



Accepted Article

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This manuscript has been accepted after peer review and appears as an Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

To be cited as: ChemCatChem 10.1002/cctc.201801948

Link to VoR: http://dx.doi.org/10.1002/cctc.201801948



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Metal-free Semiconductor Photocatalysis for sp² C-H Functionalization with Molecular Oxygen

Meifang Zheng,¹ Indrajit Ghosh,² Burkhard König,^{2*} and Xinchen Wang^{1*}

Abstract: Designing metal-free catalysts for solar energy conversion is a long-standing challenge in semiconductor photoredox catalysis (SPC). With visible-light-responsive hexagonal boron carbon nitride (h-BCN) as a non-metal photocatalyst, this system affords C-H/N-H coupling products with broad substitution tolerance and high efficiency with molecular oxygen as the terminal oxidant. The catalyst exhibits remarkable performance for the selective C-H functionalization of electron-rich arenes to C-N products (yields up to 95%) and good stability (6 recycles). Both nitrogen heteroarenes and amine salts are competent coupling nucleophiles. Mechanically, the reactive oxygen species are superoxide anion radical (O2-•) and H₂O₂, which are proved by electron spin resonance (ESR) data, KIstarch, and control experiments. In addition, kinetic isotope effect (KIE) experiments indicate that C-H bond cleavage is not involved in the rate limiting step. This semiconductor-based photoredox system allows for C-H amination free of any metals, ligands, strong oxidants, and additives. It provides a complementary avenue to C-H functionalizations and enables synthetic applications efficiently in a sustainable manner.

Semiconductors have shown great potential in driving several important reactions (e.g., water splitting, CO2 reduction, and environmental remediation) over the last decades.^[1] The photocatalytic ability is thermodynamically determined by the redox window caused by photoinduced electrons (e⁻) (produced at conduction band, CB) and holes (h⁺) (produced at valence band, VB), that is, the reaction can proceed only if the redox potential of the photocatalyst is greater than that of the reactants.^[2] Most metal-based semiconductors are thermodynamically capable of triggering those reactions, however, wider bandgap means shorter wavelength absorption. Thus, recent efforts focus on the development of metal-free materials for relevant chemical reactions because electronic transition in conjugated systems could be stimulated by visible light.^[3] It also has the benefits of containing earth-abundant elements and meeting environmental-friendly principles. Among the reported metalfree semiconductor photocatalysts, h-BCN has drawn interdisciplinary attention because its balance in suitable bandgap and efficient visible-light responsiveness. Besides, it is an inexpensive and easily-available material, and

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exhibits good catalytic performance and high stability under visible light photoredox conditions.^[4]

Direct transformation of ubiquitous, but chemically inert, aryl C-H bonds can provide efficient and expedient access to arenes with diverse structural properties. Carbon-carbon (C-C), carbon-oxygen (C-O), or carbon-nitrogen (C-N) bonds are formed without prior functionalization of the arenes as halides, trifluoroates, or boronic acids or their derivatives.^[5] In recent years, certain homogeneous efforts have been made to C-H functionalizations with high efficiency.^[6] Despite the indisputable advances and high efficiency, reported methods often require elevated reaction temperatures, stoichiometric amounts of strong oxidants, precious metals with ligands, and the installation and removal of directing groups. Therefore, a heterogeneous system with O₂ as the only oxidant for C-H functionalization may allow to address most of the aforementioned challenges. Herein, for the first time, semiconductor photoredox catalysis (SPC) is applied to oxidative photoredox manifolds with oxygen and visible light driven C-H activation.



Figure 1. Structure and optical characterization of *h*-BCN. (a) TEM of *h*-BCN. (b) UV-vis DRS of *h*-BCN and inset is the picture of *h*-BCN. (c) The UPS of *h*-BCN. (d) The valence band and conductiopn band of *h*-BCN.

Transmission electron microscope (TEM) spectra of h-BCN are recorded and shown in Figure 1 a. In designing organic photosynthesis, it is crucial that the catalytic material is visible-light responsive. Based on the previous reports, carbon-free h-BN (hexagonal boron nitride) material is a typical insulator with a wide bandgap of about 5.5 eV, and the doping of carbon narrows the band gap (see the synthesis of h-BCN in the SI), and thus turning the insulator

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into a visible light responsive semiconductor.^{4b} As shown in Figure 1b, the bandgap was estimated to be 2.75 eV by ultraviolet-visible diffuse reflectance spectroscopy (UV-vis DRS). The valence band was determined via ultraviolet photoelectron spectrometer (UPS) and the valence band level of *h*-BCN is 6.18 eV vs. vacuum according to UPS spectra (Figure 1c). The VB level is +1.78 V vs. NHE at pH = 7, and the CB level is -0.97 V vs. NHE at pH = 7 (Figure 1d). Besides, photoluminescence lifetimes dynamically play an important role in photocatalysis, the average PL lifetime of as-obtained *h*-BCN material was 2.73 ns (Figure S2).

