## An Unpaired Electron-Based Hole-Transporting Molecule: Triarylamine-Combined Nitroxide Radicals

5 Takashi Kurata<sup>a</sup>, Kenichiroh Koshika<sup>a</sup>, Fumiaki Kato<sup>a</sup>, Junji Kido<sup>b</sup> and Hiroyuki Nishide<sup>\*a</sup>

<sup>a</sup> Department of Applied Chemistry, Waseda University, Tokyo 169-8555, Japan <sup>b</sup> Department of Polymer Science and Engineering, Yamagata University, Yonezawa 992-8510, Japan

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(2.1) Synthesis of *N*,*N*-*Bis*(4-methoxyphenyl)-4-(*N*'-t-butyl-*N*'-oxyamino)phenylamine **1** 



 $N, N-Bis (4-methoxy phenyl) - 4 - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl siloxy) amino) phenylamine \ {\bf 4} - (N'-t-butyl-N'-(t-butyl dimethyl silox) amino) phe$ 

4-Bromo-(*N-t*-butyl-*N*-(*t*-butyldimethylsiloxy))aniline (2.30 g, 6.41 mmol) and *N*, *N*-bis (4-methoxyphenyl)amine (1.46 g, 6.37 mmol) were dissolved in toluene (16.0 ml). To this solution,  $Pd_2(dba)_3$  (dba: dibenzylideneacetone, 0.073 mg, 0.080 mmol), NaO-*t*-C<sub>4</sub>H<sub>9</sub> (1.23 g, 12.8 mmol), and

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tri-*t*-butylphosphine (0.049 g, 0.240 mmol) were added and stirred at 90°C for 12 h under argon. The resulting solution was concentrated, then extracted with ether and water. The ether layer was dried over 35 sodium sulfate, and concentrated. The residue was chromatographed on deactivated silica-gel (hexane/ethylacetate, 3/1) to yield a yellowish oil (2.60 g). Yield 81%. δ<sub>H</sub>(500 MHz; CDCl<sub>3</sub>), -0.10 (s, 6 H, SiCH<sub>3</sub>), 0.88 (s, 9 H, Si*t*-Bu), 1.08 (s, 9 H, *t*-Bu), 3.78 (s, 6 H, OCH<sub>3</sub>), 6.79-6.82 (m, 6 H, Ar), 6.99-7.00 (m, 4 H, Ar), 7.03-7.04 (br, 2 H, Ar); δ<sub>C</sub>(125 MHz; CDCl<sub>3</sub>) -4.7, 18.0, 26.2, 31.6, 55.5, 60.7, 68.0, 114.5, 120.5, 125.8, 141.6, 144.6, 145.4, 155.3; MS *m*/*z* (EI) 506 [M]<sup>+</sup>, C<sub>30</sub>H<sub>42</sub>N<sub>2</sub>O<sub>3</sub>Si requires 40 506.3; Found: C, 71.2; H, 8.2; N, 5.6. C<sub>30</sub>H<sub>42</sub>N<sub>2</sub>O<sub>3</sub>Si requires C, 71.1; H, 8.4; N, 5.5.

N,N-Bis(4-methoxyphenyl)-4-(N'-t-butyl-N'-oxyamino)phenylamine 1

To a solution of **4** (0.480 g, 0.948 mmol) in 138 ml of THF was added tetrabutylammonium fluoride (7.23 g, 27.7 mmol), which was then stirred for 3 h under argon. To this solution, 3.2 g (13.8 mmol) of Ag<sub>2</sub>O was added, and the mixture was stirred for 11 h. The solution was filtered, and the 45 filtrate was evaporated. The crude product was purified by the chromatography on deactivated silica gel with hexane/ethylacetate (5/1 v/v) to afford a red powder (257 mg). Yield 69%. S m/z (EI) 391 [M]<sup>+</sup>, C<sub>24</sub>H<sub>27</sub>N<sub>2</sub>O<sub>3</sub> requires 391.5; IR(NaCl, cm<sup>-1</sup>) 1585, 1504 1240, 1184, 1034, 827, 579, 530; ESR g = 2.0060, triplet,  $a_{\rm N} = 1.30$  mT; Found: C, 73.2; H, 7.0; N, 6.8. C<sub>24</sub>H<sub>27</sub>N<sub>2</sub>O<sub>3</sub> requires C, 73.6; H, 6.9; N, 7.2.

