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Role of TBATB in nano indium oxide catalyzed C-S bond formation

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Nano sized indium oxide is found to be an efficient catalyst for the conversion of thiols to sulfides using Na_2CO_3 as base and TBATB as reagent in DMSO at 110°C . Here *in situ* generation of bromo intermediate by TBATB takes place through indium surface. A variety of aryl sulfides can be synthesized in excellent yields from less reactive chlorides, boronic acids and thiols.

The applications of metal-nanoparticle catalysis in organic synthesis has received considerable interest in recent years¹. One of the important applications is toward the C-S bond formation has increased tremendously because of its high efficiency and compatibility with eco-friendly reaction media². Transition metal-catalyzed cross-coupling is one of the most commonly used reactions in the construction of C-S bonds, in which the formation of diaryl sulfide motifs is particularly valuable due to its significance in biologically active molecules and chemical materials³. During the past decades, various Cu^{4,5}, Ni⁶, Pd^{7,8}, Co⁹, and Fe^{10,11} catalytic systems have been developed that allow aryl halides and aryl boronic acids that couple with arylthiols under mild reaction conditions. In the recent decades, however, indium-based¹² catalytic systems have attracted considerable attention due to their high reactivity, low cost and lower toxicity. The indium-catalyzed C-S cross coupling of organyl halides with dichalcogenides was described in 2009^{13,14}. Moreover, Reddy and co-worker¹⁵ reported nano- In_2O_3 catalyzed C-S cross-coupling of aryl halides with aromatic/alkyl thiols but this protocol reported a longer reaction time. Nevertheless, to the best of our knowledge, their application as catalysts for the C-S cross-coupling reaction of thiol with arylboronic acid has yet not been discovered. We report herein a facile synthesis of aryl thioethers employing nano indium oxide as catalyst in several transformations (Fig. 1). The catalyst efficiency can be increased by using TBATB (tetrabutylammonium tribromide).

Results

Indium oxide nanoparticles (NPs) could be synthesized following a reported method¹⁶ with minor modifications. In a typical procedure, 0.10 mol ratio of $\text{In}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were added to 20 ml distilled water in a three necked round-bottom flask and stirred at 100°C for 30 min. 0.12 M NaOH solution were added dropwise until white precipitate was obtained ($\text{pH} = 9$). The obtained precipitate was centrifuged and washed three times with double distilled water. The final white product was calcined at 400°C . After calcination, the colour of the powder turned from white to light yellow indicating that the resultant product is In_2O_3 . To investigate the composition and topography of the final calcination product, powder XRD, scanning electron microscopy (SEM) image and EDS were carried out. Figures (2) and (3) shows the typical transmission electron microscopy (TEM) image and scanning electron microscopy (SEM) image of indium oxide nanoparticles, where the sizes are estimated to be 10–20 nm.

The N_2 adsorption and desorption isotherm for nano indium oxide is type IV (Fig. 4). The surface area and average pore diameter of the prepared nano- In_2O_3 were $66.9 \text{ m}^2 \text{ g}^{-1}$ and 7.7 nm, respectively.

To optimize the reaction conditions a series of experiments were performed under varying reaction parameters, such as solvent, time, temperature and base for a representative C-S cross coupling reaction. In the preliminary phase of optimization, thiophenol and allyl chloride was chosen as a standard substrate and the trials were performed with different catalysts, ligands, and solvents at different temperature

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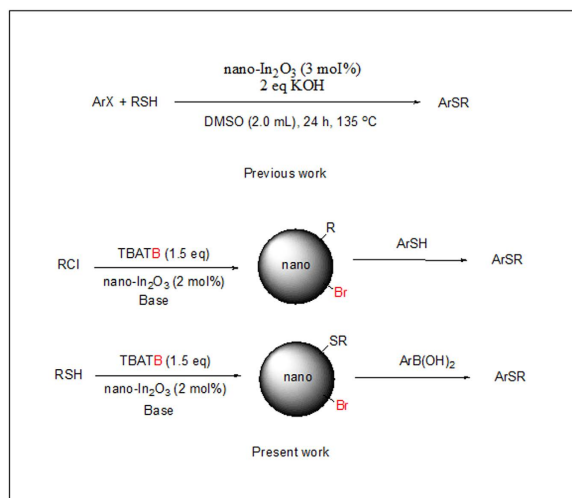


Figure 1. Synthesis of aryl sulfide.

(Table 1). Nano- In_2O_3 was found to be the best choice among the various catalysts (Table 1, entry 1). The results shown that 2 equiv Na_2CO_3 and 1.5 equiv TBATB with 2 mol% nano- In_2O_3 were the best concentrations for the transformation to occur within a reasonable time period. When 5 mol% of catalyst was used, no appreciable change with respect to yield was observed (Table 1, entry 3). Nevertheless, other catalyst (Co_2CO_3) gave low yield. The coupling reaction was investigated in various solvents such as CH_2Cl_2 , DMSO, CH_3CN and CH_3COOH . DMSO was found to be the best solvent.

Having optimized conditions (Table 1 entry 1) for C-S reaction, we continued our pursuit with a variety of aromatic and aliphatic substrates (Fig. 5). As shown in Fig. 5, aryl thiols bearing electron-donating groups such as methoxy, methyl groups (**3f-g**) efficiently couple with allyl chlorides to yield the corresponding arylsulfide in excellent yields (88–89%). However, arylthiols with electron withdrawing groups gave the corresponding arylsulfides in lower yields (**3i-j**) and benzylthiols gave moderate to good yields (**3b**).

