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SYNTHESIS AND PHOTOPHYSICAL PROPERTIES OF 5-*N*-ARYLAMINOTHIAZOLES WITH SULFUR-CONTAINING GROUPS ON THE AROMATIC RING AT THE 2-POSITION

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Abstract – 5-Amino-2-(4-methylsulfanylphenyl)thiazoles were prepared by reacting 4-methylsulfanylbenzthioamides and *N*,*N*-diarylthioformamides. Demethylaiton of the resulting thiazoles gave 4-sulfhydrylphenylthiazoles. Starting from these thiazoles, a range of thiazoles with sulfur-containing functional groups were prepared. Oxidation of the thiazoles also gave thiazoles with sulfenyl and sulfonyl groups. The photophysical properties of a series of thiazoles were determined. The effects of sulfur-containing functional groups on the electronic structures of the thiazoles were elucidated by DFT calculations. Oxidation of the divalent sulfur atoms introduced to thiazoles helped to lower the energy levels of the LUMOs of the resulting thiazoles.

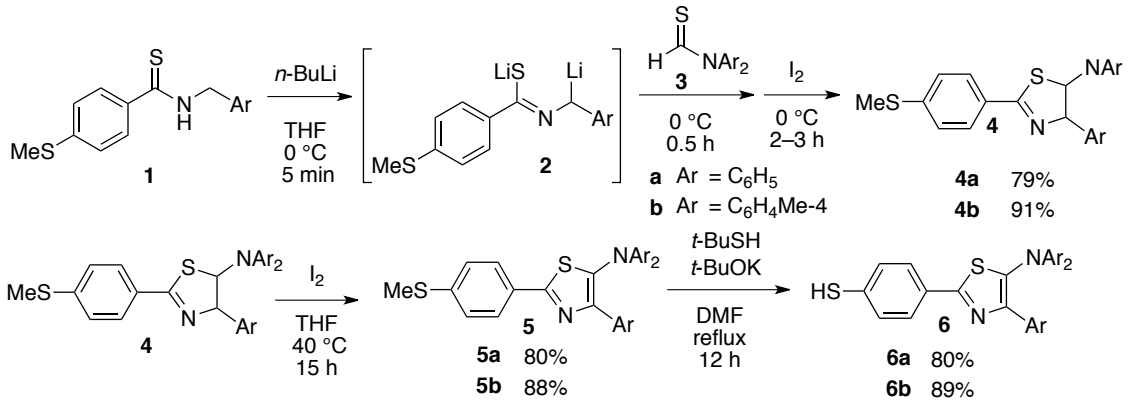
INTRODUCTION

The development of a wide range of fluorescent molecules is of paramount importance since they have been shown to be useful in a variety of applications in the material sciences,[1] in the sensing of hazardous compounds and metals,[2] and in the biomolecular sciences.[3] Most low-molecular-weight fluorescent compounds possess ring-fused polycyclic aromatic moieties. In contrast, we have focused on monocyclic aromatic compounds that have thiazole cores.[4] In particular, we recently established synthetic methods for compounds with *N*-arylamino groups at the 5-position of thiazoles[5] in a series on main group chemistry.[6] We also determined their fundamental photophysical properties[5b] and used them in white-light emission,[7] the generation of radical cations showing near-infrared absorption,[8] and the detection of halogenated solvents via vapochromic behaviors.[9] In some cases, pyridyl groups were used as anchor moieties to interact with Lewis acidic compounds. Sulfur-containing functional groups may be useful as alternative anchor moieties, since thiols and sulfonic acids[10] are acidic and nucleophilic, and the sulfur atom can be

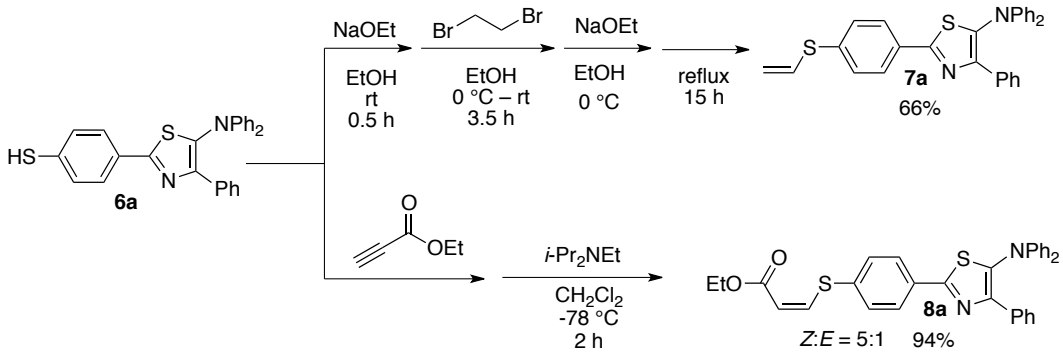
di-, tetra-, or hexavalent. We report herein the synthesis and properties of 5-*N*-aminothiaozoles with sulfur-containing groups on the aromatic ring at the 2-position. Their photophysical properties and electronic structures are also described.

RESULTS AND DISCUSION

5-Amino-2-(4-methylsulfanylphenyl)thiazoles **5** were prepared according to our previous synthetic methods (Scheme 1).[5a,b] Thioamides **1** initially reacted with BuLi to generate thioamide dianions **2**. *N*,*N*-Diarylthioformamides **3** were added to the resulting solution, and treatment with iodine gave thiazolines **4**. Oxidation of the isolated **4** with iodine proceeded smoothly to give the expected thiazoles **5** in high yields. Demethylation of **5** was achieved by reacting it with *t*-BuSH and *t*-BuOK[11] to give thiols **6**.



