Self-Contained Photoacid Generator Triggered by Photocyclization of Triangle Terarylene Backbone

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S *Supporting Information*

ABSTRACT: We herein propose a new type of efficient neutral photoacid generator. A photoinduced 6π-electrocyclization reaction of photochromic triangle terarylenes triggers subsequent release of a Brønsted acid, which took place from the photocyclized form. A H-atom and its conjugate base were introduced at both sides of a 6π-system to form the *self-contained* photoacid generator. UV irradiation to the 6π-system produces a cyclohexa-1,3-diene part with a H-atom and a conjugate base on the sp^3 C-atoms at 5- and 6-positions, respectively, which spontaneously release an acid molecule quantitatively forming a polyaromatic compound. A net quantum yield of photoacid generation as high as 0.52 under ambient conditions and a photoinitiated cationic polymerization of an epoxy monomer are demonstrated.

Photoacid generators (PAGs) have been widely used for a vast range of practical applications including microlithographic imaging with photoresists, photocuring, and rapid-prototyping (3D printing), in which PAGs are employed as a phototrigger of cationic polymerization.[1−3] In recent works, use was also found for photodynamic therapy[4] and photocontrol of enzymatic acitivity.[5] Onium salt type PAGs such as diphenyliodonium and triarylsulfonium salts have been at the forefront for more than 30 years since they were developed by Crivello.[6] More recently, chemical modifications to the substituents of the onium derivatives sensitized them to the visible range and two-photon activation.[7−10] Nonionic type PAGs represented by *N*-oxyimidesulfonate derivatives have also been in use for many years.[11,12] Both the onium salt type and nonionic type PAGs undergo homolytic bond cleavage reaction after light irradiation.[2,12] Photogenerated radical species need to extract a H-atom from solvent molecules or other H-sources to generate a Brønsted acid, which gives rise to medium-dependent sensitivity and complicated fragments remaining in the systems. A number of caged compounds with photoremovable protecting groups such as *ortho*-nitrobenzyl and benzoin derivatives release Brønsted acids.[13] The nitrobenzyl derivatives[13,14] were also used for a photolithographic application, while the quantum yield of photoacid release was relatively small.[15] Although the benzoin derivatives show good quantum yields for release of carboxylic

acids as high as 0.6,[13] the acid release processes often require an external proton source such as protic solvents.[13] To our best knowledge, there has been no report on PAGs which exhibit a photoacid release with high quantum efficiency over 0.5 based on a self-contained unimolecular system.

We herein propose a PAG based on a self-contained mechanism for acid generation. A chemical reaction for acid generation is combined with a photochromic reaction. Although there have been several examples of pK_a change of acidic groups combined with photochromism of diarylethenes[16] and spiropyrans,[17] the intended release of acid molecules has never been discussed. Among various photochromic systems, 6π-electrocyclization is known to proceed efficiently even in solid state for diarylethenes and their aromatic analogues,[18,19] which is coupled with acid release as a subsequent reaction. A number of chemical reactions[20−25] were integrated with the 6π-based photoreactions. The change in electron-delocalization state upon photoirradiation also induced the change in Lewis acidity of boron[26] or imidazolium[24] moiety. Meanwhile, the 6π-cyclization reaction followed by the oxidative dehydrogenation was classically used for the formation of aromatic (poly)cycles including helicenes.[27] However, their use from the viewpoint of acid generation has so far been ignored. Hydrogen and its conjugate base (X) are herein introduced at both ends of the 6π-system (Scheme 1). The 6π-

## Scheme 1. Photoacid Generation Reaction Proposed in the Present Work
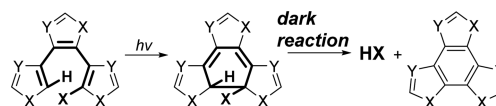
system undergoes pericyclization reaction to form a cyclohexa-1,3-diene moiety with a hydrogen (H) and conjugate base (X) pair at adjacent positions upon photoirradiation. The photoproduced cyclized compound is expected to show spontaneous elimination of an acid molecule (HX) in dark conditions, producing a chemically definable and stable fused polycycle with four aromatic rings.

1a (Scheme 2) was designed based on a photochromic bis(thiazolyl)benzothiophene molecule with methyl groups on

Scheme 2. Synthesis of PAG-1a[a]
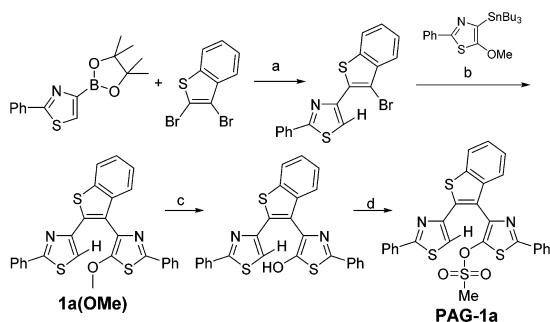
[a]Reagents and conditions: (a) PPh$_3$ (0.11 mol equiv), Pd(PPh$_3$)$_4$ (0.074 mol equiv), 2 M K$_3$PO$_4$ aq./1,4-dioxane; (b) Pd(PPh$_3$)$_4$ (0.070 mol equiv), CsF (2.3 mol equiv), toluene; (c) BBr$_3$ (5.0 mol equiv), dichloromethane; (d) MsCl (2.2 mol equiv), NEt$_3$, dichloromethane.