First, we optimized the reaction conditions using 1,3,5trimethoxybenzene (1a) and pyrazole (2a) as model substrates (Table 1). After investigating the solvents, we obtained a satisfactory yield of the amination product 3a using DMSO as the solvent (SI, Table S1; Table 1, entry 1). The AQY (apparent quantum yield) is ca. 1.0% at 450 nm (see the details in the SI). Additionally, the control experiments indicated that oxygen, visible light, and photocatalyst were indispensable for this transformation (Table 1, entries 2-4). The general homogeneous organometallic photosensitizers, such as Ru(bpy)₃Cl₂ and Ir(bpy)₃, are unable to activate the arene C-H bond due to their lower oxidation potential (Table 1, entries 5-6). Homogeneous dyes, such as Eosin Y and Rh-6G, failed to oxidize the arene sp² C–H bond (Table 1, entries 7-8). Previous accomplishes with DDQ and the acridinium salt (9-mesityl-3,6-di-tert-butyl-10-phenylacridiniumtetrafluoroborate) were tested with 1a and 2a as the model substrates under O₂ atmosphere, the yields were inferior comparing with that of using BCN as the photocatalyst (entries 9–10). $^{[5c,\ 5e]}$ We also compared the performance of *h*-BCN with other heterogeneous photocatalysts, and results show the activity of h-BCN is better than that of TiO₂ (P25) and CdS under visible light irradiation (Table 1, entries 11-12) in our reaction conditions.

`0 I

	HNN	blue LEDs	
	1a 2a		3a
entry	cat.	solvent	yield ^[a]
1	<i>h</i> -BCN	DMSO	93% (91%)
2 ^[b]	<i>h</i> -BCN	DMSO	trace
3 ^[c]	h-BCN	DMSO	n.d.
4	-	DMSO	n.d.
5	Ru(bpy) ₃ Cl ₂	DMSO	n.d.
6	lr(bpy)3	DMSO	n.d.
7	Eosin Y	DMSO	n.d.
8	Rh-6G	DMSO	n.d.
9	DDQ	CH₃CN	21%
10	Acridinium	DCE	75%
11	TiO ₂	DMSO	n.d.
12	CdS	DMSO	5%

catalyst

[a] Unless otherwise noted, the reaction was carried out with 12 mg of catalyst, 0.2 mmol of **1a**, 0.8 mmol of **2a**, and 1 mL solvent at r.t. with 1 atmosphere of O_2 balloon for 48 h under 3 w blue LEDs illumination. Yield was determined by gas chromatography. DMSO is short for dimethyl sulfoxide. DCE is short for 1,2-dichloroethane. "n.d." means "not detected". [b] The reaction was carried out without light.



[a] Standard reaction conditions: 0.2 mmol **1**, 4 or 5 equivalents of **2**, 12 mg *h*-BCN, and 1-1.5 mL DMSO were added in a photoreactor, followed by 48-72 h visible light irradiation.

With optimized reaction conditions in hand (Table 1, entry 1), we investigated different electron-rich arenes in the next set of experiments. As shown in Table 2, this methodology can be applied to different aromatic C-H bonds. With anisole as substrate, the corresponding C-N coupling products were obtained in good yields with a 2:1 ratio of the para- and ortho-products 3b. Furthermore, naphthalene and its derivative could couple to pyrazoles with good isolated yields (3c-3e). In particular, the reaction with trimethyl benzene did not show benzylic oxidation and gave 48% yield of the corresponding C-H N-arylation product 3f. The acetyl group on naphthalene remains unchanged and a 95% yield of 3g was obtained. With 1,4-dimethylpyrazole as the substrate, 21% yield of 3h was isolated. A diverse range of Ncontaining nucleophiles could be directly coupled with arenes in this heterogeneous photoredox system (Table 3). Imidazoles and trizoles were compatible with this SPC system with good to excellent yields (3i-3m). Besides, anilines could be obtained from this catalytic sequence by using an ammonium salt as the nitrogen source. Primary

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amines are important building blocks due to the presence of a synthetically versatile NH₂ group. Traditionally, anilines are prepared via a nitration/hydrogenation sequence and the process requires harsh conditions. Wu's group reported a one-step synthesis of anilines from benzene with ammonia as the amine source using a combination of an acridinium salt and cobalt catalysis.^[7] Starting from these observations, we screen a variety of commercially available ammonium salts, such as H₄N⁺OAc⁻, H₄N⁺HCO₃⁻, and (H₄N⁺)₂CO₃^{2⁻}. Among them, ammonium carbamate (H₄N⁺H₂NCO₂⁻) was best suited for the reaction (Table S2 in the SI). Using 5.0 equivalents of ammonium carbamate with anisole, it resulted in the formation of a 5:1 ratio mixture of para- and orthoanisidine yield of 41% (**3q**). Delightfully, a 53% yield of naphthalen-1-amine **3p** was obtained under catalytic conditions nearly identical to those applied to azoles.

The recyclability of the catalyst was studied. The catalyst was recovered by centrifugation and reused for at least five more times without losing catalytic efficiency in C–N arylation (Figure 2). This demonstrates the high stability of *h*-BCN during the prolonged photochemical operation. Raman spectra were identical before and after the reaction, which indicate the stability of the catalysts as well (Figure S3).