50 (2.2) Synthesis of  $N-\{4-(N'-t-Butyl-N'-oxyamino)phenyl\}-N-(4-methoxyphenyl)-4-(1-oxyl-3-int)-4-(1-oxyl-$ 

oxide-4,4,5,5-tetramethylimidazolin-2-yl)phenylamine 3



2-(4-Bromophenyl)-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine 5

A solution of 2,3-bis(hydroxyamino)-2,3-dimethylbutane sulfate (5.35 g, 21.7 mmol) and K<sub>2</sub>CO<sub>3</sub> (15.0 g, 109 mmol) in methanol (73 ml) was stirred for 30 min under argon. 4-Bromobenzaldehyde 60 (2.00 g, 10.8 mmol) was added to this solution and stirred for 24 h at room temperature. The mixture was filtered and washed with ether. The filtrate was evaporated to afford a yellow-oil which was dissolved in ether, and then washed with water. The organic layer was dried over sodium sulfate. After concentration under vacuum, ethanol and benzene were added to the residue, and the resultant precipitate was filtered to afford a colorless powder (1.94 g). Yield 57%. *δ*<sub>H</sub> (500 MHz; DMSO-*d*<sub>6</sub>), 65 1.02 (*s*, 6 H, CH<sub>3</sub>), 1.06 (*s*, 6 H, CH<sub>3</sub>), 4.47 (s, 1 H, C*H*), 7.41 (d, 2 H, *J* = 9.0 Hz, Ar), 7.50 (d, 2 H, *J* = 8.0 Hz, Ar), 7.76 (s, 2 H, OH); *δ*<sub>C</sub>(125 MHz; DMSO-*d*<sub>6</sub>), 17.2, 24.7, 66.1, 89.5, 120.2, 128.2, 130.4, 141.4; FAB MS *m*/z 315 [M]<sup>+</sup>, C<sub>13</sub>H<sub>19</sub>BrN<sub>2</sub>O<sub>2</sub> requires 315.2; Found: C, 49.7; H, 5.9; N, 8.9.

2-(4-Bromophenyl)-1,3-bis(t-butyldimethylsiloxy)-4,4,5,5-tetramethylimidazolidine 6

A DMF solution (27.8 ml) of 5 (3.50 g, 11.1 mmol), *t*-butyldimethylsilyl chloride (8.35 g, 55.5 mmol), and imidazole (7.55 g, 111 mmol) was stirred for 24 h at 50°C. After condensation of the solution under vacuum, the crude product was extracted with ether, and washed with water. The ether layer was dried over magnesium sulfate, and concentrated under reduced pressure. The residue was chromatographed on silica gel with hexane as the eluent to give a white powder (4.79 g). Yield 79%.
δ<sub>H</sub>(500 MHz; CDCl<sub>3</sub>), -0.86 (s, 6 H, SiCH<sub>3</sub>), -0.06 (s, 6 H, SiCH<sub>3</sub>), 0.77 (s, 18 H, Si-*t*-Bu), 1.13 (s, 12 H, CCH<sub>3</sub>), 4.55 (s, 1 H, CH), 7.23 (d, 2 H, *J* = 8.0 Hz, Ar), 7.40 (d, 2 H, *J* = 8.0 Hz); δ<sub>C</sub>(125 MHz; CDCl<sub>3</sub>), -5.0, -3.8, 17.1, 17.9, 24.8, 26.2, 68.0, 93.6, 121.8, 130.7, 132.4, 140.7; MS *m*/z 544 [M+1]<sup>+</sup>, 542 [M-1]<sup>+</sup>, C<sub>25</sub>H<sub>47</sub>BrN<sub>2</sub>O<sub>2</sub>Si<sub>2</sub> requires 543.7; Found: C, 55.2; H, 8.9; N, 5.1, C<sub>25</sub>H<sub>47</sub>BrN<sub>2</sub>O<sub>2</sub>Si<sub>2</sub> requires C, 55.2; H, 8.7; N, 5.1.

