programmed to produce the multiple acid molecules. To evaluate the acid release quantitatively, with or without UV irradiation to the sample, the concentration of the TTF radical cation was monitored (Fig. 4). At the initial state ($t = 0$), the generation of TTF radical cation with high concentration was already detected from the UV-irradiated sample. It is likely that UV irradiation for 15 min can induce the acid generation

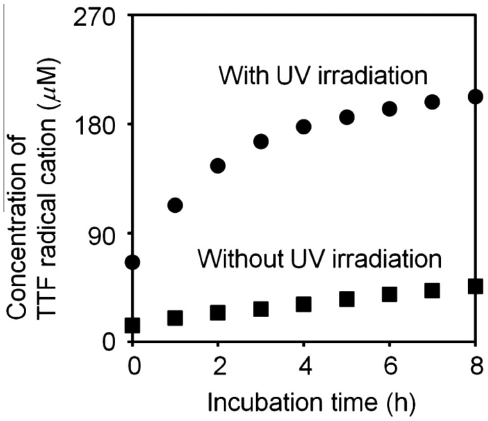


Figure 4. Time-courses of the concentration change of TTF radical cation in the samples containing 100 μM **7** and 600 μM TTF in acetonitrile. The samples were treated with or without UV irradiation for 15 min and incubated at room temperature. The absorption changes at 434 nm are plotted.

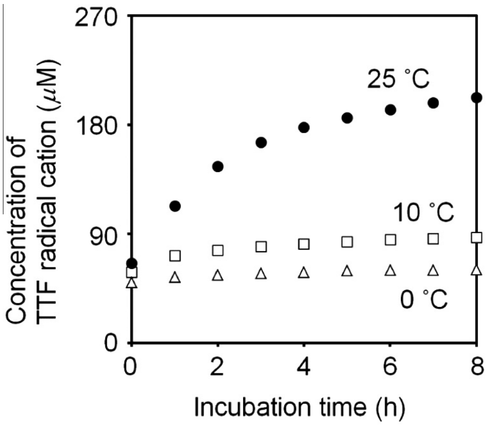


Figure 5. Influence of temperature on the concentration changes of TTF radical cation in the samples containing 100 μM **7** and 600 μM TTF in acetonitrile. The samples were treated with or without UV irradiation for 15 min and incubated at various temperatures. The absorption changes at 434 nm are plotted.

from **7**. This result also suggests that the first molecule should be immediately released after the photo-triggered elimination of the photo-cleavable group. The increase of the concentration of TTF radical cation was continuously observed from the UV-irradiated sample. This result means that the second and the third acid molecules should be gradually released. Since these intermediates such as the azaquinone methide species as proposed in Scheme 1 are stabilized in the organic solvent, the elimination rate decreases, comparing to that in water. [22–24] The concentration of TTF radical cation at the initial state (just after UV irradiation) was 66 μM. This means that the same amount of acid should be generated from UV irradiation. After 8 h incubation in the dark at room temperature, the concentration increased to 200 μM. This value was about three times larger than that at the initial state. These results strongly suggest that all photo-reacted compounds can finally release three equivalents of acid. From ^{1}H NMR measurements, compound **7** (1 mM) can be maintained in acetonitrile containing 1 mM methanesulfonic acid after 1 h incubation at room temperature.[25] These data indicate that UV irradiation should be triggered for the acid generation. In other words, the amount of acid produced from **7** can be restrictedly controlled by UV irradiation. In summary, it was proved that **7** can work as a photo acid generator with automatic amplification system.

Influence of the reaction temperature on the acid generation from **7** was investigated (Fig. 5). Under the same condition as above except for the solution temperature, the time-courses of the concentration changes of TTF radical cation were evaluated at various temperatures. By decreasing the reaction temperature, the rate of the concentration change was reduced. In particular, at 0 °C, the generation of TTF radical cation was largely suppressed. These data mean that the decrease of the reaction temperature can suppress the initial release of acid molecules. It is suggested that the control of the acid generation can be accomplished by temperature changes.

Finally, the acid generation with **7** followed by TTF radical cation was performed in the polymer matrix. The yellow-colored transparent films of PVP with TTF and **7** were prepared, and UV was irradiated at the left side of the film (Fig. 6). Apparently, the film color turned dark. From the absorption spectra, correspondingly the increase of the absorption band around 550 nm was observed after 7 h irradiation. These data indicate that the acid amplification system worked in the polymer matrix. The TTF radical cation can exist at least for two weeks in the films. Although the reaction efficiency decreased comparing to the solution states, it is likely that the accessibility between acid and TTF and TTF themselves should be restricted in the film state, and subsequently the protonation of TTF and the intermolecular electron transfer between the neutral TTF and the protonated TTF should be suppressed. The decrease of the absorption band around 450 nm was observed. It is presumed that the UV irradiation could induce the degradation of TTF radical cation.