Scheme 1. Synthesis of 2-(4-mercaptophenyl)-5-aminothiazoles

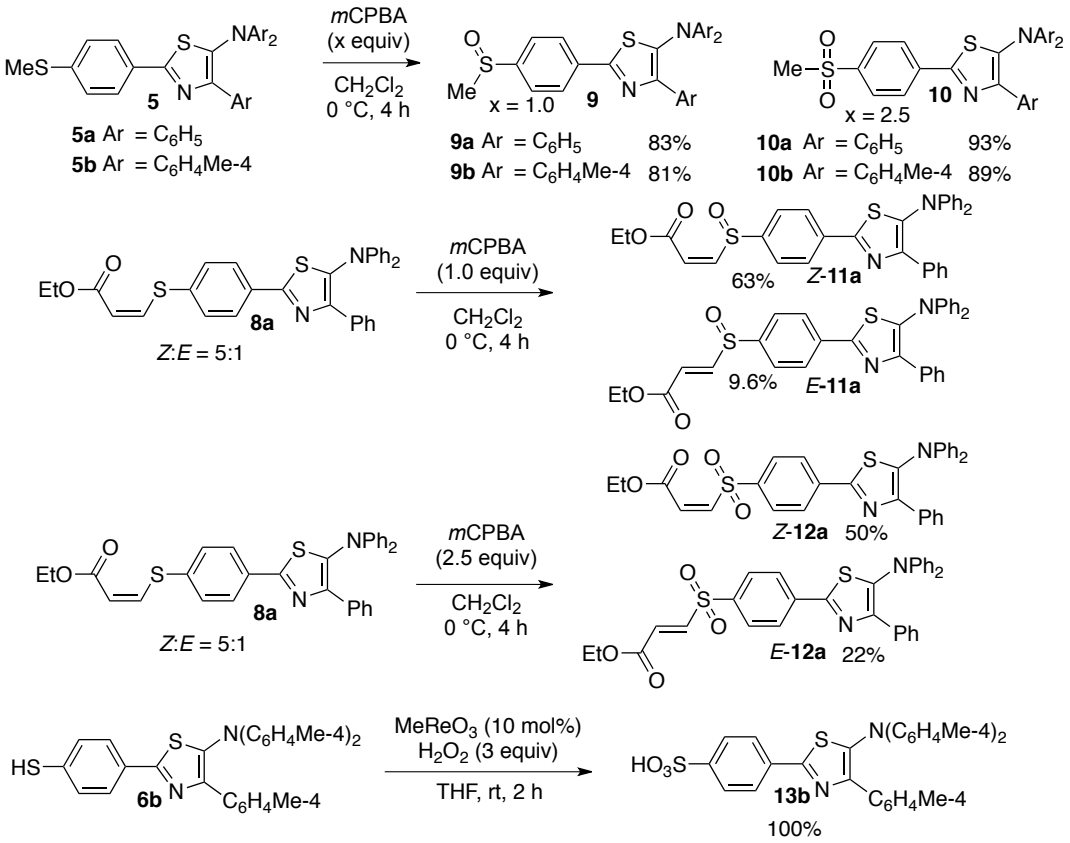


Scheme 2. Synthesis of 2-(4-enesulfanylphenyl)-5-aminothiazoles

To determine the effect of the substituents on the sulfur atom on photophysical properties, alkenyl groups were attached to the sulfur atom (Scheme 2). Thiol **6a** reacted with 1,2-dibromoethane, and the elimination of HBr gave *S*-ethenyl derivative **7a**.[12] The direct addition of **6a** to ethyl propiolate[13] also took place with high efficiency to give **8** with a *Z*:*E* selectivity of 5:1.

Finally, the resulting sulfanylthiazoles **5**, **6**, and **8a** were oxidized (Scheme 3). *m*-Chloroperoxybenzoic acid (*m*CPBA) worked very well to oxidize **5** and **8a** to selectively give sulfoxides **9** and **11a** and sulfones

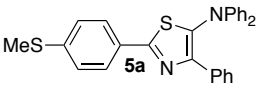
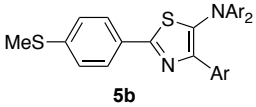
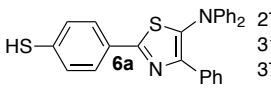
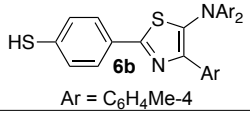
10 and **12a**, depending on the amount of *m*CPBA used. The starting **8a** was used as a stereoisomeric mixture, but, fortunately, the products **11a** and **12a** could be separated by column chromatography on silica gel. The combination of rhenium oxide and hydrogen peroxide[14] quantitatively oxidized the thiol **6** to the corresponding sulfonic acids **13**. However, the product **13a** derived from **6a** was highly insoluble and could not be characterized except by mass spectroscopy. In contrast, the introduction of *p*-tolyl groups enhanced the solubility of **13b**.



Scheme 3. Oxidation of thiazoles having sulfur-containing functional groups

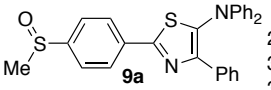
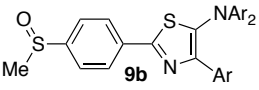
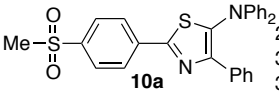
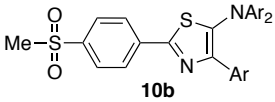
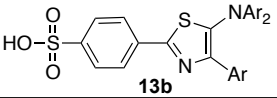
The photophysical properties of the obtained thiazoles were examined. The UV-visible and fluorescence spectra measured in $CHCl_3$ are shown in Tables 1–3. The longest maximum absorption of **5a** was observed at 366 nm (Table 1). The introduction of methyl groups to the phenyl groups on the nitrogen atom and at the 4-position red-shifted the absorption by 10 nm. More drastic bathochromic shifts in emission were observed between **5a**, **6a** and **5b**, **6b**. There was little difference in these properties between thiazoles **5** with a MeS group and **6** with a SH group. Sulfoxides **9** derived from **5** exhibited red shifts in their absorption and emission spectra of about 20 nm (Table 2). Further bathochromic shifts were achieved by the oxidation of **9**. In these cases, there was no decrease in the quantum yields of the emissions of **9** and **10**. Sulfonic acid **13b** showed properties similar to those of sulfoxide **9b**. Large Stokes shifts of these compounds may be due to the conformational changes via the rotation through the carbon-nitrogen bonds at the 5-positions of the thiazoles.

Table 1. UV-vis and fluorescence spectra of thiazoles in $CHCl_3$

thiazole	UV-vis λ_{abs} (nm)[a]	log ε	fluorescence λ_{em} (nm)[b]	Stokes shift [cm^{-1}] (nm)	Φ_F[c]	thiazole	UV-vis λ_{abs} (nm)[a]	log ε	fluorescence λ_{em} (nm)[b]	Stokes shift [cm^{-1}] (nm)	Φ_F[b]
 **5a**	284 316 366	4.38 4.28 4.06	466	[5863] (100)	0.39	 **5b**	286 326 376	4.49 4.31 4.11	493	[6312] (117)	0.48
 **6a**	276 310 376	4.45 4.34 4.12	464	[5044] (88)	0.38	 **6b** Ar = C_6H_4Me-4	276 324 380	4.60 4.25 4.08	492	[5911] (112)	0.34

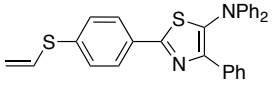
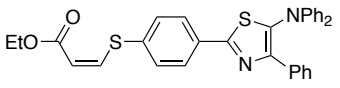
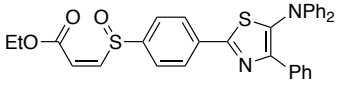
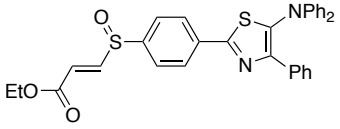
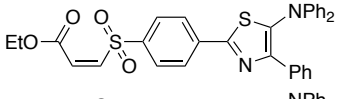
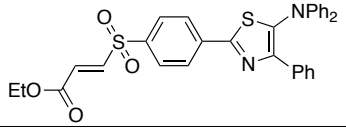
[a] In $CHCl_3$. [thiazole] = 1 x 10^{-5} M. [b]Excited at 350 nm. [c] Quinine sulfate was used as a reference for Φ_F (λ_{ex} = 350 nm).
[d] Excited at 350 nm.

