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Mono- and Ditopic Bisfunctionalization of Graphene

Kathrin C. Knirsch⁺, Ricarda A. Schäfer⁺, Frank Hauke, and Andreas Hirsch^{*}

Abstract: For the first time, the bisfunctionalization of graphene by employing two successive reduction and covalent bond forming steps is reported. Bulk functionalization in dispersion and functionalization of individual sheets deposited on surfaces have both been carried out. Whereas in the former case attacks from both sides of the basal plane are possible and can lead to strain-free architectures, in the latter case, retrofunctionalizations can become important when the corresponding anion of the addend is a sufficiently good leaving group.

Multiple covalent functionalization of synthetic carbon allotropes, such as fullerenes, carbon nanotubes, and graphene, with different addends represents an attractive concept for the design and combination of specific chemical, physical, and materials properties. As a consequence, promising practical applications of nanocarbons such as in sensors,^[1] nanocomposites,^[2] and biomedical products^[3] can be targeted. The construction of molecular architectures consisting of a carbon allotrope core and two or more different covalently attached functionalities has so far been realized with fullerenes^[4-10] and carbon nanotubes,^[11-15] whereas examples for mixed graphene derivatives are still elusive. One of the most efficient methods for the functionalization of graphene is the reduction/exfoliation of graphite with alkaline metals in suitable solvents followed by quenching of the intermediately formed graphenides with electrophiles (Scheme 1a). We have recently shown that alkylated,



Scheme 1. a) Reductive functionalization and b) reductive retrofunctionalization of graphene.

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arylated, and hydrogenated graphenes with high degrees of addition on both sides of the basal plane can be prepared in this way.^[16-18] In the case of related reductive functionalizations of carbon nanotubes and fullerenes, we^[19] and others^[20] have demonstrated that such reactions can be reversible. It has not yet been shown, but it is reasonable to assume that related reversible processes such as that depicted in Scheme 1 b can also play a role in graphene chemistry. It is important to keep in mind that: a) covalent addition reactions on fullerenes and carbon nanotubes are monotopic (only exohedral addend binding can take place), whereas addend binding on graphene can be both monotopic (when the sheets are supported on a surface) or ditopic (in dispersion); b) exhaustive homotopic additions will eventually lead to an increase in strain energy (eclipsing addend interactions, deviation from normal bond angles); c) ditopic addition can lead to more stable and less strained geometries, including complete strainfree graphane with an all-chair configuration of the sixmembered carbon rings.^[18,21,22] It is to be expected that the degree of retrofunctionalization (Scheme 1b) represents an interplay between the strain energy of the graphene adduct itself and the stability of the leaving group R⁻. We now present for the first time a) a reaction sequence that allows the successful bisfunctionalization of graphene and b) an investigation of the topicity and leaving group dependence of the retrofunctionalization.

As subsequent addition reactions we chose the treatment of graphenides with diazonium salts^[16] and alkyl iodides.^[17] To investigate the influence of graphene topicity, we carried out the addition to graphenides in dispersion (double-sided bulk functionalization) and to CVD graphenide supported on a Si/SiO₂ surface (single-sided functionalization). For the bulk functionalization, pristine natural graphite **G**_P was exfoliated by wet chemical reduction using Na/K alloy in 1,2-dimethoxyethane (DME). After this activation, the negatively charged graphenide sheets were treated with the first electrophile. After work-up, a second activation with Na/K alloy was initiated followed by the addition of the second electrophile.

For the synthesis of 4-methoxyphenyl-hexyl-graphene G_{AB} we used 4-methoxyphenyldiazonium tetrafluoroborate A as the first and *n*-hexyl iodide B as the second electrophile (Scheme 2).