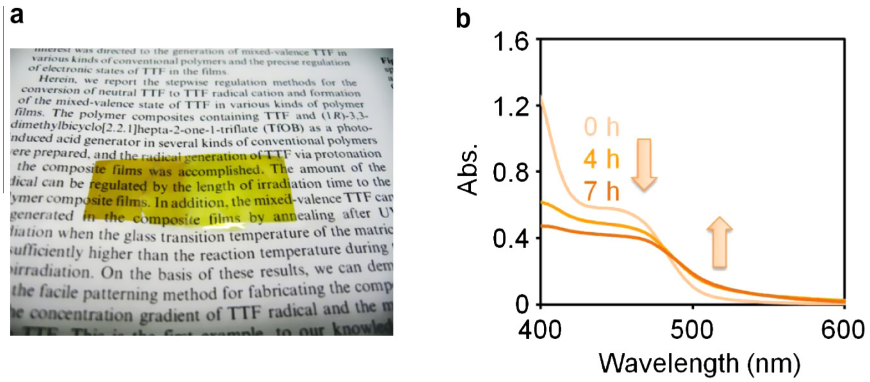


Figure 6. Acid generation in PVP films. (a) Appearance of the film with (left) or without (right) UV irradiation for 7 h at room temperature. (b) Time-course of the absorption change of the film by UV irradiation.

Conclusion

We demonstrate the radical generation via the amplification mechanism. As a result, from a single photon, three radicals can be obtained. This system is promised to be valid for preparing the stable materials with higher amount of spin sources. Furthermore, our photo acid generator involves many advantages in terms of a molecular release: (1) The multiple molecules can be released by the single photon. The maximum reaction quantum yield in our system can be theoretically three because of the amplified system. The effective molecular release is expected even with the weak incident light. (2) In addition, light-driven system is versatile for a wide variety of applications such as in biotechnology as well as in the circuit fabrication because the photoreaction can proceed with high time- and site-specificity without additives. (3) Molecular release can automatically proceed once the light is irradiated. The releasing molecules can be changed from acid. (4) Different from the conventional acid generators, our system can proceed without assistance of acid. Thereby, the amount of the released molecules can be regulated restrictedly. Moreover, by introducing or changing substituents, the tuning of the releasing rate or the light wavelength for the initiation can be tuned. Thus, our concept is also valid for developing the scaffold for light-driven molecular release system.

Acknowledgements

This work was partially supported by the Kansai Research Foundation for the promotion of technology (for K.T.). This work was partially supported by a Grant-in-Aid for Scientific Research on Innovative Areas 'New Polymeric Materials Based on Element-Blocks (No. 2401)' (25102521) of The Ministry of Education, Culture, Sports, Science, and Technology, Japan.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2014.01.092.