Having same standard reaction conditions, we explored the scope of thiols with arylboronic acids (Fig. 6). A broad range of functional groups, such as ether, halides, ester, etc. were tolerated under the standard reaction condition to provide the expected products, **5a-x** in good to excellent yields. Aryl thiols containing electron withdrawing and electron donating group were coupled to furnish the corresponding diarylsulfides in good to excellent yields. It is noteworthy that our protocol could also be extended to alkyl thiols giving good yields. Quite significantly, a wide range of boronic acids that incorporate electron donating groups (**5b-e**) and electron-withdrawing groups at the ortho, meta, and para positions are readily tolerated. However, low yields of respective diarylsulfides were obtained with 3-nitro-phenylboronic acid, 3,5-dichlorophenyl boronic acid and 4-chlorophenylboronic acid (**5f-g**, **5s**).

On the basis of previous literature reports¹⁷, the proposed reaction pathway for these reactions is based on oxidative addition followed by reductive elimination (Fig. 7). The consequent oxidative addition (pathway1) of $\text{In}(\text{nano})$ with allyl chloride may provide intermediate $\text{RIn}(\text{nano})\text{Br}$ (A) or $\text{RIn}(\text{nano})\text{Cl}$ A^1 . The product yield increased suddenly on addition of TBATB and might be it follows the formation of intermediate (A) largely rather than A^1 . Then in presence of base thiol react with A can give intermediate B, which undergoes a reductive elimination to provide the target product and to regenerate the catalyst $\text{In}(\text{nano})$.

In pathway 2, ArSH on oxidative addition to form intermediate A' and in presence of base arylboronic acid react with A' to form intermediate B' which undergo reductive elimination to form the product. The main significance of this work that $\text{In}(\text{nano})$ provides large surface area for which the Br^- can easily form intermediate A or A' .

After completion of reaction the catalyst was recovered by centrifugation and reused for the fresh reaction of aryl thiol with allyl chloride/boronic acid and no loss of activity was observed (Fig. 8).

We have reported a general synthetic protocol for the C-S bond, using nano-indium-catalyst. In this protocol, we recommend the use of 2 mol% indium-catalyst, TBATB (1.5 equiv) Na_2CO_3 (2 equiv), and DMSO as the solvent. We found the main advantages of this protocol were low toxicity of the catalyst, good turnover and high yield of products.

Methods

General Information. All solvents and chemicals were purchased commercially and used without further purification. Melting points were recorded on an electrothermal digital melting point apparatus and were uncorrected. Column chromatography was generally performed on silica gel (230–400 mesh)

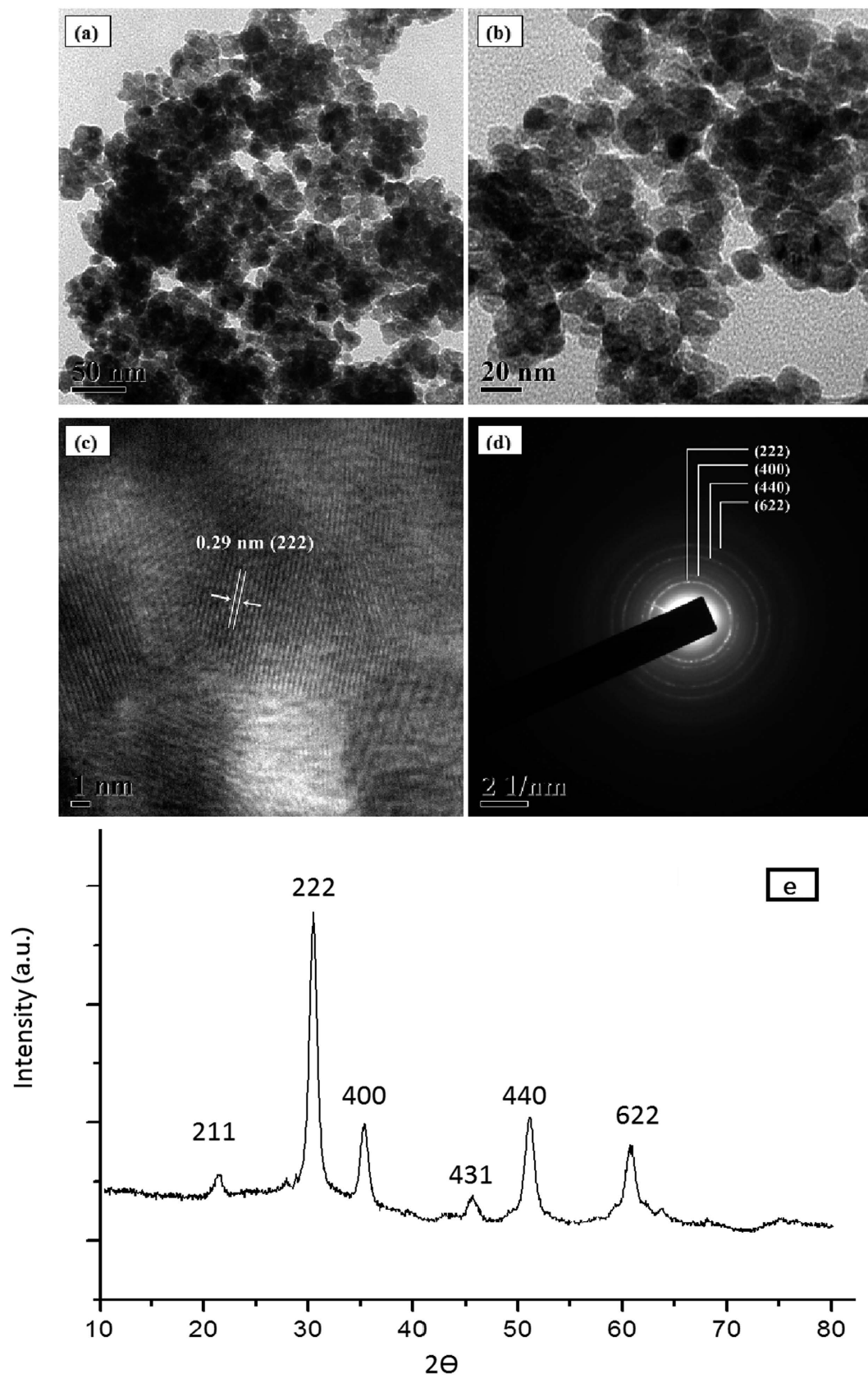


Figure 2. TEM-images of In_2O_3 nanoparticles at (a,b) lower and (c) higher magnification (d) SAED pattern (e) powder XRD.

