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Polymer surface patterning *via* Diels–Alder trapping of photo-generated thioaldehydes†

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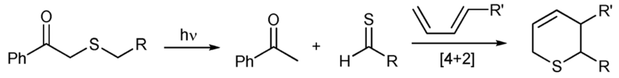
An efficient method for polymer surface patterning *via* Diels–Alder trapping of photo-generated thioaldehydes is presented. It is demonstrated that thioaldehyde end-groups generated by photolysis of phenacyl sulfides can be quantitatively trapped with various dienes. Poly(ethylene glycol) is immobilized on a surface in a spatially controlled fashion *via* irradiation through a shadow mask.

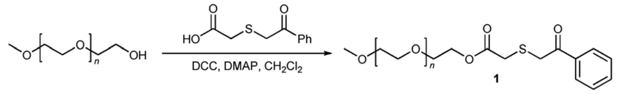
Spatially controlled functionalization of surfaces can be realized by employing photo-induced reactions. The immobilization of biomolecules such as carbohydrates,[1] proteins[2] and peptides[3] is of special interest within this context. Photoinitiated thiol–ene[4] and thiol–yne[5] reactions are common strategies for light-induced surface modifications. Spatial control of the popular copper catalyzed azide–alkyne *click* reaction was realized by photoreduction of Cu(II) to Cu(I).[6] In recent years, several methods for the light-induced formation of reactive groups on surfaces have been developed which avoid the loss of spatial resolution through diffusion of the photoactive component. Functional groups such as cyclooctynes,[7] nitrile imines,[8] oximes[9] and *o*-naphthoquinone methides[10] can be utilized for the highly efficient ligation of an appropriate reaction partner. We recently introduced a novel UV light-triggered *click* methodology *via* Diels–Alder conjugation of *o*-quinodimethanes (photoenols).[11] It was demonstrated in a recent publication that the photoenol strategy represents an efficient tool for spatially controlled surface (bio)functionalization.[3] Our group has also established hetero-Diels–Alder (HDA) reactions of thiocarbonyl compounds at ambient temperature as efficient conjugation tools.[12] Photofragmentation of phenacyl sulfides is a mild and efficient method for the preparation of highly reactive thioaldehydes which can be trapped *in situ* by various dienes to give the Diels–Alder adducts (Scheme 1).[13]

Herein, we demonstrate – for the first time – that the Diels–Alder trapping of photo-generated thioaldehydes represents an efficient method for spatially controlled (polymer) surface patterning. To perform model reactions in solution, phenacyl sulfide functionalized poly(ethylene glycol) (**1**) was synthesized by esterification with (phenacylthio)acetic acid (Scheme 2). A 36 W compact fluorescent lamp with an absorbance maximum of 355 nm was employed as a light source (see Fig. S2, ESI† for an absorption spectrum of **1** and an emission spectrum of the employed lamp).

Degassed solutions of **1** and 1.5 equivalents of various dienes (2,3-dimethyl-1,3-butadiene, *trans*,*trans*-2,4-hexadien-1-ol, cyclohexadiene, cyclopentadiene and *trans*,*trans*-2,4-hexadienoic acid) in dichloromethane were irradiated at ambient temperature and the progress of the reactions was monitored by electrospray ionization mass spectrometry (ESI-MS) as depicted in Fig. 1. Full conversion was achieved with all investigated dienes after 30 min irradiation (for a kinetic investigation of the reaction with *trans*,*trans*-2,4-hexadien-1-ol see Fig. S3, ESI†).



Scheme 1 Photolytic cleavage of phenacyl sulfides yielding acetophenone and thioaldehydes that can be trapped with a diene to give the Diels–Alder adduct.



Scheme 2 Synthesis of phenacyl sulfide functionalized PEG **1**.