Thermogravimetric analysis coupled with mass spectrometry (TGA-MS; Figure 1) revealed a mass loss of -20.6%(black curve) in the G_{AB} relative to the starting material (gray curve). The large mass loss correlates with the characteristic fragments of the 4-methoxyphenyl as well as hexyl units detected by mass spectrometry. Signals for m/z 39, 77, 78, 107, and 108 (see Scheme S1) are observed at about 510°C (see Figure S1, top and center). These mass fragments can be assigned to allyl (m/z 39), phenyl (m/z 77, 78), and methoxyphenyl units (m/z 107, 108), which clearly demonstrates the

 ^[*] K. C. Knirsch,^[+] R. A. Schäfer,^[+] Dr. F. Hauke, Prof. Dr. A. Hirsch Department of Chemistry and Pharmacy & Joint Institute of Advanced Materials and Processes (ZMP) Friedrich-Alexander University of Erlangen-Nürnberg Henkestrasse 42, 91054 Erlangen (Germany) E-mail: andreas.hirsch@fau.de

^{[&}lt;sup>+</sup>] These authors contributed equally to this work.

Communications



Scheme 2. Stepwise reductive activation of graphite G_P and G_A with Na/K alloy in DME and subsequent addition of the electrophiles 4-methoxyphenyldiazonium tetrafluoroborate **A** and *n*-hexyl iodide **B** to afford the bisfunctionalized graphene derivative G_{AB} .



Figure 1. TG profile of the 4-methoxyphenyl-hexyl-functionalized reaction product G_{AB} (black) and pristine graphite G_P (gray) along with characteristic mass fragments of G_{AB} which can be assigned to the aryl (*m*/*z* 39) and alkyl groups (*m*/*z* 43).

successful binding of methoxyphenyl addends that were introduced by the corresponding diazonium precursor. The mass fragments m/z 43 (propyl), 57 (butyl), 71 (pentyl), and 85 (hexyl; see Scheme S1) with a maximum intensity at 480 °C (see Figure S1, bottom), on the other hand, prove the alkylation by *n*-hexyl iodide.

We then applied statistical Raman spectroscopy (SRS)^[23] as a very powerful tool to investigate the covalent binding of addends and thus the composition of GAB. To analyze the basal C(sp³) centers formed on covalent binding of the addends, we determined the mean ratio of the intensities of the defect-induced D band and of the graphitic G band (mean $I_{\rm D}/I_{\rm G}$ ratio). This ratio serves as a measure of the degree of functionalization. A mean I_D/I_G ratio of 0.7 (Figure 2a, Table S2) was observed for the first covalent adduct G_A (cf. G_P in Figure S2, Table S2). In the final mixed adduct G_{AB} , the mean $I_{\rm D}/I_{\rm G}$ ratio increased further to 1.4 (Figure 2b, Table S2). At the same time, the statistical distribution of the $I_{\rm D}/I_{\rm G}$ ratio (Figure 2b) is considerably narrowed compared with that of G_A (Figure 2a). We also carried out the same reaction sequence but in the reverse order. For this purpose, graphite G_P was first transferred into alkylated graphene G_B and then arylated to give the mixed adduct G_{BA} (Scheme 3).

A narrowing of the statistical distribution of the I_D/I_G ratio was observed after the second functionalization, which reveals a rather high homogeneity of the samples \mathbf{G}_{AB} and \mathbf{G}_{BA} (Figure 2). The intermediate \mathbf{G}_B displayed a mean I_D/I_G ratio of 1.6 (Figure 2c, Table S2), whereas the final product \mathbf{G}_{BA} exhibited a mean I_D/I_G ratio of 1.3 (Figure 2d, Table S2). In this context, it is important to see that the decreasing mean I_D/I_G ratio on going from \mathbf{G}_B to \mathbf{G}_{BA} is



Figure 2. Left: Raman histograms ($I_{\rm D}/I_{\rm C}$ ratio) of **G**_A, **G**_{AB}, **G**_B, and **G**_{BA}. Right: Averaged spectra of the respective samples, $\lambda_{\rm exc} = 532$ nm.