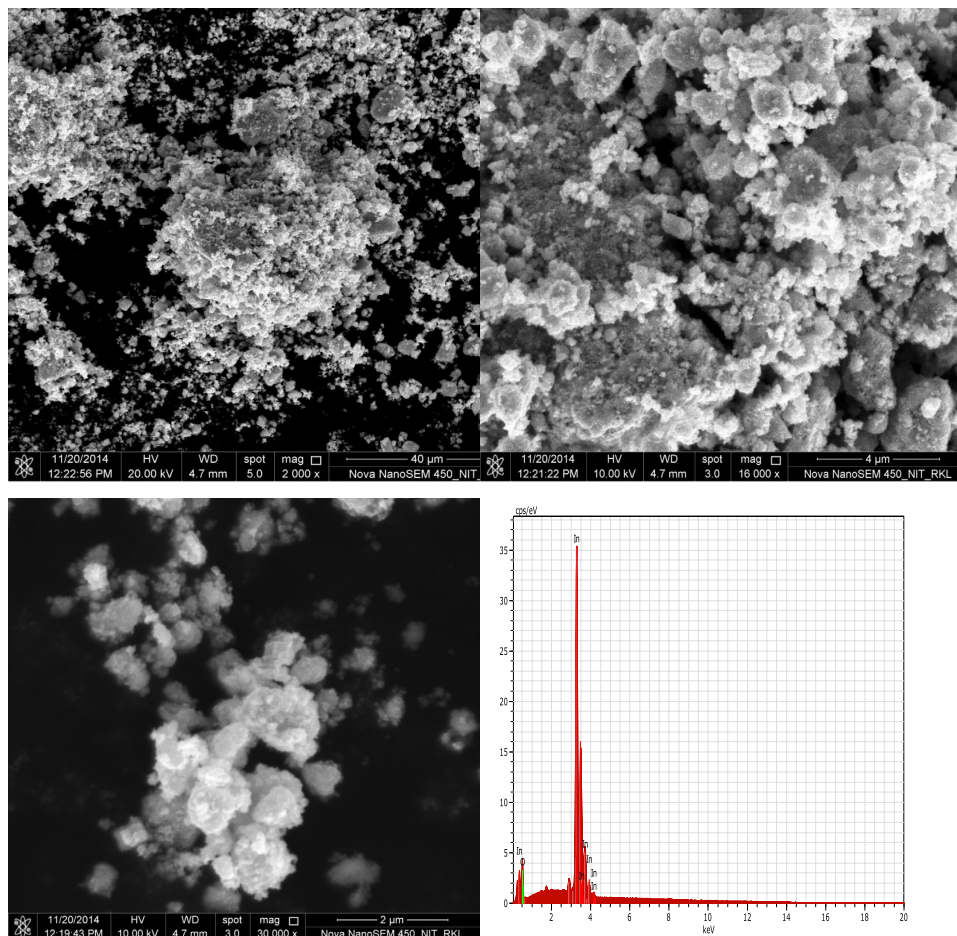


Figure 3. SEM-images of In_2O_3 nanoparticles at (a,b) lower and (c) higher magnification (d) Energy dispersive X-ray spectroscopy (EDS).

Entry	Catalyst (mol %)	Reagent (2eq) (Temp °C)	Solvent (Base 2eq)	Time (h)	Yield (%) ^d
1	Nano- In_2O_3 (2)	TBATB (110)	DMSO(Na₂CO₃)	2	99^a
		TBATB (110)	DMSO(Na ₂ CO ₃)	2	99 ^b
		TBATB (110)	DMSO(Na ₂ CO ₃)	4	45 ^c
		----- (110)	DMSO(Na ₂ CO ₃)	18	75
		TBATB (rt)	DMSO(Na ₂ CO ₃)	10	46
2	Nano In_2O_3 (2)	Br₂ (110)	DMSO(NaOH)	2	40
3	Nano- In_2O_3 (5)	TBATB (110)	DMSO(Na ₂ CO ₃)	2	95
4	Nano- In_2O_3 (2)	TBATB (130)	CH ₂ Cl ₂ (KOH)	4	65
5	Nano-Co ₃ O ₄ (5)	TBATB (110)	CH ₃ COOH(Na ₂ CO ₃)	4	40
6	Nano-Co ₃ O ₄ (10)	TBATB (110)	CH ₃ CN(Na ₂ CO ₃)	2	64

Table 1. Optimization of reaction condition for thiophenol to sulfide (Bold examples). ^aReaction was carried out at mmol scale using 0.2 mmol (22 mg) of thiophenol, (2 mol%) catalyst, bromine source (1.5 equiv) and base (2.0 equiv). ^bReaction was also carried out at gram scale using 1.10 g of thiophenol, (2 mol%) catalyst and TBATB (1.5 equiv), Na₂CO₃ (2.0 equiv). ^cWithout catalyst. ^dIsolated yield.

and reactions were monitored by thin layer chromatography (TLC) using UV light (254 nm) to visualize the course of reactions. ¹H and ¹³C Nuclear Magnetic Resonance spectra of pure compounds were acquired at 400 and 100 MHz respectively. All NMR samples were recorded in deuterated chloroform.