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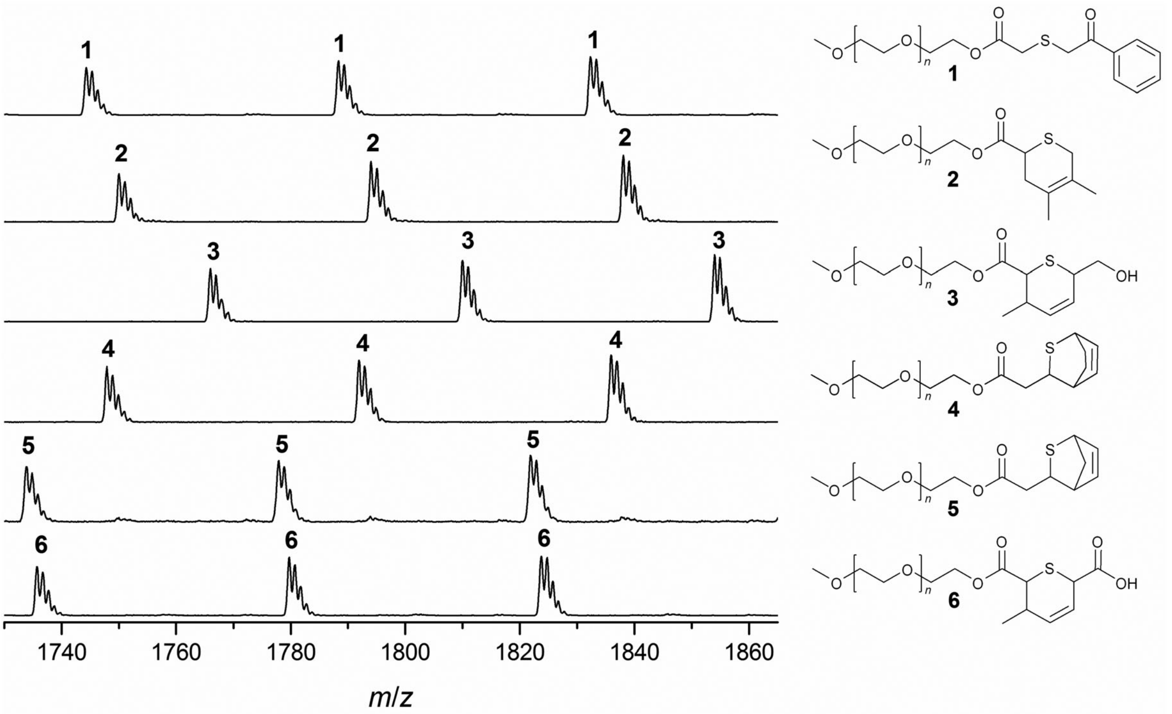

Fig. 1 ESI-MS spectra of phenacyl sulfide capped PEG (**1**) before and after 30 min irradiation with 2,3-dimethyl-1,3-butadien (**2**) *trans*,*trans*-2,4-hexadien-1-ol (**3**), cyclohexadiene (**4**), cyclopentadiene (**5**) and *trans*,*trans*-2,4-hexadienoic acid (**6**). Theoretical and measured *m*/*z*-ratios of all species are collated in Table S1 (ESI†) and are in excellent agreement with each other.

Inspection of Fig. 1 clearly indicates that close to quantitative formation of the thioaldehyde Diels–Alder adduct can be observed in all cases. It is noteworthy that not only donor-substituted dienes but even dienes bearing an electron-withdrawing group which decreases the Diels–Alder reactivity such as *trans*,*trans*-2,4-hexadienoic acid react in a quantitative fashion without any observable side products. The theoretical and measured *m*/*z*-ratios of the involved species collated in Table S1 (ESI†) are in excellent agreement. The ESI-MS investigation further demonstrates the tolerance of the method towards functional groups such as hydroxy- or carboxy-moieties. Previous investigations[13] including the synthesis of a natural product[14] and an acyl-CoA:cholesterol acyltransferase inhibitor[15] revealed the compatibility with other functional groups such as ethers, esters and amides.

When cyclopentadiene is employed as a diene a small amount of a side product (~10% peak intensity) occurs at 16 amu higher *m*/*z* ratios which may be assigned to oxidation of the thioether **5** to the corresponding sulfoxide.