80 N-(4-(1,3-Bis(t-butyldimethylsiloxy)-4,4,5,5-tetramethylimidazolidin-2-yl)phenyl)-4-methoxyphenylami

ne **7** 

A solution of **6** (5.00 g, 9.20 mmol), *p*-methoxyaniline (1.53 g, 12.4 mmol), Pd<sub>2</sub>(dba)<sub>3</sub> (0.104 g, 0.114 mmol), (*S*)-BINAP (0.214 g, 0.344 mmol) and NaO-*t*-C<sub>4</sub>H<sub>9</sub> (1.78 g, 18.5 mmol) in 15.4 ml of toluene was refluxed for 18 h under argon. After removal of the solvent under vacuum, the crude was 85 dissolved in ether and washed with water. The organic layer was dried over sodium sulfate, and concentrated under vacuum. The residue was chromatographed on silica gel with hexane/ethylacetate (9/1 v/v) as the eluent to afford a yellow oil (4.50 g). Yield 83%. *δ*<sub>H</sub>(500 MHz; CDCl<sub>3</sub>), -0.74 (s, 6 H, SiCH<sub>3</sub>), -0.03 (s, 6 H, SiCH<sub>3</sub>), 0.80 (s, 18 H, Si-*t*-Bu), 1.15 (s, 12 H, CCH<sub>3</sub>), 3.79 (s, 3 H, OCH<sub>3</sub>), 4.53 (s, 1 H, CH), 5.44 (s, 1H, NH), 6.83-6.84 (m, 4 H, Ar), 7.02 (d, 2 H, *J* = 9.0 Hz, Ar), 7.20 (d, 2 H, *J* = 90 9.0 Hz, Ar); FAB MS *m*/z 586 [M]<sup>+</sup>, C<sub>32</sub>H<sub>55</sub>N<sub>3</sub>O<sub>3</sub>Si<sub>2</sub> requires C, 65.6; H, 9.5; N, 7.2.

*N-(4-(1,3-Bis(t-butyldimethylsiloxy)-4,4,5,5-tetramethylimidazolidin-2-yl)phenyl)-N-(4-bromophenyl)-4-methoxyphenylamine* **8** 

A solution of **7** (4.50 g, 7.68 mmol), *p*-dibromobenzene (2.89 g, 12.3 mmol), Pd<sub>2</sub>(dba)<sub>3</sub> (0.093 mg, 95 0.102 mmol), (*S*)-BINAP (0.190 g, 0.305 mmol) and NaO-*t*-C<sub>4</sub>H<sub>9</sub> (1.18 g, 12.3 mmol) in 16.4 ml of toluene was refluxed under an argon atmosphere for 42 h. After removal of the solvent, the crude product was dissolved in ether and washed with water. The organic layer was dried over sodium sulfate and concentrated. The residue was purified by a chromatography on silica gel with hexane/ethylacetate (99/1 v/v) as the eluent to give a white powder (2.30 g). Yield 40%. *δ*<sub>H</sub>(500 MHz; CDCl<sub>3</sub>) -0.71 (s, 6 H, 100 SiCH<sub>3</sub>), -0.02 (s, 6 H, SiCH<sub>3</sub>), 0.81 (s, 18 H, Si-*t*-Bu), 1.14 (s, 12 H, CCH<sub>3</sub>), 3.79 (s, 3 H, OCH<sub>3</sub>), 4.56 (s, 1 H, CH), 6.80-6.86 (m, 4 H, Ar), 6.97-7.00 (m, 4 H, Ar), 7.24-7.27 (m, 4 H, Ar); *δ*<sub>C</sub>(125 MHz; CDCl<sub>3</sub>) -5.0, -3.8, 17.1, 17.9, 24.8, 26.2, 55.4, 67.7, 93.4, 113.2, 114.7, 122.3, 123.4, 123.6, 126.6, 128.9, 131.8, 140.5, 147.4, 147.5, 156.0; FAB MS *m*/*z* 740 [M]<sup>+</sup>, C<sub>38</sub>H<sub>58</sub>BrN<sub>3</sub>O<sub>3</sub>Si<sub>2</sub> requires 742.0; Found: C, 62.0; H, 8.15; N, 5.60, C<sub>38</sub>H<sub>58</sub>BrN<sub>3</sub>O<sub>3</sub>Si<sub>2</sub> requires C, 61.6; H, 7.9; N, 5.7.

105 N-(4-(1,3-Bis(t-butyldimethylsiloxy)-4,4,5,5-tetramethylimidazolidin-2-yl)phenyl)-N-[4-(N'-t-butyl-N'oxyamino)phenyl]-4-methoxyphenylamine **9** 

*t*-Butyl lithium (1.47 mmol) in hexane (1.6 M, 0.99 ml) was added to the ether solution (4.0 ml) of **8** (0.500 g, 0.675 mmol) at -78 °C under argon, and then the solution was stirred for 0.5 h. To the solution, 2-methyl-2-nitrosopropane (0.093 g, 1.07 mmol) in ether (2.1 ml) was added, and the reaction 110 mixture was stirred for 17 h at room temperature. To this solution, silver[I]oxide (0.156 g, 0.674 mmol) was added and the mixture was stirred for 0.5 h. The solution was filtered, and the insoluble part was washed with ether. After concentration of the filtrate under vacuum, the residue was dissolved in ether followed by washing with water. The ether layer was dried over sodium sulfate, and concentrated under vacuum. The crude product was chromatographed on triethylamine-mediated silica 115 with hexane/ethylacetate (4/1 v/v) as the eluent to afford a red powder (0.180 g). Yield 36%. FAB MS *m*/*z* 748 [M]<sup>+</sup>, C<sub>42</sub>H<sub>67</sub>N<sub>4</sub>O<sub>4</sub>Si<sub>2</sub> requires 748.2; IR(NaCl, cm<sup>-1</sup>) 2950, 2933, 2858, 1587 1506, 1463, 1437, 1384, 1340, 1317, 1244, 1157, 1038, 953, 831, 781; ESR *g* = 2.0052, triplet, *a*<sub>N</sub> = 1.30 mT; Found: C, 67.4; H, 9.1; N, 7.5, C<sub>42</sub>H<sub>67</sub>N<sub>4</sub>O<sub>4</sub>Si<sub>2</sub> requires C, 67.4; H, 9.0; N, 7.5.