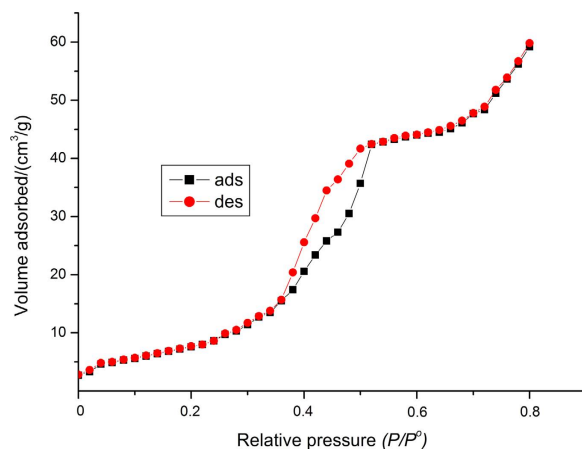


Figure 4. N₂ adsorption-desorption isotherm of indium oxide nanoparticles.

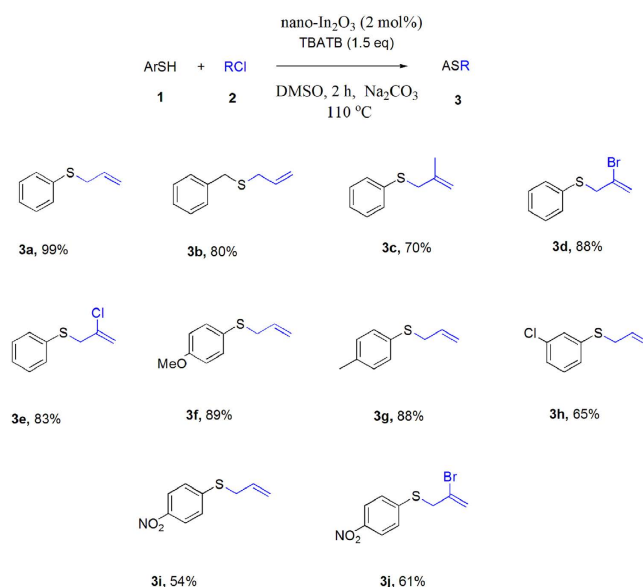


Figure 5. Synthesis of Aryl-allyl sulfide: Reactions were carried out with allyl chloride (0.2 mmol) Arylthiol (0.2 mmol), nano-In₂O₃ (2 mol%), TBATB (1.5 equiv), Na₂CO₃ (2.0 equiv) in DMSO (2 mL) for 2 h.

Chemical shifts (ppm) were recorded with tetramethylsilane (TMS) as the internal reference standard. Elemental analyses were performed on a Flash 2000 Thermo Scientific instrument at NIT Silchar. The TEM and SEM characterization were carried out at model no. CM-12 Philips TEM (IIT Kharagpur) and FEI Nova nano-SEM-450 (NIT Rourkela) respectively.

Allyl(phenyl)sulfane (3a)¹⁸. To a 10 mL glass tube, In₂O₃ nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na₂CO₃ (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and allyl chloride (15.2 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N₂ atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 25/1) to give the title compound **3a** (149 mg, 99%) as a light yellow liquid; [Found: C, 71.98; H, 6.49; C₉H₁₀S. requires C, 71.95; H, 6.71%]; R_f = 0.4 (hexane/ethyl acetate = 20/1). ¹H NMR (400 MHz, CDCl₃): δ 7.39–7.28 (m, 5H), 5.94 (m, 1H), 5.28 (dd, *J* = 1.3 Hz, *J* = 16.4 Hz, 1H), 5.13 (dd, *J* = 1.2 Hz, *J* = 10.1 Hz, 1H), 3.68 (d, *J* = 6.8 Hz, 2H). ¹³C NMR (100 MHz, CDCl₃): δ 134.9, 133.9, 130.7, 129.8, 126.9, 118.9, 37.4.

(2-methylallyl)(phenyl)sulfane (3c)²⁹. To a 10 mL glass tube, In₂O₃ nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na₂CO₃ (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and

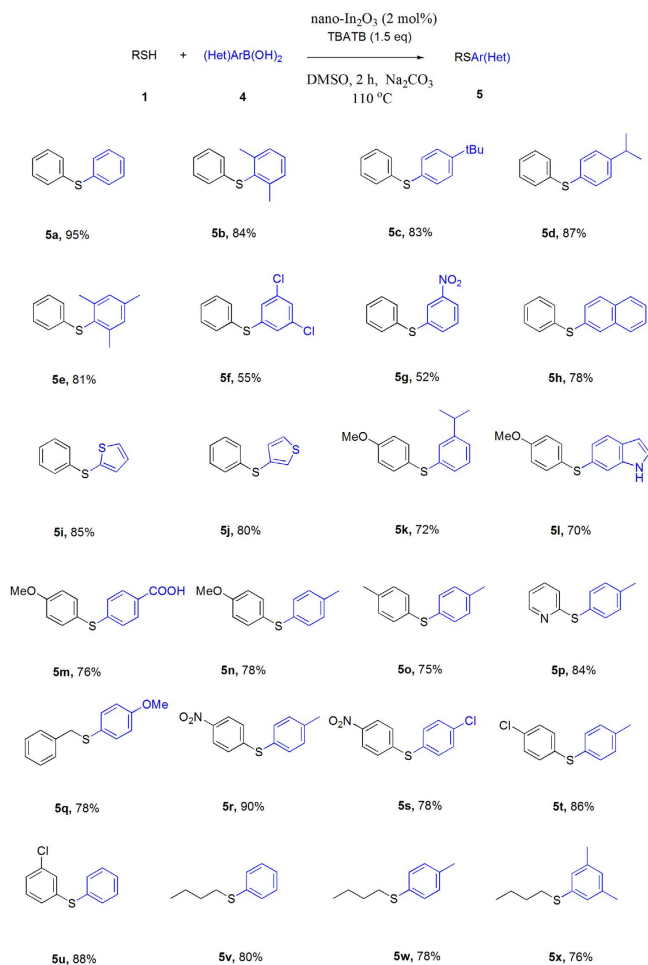


Figure 6. Coupling of thiols with arylboronic acids: Reactions were carried out with arylboronic acid (0.2 mmol), thiol (0.2 mmol), nano-In₂O₃ (2 mol%), TBATB (1.5 equiv), Na₂CO₃ (2.0 equiv) in DMSO (2 mL) for 2 h.

