Photoswitching Tripodal Single Molecular Tip for Noncontact AFM Measurements
–Synthesis, Immobilization, and Reversible Configurational Change on Gold Surface–

Supporting Information

Daiko Takamatsu, Ken-ichi Fukui, Safwan Aroua, and Yoko Yamakoshi

Department of Chemistry, Graduate School of Science, Tokyo Institute of Technology, 2-12-1
Ookayama, Meguro-ku, Tokyo 152-8551, Japan

Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka
University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan

PRESTO, Japan Science and Technology Agency, 4-1-8 Honcho Kawaguchi, Saitama 332-0012, Japan

Department of Radiology and Department of Chemistry, University of Pennsylvania, 231 South 34th
Street, Philadelphia PA 19104-6323

*Corresponding Authors.

Yoko Yamakoshi, e-mail: Yoko.Yamakoshi@uphs.upenn.edu, yamakoshi@org.chem.ethz.ch

Ken-ichi Fukui, e-mail: kfukui@chem.es.osaka-u.ac.jp

SYNTHESIS OF MOLECULAR TIPS A AND B

General. Melting points were recorded on a melting point apparatus MP-21 (Yamato Scientific Co.,
Ltd., Tokyo, Japan) and uncorrected. The $^1$H- and $^{13}$C-NMR spectra were recorded on a Mercury plus
400 (Varian Inc., CA, USA) or an AL300 (JEOL Ltd., Tokyo, Japan) in CDCl$_3$ (Merck KGaA,
Darmstadt, Germany) with the residual solvent peaks ($^1$H CHCl$_3$, δ 7.26; $^{13}$C CHCl$_3$, δ 77.0) as internal
standards unless otherwise noted. Mass spectra were obtained via FAB-MS and MALDI-TOF-MS and
recorded on a JMS-700 (JEOL Ltd.) and an AB4700 (Applied Biosystems Japan Ltd., Tokyo, Japan) or a
Bruker MALDI-TOF-TOF (Bruker, Billerica, MA, USA). IR spectra were recorded on an FT/IR-460 plus
(JASCO Co., Tokyo, Japan). UV-Vis absorption spectra were recorded in CH$_2$Cl$_2$ on a UV-265
(SHIMADZU Co., Kyoto, Japan). Column chromatography was carried out on silica gel Wakogel®
C-200 (200 mesh, Wako Pure Chemical Industries, Ltd.), and thin-layer chromatography was carried out
on silica plate Partisil® PK6F (16.0 nm, layer thickness 1000 µm, Whatman plc, Middlesex, UK).
Analytical TLC was performed on commercially coated plastic plates Silica gel 60 mesh F$_{254}$, (Merck
KgaA). All reagents were purchased from commercial suppliers as described and used without further
purification. Tetrahydrofuran (99.5%, anhydrous, inhibitor free, Kanto Chemical Co., Inc., Tokyo,
Japan), triethylamine, dichloromethane, diethyl ether (Wako Pure Chemical Industries, Ltd., Osaka, Japan), and the other reagent-grade solvents (CHCl₃, CH₃OH, benzene, and hexane, Kanto Chemical Co., Inc.) were used as received.

**Fig. S-1** Synthetic plan for photoswitching molecular tripods A and B.

### 1. Synthesis of a phenylacetylene leg part.

**Scheme S-1**

```
S1 Br
\[\text{KSAc, DMA, rt, 1 h, 90\%}\] S2 SAc
\[\text{TMS, Pd(PPh}_3\text{)}_2\text{Cl}_2, \text{PPh}_3, \text{Cul, Et}_3\text{N, THF, 40 }\degree\text{C, 1 day, 61\%}\] S3 SAc
\[\text{Bu}_4\text{NF, THF, }-20\degree\text{C, 30 min, 83\%}\]
```

Reagents and conditions: (i) KSAc, DMA, rt, 1 h, 90%; (ii) TMSA, Pd(PPh₃)₂Cl₂, PPh₃, Cul, Et₃N, THF, 40 °C, 1 day, 61%; (iii) Bu₄NF, THF, −20 °C, 30 min, 83%.