Scheme 3. Photochromism of 1a–3a, and Photogated Elimination Reaction of 1a and 2a
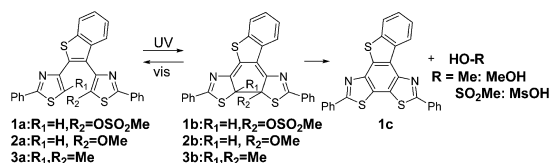
both photoreactive carbons (**3a** in Scheme 3) which showed ultimate sensitivity to UV light, giving a photon-quantitative electrocyclization reaction.[19] A H-atom and mesylate group were introduced at both ends of the 6π-system in **1a** as leaving substituents. The sequence controlled Pd-catalyzed aryl–aryl cross-coupling reactions between aromatic components using the position dependent reactivity of benzothiophene led to the synthesis of **2a**. The methoxy group of **2a** was deprotected to a hydroxyl group by BBr$_3$, and a subsequent esterification with mesyl chloride (MsCl) gave **1a** (Scheme 2). In principle, types of acids can be incorporated in this esterification process.

2a showed a reversible photochromic reaction in dry hexane as depicted in Scheme 3 with absorption spectral change accompanying isosbestic points (at 340 and 265 nm), which indicates a two-component photochromic reaction[18] (Figure 1). Upon UV irradiation, the colorless solution of **2a** with an
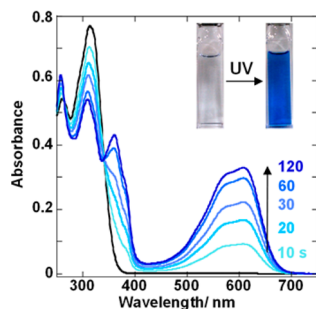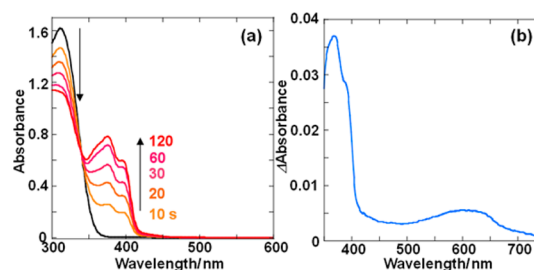

Figure 1. Absorption spectral change of **2a** by UV (313 nm) irradiation in dry hexane (2.3 × 10^{-5} M).

absorption maximum at 314 nm ($\varepsilon = 3.3 \times 10^4$ cm^{-1} M^{-1}) gave a colored solution of **2b** with a new band at 608 nm ($\varepsilon = 1.8 \times 10^4$ cm^{-1} M^{-1}). The quantum yield of the ring-cyclization reaction with irradiation at 313 nm was estimated to be 0.64 for **2a** in dry hexane. X-ray crystallographic analysis of **2a** revealed that **2a** possesses a photochromic reactive conformation in crystal with quasi-C_2 symmetry around the central hexatriene backbone, which is stabilized via S−N and CH−N interactions[19] between the central and both side units (Figure S1). Although the photochromic reactive conformation in the single crystal was stabilized in a similar manner to **3a**, the ring-cyclization efficiency was decreased from **3a** of 0.98. The chemical structures of **2a** and **3a** differ only in substituents on the reactive C-atoms at both ends of the 6π-system (Scheme 3). Therefore, the decrease in the ring-cyclization efficiency could be attributed to the absence of CH−π interactions between methyl groups and the opposing thiazolyl rings in solution.