Scheme 3. Stepwise reductive activation of graphite G_P and G_B with Na/K alloy in DME and subsequent addition of the electrophiles *n*-hexyl iodide **B** and 4-methoxyphenyldiazonium tetrafluoroborate **A** to afford the bisfunctionalized graphene derivative G_{BA} .

accompanied by the simultaneous broadening of the Raman bands. The same behavior is found for G_{AB} .

In fundamental studies, the groups of Lucchese^[24] and Cançado^[25] found a general relationship between the I_D/I_G ratio and the mean defect distance L_D (Figure 3), with a maximum I_D/I_G ratio at a certain L_{D-crit} value. The I_D/I_G ratios can be assigned to regimes either above or below L_{D-crit} . To determine the L_D value under consideration, the width of the Raman bands has to be analyzed.

A broadening of the Raman bands especially in the region between 2200–3300 cm⁻¹ is known to stem from a very high density of defects and a decreased mean defect distance $L_{\rm D}$ in the basal graphene plane (Figures 2 and 3).^[23,25] In our cases, a similar $L_{\rm D}$ value of the final products **G**_{AB} and **G**_{BA} below $L_{\rm D-crit}$ was obtained, irrespective of the reaction sequence order.

These results also show that retrofunctionalization processes such as that depicted in Scheme 1 play a minor role during the entire reaction sequence leading to the mixed



Figure 3. Correlation between the I_D/I_G ratio and the mean defect distance L_D of G_A , G_{AB} , G_B , and G_{BA} , $\lambda_{exc} = 532 \text{ nm.}^{[25]}$

products G_{AB} and G_{BA} . Functionalization is preferred over retrofunctionalization. Clearly, the final products are thermodynamically rather stable, since double-sided attacks can take place. For example, a 1,2-addition to a double bond in graphene taking place from opposite sides (see also Scheme 5 a) leads to an almost strain-free binding of the addends.

In the next step we wanted to analyze the subsequent single-sided additions to graphene. For this purpose, we used CVD graphene deposited on a Si/SiO_2 substrate. The pristine CVD graphene $G_P(CVD)$ on Si/SiO_2 was first reduced with a drop of Na/K-DME solution, and afterwards a drop of the first electrophile in DME was added (Scheme 4). After a washing step with DME, 2-propanol, water, and acetone, the resulting functionalized graphene was activated again and the second electrophile was added.



Scheme 4. a) Stepwise reductive activation of CVD graphene on a Si/SiO_2 substrate **Gp(CVD)** and **G_A(CVD)** with Na/K alloy in DME and subsequent addition of the electrophiles 4-methoxyphenyldiazonium tetrafluoroborate **A** and *n*-hexyl iodide **B** to afford **G_{AB}(CVD)**. b) The reverse addition route leading to **G_{BA}(CVD)**.

SRS showed that pristine CVD graphene $G_P(CVD)$ exhibits a mean I_D/I_G ratio of 0.2, which arises from domain boundaries (see Figures S3–S7, as well as Tables S3 and S4 for further Raman data).^[26] The reduction itself did not lead to a change in the I_D/I_G ratio (Figure S8). After the addition of *n*-hexyl iodide, however, the mean I_D/I_G ratio increased from 0.2 ($G_P(CVD)$) to 0.6 ($G_B(CVD)$; Figure 4c, see also Figure S11 and Tables S3 and S4).

This behavior demonstrated the successful alkylation leading to single-sided $G_B(CVD)$. The subsequent arylation with the corresponding diazonium salt leads to a further



Figure 4. Left: Raman histograms (I_D/I_G ratio) of $G_A(CVD)$, $G_{AB}(CVD)$, $G_B(CVD)$, and $G_{BA}(CVD)$ on a Si/SiO₂ substrate. Right: Exemplary point spectra of the respective samples, $\lambda_{exc} = 532$ nm (*: Si/SiO₂ substrate).