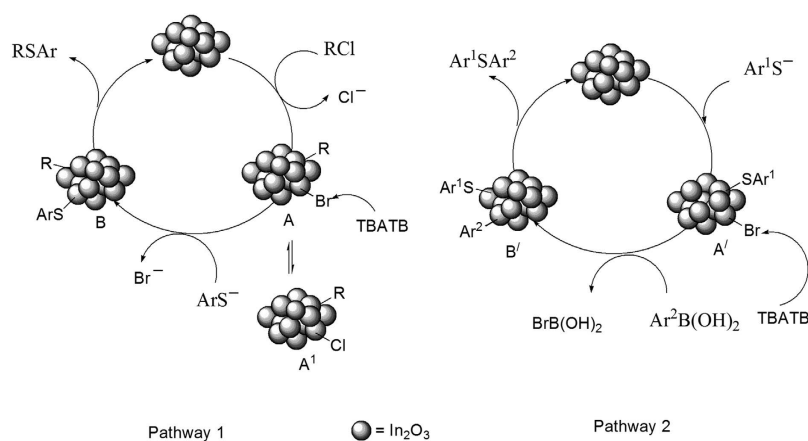


Figure 7. Plausible mechanism for C-S bond formation

2-chloro-2-methyl-propene (18.2 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N₂ atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified

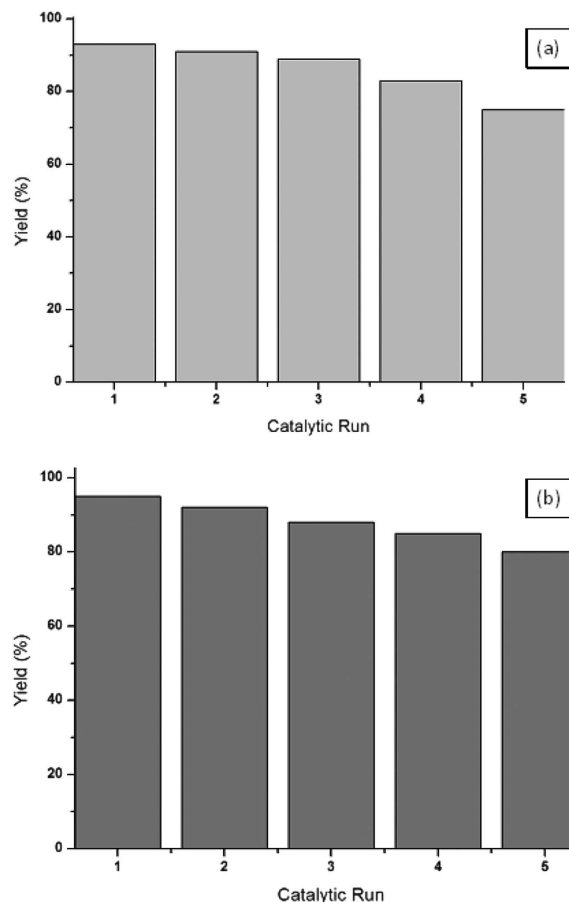


Figure 8. Recovery of In_2O_3 nps: (a) Reactions were carried out with allyl chloride (0.2 mmol) phenylthiol (0.2 mmol), nano- In_2O_3 (2 mol%), TBATB (1.5 equiv), Na_2CO_3 (2.0 equiv) in DMSO (2 mL) for 2 h. (b) Reactions were carried out with phenylboronic acid (0.2 mmol), phenylthiol (0.2 mmol), nano- In_2O_3 (2 mol%), TBATB (1.5 equiv), Na_2CO_3 (2.0 equiv) in DMSO (2 mL) for 2 h.

by column chromatography (hexane/ethyl acetate = 10/1) to give the title compound **3c** (114.8 mg, 70%) as a colourless liquid; [Found: C, 72.98; H, 7.39; $\text{C}_{10}\text{H}_{12}\text{S}$ requires C, 73.12; H, 7.36%]; R_f = 0.4 (hexane/ethyl acetate = 10/1). ^1H NMR (400 MHz, CDCl_3): δ 7.44–7.33 (m, 5H), 5.16 (d, J = 1.2 Hz, 1H), 4.89 (d, J = 1.1 Hz, 1H), 3.65 (s, 2H), 1.87 (s, 3H). ^{13}C NMR (100 MHz, CDCl_3): δ 142.4, 135.3, 131.2, 129.1, 128.2, 112.5, 42.9, 21.7.

(2-bromoallyl)(phenyl)sulfane (3d)²⁰. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2-bromo-allyl bromide (39.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **3d** (201 mg, 88%) as a colourless liquid; [Found: C, 47.16; H, 3.93; S, 14.04; $\text{C}_9\text{H}_9\text{BrS}$ requires C, 47.18; H, 3.96; S, 13.99%]; R_f = 0.4 (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.53–7.30 (m, 5H), 5.89 (d, J = 1.8 Hz, 1H), 5.50 (d, J = 1.7 Hz, 1H), 4.01 (m, 2H). ^{13}C NMR (100 MHz, CDCl_3): δ 135.2, 131.1, 129.4, 129.2, 127.5, 119.6, 45.2.

(2-chloroallyl)(phenyl)sulfane (3e). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2-chloro-allyl chloride (22 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 20/1) to give the title compound **3e** (153 mg, 83%) as a colourless liquid; [Found: C, 58.58; H, 4.80; $\text{C}_9\text{H}_9\text{ClS}$ requires C, 58.53; H, 4.91%]; R_f = 0.4 (hexane/ethyl acetate = 20/1).