UV irradiation to the **2a** solution in polar solvents such as methanol gave irreversible photobleaching reaction. The blue-colored isomer decomposed spontaneously in the dark (Figure S2). The decomposed product was isolated by HPLC, and its chemical structure was determined to be **1c** by ^{1}H NMR and X-ray crystallography (Figures S3, S4). It should be noted that the decomposition of **2b** indeed took place very slowly in hexane too. The polar solvent or the presence of acid could facilitate the elimination reaction via the E1-mechanism, stabilizing the carbocation intermediate.[20]

We then investigated the photoreaction of PAG **1a** with a mesylate (OMs) group at a reactive C-atom. Due to the limited solubility of **1a** in hexane, the photoreaction was investigated in toluene. Unlike **2a**, the UV irradiation to the **1a** solution in toluene gave a pale yellowish solution with an absorption maximum at 375 nm and no absorption above 450 nm, which never reverted to the colorless state with visible irradiation (Figure 2a). Given the formation of closed-ring isomer **1b** as a


Figure 2. (a) Absorption spectral change of **PAG-1a** by UV (313 nm) irradiation in toluene (4.7 × 10^{-5} M) under the ambient conditions. (b) Differential absorption spectrum upon UV irradiation for 3 min to **PAG-1a** in 2-MeTHF at 77 K.

primary photoproduct, it should have given an absorption band at around 600 nm, since **1b** has a similar π-system to that of **2b** (Scheme 3). However, the spectral profile after UV irradiation was identical with that of isolated **1c** (Figure S5). Interestingly, the spectral change of **1a** to **1c** accompanied an isosbestic point at 345 nm, indicating a quasi-two-components reaction system with a quantitative and immediate conversion from **1b** to **1c** even in the low-polar medium. The net photochemical quantum yield from **1a** to **1c** was estimated to be 0.52 under ambient conditions, which is among the highest values for neutral PAGs so far reported[8] but dropped to 0.40 and 0.32 in tetrahydrofran (THF) and methanol, respectively. The decrease of the quantum yields

with decreasing the solvent polarity is consistent with the previous result of **3a**, where the hydrogen bonding like CH-N interaction plays a certain role to support the photoreactive conformation.[19] However, it should be noted that the similar quasi-two-components reaction was observed regardless of solvents (Figure S6). Furthermore, since the photochemical pericyclization reaction proceeds purely through the singlet state, but neither triplet state nor radicals is involved, it is free from oxygen-sensitivity.[18,28]

The photoreaction of **1a** was also monitored by ^{1}H NMR spectral change in toluene-d_8 (Figure 3; also see Figure S7 for
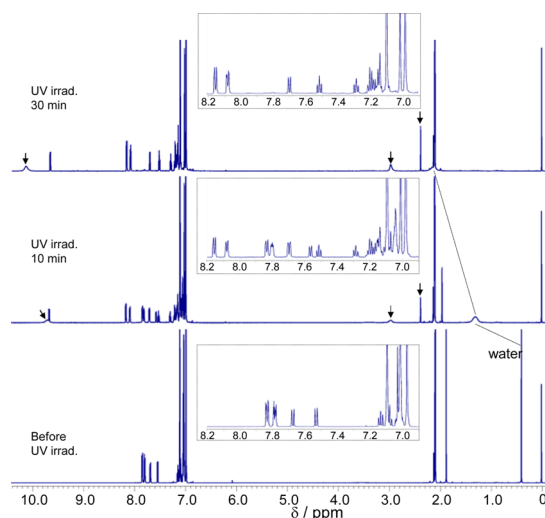

Figure 3. ^{1}H NMR spectral change of **1a** upon UV (365 nm) irradiation in toluene-d_8 (Inset: enlarged charts of aromatic region).

more details including peak assignment). Owing to the low solubility of the produced **1c**, the measurements were performed at 323 K. **1a** gave a singlet peak at 1.87 ppm corresponding to the methyl protons in the OMs group. The UV irradiation to the toluene-d_8 solution in an NMR tube diminished this peak and three peaks appeared (indicated by arrows), which originated from MsOH dispersed in toluene-d_8. The peaks at 2.36 and 2.96 ppm may correspond to methyl protons, and the broad peak above 9.5 ppm could be assigned to the OH proton in MsOH (see Figure S7). Meanwhile, the water signal shifted downfield with broadening, indicating the interaction between residual water and the released MsOH. In the aromatic region, all peaks showed downfield shifts and the chart of the final state was identical with that of **1c** with a characteristic doublet peak at 9.6 ppm. Thus, ^{1}H NMR monitoring clearly suggested the generation of MsOH and the polycycle **1c**. Similarly, the formation of **1b** could not be recognized by ^{1}H NMR. The absence of spectral evidence for the formation of closed ring isomer **1b** indicated that the acid generation from **1b** to **1c** was energetically favored and proceeded quantitatively.