increase in the mean I_D/I_G ratio to 0.9 ($\mathbf{G}_{BA}(\mathbf{CVD})$; Figure 4d, see also Figure S12 and Tables S3 and S4). Of course, the single-sided bisfunctionalization also takes place (Scheme 4). To investigate whether the bisfunctionalization can also be accomplished in the reverse order, we first allowed the diazonium salt to react with the CVD graphenide $\mathbf{G}_P(\mathbf{CVD})$. The intermediately formed $\mathbf{G}_A(\mathbf{CVD})$ exhibited a I_D/I_G ratio of 1.0 (Figure 4a, see also Figure S9 and Tables S3 and S4). Significantly, after carrying out the second treatment (reductive activation, addition of the *n*-hexyl iodide), we observed a decrease in the mean I_D/I_G ratio to 0.3 (Figure 4b, see also Figure S10 and Tables S3 and S4), a value that is very close to that of unfunctionalized $\mathbf{G}_P(\mathbf{CVD})$.

Clearly, in this case the retroreaction depicted in Scheme 4a is the predominant process. The difference between the two reaction sequences displayed in Scheme 4 can be explained by the fact that the aryl anion is the better leaving group compared with the alkyl anion. On the other hand, the difference between the double-sided bulk functionalization (Schemes 2 and 3) and the single-sided functionalization (Scheme 4) is due to the fact that strain-free addition geometries can be adopted in the former case, whereas in the latter case the increasing degree of addition leads to a decreased thermodynamic stability of the adducts (Scheme 5). This eventually leads, when sufficiently good leaving groups can be generated, to retroreactions being preferred. As pointed out above, exactly the same retroreactions have previously been observed with fullerenes and carbon nanotubes, where only monotopic, exohedral binding of addends can take place.^[19,20]





Scheme 5. Addition patterns of a) double-sided functionalized graphene (*trans*-1,2-addition) and b) single-sided functionalized graphene (*cis*-1,4-addition). Structure (a) is more stable than (b) due to the possibility of avoiding eclipsing 1,2-interactions and unfavorable bond angles. c) Equilibrium between retrofunctionalization and multiple functionalization.

In conclusion, we have accomplished for the first time, a bisfunctionalization of graphene by employing two successive reduction and covalent bond forming steps. Both bulk functionalization in dispersion and functionalization of individual sheets deposited on surfaces have been carried out. Whereas in the former case attacks from both sides of the basal plane are possible and can lead to strain-free architectures, in the latter case only monotopic attacks can be accomplished. As a consequence, a) strain energy arising from eclipsing addend interactions and unfavorable geometries is increasingly built up and b) the reduction-induced retrofunctionalization reaction can become important when the corresponding anion of the addend is a sufficiently good leaving group. These fundamental reactivity studies on the chemistry of graphene will play an important role for the design of highly integrated graphene architectures with complex and tunable functionalities.