**S-4-Iodobenzyl ethanethioate (S2)**¹ To a solution of 1-(bromomethyl)-4-iodobenzene (S1, 4.34 g, 14.6 mmol, Wako Pure Chemical Industries, Ltd.) in anhydrous N,N-dimethyl acetamide (14 mL, Kanto Chemical Co., Inc.), potassium thioacetate (1.98 g, 17.4 mmol, Wako Pure Chemical Industries, Ltd.) was added. The mixture was stirred for 1 hour at room temperature under Ar atmosphere, and subsequently poured into water and extracted with CH₂Cl₂. The combined organic extracts were washed with brine,

dried over anhydrous MgSO₄ and concentrated in vacuo. The resulting brown oil was purified by silica gel column chromatography with hexanes–CH₂Cl₂ (10:1) to give yellow oil S₂ (3.82 g, y = 90%): Rₛ 0.8 (hexane–EtOAc (2:1)); mp 40–41 °C; ¹H NMR (400 MHz, CDCl₃) δ 2.35 (s, 3H, CH₃), 4.04 (s, 2H, CH₂), 7.04 (d, J = 8.4 Hz, 2H, ArH), 7.62 (d, J = 8.4 Hz, 2H, ArH); FT-IR (KBr, cm⁻¹): 3323(s), 2985(m), 2968(s), 2310(w), 1902(s), 1671(s, C=O), 1482(m), 1398(s), 1355(s), 1306(m), 1137(m), 1106(m), 1007(m), 960(m), 884(w), 827(s), 744(s), 635(m), 530(w), 491(s).

![Diagram]

**S₄–[(Trimethylsilyl)ethynyl]benzyl ethanethioate (S₃).** A mixture of S₂ (3.50 g, 11.9 mmol), dichlorobis (triphenylphosphine)-palladium(II) (Pd(PPh₃)₂Cl₂, 99.99%, 0.42 g, 0.6 mmol, Sigma–Aldrich Co., St. Louis, MO), and triphenyl phosphine (PPh₃, 99%, 78.5 mg, 0.3 mmol, Sigma–Aldrich Co.) in a Schlenk flask was degassed and replaced with Ar for three times. The Ar flow rate was increased, the threaded stopcock was removed, and THF (30 mL), trimethylsilylacetylene (TMSA, 2.6 ml, 18.1 mmol, Tokyo Chemical Industry Co., Ltd., Tokyo, Japan) and triethylamine (Et₃N, 3.35 mL, 18.1 mmol, Wako Pure Chemical Industries, Ltd.) were added in succession by gastight syringes. After repetition of freeze-pump-thaw for three times, copper (I) iodide (CuI, 99.999%, 27.6 mg, 0.15 mmol, Sigma–Aldrich Co.) was added. The reaction mixture was stirred at 40 °C for one day under Ar atmosphere, then poured into water and extracted with CH₂Cl₂. The combined organic extracts were washed with brine, dried over anhydrous MgSO₄ and concentrated in vacuo. The resulting orange-brown oil was purified by silica gel column chromatography with hexane–EtOAc (10:1) to give yellow solids S₃ (2.15 g, 61%): Rₛ 0.7 (hexane–EtOAc (2:1)); mp 39–40 ºC; ¹H NMR (400 MHz, CDCl₃) δ 0.25 (s, 9H, TMS), 2.35 (s, 3H, –CH₃), 4.09 (s, 2H, –CH₂–), 7.21 (d, J = 8.4 Hz, 2H, ArH), 7.39 (d, J = 8.4 Hz, 2H, ArH).

---

S-4-Ethynylbenzyl ethanethioate (3). A 1.0 M solution of tetrabuthylammonium fluoide trihydrate (Bu₄NF, 1.32 g, 4.2 mmol, Wako Pure Chemical Industries, Ltd) in THF (4.2 mL) was added to a stirred solution of S3 (1.0 g, 3.8 mmol) in THF (10 mL) at –20 ºC in dropwise over 30 min. The reaction mixture was stirred for 30 min at –20 ºC under Ar atmosphere and subsequently was poured into water and extracted with CH₂Cl₂. The combined organic extracts were washed with brine, dried over anhydrous MgSO₄ and concentrated in vacuo. The resulting orange oil was purified by silica gel column chromatography with hexane–EtOAc (2:1) to give orange oil 3 (0.60 g, 83%): R_f 0.6 (hexane–EtOAc (2:1)); ¹H NMR (400 MHz, CDCl₃) δ 2.35 (s, 3H, –C₃H₃), 3.06 (s, 1H, ˷C₃H), 4.09 (s, 2H, –C₂H₂–), 7.24 (d, J = 8.4 Hz, 2H, ArH), 7.42 (d, J = 8.4 Hz, 2H, ArH).
II. Synthesis of an adamantane core part.