Table 2. UV-vis and fluorescence spectra of oxidized thiazoles in $CHCl_3$

thiazole	UV-vis λ_{abs} (nm)[a]	log ε	fluorescence λ_{em} (nm)[b]	Stokes shift [cm^{-1}] (nm)	Φ_F[b]	thiazole	UV-vis λ_{abs} (nm)[a]	log ε	fluorescence λ_{em} (nm)[b]	Stokes shift [cm^{-1}] (nm)	Φ_F[b]
 **9a**	290 332 384	4.35 3.96 3.98	493	[5758] (109)	0.61	 **9b**	268 332 394	4.51 3.99 3.95	514	[5926] (120)	0.53
 **10a**	290 334 396	4.22 3.81 3.84	509	[5606] (113)	0.59	 **10b**	266 338 409	4.76 3.98 4.01	530	[5642] (121)	0.45
						 **13b**	262 316 390	4.44 3.96 3.68	502	[5721] (112)	0.32

[a] In $CHCl_3$. [thiazole] = 1 x 10^{-5} M. [b]Excited at λ_{ex}.

Table 3. UV-vis and fluorescence spectra of oxidized thiazoles in $CHCl_3$

thiazole		UV-vis λ_{abs} (nm)[a]	log ε	fluorescence λ_{em} (nm)[b]	Φ_F[b]	Stokes shift [cm^{-1}] (nm)
	**7a**	282 328 372	4.52 4.28 4.14	468	0.44	[5514] (96)
	**8a**	286 330 384	4.54 4.35 4.16	474	0.48	[4945] (90)
	***Z*-11a**	264 336 394	4.62 4.02 4.04	494	0.093	[5138] (100)
	***E*-11a**	256 332 396	4.54 4.02 4.01	498	0.13	[5300] (102)
	***Z*-12a**	264 336 410	4.59 3.98 4.03	506	0.042	[4627] (96)
	***E*-12a**	260 336 414	4.54 4.00 4.04	510	0.14	[4547] (96)

[a] In $CHCl_3$. [thiazole] = 1 x 10^{-5} M. [b]Excited at λ_{ex}.

Replacement of a methyl group of **5a** with an ethenyl group had almost no effect on the photophysical properties as in **7a**. In contrast, the introduction of an ethoxycarbonyl group to the terminal carbon of the ethenyl group shifted the absorption and emission spectra to longer wavelengths as in **8a**. Oxidation of **8a** was expected to induce further bathochromic shifts. In fact, as with **5**, **9**, and **10**, maximum absorption and emission of **11a** and **12a** were observed at longer wavelengths, but the efficiency of the emission dramatically decreased, so much so that it was almost quenched.

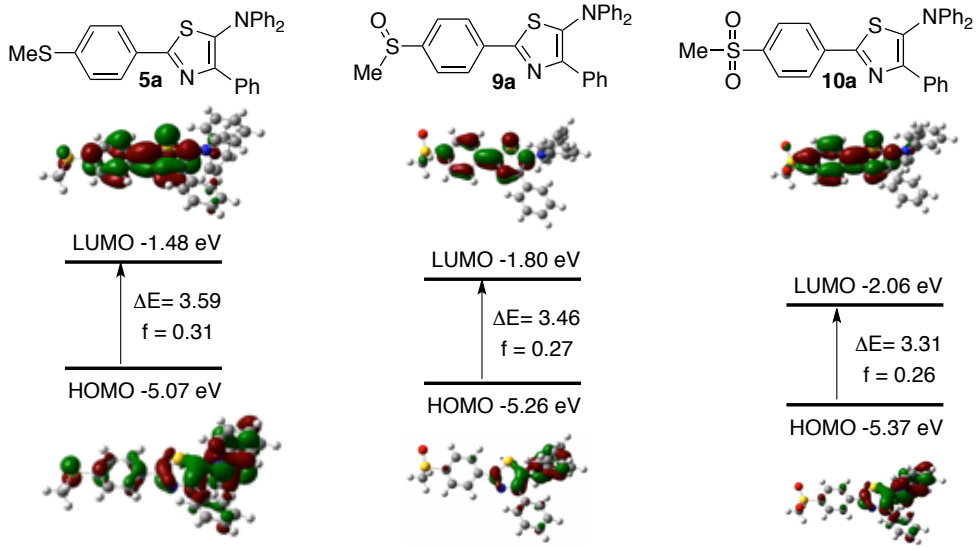


Figure 1. Energy levels and Khon-Sham plots of HOMO and LUMO of **5a**, **9a** and **10a**[a]
[a]DFT, TD-DFT (TD/B3LYP/6-31+G(d,p)) calculations were carried out with the use of optimized structures at B3LYP/6-31+G(d,p). Gas-phase energies are shown.

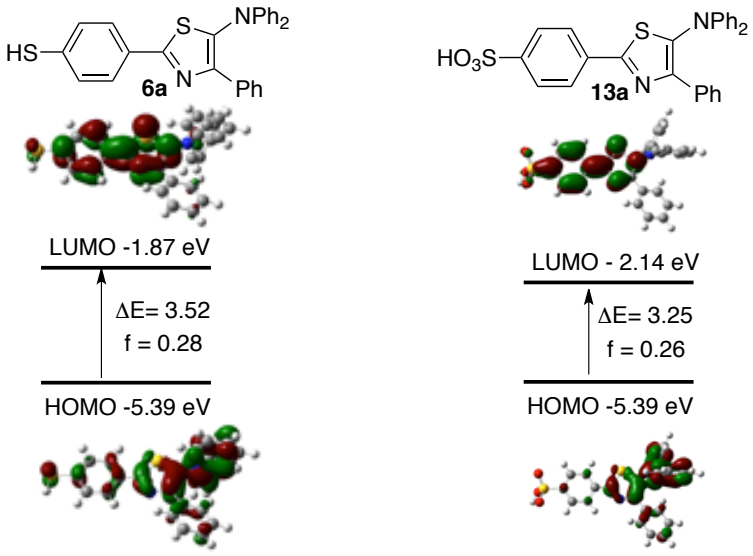


Figure 2. Energy levels and Khon-Sham plots of HOMO and LUMO of **6a** and **13a**[a]