Figure 2. Evaluation of catalytic recycling.

An intermolecular KIE experiment was carried out to study the heterogeneous radical pathway of this photochemical system (Figure S4). The KIE of 1.30 was observed from nuclear magnetic resonance (NMR) data (Figure 3a), which revealed that the C-H bond cleavage of the arene might not be involved in the rate-determining step. Then, the mechanism was studied by control experiments and ESR. The coupling reaction totally stopped with the addition of TEMPO or 1,1-diphenylethene under the standard conditions (see details in the SI). The results indicate a radical process. An ESR experiment was conducted employing 5,5-dimethyl-1-pyrroline-N-oxide (DMPO) as a spin trap. The spectra show the characteristic peaks of DMPOO₂, demonstrating the formation of the superoxide radical (Figure 3b).^[8] The observations strongly suggest that oxygen plays a critical role as electron acceptor. Namely, O2 accepts the electrons from the conduction band to form $O_2^{-\bullet}$. The light-excited electrons in *h*-BCN possess a strong thermodynamical driving force to reduce O_2 (E^o, $(O_2/O_2^{-\bullet}) = -0.16$ V vs. NHE at pH = 7) to superoxide $O_2^{-\bullet}$.^[9] Molecular O_2 has a ground state potential that is unable to seize electrons from arenes $(E^{\circ}, (1b/1b^{*+} = 1.63 \text{ V vs. NHE at pH} = 7)$. Besides, the potential of the valence band (+1.78 V vs. NHE at pH = 7)

can not oxidize –OH to hydroxyl radicals (E° , (–OH/•OH) = 2.02 V vs. NHE at pH = 7). So it is thermodynamically unfeasible to produce hydroxyl radicals with BCN materials under visible light. This is beneficial for the formation of the target products, because hydroxyl radicals may cause photodegradation and thus probably decrease the yield.^[10] Therefore, the *h*-BCN catalyst produces light induced electrons and holes under the illumination of blue LEDs. The holes could accept electrons from the arenes to generate the aryl cation radical intermediate. And the photo-exited electrons of *h*-BCN would be accepted by oxygen generating $O_2^{-\bullet}$.



Figure 3. Investigation for mechanistic insights. (a) The intermolecular KIE experiment. (b) ESR spectra of a solution of *h*-BCN $(3.0 \times 10^{-3} \text{ M})$, **1a** (0.10 M), and DMPO (0.50 M) in DMSO.



Figure 4. The proposed mechanism for the photocatalytic C-H amination by *h*-BCN with visible light.

Based on the above experiments and previous reports,^[6c, 10b, 11] we propose a possible mechanism (Figure 4). Initially, *h*-BCN is excited to produce electrons and holes by blue LEDs. Then, an arene carbon cation radical **A** is generated upon photoinduced electron transfer (PET) from the arene to the catalyst (valence band level of +1.78 V vs. NHE at pH = 7). The radical cation **A** then acts as electrophilic partner for nitrogen nucleophiles. That is, the nucleophile **2a** forms a σ -

adduct with cation radical **A** via direct C–H aryl amination to generate intermediate **B**, neutralizing the charge. The subsequent deprotonation of intermediate **B** forms intermediate **C**. Subsequent oxidative aromatization of intermediate **C** yields the final aminated product **3**. Oxygen plays an important role as terminal oxidant in this two-electron and two-proton loss process.¹²

In summary, we have developed a simple metal-free pathway for the C-H amination of arenes with a SPC system at ambient conditions. This approach exploits a recyclable catalyst that is capable of oxidizing arenes through a single electron transfer (SET) to generate the corresponding cation radicals under visible light illumination. Oxygen serves as both the terminal oxidant and the electron mediator, which is distinct from the previous reports using homogeneous photoredox systems. N-arylated compounds are obtained in good to excellent yields with various nitrogen nucleophiles. Although the semiconductor photoredox catalytic system for C-H functionalization is currently limited to electron-rich arenes, further improvement of BCN materials is currently on the way in our laboratory. The semiconductor system for organic synthesis expands our knowledge of chemical reactivity and provides a complementary environmentally friendly synthetic protocols to C-H functionalization.

Acknowledgements

This work was financially supported by the National Key R&D Program of China (2018YFA0209301), the National Natural Science Foundation of China (grant nos. 21425309, 21702030, 21761132002, and 21861130353), Postdoctoral Science Foundation (2018M630726), and the 111 Project (D16008). We thank BayChina for financial support.

Conflict of interest

The authors declare no conflict of interest.

Keywords: Heterogeneous Catalysis • Visible Light• Semiconductor Photoredox Catalysis • C-H Fuctionalization • Radical

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- [12] Upon the addition of KI and starch to the solution of the N₂ flushed reactor, the solution did not change colour; but under the standard reaction conditions with oxygen, the solution were observed in blue colour. The observations indicate the presence of H_2O_2 in the photocatalytic process.

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Semiconductor photoredox catalysis (SPC) offers a simple and environment-friendly access to the construction of C–N bonds. This heterogeneous system provides a green route to the selective C–H amination of arenes with molecular oxygen as the only oxidant.



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