Scheme S-2

Reagents and conditions: (i) t-BuBr, AlCl₃, PhH, reflux, 2 h; (ii) [bis(trifluoroacetoxy)iodo]benzene, I₂, CHCl₃, rt, 24 h, 13% (2 steps); (iii) TMSA, Pd(PPh₃)₂Cl₂, PPh₃, Et₃N, Cul, THF, reflux, 4 days, 85%; (iv) Pd(PPh₃)₂Cl₂, PPh₃, Cul, Et₃N, THF, reflux, 5 days, 20%; (v) Bu₄NF, THF, –20 ºC, 30 min, 56%.

1,3,5,7-Tetrakis(4-iodophenyl)adamantane (1).³ To a solution of 1-bromoadamantane (S4, 3.00 g, 13.9

mmol, Tokyo Chemical Industry CO., Ltd.) in benzene (30 mL), t-BuBr (3.2 mL, 27.9 mmol, Wako Pure Chemical Industries, Ltd.) and AlCl₃ (160 mg, 1.2 mmol, Sigma-Aldrich Co.) were added and the reaction mixture was refluxed for 2 hours. The mixture was then cooled to room temperature and filtered and subsequently the obtained residue was washed with benzene (20 mL), water (20 mL) and CHCl₃ (50 mL). The residue was dried and purified by washing with CHCl₃ in Soxhlet apparatus for 24 hours. The insoluble residue was dried to give 1,3,5,7-tetrakis(4-iodophenyl)adamantane as colorless solids (2.7 g). To a suspension of 1,3,5,7-tetrakis(4-iodophenyl)adamantane (1.00 g) in CHCl₃ (25 mL), iodine (1.15g, 4.53 mmol) was added then the reaction mixture was stirred at room temperature until all iodine was dissolved. Subsequently the [bis(trifluoroacetoxy)iodo]benzene (PhI(OCOCF₃)₂, 1.95 g, 4.5 mmol, Wako Pure Chemical Industries, Ltd.) was added and resulting suspension was stirred for 24 hours at room temperature under Ar atmosphere. After removal of a pink solid by filtering reaction suspension, the filtrate (CHCl₃ solution) was washed with 5% aqueous NaHCO₃ (50 mL), water (50 mL) and brine (50 mL). The organic layer was dried over anhydrous MgSO₄ and concentrated to dryness giving crude mixture (colorless solids, 2.1 g) which was crystallized from CHCl₃–MeOH (9:1) to give colorless crystals 1 (0.65 g, 13.4%): mp >250 °C; ¹H NMR (400 MHz, CDCl₃) δ 2.06(s, 12H, adamantane CH₂), 7.18 (d,  J = 8.8 Hz, 8H, ArH), 7.67 (d,  J = 8.6 Hz, 8H, ArH); FT-IR (KBr, cm⁻¹): 3073(w), 2928(s), 2851(m), 1897(w), 1485(s), 1444(w), 1392(m), 1355(w), 1181(w), 1066(w), 1002(s), 890(w), 819(s), 777(s), 711(w), 659(w), 555(w), 524(m). Anal. Calcd for C₃₄H₂₈I₄: C, 43.25; H, 2.99; Found: C, 43.26; H, 2.97.

Fig. S-4 ¹H NMR spectrum of 1.
Fig. S-5 FT-IR spectrum of 1.

Trimethyl[4-[3,5,7-tris(4-iodophenyl)adamantan-1-yl]phenylethynyl]silane (2).

Fig. S-6 $^1$H NMR spectrum of 2.
Fig. S-7 $^1$H-$^1$H COSY spectrum of 2.

Fig. S-8 $^{13}$C NMR spectrum of 2.
Fig. S-9 FT-IR spectrum of 2.