To elucidate the effect of sulfur-containing functional groups on the electronic structures of 5-aminothiazoles, DFT calculations were performed for compounds **5a**, **9a**, **10a**, **6a**, and **13a** at the B3LYP/6-31+G(d,p) level.[15] The energy levels are shown in Figures 1 and 2 along with a Kohn-Sham

plot. In all cases, HOMOs are localized on the diphenylamino groups, whereas LUMOs are on the thiazole rings and aromatic groups at the 2-positions. While sulfur-containing functional groups do not contribute to these HOMOs and LUMOs, they influence their energy levels. Oxidation of the MeS group in **5a** reduces the energy levels of the HOMOs and LUMOs of **9a** and **10a** (Figure 1). The degree of the decrease was greater in the case of LUMOs. Interestingly, in these cases, LUMOs are more delocalized on the phenyl ring at the 2-position, probably due to perturbation of the molecular orbitals of the S=O group. Likewise, oxidation of the SH group in **5a** did not change the energy level of HOMO, as in **13a**, whereas the energy level of LUMO decreased by 0.27 eV, resulting in the decrease in the gap between HOMO and LUMO of **13a** (Figure 2).

In summary, we have demonstrated the synthesis of 5-aminothiazoles with sulfur-containing groups at the *para*-position of the phenyl group at the 2-position of thiazoles by the combination of thioamide dianions generated from secondary thioamides and *N*,*N*-diarylthioformamides. The details of the photophysical properties of the resulting thiazoles and the results of DFT calculations were presented. Among them, thiazoles containing SH and SO_3H groups, which can be used to sense biothiols and heavy metals, showed fluorescence from the blue to green regions. Further studies on the application of thiazole-based photoluminescent molecules are underway by our group.

EXPERIMENTAL

Characterization: The IR spectra were obtained on a JASCO FT-IR 410 spectrophotometer. ^{1}H NMR and ^{13}C NMR spectra were measured on a JNM α-400 spectrometer. Chemical shifts of ^{1}H and ^{13}C are reported in δ values referred to tetramethylsilane, $CDCl_3$ as an internal standard, respectively. The mass spectra (MS) and high resolution mass spectra (HRMS) were taken on a JMS-700 mass spectrometer. Melting points were determined using a SRS MPA 100 optimelt automated melting point system. UV/Vis spectra were measured on a HITACHI U-4100 UV/vis-NIR spectrometer. Fluorescence spectra were measured on a FluoroMax-4 and a JASCO spectrofluorometer FP-8500.

Typical procedure for the preparation of *N*-arylmethyl-4-(methylsulfanyl)benzthioamides 1. *N*-Benzyl-4-(methylsulfanyl)benzothioamide (1a). To a solution of 4-(methylsulfanyl)benzaldehyde (0.39 mL, 3.0 mmol) in DMF (1 mL) was added sulfur (0.107 g, 3.3 mmol) at rt. To this was added benzylamine (0.43 mL, 3.9 mmol), and DMF (2 mL), and the mixture was stirred for 4 h at 80 °C. The resulting mixture was poured into water, and extracted with Et_2O. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 4 : 1) to give **1** (0.72 g, 88%) as a yellow solid; mp 133-135 °C; ^{1}H NMR ($CDCl_3$) δ 2.49 (s, 3H), 5.00 (d, *J* = 5.0 Hz, 2H), 7.21 (d, *J* = 8.7 Hz, 2H), 7.40 (m, 5H), 7.63 (br, 1H), 7.71 (d, *J* = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 15.7, 48.7, 124.6, 126.0, 126.1, 126.2, 127.5, 127.9, 128.2, 129.0, 129.8, 136.2,

137.4, 197.89; MS (EI) *m/z* 273(M^+); HRMS (EI) Calcd for $C_{15}H_{15}NS_2$: 273.0646. Found: 273.0633.

***N*-(4-Methylbenzyl)-4-(methylsulfanyl)benzothioamide (1b):** a yellow solid; mp 123-125 °C; ^{1}H NMR ($CDCl_3$) δ 2.36 (s, 3H), 2.48 (s, 3H), 4.92 (d, *J* = 5.4 Hz, 2H) 7.18 (d, *J* = 4.4 Hz, 2H, Ar), 7.20 (d, *J* = 3.4 Hz 2H, Ar), 7.28 (d, *J* = 7.8 Hz, 2H, Ar), 7.62 (br, 1H, NH), 7.70 (d, *J* = 8.3 Hz, 2H, Ar); ^{13}C NMR ($CDCl_3$) δ 15.7 (SCH_3), 21.7 ($C_6H_4CH_3$), 50.7 (CH_2), 124.3, 125.9, 126.2, 127.5, 127.8, 128.7, 129.0, 130.3, 133.1, 137.3, 137.8, 143.2 (Ar), 197.6 (S=C); MS (EI) *m/z* 287(M^+); HRMS (EI) Calcd for $C_{16}H_{17}NS_2$: 287.0802. Found: 287.0806.

Typical procedure for the preparation of thiazolines 4. 2-(4-(Methylsulfanyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazoline (4a). To a solution of *N*-benzyl-4-(methylsulfanyl)benzothioamide (**1**) (0.274 g, 1.0 mmol) in THF (2.0 mL) was added slowly 1.67 M solution of *n*-butyllithium (1.4 mL, 2.0 mmol) at 0 °C, and the mixture was stirred for 5 min at this temperature. To this was added a solution of *N*,*N*-diphenylthioformamide (**3**) (0.214 g, 3.0 mmol) in THF (1.3 mL) at 0 °C, and the mixture was stirred for 30 min at this temperature. To this was added iodine (0.765 g, 3.0 mmol) at 0 °C, and the mixture was stirred for 2 h at this temperature. The resulting mixture was poured into a saturated aqueous solution of $Na_2S_2O_3$, and extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 10 : 1) to give **4a** (0.36 g, 72%) as an orange solid; mp 142 -143 °C; ^{1}H NMR ($CDCl_3$) δ 2.50 (s, 3H), 5.99 (d, *J* = 8.0 Hz, 1H), 6.30 (d, *J* = 7.8 Hz, 1H), 7.04 (m, 6H), 7.24-7.31 (m, 11H), 7.72 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 15.7, 81,82, 82.22, 122.6, 122.9, 124.2, 125.5 126.1, 127.2, 127.9, 128.6, 129.5, 130.1, 140.1, 145.6, 167.7; MS (EI) *m/z* 452 (M^+); HRMS (EI) Calcd for $C_{28}H_{24}N_2S_2$: 452.1381. Found: 452.1354.