References and notes

1. Fahrenbach, A. C.; Bruns, C. J.; Cao, D.; Stoddart, J. F. *Acc. Chem. Res.* **2012**, *45*, 1581.
2. (a) Oyaizu, K.; Kawamoto, T.; Suga, T.; Nishide, H. *Macromolecules* **2010**, *43*, 10382; (b) Suga, T.; Ohshiro, H.; Sugita, S.; Oyaizu, K.; Nishide, H. *Adv. Mater.* **2009**, *21*, 1627; (c) Suga, T.; Sugita, S.; Ohshiro, H.; Oyaizu, K.; Nishide, H. *Adv. Mater.* **2011**, *23*, 751; (d) Inagi, S.; Naka, K.; Chujo, Y. *J. Mater. Chem.* **2007**, *17*, 4122.
3. Tanaka, K.; Ishiguro, F.; Chujo, Y. *Langmuir* **2010**, *26*, 1152.
4. Tanaka, K.; Ishiguro, F.; Chujo, Y. *Langmuir* **2010**, *26*, 10254.
5. (a) Tanaka, K.; Ishiguro, F.; Kunita, T.; Chujo, Y. *J. Polym. Sci. A: Polym. Chem.* **2009**, *47*, 6441; (b) Tanaka, K.; Matsumoto, T.; Nakamura, K.; Kawabe, S.; Chujo, Y. *Synth. Met.* **2013**, *180*, 49; (c) Tanaka, K.; Matsumoto, T.; Chujo, Y. *Synth. Met.* **2013**, *163*, 13; (d) Tanaka, K.; Matsumoto, T.; Ishiguro, F.; Chujo, Y. *J. Mater. Chem.* **2011**, *21*, 9603.
6. Tanaka, K.; Kunita, T.; Ishiguro, F.; Naka, K.; Chujo, Y. *Langmuir* **2009**, *25*, 6929.
7. (a) Crivello, J. V. *J. Polym. Sci. A: Polym. Chem.* **1999**, *37*, 4241; (b) Jeon, S.; Malyarchuk, V.; Rogers, J. A.; Wiederrecht, G. P. *Opt. Express* **2006**, *14*, 2300; (c) Kim, E. K.; Ekerdt, J. G.; Willson, C. G. *J. Vac. Sci. Technol., B* **2005**, *23*, 15154; (d) Moon, S.-Y.; Kim, J.-M. *J. Photochem. Photobiol., C* **2007**, *8*, 157.
8. (a) Wang, M.; Yueh, W.; Gonsalves, K. E. *J. Photopolym. Sci. Technol.* **2007**, *5*, 751; (b) Ito, H. *Adv. Polym. Sci.* **2005**, *172*, 37; (c) Ito, H. *J. Polym. Sci. A: Polym. Chem.* **2003**, *41*, 3863; (d) Asakura, T.; Yamato, H.; Ohwa, M. *J. Photopolym. Sci. Technol.* **2006**, *19*, 335.
9. (a) Pohlers, G.; Scaiano, J. C.; Sinta, R.; Brainard, R.; Pai, D. *Chem. Mater.* **1997**, *9*, 1353; (b) Schlegel, L.; Ueno, T.; Shiraishi, H.; Hayashi, N.; Iwayanagi, T. *Chem. Mater.* **1990**, *2*, 299.
10. (a) Sagi, A.; Weinstain, R.; Karton, N.; Shabat, D. *J. Am. Chem. Soc.* **2008**, *130*, 5434; (b) Meyer, Y.; Richard, J.-A.; Massoneau, M.; Renard, P. Y.; Romieu, A. *Org. Lett.* **2008**, *10*, 1517; (c) Blencowe, C. A.; Russell, A. T.; Greco, F.; Hayes, W.; Thornthwaite, D. W. *Polym. Chem.* **2011**, *2*, 773; (d) Grinda, M.; Clarhaut, J.; Renoux, B.; Tranoy-Opalinski, I.; Papot, S. *Med. Chem. Commun.* **2012**, *3*, 68.
11. Lindsay, D. M.; Dohle, W.; Jensen, A. E.; Kopp, F.; Knoche, P. *Org. Lett.* **2002**, *4*, 1819.
12. Lee, H. M.; Oberhuber, C.-N.; Shair, M. D. *J. Am. Chem. Soc.* **2008**, *130*, 16864.
13. Jacqueemard, U.; Bénéteau, V.; Lefoix, M.; Routier, S.; Mérour, J.-Y.; Coudert, G. *Tetrahedron* **2004**, *60*, 10039.
14. Mocanu, G.; Constantin, M.; Carpov, A. *Angew. Makromol. Chem.* **1996**, *241*, 4168.
15. Azumiya, I.; Kagechika, H.; Yamaguchi, K.; Shudo, K. *Tetrahedron* **1995**, *51*, 5277.
16. Kostianen, M. A.; Smith, D. K.; Ikkata, O. *Angew. Chem., Int. Ed.* **2007**, *46*, 7600.
17. Choi, S. K.; Thomas, T.; Li, M.-H.; Kotlyar, A.; Desai, A.; Baker, J. R., Jr. *Chem. Commun.* **2010**, 2632.
18. Griffin, D. R.; Patterson, J. T.; Kasko, A. M. *Biotechnol. Bioeng.* **2010**, *107*, 1012.
19. Kobayashi, Y.; Yoshioka, M.; Saigo, K.; Hashizume, D.; Ogura, T. *J. Am. Chem. Soc.* **2009**, *131*, 9995.
20. Giffard, M.; Alonso, P.; Garin, J.; Gorgues, A.; Nguyen, T. P.; Richomme, P.; Robert, A.; Roncali, J.; Uriel, S. *Adv. Mater.* **1994**, *6*, 298.
21. Hiinig, S.; KieJlich, G.; Quast, H.; Scheutzow, D. *Liebigs Ann. Chem.* **1973**, *2*, 310.
22. Erez, R.; Shabat, D. *Org. Biomol. Chem.* **2008**, *6*, 2669.
23. Weinstain, R.; Sagi, A.; Karton, N.; Shabat, D. *Chem. Eur. J.* **2008**, *14*, 6857.
24. Sagi, A.; Segal, E.; Satchi-Fainaro, R.; Shabat, D. *Bioorg. Med. Chem.* **2007**, *15*, 3720.
25. See Figure S1 in the Supporting information.