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- [1] Y. Shao, J. Wang, H. Wu, J. Liu, I. A. Aksay, Y. Lin, *Electro-analysis* 2010, 22, 1027–1036.
- [2] H. Kim, A. A. Abdala, C. W. Macosko, *Macromolecules* 2010, 43, 6515-6530.
- [3] M. Prato, K. Kostarelos, A. Bianco, Acc. Chem. Res. 2008, 41, 60-68.
- [4] J. Iehl, J.-F. Nierengarten, Chem. Commun. 2010, 46, 4160-4162.
- [5] F. Hörmann, W. Donaubauer, F. Hampel, A. Hirsch, *Chem. Eur. J.* 2012, *18*, 3329–3337.
- [6] F. Hörmann, M. Brettreich, W. Donaubauer, F. Hampel, A. Hirsch, Chem. Eur. J. 2013, 19, 2814–2825.
- [7] F. Hörmann, A. Hirsch, Chem. Eur. J. 2013, 19, 3188-3197.
- [8] A. Gmehling, A. Hirsch, *Eur. J. Org. Chem.* 2013, 5093-5105.
 [9] A. Hirsch, M. Brettreich, *Fullerenes: Chemistry and Reactions*,
- VCH, Weinheim, 2004.
 [10] J. López-Andarias, A. Bolag, C. Nancoz, E. Vauthey, C. Atienza, N. Sakai, N. Martin, S. Matile, *Chem. Commun.* 2015, *51*, 7543– 7545.
- [11] F. G. Brunetti, M. A. Herrero, J. de M. Muñoz, A. Díaz-Ortiz, J. Alfonsi, M. Meneghetti, M. Prato, E. Vázquez, J. Am. Chem. Soc. 2008, 130, 8094–8100.
- [12] Z. Zhao, Z. Yang, Y. Hu, J. Li, X. Fan, Appl. Surf. Sci. 2013, 276, 476–481.
- [13] F. Hof, S. Bosch, S. Eigler, F. Hauke, A. Hirsch, J. Am. Chem. Soc. 2013, 135, 18385–18395.
- [14] F. Hof, R. A. Schäfer, C. Weiss, F. Hauke, A. Hirsch, Chem. Eur. J. 2014, 20, 16644–16651.
- [15] L. Rodríguez-Pérez, R. García, M. A. Herranz, N. Martín, *Chem. Eur. J.* 2014, 20, 7278–7286.
- [16] J. M. Englert, C. Dotzer, G. Yang, M. Schmid, C. Papp, J. M. Gottfried, H.-P. Steinrück, E. Spiecker, F. Hauke, A. Hirsch, *Nat. Chem.* 2011, *3*, 279–286.
- [17] J. M. Englert, K. C. Knirsch, C. Dotzer, B. Butz, F. Hauke, E. Spiecker, A. Hirsch, *Chem. Commun.* 2012, 48, 5025-5027.
- [18] R. A. Schäfer, J. M. Englert, P. Wehrfritz, W. Bauer, F. Hauke, T. Seyller, A. Hirsch, Angew. Chem. Int. Ed. 2013, 52, 754–757; Angew. Chem. 2013, 125, 782–786.
- [19] Z. Syrgiannis, B. Gebhardt, C. Dotzer, F. Hauke, R. Graupner, A. Hirsch, Angew. Chem. Int. Ed. 2010, 49, 3322–3325; Angew. Chem. 2010, 122, 3394–3397.
- [20] a) R. Kessinger, J. Crassous, A. Herrmann, M. Rüttimann, L. Echegoyen, F. Diederich, *Angew. Chem. Int. Ed.* **1998**, *37*, 1919–1922; *Angew. Chem.* **1998**, *110*, 2022–2025; b) N. N. P. Moonen, C. Thilgen, L. Echegoyen, F. Diederich, *Chem. Commun.* **2000**, 335–336.
- S. Eigler, A. Hirsch, Angew. Chem. Int. Ed. 2014, 53, 7720-7738; Angew. Chem. 2014, 126, 7852-7872.
- [22] J. O. Sofo, A. S. Chaudhari, G. D. Barber, *Phys. Rev. B* 2007, 75, 153401.
- [23] J. M. Englert, P. Vecera, K. C. Knirsch, R. A. Schäfer, F. Hauke, A. Hirsch, ACS Nano 2013, 7, 5472–5482.
- [24] M. M. Lucchese, F. Stavale, E. H. Martins Ferreira, C. Vilani, M. V. O. Moutinho, R. B. Capaz, C. A. Achete, A. Jorio, *Carbon* 2010, 48, 1592–1597.
- [25] L. G. Cançado, A. Jorio, E. H. M. Ferreira, F. Stavale, C. A. Achete, R. B. Capaz, M. V. O. Moutinho, A. Lombardo, T. Kulmala, A. C. Ferrari, *Nano Lett.* **2011**, *11*, 3190–3196.
- [26] N. Hosoya, Y. Akaho, M. Inoue, S. Sahoo, M. Tachibana, *Appl. Phys. Lett.* **2014**, *105*, 023108.

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