To demonstrate the potential of the photo-HDA reaction for spatially controlled surface patterning, the phenacyl sulfide containing silane **7** was synthesized from (phenacylthio)acetic acid and commercially available (3-aminopropyl)triethoxysilane (see ESI† for details) and reacted with activated silicon wafers. Successful silanization was confirmed by X-ray photoelectron spectroscopy (XPS). Fig. 2a shows the C1s spectrum of a Si-wafer after silanization with **7**. The main peak in the C1s spectrum at 285.0 eV is assigned to hydrocarbon atoms (C–C, C–H), the component at 286.1 eV is attributed to C–N,[16] and the component at 288.2 eV can be assigned to the C=O groups,[16] both confirming successful silanization. The silicon wafers were subsequently immersed in a CH_2Cl_2 solution of cyclopentadienyl capped poly(ethylene glycol) (PEG-Cp) and irradiated for 60 min as depicted in Scheme 3. After the photo-reaction with PEG-Cp a new main peak at 286.6 eV reflecting the C–O binding energy[16,17] is present in the C1s spectrum (Fig. 2b). This finding indicates the coupling of PEG to the surface. It has to be noted that due to the high C–O intensity the weak C–N component is no longer distinguishable.

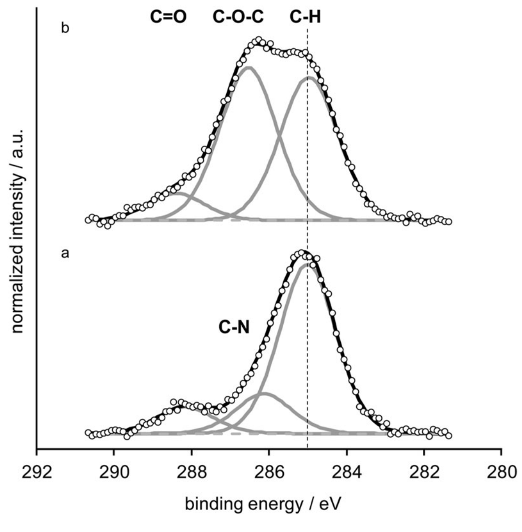

Fig. 2 Comparison of the C1s XPS spectra of Si wafers after silanization with **7** (a) and after subsequent photo-reaction with PEG-Cp (b). The spectra are normalized to maximum intensity.

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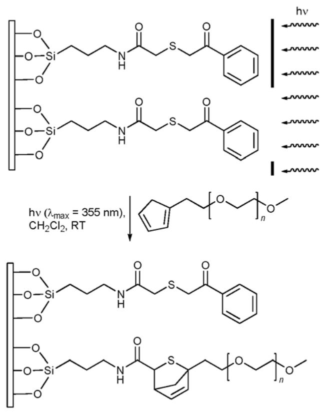

Scheme 3 Surface patterning *via* HDA trapping of photo-generated thioaldehydes with PEG-Cp.

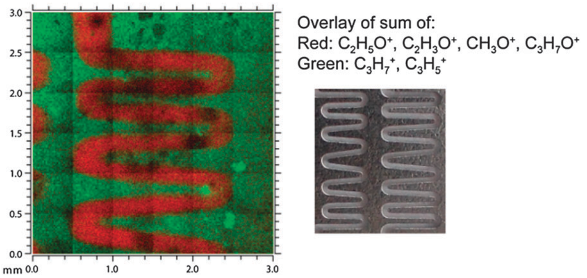

Fig. 3 ToF SIMS image of a silicon wafer patterned with poly(ethylene glycol) employing the shadow mask shown on the right. An overlay of positive secondary ions is depicted. Red: PEG fragments ($C_2H_5O^+$, $C_2H_3O^+$, CH_3O^+, and $C_3H_7O^+$), green: alkyl fragments ($C_3H_7^+$, $C_3H_5^+$).

To generate a polymer surface patterning, the silicon wafers were covered with a micropatterned shadow mask (Fig. 3) before irradiation. Analysis of the photo-patterning was conducted by time-of-flight secondary ion mass spectrometry (ToF-SIMS), which enables the spatially resolved analysis of molecular patterns on solid substrates.[18] Inspection of Fig. 3 clearly reveals that characteristic mass fragments of PEG ($C_2H_5O^+$, $C_2H_3O^+$, CH_3O^+, $C_3H_7O^+$) can only be found in the irradiated area thus confirming the site-specific immobilization of PEG-Cp.

In summary, we have shown that thioaldehyde polymer end-groups generated by photolysis of phenacyl sulfides can be quantitatively trapped in a Diels–Alder reaction employing different dienes. We have further demonstrated that the trapping of photo-generated thioaldehydes attached to a surface with a diene functionalized polymer enables a spatially controlled surface patterning. The extremely fast and efficient reaction and the straightforward synthesis of (phenacylthio)acetic acid make this method a convenient strategy for applications demanding a light-triggered reaction.

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