2-(4-(Methylsulfanyl)phenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazoline (4b): an orange solid, mp 43-45 °C; ^{1}H NMR ($CDCl_3$) δ 2.27 (s, 6H), 2.32 (s, 3H), 2.50 (s, 3H), 5.92 (d, *J* = 3.4 Hz, 1H), 6.23 (d, *J* = 3.9 Hz, 1H), 6.91 (d, *J* = 8.3 Hz, 4H), 7.11-7.28 (m, 10H), 7.72 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 14.8, 20.5, 21.0, 81.8, 82.0, 123.1, 125.1, 126.1, 128.5, 129.2, 129.5, 129.7, 130.0, 132.9, 137.2, 142.8, 143.3, 167.3; MS (EI) *m/z* 494 (M^+); HRMS (EI) Calcd for $C_{31}H_{30}N_2S_2$: 494.1850. Found: 494.1825.

Typical procedure for the preparation of thiazoles 5. 2-(4-(Methylsulfanyl)phenyl)-*N*,*N*-dimethyl-4-phenyl-5-aminothiazole (5a). To a solution of 2-(4-(methylsulfanyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazoline (**4a**) (0.227 g, 0.5 mmol) in THF (8.0 mL) was added iodine (0.261 g, 1.0 mmol) at rt, and the mixture was stirred under reflux for 2 h. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 20 : 1) to give **5a** (0.058 g, 26%) as an orange solid; mp. 184-185 °C; ^{1}H NMR ($CDCl_3$) δ 2.45 (s, 3H, SCH_3), 6.90-7.35 (m, 16H, Ar), 7.85 (m, 3H, Ar); ^{13}C NMR ($CDCl_3$) δ 15.9 (SCH_3), 120.1, 122.2, 123.8, 125.1, 126.7, 127.3, 128.3, 128.4, 129.0, 130.0, 130.1, 133.3, 139.4, 146.4, 148.7 (Ar), 163.1 (SC=N); MS (EI) *m/z* 450 (M^+); HRMS (EI) Calcd for $C_{28}H_{22}N_2S_2$: 450.1224. Found: 450.1227.

2-(4-(Methylsulfanyl)phenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazole (5b): a yellow solid; mp 177-178 °C; ^{1}H NMR ($CDCl_3$) δ 2.27 (s, 6H), 2.30 (s, 3H), 2.52 (s, 3H), 7.02 (s, 8H), 7.08 (d, *J* = 8.3 Hz, 2H), 7.26 (d, *J* = 6.8 Hz, 2H), 7.88 (dd, *J* = 8.3, 11.7 Hz, 4H); ^{13}C NMR ($CDCl_3$) δ 14.8, 20.4, 21.4, 120.4, 122.0, 125.2, 125.6, 126.9, 127.2, 128.1, 129.0, 130.6, 130.8, 131.9, 132.3, 139.3, 144.4, 162.7; MS (EI) *m*/*z* 492 (M^+); HRMS (EI) Calcd for $C_{31}H_{28}N_2S_2$: 492.1694. Found: 492.1764.

Typical procedure for the preparation of thiols 6. 2-(4-Sulfhydrylphenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (6a). To a solution of 2-(4-(methylsulfanyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (**5**) (0.905 g, 2.0 mmol) in DMF (15 mL) was added *t*-BuOK (1.47 g, 13.1 mmol) at rt. To this was added *t*-BuSH (1.1 mL, 10 mmol) and the mixture was under refluxed for 11.5 h. After cooling at 0 °C, the mixture was poured into a saturated ammonium chloride aqueous solution (pH ≈ 7). The resulting mixture was washed several times with water. The mixture was extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$ and concentrated *in* vacuo. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 15 : 1) to give **6a** (0.70 g, 80%) as an yellow solid; mp 158-160 °C; ^{1}H NMR ($CDCl_3$) δ 3.55 (s, 1H), 6.99 (m, 2H), 7.11 (m, 4H), 7.21-7.25 (m, 8H), 7.82 (d, *J* = 8.3 Hz, 2H), 7.92 (d, *J* = 8.3 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 120.6, 122.3, 123.9, 125.9, 126.6, 127.5, 128.4, 129.0, 130.0, 131.3, 133.3, 139.7, 146.4, 148.8, 162.7; MS (EI) *m*/*z* 436 (M^+); HRMS (EI) Calcd for $C_{27}H_{20}N_2S_2$: 436.1098. Found: 436.1084.

2-(4-Sulfhydrylphenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazole (6b): a yellow solid; mp 77-80 °C; ^{1}H NMR ($CDCl_3$) δ 2.26 (s, 6H), 2.29 (s, 3H), 3.54 (s, 1H), 6.99 (s, 8H), 7.07 (d, *J* = 8.7 Hz, 2H), 7.29 (d, *J* = 8.2 Hz, 2H), 7.81 (d, *J* = 8.7 Hz, 2H), 7.89 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 20.6, 21.3, 117.3, 120.4, 122.0, 125.8, 126.5, 127.5, 128.1, 129.0, 129.9, 130.6, 131.5, 132.4, 133.6, 137.7, 139.5, 144.4, 148.4, 162.4; MS (EI) *m*/*z* 478 (M^+); HRMS (EI) Calcd for $C_{30}H_{26}N_2S_2$: 478.1537. Found: 478.1561.

Synthetic procedure of 2-(4-ethenylthiophenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (7a). A solution of 2-(4-sulfhydrylphenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (**6**) (0.212 g, 0.5 mmol) and sodium ethoxide (0.038 g, 0.5 mmol) in EtOH (5.0 mL) was stirred for 30 min at rt. After that time, the solution was slowly added to a pre-cooled (0 °C) stirring solution of 1,2-dibromoethane (0.07 mL, 0.8 mmol) in EtOH (2.0 mL) within 1 h under Ar. Stirring was continued for an additional 1 h at room temperature. A solution of sodium ethoxide (1.3 mmol) in EtOH (8.0 mL) was then added under the same reaction conditions. The reaction mixture was stirred under reflux overnight under Ar. After that, the resulting mixture was cooled and treated with water, extracted with CH_2Cl_2, washed with water and brine. The organic layer was dried over $MgSO_4$ and concentrated *in* vacuo. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 20 : 1 then 9 : 1) to give **7a** (0.15 g, 67%) as a yellow solid; mp 153-155 °C; ^{1}H NMR ($CDCl_3$) δ 5.48 (t, *J* = 8.3 Hz, 2H), 6.58 (dd, *J* = 16.6, 9.8 Hz, 1H), 7.00 (m, 2H), 7.13 (m, 4H), 7.21-7.28 (m, 8H), 7.40 (d, *J* = 8.8 Hz, 2H), 7.92 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 117.4, 120.6,

125.9, 127.4, 128.4, 128.8, 129.0, 130.1, 130.5, 131.4 132.4, 133.3, 137.2, 139.9, 146.6, 148.8, 162.6; MS (EI) *m/z* 462 (M^+); HRMS (EI) Calcd for $C_{29}H_{22}N_2S_2$: 462.1224. Found: 462.1248.