Fig. S-10 FAB-MS spectrum of 2.
III. Conjugation of legs and an adamantane core.

\[
\text{Pd(PPh₃)₂Cl₂, PPh₃, Et₃N, CuI, reflux, 5 days, Ar, 20%}
\]

\[
\text{Trimethyl[4-[3,5,7-tris-[4-(4-acetylsulfanyl)methylphenylethylnyl]phenyl]adamantan-1-yl]phenylethynyl]silane (4).}
\]

Fig. S-11 \textsuperscript{1}H NMR spectrum of 4.
Fig. S-12. $^{13}$C NMR spectrum of 4.

Fig. S-13 FT-IR spectrum of 4.
4-[3,5,7-Tris-[4-(4-acetylsulfanyl)methylphenylethynyl]phenyl]adamantan-1-yl]phenylethyne (5).

**Fig. S-14** $^1$H NMR spectrum of 5.

**Fig. S-15** FT-IR spectrum of 5.
**Fig. S-16** MALDI-TOF-MS spectrum of 5.

**IV. Syntheses of azobenzene apex parts**

<table>
<thead>
<tr>
<th>Scheme S3</th>
<th>Scheme S4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Scheme S3" /></td>
<td><img src="image" alt="Scheme S4" /></td>
</tr>
</tbody>
</table>

Reagents and conditions: (i) MnO₂, PhH, reflux, 4 h, 49%; (ii) TMSA, Pd(PPh₃)₂Cl₂, PPh₃, Cul, Et₃N, THF, reflux, 2 days, 48%; (iii) CH₃OH, c.H₂SO₄, reflux, 38 h, 93%; (iv) Oxone®, CH₂Cl₂, water, rt, 1 h, 95%; (v) 4-iodoaniline, acetic acid, rt, 1 day, 76%.
(E)-1,2-Bis(4-bromophenyl)diazene (7).

Fig. S-17 $^1$H NMR spectrum of 7.

Fig. S-18 FT-IR spectrum of 7.
(E)-1-(4-Bromophenyl)-2-[4-[(trimethylsilyl)ethynyl]phenyl]diazene (8).

Fig. S-19 $^1$H NMR spectrum of 8.

Fig S-20 $^{13}$C NMR spectrum of 8.
Fig. S-21 FT-IR spectrum of 8.

Fig. S-22 FAB-MS spectrum of 8.
Methyl 4-aminobenzoate (10).^4

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{\textbf{1H NMR spectrum of 10.}}
\end{figure}

Methyl 4-nitrosobenzoate (11).^5

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{\textbf{1H NMR spectrum of 11.}}
\end{figure}

Fig. S-25 FT-IR spectrum of 11.

(E)-Methyl 4-[(4-iodophenyl)diazenyl]benzoate (12).\(^5\)

Fig. S-26 \(^1\)H NMR spectra of 12.
Fig. S-27 $^{13}$C NMR spectrum of 12.

Fig. S-28 FT-IR spectrum of 12.

Fig. S-29 FAB-MS spectrum of 12.
**Fig. S-30** UV–Vis absorption spectrum of azobenzene 12 in CH₂Cl₂. Black line: spectra of initial and after Vis light (450 ±10 nm) irradiation. Colored lines: spectra after UV light (360 ±10 nm) irradiation.

**V. Synthesis of photoswitching tripod 13**

![Chemical structure of tripod 13](image)

**Fig. S-31** $^1$H NMR spectrum of 13.

**Fig. S-32** $^{13}$C NMR spectrum of 13.

**Fig. S-33** FT-IR spectrum of 13.
**Fig. S-34** MALDI-TOF-MS spectrum of 13.

**Fig. S-35** Differential UV–Vis spectrum of 13.
VI. Synthesis of photoswitching tripod 14

(E)-Methyl

![Image of synthetic reaction and product structure]

Fig. S-36 ¹H NMR spectrum of 14.
Fig. S-37 $^{13}$C NMR spectrum of 14.

Fig. S-38 FT-IR spectrum of 14.

Fig. S-39 FAB-HR-MS spectra of 14.
Fig. S-40 Differential UV–Vis spectrum of 13.

Fig. S-41 MALDI-TOF-MS spectrum of 13.