^1H NMR (400 MHz, CDCl_3): δ 7.94–7.86 (m, 5H), 5.77–5.64 (m, 2H), 3.88 (d, $J=6.3$ Hz, 2H). ^{13}C NMR (100 MHz, CDCl_3): δ 140.8, 137.7, 133.9, 128.4, 126.2, 119.7, 44.1.

Allyl(*p*-tolyl)sulfane (3g)²¹. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), 4-methylthiophenol (24.8 mg, 0.2 mmol) and allyl chloride (15.2 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **3g** (144 mg, 88%) as a colourless liquid; [Found: C, 73.13; H, 7.31. $\text{C}_{10}\text{H}_{12}\text{S}$ requires C, 73.12; H, 7.36%]; $R_f=0.5$ (hexane/ethyl acetate = 10/1). ^1H NMR (400 MHz, CDCl_3): δ 7.38 (d, $J=8.1$ Hz, 2H), 7.03 (d, $J=7.9$ Hz, 2H), 5.74–5.55 (m, 1H), 5.16–5.06 (m, 2H), 3.58 (d, $J=7.6$ Hz, 2H), 2.35 (s, 3H). ^{13}C NMR (100 MHz, CDCl_3): δ 138.7, 134.2, 132.8, 131.6, 129.5, 117.9, 37.2, 20.1

allyl(3-chlorophenyl)sulfane (3h). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), 3-chlorothiophenol (28.8 mg, 0.2 mmol) and allyl chloride (15.2 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **3h** (105 mg, 65%) as a yellow liquid; [Found: C, 58.58; H, 4.94; $\text{C}_9\text{H}_9\text{ClS}$ requires C, 58.53; H, 4.91%]; $R_f=0.5$ (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.38–7.29 (m, 4H), 5.86–5.75 (m, 1H), 5.27 (dd, $J=1.1$ Hz, $J=16.1$ Hz, 1H), 5.17 (dd, $J=1.3$ Hz, $J=10.2$ Hz, 1H), 3.59 (d, $J=6.1$ Hz, 2H). ^{13}C NMR (100 MHz, CDCl_3): δ 137.7, 134.2, 132.5, 128.9, 127.9, 125.6, 124.3, 117.7, 35.9.

Allyl(4-nitrophenyl)sulfane (3i)²². To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), 4-nitrothiophenol (31 mg, 0.2 mmol) and allyl chloride (15.2 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **3i** (105 mg, 54%) as a yellow solid, mp 39–41 °C; [Found: C, 55.31; H, 4.66; N, 6.99; $\text{C}_9\text{H}_9\text{NO}_2\text{S}$ requires C, 55.37; H, 4.65; N, 7.17%]; $R_f=0.6$ (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 8.45 (d, $J=8.1$ Hz, 2H), 7.38 (d, $J=8.6$ Hz, 2H), 5.89–5.83 (m, 1H), 5.36 (dd, $J=1.1$ Hz, $J=16.3$ Hz, 1H), 5.27 (dd, $J=1.4$ Hz, $J=10.1$ Hz, 1H), 3.76 (d, $J=6.3$ Hz, 2H). ^{13}C NMR (100 MHz, CDCl_3): δ 147.8, 146.7, 133.9, 127.8, 124.8, 119.4, 35.2.

(2-bromoallyl)(4-nitrophenyl)sulfane (3j). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), 4-nitrothiophenol (31 mg, 0.2 mmol) and 2-bromo-allyl bromide (39.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at the corresponding temperature for 2 h. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 10/1) to give the title compound **3j** (167 mg, 61%) as a colourless liquid; [Found: C, 39.49; H, 2.99; N, 5.01; $\text{C}_9\text{H}_8\text{BrNO}_2\text{S}$ requires C, 39.43; H, 2.94; N, 5.11%]; $R_f=0.4$ (hexane/ethyl acetate = 10/1). ^1H NMR (400 MHz, CDCl_3): δ 8.20 (d, $J=9.1$ Hz, 2H), 7.36 (d, $J=8.2$ Hz, 2H), 5.77 (d, $J=2.9$ Hz, 1H), 5.47 (d, $J=2.6$ Hz, 1H), 4.01 (s, 2H). ^{13}C NMR (100 MHz, CDCl_3): δ 143.1, 139.2, 125.7, 124.9, 121.1, 44.8.

Diphenyl sulfide (5a)²³. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and phenylboronic acid (24.4 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5a** (177 mg, 95%) as a colourless liquid; [Found: 77.55; H, 5.47; $\text{C}_{12}\text{H}_{10}\text{S}$ requires C, 77.37; H, 5.41%]; $R_f=0.4$ (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.40 – 7.27 (m, 10H). ^{13}C NMR (100 MHz, CDCl_3): δ 135.5, 131.2, 129.2, 127.7.

2, 6-Dimethylphenyl phenyl sulfide (5b)²⁴. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2,6-dimethyl-phenylboronic acid (30 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 20/1) to give the title compound **5b** (180 mg, 84%) as a colourless liquid; [Found: C, 78.65; H, 6.54; $\text{C}_{14}\text{H}_{14}\text{S}$ requires C, 78.45; H, 6.58%]; $R_f=0.4$ (hexane/ethyl acetate = 20/1).

^1H NMR (400 MHz, CDCl_3): δ 7.28–7.22 (m, 5H), 7.10–6.96 (m, 3H), 2.46 (s, 6H). ^{13}C NMR (100 MHz, CDCl_3): δ 144.1, 138.2, 130.7, 129.4, 128.4, 128.0, 125.3, 124.0, 21.4.

4-*tert*-Butylphenyl phenyl sulfide (5c). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 4-*tert*-butylphenylboronic acid (35.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5c** (201 mg, 83%) as a colourless liquid; R_f = 0.6 (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.35–7.19 (m, 9H), 1.31 (s, 9H). ^{13}C NMR (100 MHz, CDCl_3): δ 150.4, 136.1, 131.0, 130.4, 130.1, 129.2, 126.4, 126.1, 34.6, 31.4.