Synthetic procedure of ethyl 3-((4-(5-(diphenylamino)-4-phenyl-2-thiazolyl)phenyl)sulfanyl)-acrylate (8a). A solution of 2-(4-sulfhydrylphenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (**6a**) (0.443 g, 1.0 mmol) and *i*-Pr_2NEt (0.05 mL, 0.25 mmol) in CH_2Cl_2 (3 mL) was stirred at -78 °C for 0.5 h. Ethyl propiolate (0.1 mL, 1.0 mmol) was added dropwise, and the reaction mixture was stirred at -78 °C for 2 h. The mixture was passed through a column of silica (2 cm x 1 cm) with Et_2O. The solvent was removed *in vacuo*, and the residue was purified by column chromatography (SiO_2, hexane : EtOAc = 9 : 1) to give **8a** (0.51 g, 97%) as a yellow solid as a mixture of *Z* and *E* isomers (*Z* : *E* = 5 : 1); mp. 48-50 °C; ***Z* isomer** : ^{1}H NMR ($CDCl_3$) δ 1.35 (t, *J* = 7.3 Hz, 3H), 4.28 (q, *J* = 7.3 Hz, 2H), 5.97 (d, *J* = 10.1 Hz, 1H), 7.00 (m, 2H), 7.13 (m, 4H), 7.3 (m, 8H), 7.52 (d, *J* = 9.0 Hz, 2H), 7.9 (m, 4H); ***E* isomer** : ^{1}H NMR ($CDCl_3$) δ 1.25 (t, *J* = 7.3 Hz, 3H), 4.15 (q, 7.3 Hz, 2H), 5.72-5.76 (d, *J* = 15.6 Hz, 1H), 7.00 (m, 1H), 7.13 (m, 4H), 7.2-7.4 (m, 8H), 7.52 (d, *J* = 9 Hz, 2H), 7.8 (d, *J* = 15.6 Hz, 1H) 7.94 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 14.3, 60.4, 114.1 (***Z*** SCH=CH), 116.4 (***E*** SCH=CH), 121.5, 123.2, 126.9, 127.1, 127.4, 128.1, 128.2, 129.2, 130.8, 132.7, 133.2, 133.6, 138.2, 140.3, 145.6 (***E*** Ar or SCH=CH), 146.4 (***Z*** Ar or SCH=CH), 148.1 (***Z*** Ar or SCH=CH), 148.9 (***E*** Ar or SCH=CH), 162.0, 166.4; MS (EI) *m/z* 534 (M^+); HRMS (EI) Calcd for $C_{32}H_{26}N_2O_2S_2$: 534.1436. Found: 534.1441.

Typical procedure for the preparation of sulfoxides 9.

2-(4-(Methylsulfinyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (9a). To a solution of 2-(4-(methylsulfanyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (**5a**) (0.226 g, 0.5 mmol) in CH_2Cl_2 (4 mL) was added *m*CPBA (0.113 g, 75%, 0.5 mmol) slowly at 0 °C, and the mixture was stirred for 4 h at this temperature. The resulting mixture was washed with saturated aqueous solution of $Na_2S_2O_3$, $NaHCO_3$ and water. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 1 : 1.5) to give the thiazole **9a** (0.19 g, 83%) as a yellow solid; mp 185-187 °C; ^{1}H NMR ($CDCl_3$) δ 2.75 (s, 3H), 7.00 (d, *J* = 5.9 Hz, 2H), 7.12 (d, *J* = 5.9 Hz, 5H), 7.23 (d, *J* = 7.36 Hz, 6H), 7.70 (d, *J* = 7.32 Hz, 2H), 7.93 (d, *J* = 6.88 Hz, 2H), 8.11 (d, *J* = 8.24 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 43.8 (S(=O)CH$_3$), 121.4, 123.3, 124.0, 126.9, 127.4, 128.1, 128.2, 129.2, 133.0, 136.4, 140.9, 146.3, 147.1, 161.3; MS (EI) *m/z* 466 (M^+); HRMS (EI) Calcd for $C_{28}H_{22}N_2OS_2$: 466.1174. Found: 466.1153.

2-(4-(Methylsulfinyl)phenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazole (9b). a yellow solid; mp 181-183 °C; ^{1}H NMR ($CDCl_3$) δ 2.27 (s, 6H), 2.30 (s, 3H), 2.76 (s, 3H), 7.01 (m, 8H), 7.09 (d, *J* = 8.7 Hz, 2H), 7.69 (d, *J* = 8.7 Hz, 2H), 7.89 (d, *J* = 8.2 Hz, 2H), 8.11 (d, *J* = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 20.0, 21.3, 44.5, 120.5, 122.1, 123.1, 124.7, 126.0, 126.4, 127.6, 128.1, 129.0, 129.7, 13.04, 130.6, 132.5, 136.5, 137.8, 140.8, 144.3, 147.0, 148.6, 161.0; MS (EI) *m/z* 508 (M^+); HRMS (EI) Calcd for $C_{31}H_{28}N_2OS_2$:

508.1643. Found: 508.1625.

Typical procedure of sulfones 10. 2-(4-(Methylsulfonyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (10a). A solution of 2-(4-(methylsulfanyl)phenyl)-*N*,*N*-diphenyl-4-phenyl-5-aminothiazole (0.220 g, 0.5 mmol) and *m*CPBA (0.287 g, 75%, 1.25 mmol) in CH_2Cl_2 (4 mL) was stirred at rt for 16 h. The resulting mixture was washed with saturated aqueous solution of $Na_2S_2O_3$ and $NaHCO_3$. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 2 : 1) to give **10a** (0.22 g, 93%) as a yellow solid; mp 252-254 °C; ^{1}H NMR ($CDCl_3$) δ 3.09 (s, 3H), 7.01 (t, *J* = 8.7 Hz, 2H), 7.12 (d, *J* = 9.1 Hz, 3H), 7.26 (m, 8H), 7.91 (d, *J* = 6.9 Hz, 2H), 8.00 (d, *J* = 8.72 Hz, 2H), 8.14 (d, *J* = 8.68 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 44.5, 121.6, 123.5, 126.8, 127.4, 128.0, 128.3, 129.3, 129.5, 132.9, 138.7, 141.0, 142.0, 146.3, 149.2, 160.2; MS (EI) *m*/*z* 482 (M^+); HRMS (EI) Calcd for $C_{28}H_{22}N_2O_2S_2$: 482.1123. Found: 482.1114.