*N-{4-(N'-t-Butyl-N'-oxyamino)phenyl}-N-(4-methoxyphenyl)-4-(1-oxyl-3-oxide-4,4,5,5-tetramethylimid* 120 *azolin-2-yl)phenylamine* **3** 

To a THF solution (4.8 ml) of **9** (0.360 g, 0.481 mmol) was added tetrabutylammonium fluoride (0.628 g, 2.40 mmol), and the solution was stirred for 1 h. Sodium periodate (0.108 g, 0.507 mmol) in water (2 ml) was added to the solution, and the mixture was stirred for 0.5 h. After concentration under vacuum, the residue was dissolved in ether and washed with water. The organic layer was dried over 125 sodium sulfate, and the solvent was evaporated. The crude product was purified by flash-chromatography on deactivated silica gel with hexane/ethylacetate (2/1 v/v) as the eluent to give a deep purple powder (0.113 g). Yield 46%. FAB MS m/z 519 [M+2H]<sup>+</sup>, C<sub>30</sub>H<sub>30</sub>N<sub>4</sub>O<sub>4</sub> requires 516.8; IR(NaCl, cm<sup>-1</sup>) 2992, 1604, 1585, 1506, 1417, 1388, 1362, 1319, 1292, 1242, 1134, 1082, 1034, 829, 538; ESR(THF, rt): g = 2.0057, Lorentzian line width: 0.29, <sup>14</sup>N hyperfine splitting parameter (spin,

130 number): 0.653 mT (1, 1), 0.381 mT (1, 2); Found: C, 69.3; H, 7.4; N, 10.7, C<sub>30</sub>H<sub>30</sub>N<sub>4</sub>O<sub>4</sub> requires C,

69.6; H, 7.2; N, 10.8.

(2) ESR spectra during electrochemical oxidation of the diradical 3

Fig.S1 shows the ESR spectra changes of 3 during the electrochemical oxidation. Potentials in each

electrochemical measurement were referenced to the ferrocene/ferrocenium couple.



145 Fig.S1 ESR signal changes during electrochemical oxidation of the diradical 3 in a CH<sub>2</sub>Cl<sub>2</sub> solution (0.1 M (C<sub>4</sub>H<sub>9</sub>)<sub>4</sub>NBF<sub>4</sub>,).

(3) SQUID measurements of the diradiclal 3

Fig. S2 shows the magnetization plots and  $\chi T$  vs *T* plots of **3** in polystyrene. The  $\chi T$  vs *T* plots were fitted to the Bleaney-Bowers expression<sup>1</sup>:  $\chi_{mol}T = N_b g^2 \mu_B^2 T/k \{3 + \exp(-2J/kT)\}(T-\theta)$ , where,  $N_b$ , g,  $\mu_B$ , and  $k_B$  are the molar of the spin sites, *g*-factor, Bohr magneton and Boltzmann constant. The exchange coupling parameters for **3** were estimated to be J/k = 26.1 K and  $\theta = -0.20$  K.



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**Fig. S2** (a)  $\chi_{mol}T$  vs *T* plots of the diradical **3** and theoretical curve calculated by the Bleaney-Bowers expression (solid line), and (b) normalized magnetization plots of **3** diluted in polystyrene. 1.9 (closed circle), 3(open square), 5 K (open diamond) with theoretical Brillourin curves for S = 1/2 (dashed line), 2/2 (solid line), and 3/2 (dotted line).

## (4) J-E Characteristics of the hole-only devices

Current density-electric field characteristics of the hole-only devices, 165 ITO/radical:polycarbonate/Au, are given in Fig. S3.



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**Fig. 3** Current density vs electric field plots for the monoradical **1** (closed circle), **2** (closed square) and the diradical **3** (open circle) in polycarbonate [ITO/radical: polycarbonate (150 nm)/Au (200 nm)].