4-isopropylphenyl(phenyl)sulfide (5d)²⁵. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 4-isopropylphenylboronic acid (35.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 25/1) to give the title compound **5d** (198 mg, 87%) as a colourless liquid; R_f = 0.6 (hexane/ethyl acetate = 25/1). ^1H NMR (400 MHz, CDCl_3): δ 7.44–7.22 (m, 9H), 3.03–2.92 (m, 1H), 1.27 (d, J = 7.2 Hz, 6H). ^{13}C NMR (100 MHz, CDCl_3): δ 148.7, 136.7, 131.4, 131.0, 130.6, 129.4, 128.4, 127.3, 127.2, 126.3, 33.6, 23.4.

(2,4,6-trimethyl-phenyl)-phenyl sulfide (5e)²⁵. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2,4,6-trimethyl-phenylboronic acid (32.8 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 20/1) to give the title compound **5e** (185 mg, 81%) as a colourless liquid; [Found: C, 78.86; H, 7.17; $\text{C}_{15}\text{H}_{16}\text{S}$ requires C, 78.90; H, 7.06%]; R_f = 0.4 (hexane/ethyl acetate = 20/1). ^1H NMR (400 MHz, CDCl_3): δ 7.38–7.31 (m, 2H), 7.28–7.18 (m, 3H), 6.96–6.88 (m, 2H), 2.47 (s, 6H), 2.39 (s, 3H). ^{13}C NMR (100 MHz, CDCl_3): δ 143.4, 139.3, 138.4, 129.4, 128.0, 127.7, 125.8, 124.4, 21.6, 21.1.

3,5-Dichlorophenyl phenyl sulfide (5f). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 3,5-dichlorophenylboronic acid (38 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5f** (140 mg, 55%) as a colourless liquid; R_f = 0.6 (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.64–7.54 (m, 5H), 7.37–7.26 (m, 3H). ^{13}C NMR (100 MHz, CDCl_3): δ 140.9, 133.2, 132.7, 131.5, 129.6, 129.3, 128.5, 122.2.

3-Nitrophenyl phenyl sulfide (5g). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 3-nitrophenylboronic acid (33.4 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5g** (120 mg, 52%) as a pale yellow liquid; R_f = 0.6 (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.97–7.78 (m, 4H), 7.44–7.36 (m, 5H). ^{13}C NMR (100 MHz, CDCl_3): δ 134.7, 133.9, 132.3, 129.2, 129.0, 128.9, 128.6, 128.2, 123.4, 120.2.

2-Naphthalyl phenyl sulfide (5h). To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2-naphthylboronic acid (34.4 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5h** (184 mg, 78%) as a white solid; mp 50–51 °C; R_f = 0.5 (hexane/ethyl acetate = 15/1). ^1H NMR (400 MHz, CDCl_3): δ 7.86–7.76 (m, 4H), 7.50–7.42 (m, 8H). ^{13}C NMR (100 MHz, CDCl_3): δ 135.7, 133.6, 133.2, 132.7, 130.8, 129.6, 129.4, 128.8, 128.4, 127.4, 127.1, 127.0, 126.9, 126.2.

2-(Phenylthio)thiophene (5i)²⁴. To a 10 mL glass tube, In_2O_3 nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na_2CO_3 (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 2-thiopheneboronic acid (25.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N_2 atmosphere. The

tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5i** (163 mg, 85%) as a colourless liquid; [Found: C, 62.59; H, 4.11; C₁₀H₈S₂ requires C, 62.46; H, 4.19%]; R_f = 0.6 (hexane/ethyl acetate = 15/1). ¹H NMR (400 MHz, CDCl₃): δ 7.51 (dd, *J* = 4.4 Hz, 1H), 7.34–7.22 (m, 6H), 7.16–7.11 (m, 1H). ¹³C NMR (100 MHz, CDCl₃): δ 138.7, 136.0, 131.5, 131.2, 128.9, 128.1, 127.4, 126.1.

3-(Phenylthio)thiophene (5j)²⁴. To a 10 mL glass tube, In₂O₃ nanoparticles (1.1 mg, 0.004 mmol), TBATB (144 mg, 0.3 mmol), Na₂CO₃ (42 mg, 0.4 mmol), thiophenol (22 mg, 0.2 mmol) and 3-thiopheneboronic acid (25.6 mg, 0.2 mmol) were dissolved in DMSO (2 mL) under N₂ atmosphere. The tube was sealed and the mixture was stirred at 110 °C. The reaction mixture was filtered and the solvent evaporated in vacuo to give the crude product, which was purified by column chromatography (hexane/ethyl acetate = 15/1) to give the title compound **5j** (161 mg, 80%) as a colourless liquid; [Found: C, 62.56; H, 4.09; C₁₀H₈S₂ requires C, 62.46; H, 4.19%]; R_f = 0.6 (hexane/ethyl acetate = 15/1). ¹H NMR (400 MHz, CDCl₃): δ 7.37–7.34 (m, 2H), 7.26–7.13 (m, 8H), 7.07 (dd, *J* = 8.2 Hz, 1H). ¹³C NMR (100 MHz, CDCl₃): δ 137.8, 131.6, 129.2, 128.9, 128.6, 128.1, 126.7, 126.0.