2-(4-(Methylsulfonyl)phenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazole (10b): a yellow solid; mp 202-204 °C; ^{1}H NMR ($CDCl_3$) δ 2.27 (s, 6H), 2.30 (s, 3H), 3.09 (s, 3H), 7.01 (m, 8H), 7.09 (d, *J* = 8.7 Hz, 2H), 7.87 (d, *J* = 8.2 Hz, 2H), 7.98 (d, *J* = 8.2 Hz, 2H), 8.13 (d, *J* = 8.7 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 20.7, 21.3, 44.5, 120.4, 121.0, 121.5, 121.6, 125.8, 126.2, 126.7, 126.9, 127.0, 127.3, 127.9, 128.8, 129.0, 129.4, 129.7, 129.9, 130.2, 132.9, 144.3, 165.2; MS (EI) *m*/*z* 524 (M^+); HRMS (EI) Calcd for $C_{31}H_{28}N_2O_2S_2$: 524.1592. Found: 524.1593.

Synthetic procedure of ethyl (*Z*)-3-((4-(5-(diphenylamino)-4-phenyl-2-thiazolyl)phenyl)sulfinyl)-acrylate (11a). To a solution of ethyl 3-((4-(5-(diphenylamino)-4-phenyl-2-thiazolyl)phenyl)thio)-acrylate (**8a**) (0.131 g, 0.25 mmol) in CH_2Cl_2 (2 mL) was added *m*CPBA (0.0622 g, 75%, 0.27 mmol) slowly at 0 °C, and the mixture was stirred for 4 h at this temperature. The resulting mixture was washed with saturated aqueous solution of $Na_2S_2O_3$, $NaHCO_3$ and water. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 4 : 1) to give ***Z*-11a** (0.085 g, 63%) and ***E*-11a** (0.013 g, 9.6%) as a yellow solid: *Z*-**11a**; mp 58-60 °C; ^{1}H NMR ($CDCl_3$) δ 1.35 (t, *J* = 7.32 Hz, 3H), 4.29 (q, *J* = 7.32 Hz, 2H), 6.26 (d, *J* = 10.6 Hz, 1H), 6.81 (d, *J* = 10.6 Hz, 1H), 7.02 (m, 1H), 7.12 (m, 4H), 7.24 (m, 8H), 7.93 (d, *J* = 6.4 Hz, 4H), 8.08 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 13.4, 61.8, 120.6, 122.2, 123.5, 124.0, 124.5, 125.2, 126.2, 126.5, 127.3, 127.7, 128.2, 128.4, 128.9, 130.0, 133.0, 136.4, 140.9, 145.4, 146.3, 148.9, 154.4, 156.3, 161.3, 164.3; MS (EI) *m*/*z* 550 (M^+); HRMS (EI) Calcd for $C_{32}H_{26}N_2O_3S_2$: 550.1385; Found: 550.1393. ***E*-11a**; mp 55-58 °C; ^{1}H NMR ($CDCl_3$) δ 1.31 (t, *J* = 7.32 Hz, 3H), 4.23 (q, *J* = 7.32 Hz, 2H), 6.75 (d, *J* = 15.1 Hz, 1H), 7.02 (m, 1H), 7.12 (m, 4H), 7.24 (m, 8H), 7.51 (d, *J* = 15.1 Hz, 1H), 7.69 (d, *J* = 8.2 Hz, 2H), 7.91 (d, *J* = 6.8 Hz, 2H), 8.12 (d, *J* = 8.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 16.2, 61.2, 120.7, 122.4, 124.4, 126.5, 127.4, 127.7, 128.2, 128.4, 129.0, 130.1, 138.1, 141.3, 142.7, 146.3, 149.1, 154.1, 160.9, 164.7; MS (EI) *m*/*z* 550 (M^+); HRMS (EI) Calcd for $C_{32}H_{26}N_2O_3S_2$: 550.1385. Found: 550.1380.

Synthetic procedure of ethyl (*Z*)-3-((4-(5-(diphenylamino)-4-phenyl-2-thiazolyl)phenyl)sulfonyl)-acrylate (12a). A solution of ethyl 3-((4-(5-(diphenylamino)-4-phenyl-2-thiazolyl)phenyl)thio)acrylate (**8a**) (0.137 g, 0.25 mmol) and *m*CPBA (0.145 g, 75%, 0.63 mmol) in CH_2Cl_2 (3 mL) was stirred at rt for 18 h. The resulting mixture was washed with saturated aqueous solution of $Na_2S_2O_3$ and $NaHCO_3$. The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane : EtOAc = 4 : 1) to give ***Z*-12a** (0.072 g, 50%) and ***E*-12a** (0.032 g, 22%) as a yellow solid; mp 162-164 °C; ^{1}H NMR ($CDCl_3$) δ 1.40 (t, *J* = 7.3 Hz, 3H), 4.39 (q, *J* = 7.4 Hz, 2H), 6.55 (d, *J* = 1.92 Hz, 2H), 7.02 (t, *J* = 7.3 Hz, 2H), 7.12 (d, *J* = 7.3 Hz, 3H), 7.22-7.32 (m, 8H), 7.91 (d, *J* = 8.3 Hz, 2H), 8.05 (d, *J* = 8.8 Hz, 2H), 8.14 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 14.0, 62.2, 121.6, 123.5, 126.7, 127.4, 128.2, 128.9, 129.3, 132.3, 132.9, 135.0, 138.9, 139.9, 142.1, 146.3, 149.2, 160.2, 163.8; MS (EI) *m/z* 566 (M^+); HRMS (EI) Calcd for $C_{32}H_{26}N_2O_4S_2$: 566.1334. Found: 566.1318.

***E*-12a**: mp 46-48 °C; ^{1}H NMR ($CDCl_3$) δ 1.31 (t, *J* = 7.4 Hz, 3H), 4.26 (q, *J* = 7.3 Hz, 2H), 6.87 (d, *J* = 15.1 Hz, 1H), 7.02 (t, *J* = 7.3 Hz, 2H), 7.12 (d, *J* = 7.8 Hz, 4H), 7.25 (m, 7H), 7.36 (d, *J* = 15.6 Hz, 1H), 7.90 (m, 2H), 7.96 (d, *J* = 8.8 Hz, 1H), 8.02 (d, *J* = 8.8 Hz, 1H), 8.15 (d, *J* = 8.8 Hz, 1H), 8.18 (d, *J* = 8.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 16.7, 62.4, 120.9, 122.4, 127.5, 128.5, 129.1, 130.1, 130.4, 132.8, 139.2, 142.3, 146.3, 148.4, 159.9, 163.2; MS (EI) *m/z* 566 (M^+); HRMS (EI) Calcd for $C_{32}H_{26}N_2O_4S_2$: 566.1334. Found: 566.1313.