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(5) J-L-V Characteristics of the organic light-emitting diode

The current density-voltage and luminance-voltage characteristics of the organic light-emitting diodes, ITO/copper phthalosyanine (CuPc):polycarbonate/*N*, *N*'-di(1-naphthyl)-*N*, *N*'-diphenyl-(1, 1'-biphenyl)-4, 4'-diamine (NPD)/tris(8-hydroxyquinoline) aluminum (Alq<sub>3</sub>)/Ca/Al are shown in

180 Fig.S4. The CuPc molecule was dissolved in the THF solutions of the polycarbonate at 1.6 mmol/g

ratio. The device emitted yellowish-green light ( $\lambda_{max} = 520 \text{ nm}$ ) derived from the Alq<sub>3</sub> layer.



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**Fig. S4** Current density-luminance-voltage characteristics of the OLED device with the configuration of ITO/CuPc:polycarbonate (20 nm)/NPD (40 nm)/Alq<sub>3</sub> (60 nm)/Ca (20 nm)/Al (100 nm).

(6) Materials and measurements

190 2,3-Bis(hydroxyamino)-2,3-dimethylbutane

sulfate,<sup>2</sup>

4-bromo-*N*-*t*-butyl-*N*-(*t*-butyldimethylsiloxy)phenylamine,<sup>3</sup>

N-t-butyl-N-(4-t-butylphenyl)-N-oxyamine<sup>4</sup> and tris(4-methoxyphenyl)amine<sup>5</sup> were synthesized according to the literature. Deactivated silica gel was prepared by treatment with triethylamine followed by washing with eluents.

<sup>195</sup> The <sup>1</sup>H- and <sup>13</sup>C-NMR spectra were obtained using a JEOL lambda 500 or a Bruker AVANCE-600 spectrometer. The ESR, MS and FAB-MS spectra were recorded using a JEOL JES-TE200 ESR, a Shimadzu DC-MS 17A and a JEOL JMS-SX102A spectrometer, respectively.

The electrochemical measurements were carried out in a 0.1 M (C<sub>4</sub>H<sub>9</sub>)<sub>4</sub>NBF<sub>4</sub>-CH<sub>2</sub>Cl<sub>2</sub> solution. The working and counter electrodes were a platinum disk and a platinum wire. The cyclic voltammetry was 200 performed in the presence of a Ag/AgCl reference electrode using a BAS 100B/W electrochemical analyzer. The electrolytic ESR measurements were carried out with a silver wire as a quasi-reference electrode using a Nikko Keisoku NPGS-301 potentiogalvanostat and a JEOL JES-TE200 ESR spectrometer, and potentials were carefully referenced to the ferrocene/ferrocenium redox potential.

The magnetization and static magnetic susceptibility were measured using a Quantum Design

205 MPMS-XL SQUID magnetometer. The magnetization was measured from 0.1 to 7 T at 1.9, 3 and 5 K. The static magnetic susceptibility was measured from 2 to 240 K in a magnetic field of 0.5 T.

The *J-E* characteristics were obtained using a Keithley 2400 Source Meter. The polycarbonate films containing a radical (1.6 mmol/g) were prepared by spin coating of the THF solutions on ITO glass substrates (Asahi Glass. Co.), followed by removal of the solvent under vacuum (40°C, 30 min). 210 The aluminum cathode was vapor-deposited on the organic layers at a pressure of  $2 \times 10^{-5}$  Torr. The organic films for the time-of-flight measurement were prepared on an ITO substrate by drop-casting of the THF solutions (1.6 mmol radical/g polycarbonate). For the control device, the content of the dispersed hole-transporting molecules in polycarbonate, tris(4-methoxyphenyl)amine/*N-t*-butyl-*N*-(4-*t*-butylphenyl)-*N*-oxyamine/polycarbonate, was 0.8 215 mmol/0.8 mmol/1.0 g. After removal of the solvent under vacuum for 30 min at 40°C, CuPc (100 nm)

- and a semi-transparent aluminum anode (20 nm) were vapor-deposited on the organic film. The time-of-flight measurement was carried out using a TOF 401 instrument (Sumitomo Heavy Industries Advanced Machinery, Co.). All time-of-flight measurements provided typical dispersed transient photocurrent signals, and the mobility at room temperature was calculated using the equation,  $\mu = 220 d/t_{tr} \cdot E$ , where *d*,  $t_{tr}$  and *E* represent the thickness, transient time and electric field, respectively. The transition time ( $t_{tr}$ ) was determined from the inflection point in the double-logarithmic plots as a
  - function of time and hole-drift mobility.
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