References

- Li, X. H., Baar, M., Blechert, S. & Antonietti, M. Facilitating room-temperature Suzuki coupling reaction with light: Mott-Schottky photocatalyst for CC-coupling. *Sci. Rep.* **3**, 1–6 (2013).
- Kundu, D., Chatterjee, T. & Ranu, B. C. Magnetically Separable CuFe₂O₄ Nanoparticles Catalyzed Ligand-Free C-S Coupling in Water: Access to (E)- and (Z)-Styrenyl-, Heteroaryl and Sterically Hindered Aryl Sulfides. *Adv. Synth. Catal.* **355**, 2285–2296 (2013).
- Wang, L., He, W. & Yu, Z. Transition-metal mediated carbon-sulfur bond activation and transformations. *Chem. Soc. Rev.* **42**, 599–621 (2013).
- Ley, S. V. & Thomas, A. W. Modern Synthetic Methods for Copper-Mediated C(aryl)-O, C(aryl)-N, and C(aryl)-S Bond Formation. *Angew. Chem. Int. Ed.* **42**, 5400–5449 (2003).
- Rout, L., Sen, T. K. & Punniyamurthy, T. Efficient CuO-nanoparticle-catalyzed C-C cross-coupling of thiols with iodobenzene. *Angew. Chem.* **119**, 5679–5682 (2007).
- Gogoi, P., Hazarika, S., Sarma, M. J., Sarma, K. & Barman, P. Nickel-Schiff base complex catalyzed C-S cross-coupling of thiols with organic chlorides. *Tetrahedron* **70**, 7484–7489 (2014).
- Migita, T. *et al.* The palladium catalyzed nucleophilic substitution of aryl halides by thiolate anions. *Bull. Chem. Soc. Jpn.* **53**, 1385–1389 (1980).
- Mao, J., Jia, T., Frensch, G. & Walsh, P. J. Palladium-Catalyzed Debenzylative Cross-Coupling of Aryl Benzyl Sulfides with Aryl Bromides: Synthesis of Diaryl Sulfides. *Org. Lett.* **16**, 5304–5307 (2014).
- Wong, Y. C., Jayanth, T. T. & Cheng, C. H. Cobalt-catalyzed aryl-sulfur bond formation. *Org. Lett.* **8**, 5613–5616 (2006).
- Carril, M., Correa, A., & Bolm, C. Iron-Catalyzed Sonogashira Reactions. *Angew. Chem.* **120**, 4940–4943 (2008).
- Ku, X., Huang, H., Jiang, H. & Liu, H. Efficient iron/copper cocatalyzed S-arylations of thiols with aryl halides. *J. Comb. Chem.* **11**, 338–340 (2009).
- Seo, W. S., Jo, H. H., Lee, K. & Park, J. T. Preparation and Optical Properties of Highly Crystalline, Colloidal, and Size-Controlled Indium Oxide Nanoparticles. *Adv. Mater.* **15**, 795–797 (2003).
- Mumbunjong, W. *et al.* Indium-mediated cleavage of diphenyl diselenide and diphenyl disulfide: efficient one-pot synthesis of unsymmetrical diorganyl selenides, sulfides, and selenoesters. *Tetrahedron* **65**, 2467–2471 (2009).
- Ranu, B. C. & Mandal, T. Indium (I) iodide-promoted cleavage of diaryl diselenides and disulfides and subsequent condensation with alkyl or acyl halides. One-pot efficient synthesis of diorganyl selenides, sulfides, selenoesters, and thioesters. *J. Org. Chem.* **69**, 5793–5795 (2004).
- Reddy, V. P., Kumar, A. V., Swapna, K. & Rao, K. R. Nano indium oxide as a recyclable catalyst for C-S cross-coupling of thiols with aryl halides under ligand free conditions. *Org. Lett.* **11**, 1697–1700 (2009).
- Zhuang, Z., Peng, Q., Liu, J., Wang, X. & Li, Y. Indium hydroxides, oxyhydroxides, and oxides nanocrystals series. *Inorg. Chem.* **46**, 5179–5187 (2007).
- Jammi, S., Barua, P., Rout, L., Saha, P. & Punniyamurthy, T. Efficient ligand-free nickel-catalyzed C-S cross-coupling of thiols with aryl iodides. *Tetrahedron Lett.* **49**, 1484–1487 (2008).
- Lin, Y. A., Chalker, J. M., Floyd, N., Bernardes, G. J. L. & Davis, B. G. Allyl sulfides are privileged substrates in aqueous cross-metathesis: application to site-selective protein modification. *J. Am. Chem. Soc.* **130**, 9642–9643 (2008).
- Streiff, S. P., Ribeiro, N. & Dausaubry, L. Synthesis of allylsilanes by reductive lithiation of thioethers. *J. Org. Chem.* **69**, 7592–7598 (2004).
- Bates, C. G., Gujadhur, R. K. & Venkataraman, D. A general method for the formation of aryl-sulfur bonds using copper (I) catalysts. *Org. Lett.* **4**, 2803–2806 (2002).
- Rathgeb, X., March, S. & Alexakis, A. One-pot asymmetric conjugate addition-trapping of zinc enolates by activated electrophiles. *J. Org. Chem.* **71**, 5737–5742 (2006).
- Tang, R. Y., Zhong, P. & Lin, Q. L. Sulfite-promoted one-pot synthesis of sulfides by reaction of aryl disulfides with alkyl halides. *Synthesis* 85–91 (2007) doi: 10.1055/s-2006-950363.
- Park, N., Park, K., Jang, M., & Lee, S. One-pot synthesis of symmetrical and unsymmetrical aryl sulfides by Pd-catalyzed couplings of aryl halides and thioacetates. *J. Org. Chem.* **76**, 4371–4378 (2011).
- Uyeda, C., Tan, Y., Fu, G. C. & Peters, J. C. A New Family of Nucleophiles for Photoinduced, Copper-Catalyzed Cross-Couplings via Single-Electron Transfer: Reactions of Thiols with Aryl Halides Under Mild Conditions (0 °C). *J. Am. Chem. Soc.* **135**, 9548–9552 (2013).
- Gogoi, P., Kalita, M. & Barman, P. An Efficient Protocol for the Carbon-Sulfur Cross-Coupling of Sulfonyl Chlorides with Arylboronic Acids using a Palladium Catalyst. *Synlett* **25**, 866–870 (2014).

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Author Contributions

P.G. developed the idea and designed the experiments. S.H. performed the experiments. S.H. and S.K.B. analyzed the data, and discussed the results. P.B. and P.G. wrote the paper.

Additional Information

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