Synthetic procedure of 4-(4,*N*,*N*-tris(4-methylphenyl)-5-aminothiazol-2-yl)benzenesulfonic acid (13b). To a solution of 35% hydrogen peroxide (1 mL, 10 mmol) in THF (4 mL) at rt was added a solution of methyltrioxorhenium (0.0244 g, 0.1 mmol) in THF (2 mL). This yellow mixture was stirred for 1 min. Then a solution of 2-(4-sulfhydrylphenyl)-4,*N*,*N*-tri(4-methylphenyl)-5-aminothiazole (**6b**) (0.475 g, 1 mmol) in THF (6 mL) was added and the stirring was continued for 4 h. After completing the reaction (monitored by TLC), a catalytic amount of MnO_2 was added. The organic phase was concentrated under reduced pressure to afford the crude product, which was purified by column chromatography (silicic acid, $CHCl_3$: MeOH = 5 : 1) to give **13b** (0.50 g, quant) as a brown solid; mp 208-210 °C; ^{1}H NMR ($CDCl_3$) δ 2.23 (br, 9H), 6.95 (d (br), *J* = 28.4 Hz, 10H), 7.70 (br, 7H); ^{13}C NMR ($CDCl_3$) δ 20.7, 21.3, 122.1, 122.2, 125.5, 127.1, 127.6, 127.8, 129.2, 129.5, 129.7, 129.9, 130.1, 131.6, 136.2, 138.2, 141.8, 145.9, 148.4, 161.6; MS (EI) *m/z* 525 (M^+); HRMS (EI) Calcd for $C_{30}H_{26}N_2O_3S_2$: 526.1385. Found: 526.1397.

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This paper is dedicated to Professor Kiyoshi Tomioka on the occasion of his 70th birthday.

REFERENCES AND NOTES

1. For recent reviews, see a) T. Nelson, S. Fernandez-Alberti, A. E. Roitberg, and S. Tretiak, *J. Phys. Chem. Lett.*, 2017, **8**, 3020; b) X. Cao, D. Zhang, S. Zhang, Y. Tao, and W. Huang, *J. Mater. Chem. C*, 2017, **5**, 7699; c) C.-C. Ko and V. W.-W. Yam, *Acc. Chem. Res.*, 2018, **51**, 149.
2. For recent reviews, see a) E. V. Antina, N. A. Bumagina, A. L. V'yugin, and A. V. Solomonov, *Dyes Pigments*, 2017, **136**, 368; b) D. Wu, L. Chen, W. Lee, G. Ko, J. Yin, and J. Yoon, *Coord. Chem. Rev.*, 2018, **354**, 74; c) Dhanjai, A. Sinha, L. Wu, X. Lu, J. Chen, and R. Jain, *Anal. Chim. Acta*, 2018, **998**, 1.
3. For recent reviews, see a) A. Chevalier, P.-Y. Renard, and A. Romieu, *Chem. Asian J.*, 2017, **12**, 2008; b) A. Salek-Maghsoudi, F. Vakhshiteh, R. Torabi, S. Hassani, M. R. Ganjali, P. Norouzi, M. Hosseini, and M. Abdollahi, *Biosens. Bioelectron.*, 2018, **99**, 122; c) G. G. Dias, A. King, F. de Moliner, M. Vendrell, and E. N. da Silva Júnior, *Chem. Soc. Rev.*, 2018, **47**, 12.
4. For recent examples of thiazole-based fluorescent compounds, see a) K. I. Lugovik, A. V. Popova, A. K. Eltyshev, E. Benassi, and N. P. Belskaya, *Eur. J. Org. Chem.*, 2017, 4175; b) S. Tong, S. Zhao, Q. He, Q. Wang, M.-X. Wang, and J. Zhu, *Angew. Chem. Int. Ed.*, 2017, **56**, 6599; c) S. H. Habenicht, P. Rohland, J. Reichel, T. Biver, P. Minei, D. Jakobi, A. Pucci, D. Weiß, R. Beckert, and H. Görls, *Synthesis*, 2018, **50**, 303; d) M. A. Potopnyk, R. Lytvyn, Y. Danyliv, M. Ceborska, O. Bezvikonnyi, D. Volyniuk, and J. V. Grazulevicius, *J. Org. Chem.*, 2018, **83**, 1095.
5. a) T. Murai, F. Hori, and T. Maruyama, *Org. Lett.*, 2011, **13**, 1718; b) K. Yamaguchi, T. Murai, S. Hasegawa, Y. Miwa, S. Kutsumizu, T. Maruyama, T. Sasamori, and N. Tokitoh, *J. Org. Chem.*, 2015, **80**, 10742; c) T. Murai, K. Yamaguchi, T. Hayano, T. Maruyama, K. Kawai, H. Kawakami, and A. Yashita, *Organometallics*, 2017, **36**, 2552.
6. a) T. Murai, A. Yoshida, T. Mizutani, H. Kubuki, K. Yamaguchi, T. Maruyama, and F. Shibahara, *Chem. Lett.*, 2017, **46**, 1017; b) Y. Maekawa, K. Kuwabara, A. Sugiyama, K. Iwata, T. Maruyama, and T. Murai, *Chem. Lett.*, 2017, **46**, 1068 and references cited therein.
7. K. Yamaguchi, T. Murai, J.-D. Guo, T. Sasamori, and N. Tokitoh, *ChemistryOpen*, 2016, **5**, 434.
8. K. Yamaguchi, T. Murai, S. Kutsumizu, Y. Miwa, M. Ebihara, J.-D. Guo, and N. Tokitoh, *ChemistryOpen*, 2017, **6**, 282.
9. K. Yamaguchi, T. Murai, Y. Tsuchiya, Y. Miwa, S. Kutsumizu, T. Sasamori, and N. Tokitoh, *RSC Adv.*, 2017, **7**, 18132.
10. a) K. G. Reddie, W. H. Humphries, C. P. Bain, C. K. Payne, M. L. Kemp, and N. Murthy, *Org. Lett.*, 2012, **14**, 680; b) C. Ge, H. Wang, B. Zhang, J. Yao, X. Li, W. Feng, P. Zhou, Y. Wang, and J. Fang,

Chem. Commun., 2015, **51**, 14913; c) G. Liu, X. Xu, Y. Chen, X. Wu, H. Wua, and Y. Liu, *Chem. Commun.*, 2016, **52**, 7966.

11. A. Fermi, G. Bergamini, M. Roy, M. Gingras, and P. Ceroni, *J. Am. Chem. Soc.*, 2014, **136**, 6395.
12. J. R. Lao, H. Fernández-Pérez, and A. Vidal-Ferran, *Org. Lett.*, 2015, **17**, 4114.
13. C. W. Downey, S. Cracium, A. M. Neferu, C. A. Vivelo, C. J. Mueller, B. C. Southall, S. Corsi, E. W. Etchill, and R. J. Sault, *Tetrahedron Lett.*, 2012, **53**, 5763.
14. F. P. Ballistreri, G. A. Tomaselli, and R. M. Toscano, *Tetrahedron Lett.*, 2008, **49**, 3291.
15. M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma, O. Farkas, J. B. Foresman, and D. J. Foxet, Gaussian 09, revision D.01; Gaussian, Inc.: Wallingford, CT, 2009.