To confirm the trace of the formation of **1b** after UV irradiation, transient absorbance was monitored at 630 nm in a nanosecond laser flash photolysis measurement. The observed transient absorbance at 630 nm was, however, attributed to the decay of the triplet state of **1c** (Figures S8, S9) based on an O-quenching experiment, indicating the rapid conversion of **1b** to **1c** at least within 10 ns. The photoreaction of **1a** was then conducted at low temperature in a glass matrix of 2-methyltetrahydrofuran. Since the conversion rate of the photoreaction was low at 77 K, a differential absorption spectrum upon

the UV irradiation is shown in Figure 2b. The differential absorption profile highlights the formation of a colored species with an absorption band at 600 nm, which was similar to that for **2b** (Figure 1). Furthermore, the visible absorption band was in good agreement with the calculated one based on the optimized geometry of **1b** (Figure S10), indicating transient formation of **1b**.[28] Interestingly, the slight increase in temperature to 90 K diminished the trace of the formation of photoisomer **1b**. The photoirradiation to **1a** at 90 K directly gave the absorption spectrum of **1c** (Figure S11). The significantly short lifetime of **1b** is not ascribed to the backward reaction to **1a**, of which rate constant should be smaller than 10^{-6} s^{-1} with high thermal stability of the ring-closed form of diarylethene derivatives.[18] This kinetic consideration also supports the quantitative conversion of photochemically formed **1b** to **1c** accompanying the acid generation.

The elimination reaction from **1b** to **1c** is most likely to proceed through the carbocation intermediate **1b**$^+$ (Figure 4).[20b]
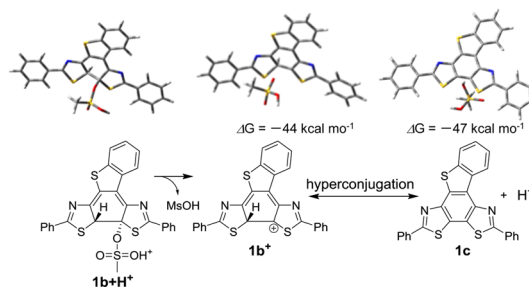

Figure 4. Acid-releasing reaction of **1b** together with optimized structures of each state.

The free energy of each state was calculated by the DFT method using the Gaussian 09 suite.[30] For the calculations of geometry optimization and subsequent frequency calculations, the CAM B3LYP functional[31] with the 6-31G(d,p) basis set was employed (Figure S12). Solvent polarity was taken into account by using the IEFPCM (solvent = methanol).[32] The carbocation intermediate **1b**$^+$ was estimated to have high stability with a relative energy of −44 kcal mol^{-1} to the proton adduct of **1b** (**1b** +**H**$^+$) which was assumed as an active substance. The arenium cation **1b**$^+$ has a coplanar structure with an extended conjugation, which is typically indicated by the sum of inner angles of the central six-membered ring of 719°. The hyperconjugation of the vicinal C−H group vertically bound to the polycyclic π-plane may also stabilize **1b**$^+$ (Figure 4).[33] The further elimination of the proton should be driven by the formation of an aromatic polycyclic **1c** with a relative energy of −3 kcal mol^{-1} to that of the **1b**$^+$ state. The elimination reaction should be catalyzed efficiently not only by free H$^+$[20b] but also by any proton-donating substance such as H$_2$O and ROH, which may facilitate the elimination of the acid group through H-bonding. Moreover, the photo-generated acid at the early stage could catalyze the subsequent elimination reaction, providing an autocatalytic photoacid generation system.

Finally, **1a** was demonstrated as a photoinitiator for the cationic polymerization of cyclohexene oxide in a preliminary photopolymerization experiment (see Scheme 4). UV irradiation to the deaerated dry solution of cyclohexene oxide with 0.2 mol % of **1a** in a glass tube triggered the polymerization of monomers with the formation of **1c**. The mixture after the UV irradiation was characterized with MALDI-MS. A periodic pattern of mass peaks with the difference in m/z of 98 clearly demonstrated the

Scheme 4. Reaction Scheme of Photoinduced Cationic Polymerization of Cyclohexene Oxide
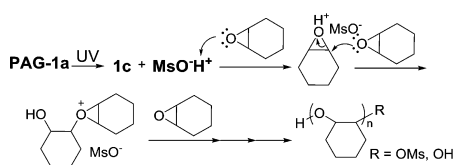
successful progress of photoinduced cationic polymerization of cyclohexene oxide (Figure S13) by the newly developed **1a**.

In summary, we propose a new type of self-contained proton-releasing PAG utilizing an efficient 6π-photocyclization reaction and a subsequent quantitative acid releasing reaction. Optimization of molecular design based on supramolecular interaction to support a photoreactive conformation[19] would lead to a further increase in the quantum yield of acid generation. Chemical modifications toward the two-photon photochromism[34] would also pave the way to efficient 3D lithography. Moreover, the reaction leaves a stable, chemically definable and fluorescent fused aromatic polycycle, which could be exploited for the synthesis of helicenes and π-stacked carrier transporting self-assembling nanowires with high spatiotemporal control.

■ ASSOCIATED CONTENT

ⓢ Supporting Information

Experimental details, crystallographic analysis of **2a**, characterization of **1c**, detailed study on photoreaction of **1a**, photopolymerization of cyclohexene oxide, and complete ref 30. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b02826.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

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